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Bottom-up Representation of Industrial Energy Efficiency Technologies in Integrated Assessment Models for the U.S. Pulp and Paper Sector

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General Acronyms

Greenhouse gas (GHG)
Carbon dioxide (CO2)
Energy-climate (EC) models
Integrated assessment models (IAM)
Cost of conserved energy (CCE)
Cost of carbon reduction (CCR), or Cost of reduced carbon (CRC)
Conservation supply curve (CSC)
Computational general equilibrium model (CGE)
Operation and maintenance (O&M)
Gross Domestic Product (GDP)
Environmental Protection Agency (EPA)
Bureau of Economic Analysis (BEA).
International Energy Agency (IEA)
United States Geological Survey (USGS)
Department of Energy (DOE)
Department of State (DOS)
Energy Information Administration (EIA)
Manufacturing Energy Consumption Survey (MECS)
Model Acronyms
ADAGE - Applied Dynamic Analysis of the Global Economy Model
AIM- The Asian-Pacific Integrated Model
AMIGA - All-Modular Industry Growth Assessment Model
BEAR - Berkeley Energy and Resources
COBRA - Cost-Optimized Burden-Sharing and Regional emission Allocation
MARKAL - MARKet ALlocation
MESSAGE - Model for Energy Supply Strategy Alternatives and their General Environmental
  Impact

Units

Energy (in petajoules -PJ, or in gigajoules - GJ)
Cost of conserved energy (CCE, $/GJ)
Energy savings per production (GJ/Tonne)
Million metric ton, or million tonne (Mt)
Million tonne of carbon (MtC)
Cost of carbon reduction (CCR, $/MtC)
Capital cost ($)
Capital recovery factor (yr-1)
Annual change in O&M costs ($/yr)
Annual total of productivity benefits ($/yr)
Annual energy savings (GJ/yr)
Lifetime of the mitigation option (years)
Annual carbon savings (tC/yr)

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Executive Summary

Adoption of efficient end-use technologies is one of the key measures for reducing greenhouse gas (GHG) emissions. How to effectively analyze and manage the costs associated with GHG reductions becomes extremely important for the industry and policy makers around the world.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions for various emission-reduction measures, because an accurate estimation of these costs is critical for identifying and choosing optimal emission reduction measures, and for developing related policy options to accelerate market adoption and technology implementation. However, accuracies of assessing GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment models (IAM) and other energy-climate models.

In this report, we first conduct a brief review of different representations of end-use technologies (mitigation measures) in various energy-climate models, followed by the problem statement, and a description of the basic concepts of quantifying the cost of conserved energy including integrating no-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i. e. , via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price, without considering benefits of avoided climate change. For example, a measure is considered cost effective when its time-discounted cost savings over the lifetime of the technology are greater than the investment cost. There are two types of treatments of no-regrets options: 1) options that include other non-energy benefits, e. g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other non-energy benefits. Various cost-effective measures in the U.S. pulp and paper sector were identified and studied in this report, regardless whether or not other benefits are included. There are many factors including market barriers and knowledge gap that contribute to slower adoption of such measures in the markets.

Based upon reviews of literature and technologies, we develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in integrated assessment models. In addition to descriptions of the pulp and paper making processes, and the mitigation measures identified in this study, the report includes tabulated databases on costs of measure implementation, energy savings, carbon-emission reduction, and lifetimes.

Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy and carbon reduction cost curves for energy efficiency measures applicable to the U.S. pulp and paper industry for the years 1994 and 2006. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity,

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production, feedstock source (e. g. , wood pulp versus waste paper recycle), efficiency measures, share of product or production to which the individual measures can be applied, and inclusion of other benefits. Costs of conserved energy (CCE) for individual mitigation measures increase with the increases in discount rates, resulting in a general increase in total costs of mitigation measures for implementation and operation. In this study, the cost data (U.S. dollars) are obtained in the currency values for the respective reference years (i. e., 1994, or 2006). A direct comparison of costs, when desired, is made by converting the existing reference-year data (e. g., 1994) to a preferred reference year (i. e., 2006). The conversions can be accomplished by multiplying the existing cost in a reference year by a Gross Domestic Product (GDP)-based inflation index for the preferred year (BEA 2011).

In this study, we included 41 mitigation measures for year 1994 and 101 mitigation measures for year 2006 in the analysis based upon data availability for each year, respectively. We also estimated potential energy savings and carbon-emission reduction corresponding to the mitigation measures for each year (1994 and 2006), respectively. In addition, we have developed and defined the concept for cost of carbon reduction (CCR) associated with the mitigation measures; therefore, the cost of carbon reduction for each mitigation measure can be established and estimated based upon available information. Main findings are included in the following.

In 1994, pulp and paper plants in the U.S. produced 97 million tonnes (Mt) pulp and 81Mt paper and paperboard (FAO 2011). Primary energy use for pulp and paper mills was approximately 2,779 petajoules (PJ); the total carbon emissions related to energy use in pulp and paper production were estimated as 31.6 million tonnes of carbon (MtC) in 1994 (Martin et al.2000; Jacobs and IPST, 2006). In 2006 pulp and paper plants in the U.S. produced 100 Mt pulp and 84 Mt paper and paperboard (FAO 2011). Primary energy use for pulp and paper mills making was approximately 2,484 PJ (EIA 2009), with the total carbon emissions related to energy use from pulp and paper making estimated as 25.9 MtC in 2006.

Based upon the information compiled from recent development of Energy Star Guide (Kramer et al.2010), the project team has identified a number of efficiency measures applied in this industry and performed additional technology reviews, interviews, and data compilation. Built upon the best available information and additional data gathered for this study, year 2006 was selected for the purpose of analysis and comparison with that of 1994.

From 1994 to 2006 the primary energy intensity of US paper production changed from 16.1 to 14.5 GJ/t (a reduction of 10%) indicating some change in efficiency technology uptakes. During the same period of time, the pulp production energy intensity decreased from 13.6 to 10.9 GJ/t (a reduction of 20%). This reduction benefited from technology uptake as well as increased waste paper recycling replacing wood pulp making. Waste paper pulp accounted for 46% in 2006 compared to 32% in 1994. Overall, from 1994 to 2006 the primary collective energy intensity of pulp and paper production has decreased from 34.3 GJ/t to 29.5GJ/t (a reduction of 14%), indicating the collective effect from efficiency technology uptakes and structure change in the U.S. pulp and paper production over the period of time.

We evaluated final energy use in the U.S. pulp and paper sector, and estimated that 2,218 petajoules (PJ) final energy was used in 1994, and 1,702 PJ final energy was used in 2006. The potential savings of final energy use from applying 41 measures was 707 PJ in 1994, while the potential savings of final energy use resulting from applying 101mitigations measures was 1,064

PJ in 2006. Therefore, the technical potential of energy savings was approximately 32% in 1994 and 62% in 2006. We have found that for each year, top ten technologies alone may contribute to approximately 70-75% of potential energy savings applicable to the U.S. pulp and paper industry.

We also identified a number of cost-effective mitigation measures for 1994 and 2006 in this study. We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 339 PJ in 1994 and 434 PJ in 2006, corresponding to 15% and 25% of total annual final energy use in the U.S. pulp and paper industry in 1994 and 2006, respectively. Implementing cost effective measures can result in significant energy savings relative to the total annual energy use in the sector.

In addition, we estimated overall potentials in carbon-emission reductions due to mitigation measures for both years (1994 and 2006), respectively. The potential reduction of carbon emissions resulting from applicable mitigations measures was estimated as 8.1 MtC in 1994 and 11.8 MtC in 2006, corresponding to 26% and 45% of total annual energy-related carbon emissions in 1994 and 2006, respectively. Applying cost-effective measures would reduce carbon emissions by 4.6 MtC in 1994, and 5.1 MtC in 2006, corresponding to 14% and 20% of annual energy-related carbon emissions in 1994 and 2006, respectively. It is clear that implementing cost effective measures can result in significant carbon-emission reduction relative to the total carbon emissions in the sector.

The development of concepts and information on costs of conserved energy and carbon reduction for the U.S. pulp and paper sector provides a better understanding of costs and carbon impact of energy efficiency measures in this industrial sector. When we consider operation and maintenance cost reduction of mitigation measures, many of them are found to be cost effective or negative cost from its life cycle cost perspective. In addition, while many energy efficiency technologies would become cost-effective to mitigate long-term climate change, it is important and necessary to incorporate new information on technology characteristics, their evolution and response to energy and carbon prices, which can be utilized by integrated assessment modelers who are seeking to enhance their empirical descriptions of technologies.

We have also concluded that based upon the cost curves derived from available information on mitigation measures for both years, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and considered in energy-climate models. Implementing existing cost effective measures can result in significant energy savings and carbon-emission reduction for both years relative to their technical potential in energy savings and carbon-emission reduction. In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide useful information on technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies.

Future efforts should also include additional business sectors such as commercial and residential buildings. This is particularly true in that the building sector appears to be the most significant sector in terms of its collective savings potential in mitigation options compared to any single industrial sector or combined. Additionally, this is also necessary (within the U.S. context as well as in the global context) if comprehensive carbon policies such as carbon offset are to be addressed.

1 Background

Pulp and paper processing converts fibrous materials, such as wood, non-wood and recycled paper, into pulp, paper and paperboard. According to the International Energy Agency (IEA 2007), over one-third of the world's energy consumption and 36% of carbon dioxide (CO_2) emissions are attributable to manufacturing industries worldwide. The large primary materials industries – paper and pulp, chemical, petrochemicals, iron and steel, cement, and other minerals and metals – account for more than two-thirds of these emissions. The pulp and paper sector generates about half of its own energy needs from biomass residues and makes extensive use of combined heat and power (CHP).

The U.S. pulp and paper industry is comprised of three primary types of producers: (1) pulp mills, which manufacture pulp from wood and other materials (such as wastepaper); (2) paper mills, which manufacture paper from wood pulp and other fiber pulp; and (3) paperboard mills, which manufacture paperboard products from wood pulp and other fiber pulp. In this report, we refer paper products from paper mills and paperboard mills collectively as "paper." In 1994 pulp and paper plants in the U.S. produced 97 Mt pulp and 81Mt paper (FAO 2011). In 2006 pulp and paper plants in the U.S. produced 100 Mt pulp and 84 Mt paper (FAO 2011).

Energy use in the pulp and paper industry is intensive and constitutes a significant portion of the pulp and paper production costs. Overall, the pulp, paper and printing industry accounts for about 5.7% of global industrial final energy use, of which printing is a very small share. In 1994 the primary energy use in the U.S. paper industry was approximately 2,779 PJ (Martin et al. 2000; Jacobs and IPST, 2006). In 2006 the primary energy use in the U.S. paper industry was approximately 2,484 PJ (or 2,354 trillion BTUs, EIA 2009). In addition, the pulp and paper industry accounts for a significant portion of carbon dioxide (CO_2) emissions worldwide.

The most important process steps to produce paper (including paperboard) are pulp making, bleaching, (chemical) recovery, pulp drying and paper making. Several processes exist to produce pulp: chemical, semi-chemical, mechanical and waste paper pulp making. Producing pulp is one of the most energy consuming processes in the paper and paper board supply chain. Figure 1illustrates a schematic overview of the pulp and papermaking process. More details of the pulp and paper making processes are included in the Appendix section.
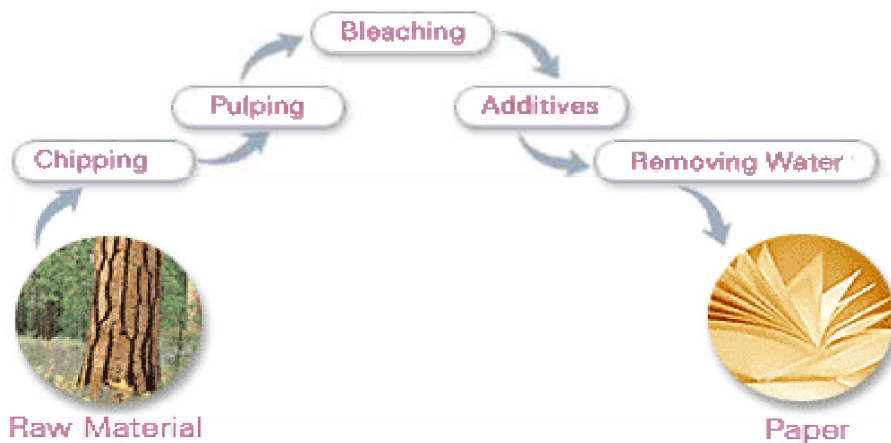
Figure 1Schematic overview of the pulp and paper making process

2 Introduction

Adoption of efficient end-use technologies is one of the key measures for reducing GHG emissions. In many cases, implementing energy efficiency measures is among the most cost effective investments that the industry could make in improving efficiency and productivity while reducing CO_2 emissions. With energy and carbon policies being considered or implemented in many parts of the world, effectively analyzing and managing the costs associated with GHG reductions becomes extremely important for industry and policy makers.

Energy-climate (EC) models are often used for analyzing the costs of reducing GHG emissions (e. g. , CO_2 emission) for various emission-reduction measures, because an accurate estimation of these costs is critical for identifying and choosing optimal emission reduction measures, and for developing related policy options to accelerate market adoption and technology implementation. However, accuracies of assessing GHG-emission reduction costs by taking into account the adoption of energy efficiency technologies will depend on how well these end-use technologies are represented in integrated assessment (IA) models and other energy-climate models. For example, if the models do not include end-use technologies with an appropriate level of detail in their modeling framework, it will be difficult to estimate, with confidence, the costs and benefits of reducing GHG emissions by adopting efficient end-use technologies.

In this report, we will first conduct a brief review of different representation of end-use technologies in various energy-climate models; then we will elaborate the statement of the problems upon which the purpose of this study will be defined. The report will then describe the basic concepts of quantifying the cost of conserved energy and carbon reduction including integrating non-regrets options. According to IPCC (2001), no-regrets opportunities for GHG emissions reduction are the options whose benefits such as reduced energy costs and reduced emissions of local or regional pollutants equal or exceed their costs to society, excluding the benefits of avoided climate change. In this report, a no-regrets option is defined as a GHG reduction option (i.e., via energy efficiency measure) that is cost effective over the lifetime of the technology compared with a given energy price and discount rate, without considering benefits of avoided climate change. There are two types of treatments of no-regrets options: 1) options that include other non-energy benefits, e.g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other non-energy benefits. Various sets of cost effective measures were identified, regardless whether or not other non-energy benefits are included. There are many factors, including market barriers and knowledge gap, which contribute to slower adoption of such measures in the markets.

We will develop information on costs of mitigation measures and technological change. These serve as the basis for collating the data on energy savings and costs for their future use in integrated assessment models. The concept description is then followed by a section on developing energy efficiency cost curves for the pulp and paper industry in the U.S. The cost curve data on mitigation measures are available over time, which allows an estimation of technological change over a decade-long historical period. In particular, the report will develop information to address technological change in energy-climate modeling, e. g., assessing the changes in costs and savings potentials between two or more historical conservation supply curves.

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The last section summarizes the conclusions and recommendations for future work. In addition, the report includes tabulated databases on costs of implementation, energy savings, carbon-emission reduction, and lifetimes as exhibited in Appendix A (1994) and Appendix B (2006). Finally, Appendix C and Appendix D of this report include descriptions of pulp and paper making processes, and the mitigation measures included in the study.

2.1 Representation of End-use Technologies in Existing Energy-climate Models

Many existing integrated assessment models originally emerged primarily from economic and energy modeling approaches that were for the most part developed for, and applied to, industrialized economies (Sanstad and Greening 1998). Increasingly, however, these models have been enhanced and extended over time, and in many cases created, to encompass the global economy at various levels of regional and sectoral disaggregation.

Factoring technological changes in both energy supply and end-use technologies may significantly affect the outcomes of estimated GHG emissions associated with energy systems in such energy-climate models. A majority of energy-climate models can handle, to various extents, the input of technological changes. In exogenous modeling of technological change, the rate of technological changes (improvement) is specified exogenously by the modelers, not the model itself. In endogenous modeling of technological change, various approaches exist, such as modeling technological changes via "learning by doing." In this case, the costs of new technologies decline overtime and their technical characteristics improve with increased market adoption. Rates of efficiency improvement and cost reduction as a function of market adoption (e. g., cumulative installed capacity) are included as input to the model. Both exogenous and endogenous modeling of technological changes can benefit from historical data. In this study, we focus particularly on two issues related to the representation of end-use technologies in energy climate models: treatment of technological change, and treatment of no-regrets options. There are two types of treatments of no-regrets options: 1) options that include other non-energy benefits, e. g., reduced operational and maintenance costs and productivity benefits; and 2) options that exclude other energy benefits.

To improve the representation of end-use technologies in energy-climate models, it is necessary to understand how end-use technologies are represented in common models. Table 1 summarizes a review of how end-use technologies are represented in seven energy-climate models reviewed in this study. End-use technologies are represented in five of the seven models. Four out of the seven models explicitly take both no-regrets options and technological change in end-use technologies into consideration.

Pending the availability of information, or body of knowledge about what is known (or even knowable), modelers commonly made one choice over another when establishing input assumptions, and methodologies for their desired models. In all of the selected models reviewed in this study, except for the MARKet ALlocation (MARKAL) model (BNL 2001), the technological change is considered in an exogenous manner. Among the six models with exogenous treatment of technological changes, only four of them include end-use technology representation, as well as concurrent no-regrets options. In addition, the levels of detail in handling technological change and no-regrets options also vary across the models. For example, in All-Modular Industry Growth Assessment (AMIGA) modeling, end-use technologies in residential and commercial sectors and some industries are represented to date (Hanson 1999).

End-use technologies are represented in Berkeley Energy and Resources (BEAR) modeling (Roland-Holst 2008). Energy savings due to overall improvements in end-use energy efficiency are represented for different sectors. However, specific technologies associated with these savings are not identified. In Cost-Optimized Burden-Sharing and Regional emission Allocation (COBRA) modeling, end-use technologies and no-regrets treatment are considered for some key energy consuming industries (Sathaye and Wagner 2006). However, the cost of policies and programs to promote no-regrets options are not included.

Table 1. A review on different representation of end-use technologies in common energy-climate models

Model	Representation of End-Use Technologies	Treatment of No-regrets Options	Technological Change Treatment in the Model	Treatment of Technological Change at End-Use Level
ADAGE - Applied Dynamic Analysis of the Global Economy, by Research Triangle Institute (Ross 2008)	No	No	Exogenous	No
AIM - The Asian-Pacific Integrated Model, by a collaborative international team led by Japan's National Institute for Environmental Studies (NIES 1997)	Yes	Yes	Exogenous	Yes
AMIGA -All-Modular Industry Growth Assessment, by Argonne National Laboratory (ANL)	Some	Yes	Exogenous	Yes
BEAR - Berkeley Energy and Resources, by UC Berkeley	Some	Yes	Exogenous	Yes
COBRA - -Optimized Burden-Sharing and Regional emission Allocation, by Lawrence Berkeley National Laboratory	Some	Yes	Exogenous	Yes
MARKAL - MARKet Allocation, by Brookhaven National Laboratory	Some	No	Endogenous	Yes, exogenous.
MESSAGE Model for Energy Supply Strategy Alternatives and their General Environmental Impact, by Austria's International Institute for Applied Systems Analysis (IIASA)	No	No	Exogenous	No

Note: CGE models are included in many IAMs, except AMIGA, COBRA, MARKAL, or MESSAGE.

Apparently, there are opportunities to improve technology representation in the selected models and many others, which can provide more accurate estimation of the costs of reducing GHG emissions due to technological changes and associated benefits.

2.2   Statement of Problem

Information on costs and saving potentials of energy efficiency measures and ways that these end-use technologies are represented in energy-climate models vary greatly from model to model. Many energy-climate models are not created to represent technology-specific costs, energy savings or GHG-emission reductions; instead, they are often restricted to evaluation of carbon prices or cap-and-trade programs without adequate consideration of issues on mitigation technologies. The difference in cost estimates can be attributed to various assumptions in economic growth, resource endowment, selection of policy instrument, treatments of no-regrets options (e. g. , including or excluding various benefits), and cost and availability of supply- or demand-side technologies.

It is important to integrate end-use technologies in large bottom-up energy-climate models. The extent of including representation of such technologies in large energy-climate models varies greatly: e. g., some without technological representation, some with representation being limited to certain sectors such as electric power generation, or some others with detailed end-use technological representation. Therefore, a major challenge is to determine the appropriate interfaces for the use of bottom-up technology or sector-specific data in energy-climate models.

Often many IA models ignore policy and programmatic costs of measure implementation; on the other hand, other non-energy benefits are also often not included or accounted for in model input. Therefore, such modeling is often inadequate to accurately estimate the real costs of reducing GHG emissions. For example, exclusion of other benefits (as one way of treating no-regret options) in models is largely because modelers either lack sufficient data or because their current model structure is not suitable for representing these options. As a result, the way in which most of these models are calibrated tends to force a prediction of positive mitigation costs. In addition, although some models that represent end-use technologies model technological change over time, none of them represents technological change in end-use technologies endogenously. This approach has limited their ability to analyze the effect of policies that promote early adoption of efficient end-use technologies to reduce their future costs.

Integrated assessment modeling of climate policy commonly uses various top-down models that describe the general economy and its interactions, and the effects of price changes. Many of these models include a sectoral representation of the economy. The existing empirical basis for modeling of sector-based technologies is often weak, and often largely arises from literature at the sectoral level rather than technology level. There is a need to investigate and improve the representation of end-use technologies in energy-climate models, in coordination with energy-climate modelers who will stand to benefit from this research.

Given the growing importance of technological improvement (e. g., energy efficiency) as an avenue to mitigate climate change, it is critical that technology characteristics, their evolution, and their response to energy and carbon price be understood better than has been the case to date. This is also particularly true of developing countries where obsolete technologies are likely to see a more rapid transformation as their markets integrate into the global economy, while newer

technologies are likely to be adopted faster due to evolving global markets and availed policy instrument or support.

2.3 Project Purpose

The overarching goal of this research is to characterize technology costs and potentials for improvement in energy efficiency in the U.S. pulp and paper sectors. The purpose of this project is to develop a technology database and modules that will be accessible to IAM groups seeking to enhance their empirical descriptions of technologies for modeling the pulp and paper sector.

In this report, we will describe concepts of cost of conserved energy (CCE) and cost of carbon reduction (CCR), and develop and present the cost curves of mitigation options based upon available historical data, with a focus on the U.S. pulp and paper sector. Effect of technological change on savings potential will be analyzed, which may become useful input for estimating future savings potential in energy-climate models.

3 Concepts for Cost Curves of Conserved Energy and Carbon Reduction

3.1 Cost of Conserved Energy Curves – with and without Other Benefits

Conservation Supply Curves (CSCs) were developed in the 1970s as a way to rank energy conservation investment along with energy supply investment in order to identify the least cost approach. CSCs can be used to show how much energy-conservation would be supplied corresponding to a specific energy price, and have long been a primary analytical tool for evaluating the economic benefits of energy efficiency. These have been constructed for the major energy demand sectors, and the energy savings have been translated into corresponding GHG emissions reductions in many countries.

A CSC plots the marginal cost of conserved energy by a mitigation option (mitigation capital cost) against the total amount of energy conserved. Equation 1 shows the parameters used in estimating the marginal cost of conserved energy (CCE) (Meier 1984). By calculating and ranking CCE value for each efficiency measure, a CSC curve can be developed by plotting the ranked CCE values consecutively on the y-axis against cumulative energy savings along the x-axis.

$$CCE = \frac{I \cdot q}{\Delta E} \quad \text{Equation 1}$$

$$q = \frac{d}{(1 - (1+d)^{-n})}, \text{Equation 2}$$

Where:

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ

I = Capital cost of mitigation option (\$)

q = Capital recovery factor (yr^{-1})

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ΔE = Annual energy savings (GJ/yr)

d = Discount rate

n = Lifetime of the mitigation option (years)

Earlier analyses of energy efficiency options typically ignored other effects of their implementation. Modification of Equation 1 to Equation 3 includes other benefits: These effects include non-energy cost changes in operation and maintenance (O&M), which may lead to a negative "M" value; as well as reduced capital cost, which may correspond to a lowered "I" value in the equation. In addition, the other effects can also include additional monetizable productivity benefits, noted as "B" in Equation 3.

The contributing factors to productivity benefits include changes in labor, material, and other resource requirements that are often monetizable, and other benefits such as reduced pollution due to decreased use of electricity and other fuels that may be more difficult to quantify, and in particular more difficult to attribute to a single mitigation measure (e. g., as shown in Table 2). In principle, adding monetizable non-energy effects that are attributable to an energy efficiency option can decrease the cost of conserved energy. These may be expressed as shown in Equation 3.

$$CCE = \frac{I \cdot q + (M - B)}{\Delta E}$$ Equation 3

Where

CCE = Cost of conserved energy for an energy-efficiency measure (or mitigation option), in \$/GJ

I = Capital cost of mitigation option (\$)

q = Capital recovery factor (yr^{-1})

M = Annual change in non-energy O&M costs (\$/yr)

B = Annual total of productivity benefits - additional non-energy cost benefits(\$/yr)

ΔE = Annual energy savings (GJ/yr)

Accounting for such "hidden benefits" requires that bottom-up models look beyond the energy markets and examine the cost considerations in light of their impact on other resource markets.

When including other non-energy benefits, ranking orders of the CCE values for efficiency measure can change significantly. Because information on productivity benefits (i.e., "B" in Equation 3) of mitigations measures selected is unavailable in this study, we will assume B value equals to zero. For including other benefits, we will consider only non-energy O&M cost changes in the cost curve development for the U.S. pulp and paper sector in this study.

3.2 Calculation of cost of carbon reduction related to energy savings

Adopting energy efficiency options can reduce carbon emissions associated with energy use in the industry. In this study, we define cost of carbon reduction (CCR) associated with mitigation measures in the pulp and paper sector, which has included the other benefits monetized for the changes in operation and maintenance. The cost of energy-related carbon reductions is treated to be the same as the cost of mitigation measures, which will then be normalized by the quantity of carbon reduction corresponding to each mitigation measure.

Mitigation cost of carbon reduction (CCR) for a mitigation measure may be expressed in Equation 4.

$$CCR = \frac{I \cdot q + (M - B)}{\Delta C}, \text{ Equation 4}$$

Where:

CCR = Cost of carbon reduction for an energy-efficiency measure (or mitigation option), in \$/tC (carbon tonne)

I = Capital cost of mitigation option (\$)

q = Capital recovery factor (yr^{-1}), determined by discount rate and lifetime of mitigation option, see Equation (2)

M = Annual change in monetizable non-energy cost from O&M changes (\$/yr)

B = Annual additional non-energy cost benefits (\$/yr)

ΔC= Annual carbon reduction (tC/yr)

Because information on productivity benefits of mitigations measures selected is not available, "B" will not be included (i.e., B=0). Therefore, for including other benefits, - we will consider only non-energy O&M cost changes in the cost curve development for the U.S. pulp and paper sector in this study.

4   Treatment of Technological Change in Climate Modeling

An important issue related to the representation of both supply and end-use technologies is how the technological change that results in mitigation improvement is taken into account in energy-climate modeling. Assumptions about technological change may include determination of efficiency levels of energy supply and end-use technologies into the near future. Therefore, the treatment of technological change is an important factor that will influence the mitigation costs and reductions in future emissions in energy-climate models. As discussed earlier, there are two common methods of including technological change in energy-climate models: exogenous modeling and endogenous modeling.

In some modeling, the rate of improvement in technology is specified exogenously by the modelers and is not determined or simulated within so-called exogenous model.

In other modeling, various approaches are implemented to model technological change endogenously . For example, one of the popular approaches is to model technological change as

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learning-by-doing where the costs of technologies decline and their technical characteristics improve with increased adoption of technologies. In this case, the external input to the model includes learning rates that specify the relationship between improvements in technology characteristics (primarily technology cost and efficiency) and the technology's cumulative installed capacity.

Overall, the input parameters required for modeling technological change in exogenous or endogenous models can be based upon estimates from analyzing historical trends. For example, Nakicenovic et al. (2000) have published curves showing the decline in costs of electricity-supply technologies over time. These time trends are typically used for exogenously specifying technological change. Sathaye and Wagner (2006) developed a simplified global energy supply and carbon cycle model, the Cost-Optimized Burden-Sharing and Regional Emission Allocation in the energy sector (COBRA-Energy). It is driven by exogenous energy demand projections and implements a scheme for international burden sharing for the 21st century, which takes into account the regional amounts of cumulative, anthropogenic emissions. Other studies estimated learning rates (Manne and Barreto 2002) and used them in endogenous modeling of technological change.

To date, there has been limited representation of demand-side technological change in the energy-climate models reviewed in this report, in part because of a lack of such information. In this study, we used the same approach developed for treating technological change in energy-climate modeling (Xu et al. 2010, Sathaye et al. 2010). This approach is based on quantifying changes in costs and savings potentials between two or more historical conservation supply curves. With this approach, cost curves of mitigation technologies are first developed for two historic periods, respectively; followed by calculating the rate of change of the savings potential at a given cost, which can be considered in energy-climate models.

5 Development of Cost Curves and Estimate of Technological Changes for the Pulp and Paper Sector

The energy efficiency of an operating pulp and paper plant is significantly affected by several elements, such as type of products, technologies, plant size, and quality of raw materials.

In 1994, pulp mills produced 97.0 Mt pulps (32% from waste paper recycling) and paper mills produced 81.0 Mt paper in the United States (FAO 2011). In 2006, pulp mills produced 100.3 Mt pulps (46% from waste paper recycling) and paper mills produced 84.3 Mt paper (FAO 2011). Table 2 shows the summary of production, estimated energy use, and associated carbon emissions in the U.S. pulp and paper sector for 1994 and 2006

The primary energy intensity of U.S. paper production changed from 16.1 to 14.5 GJ/t (a reduction of 10%) indicating some change in efficiency technology uptakes. During the same period of time, the pulp production energy intensity decreased from 13.6 to 10.9 GJ/t (a reduction of 20%). This reduction benefited from technology uptake as well as increased waste paper recycling replacing wood pulp making. In fact, waste paper pulp accounted for 46% in 2006 compared to 32% in 1994. Overall, from 1994 to 2006 the primary collective energy intensity of pulp and paper production has decreased from 34.3 GJ/t to 29.5GJ/t (a reduction of 14%), indicating the collective effect from efficiency technology uptakes and structure change in the U.S. pulp and paper production over the period of time.

The total carbon emissions associated with energy use in pulp and paper making were estimated as 31.6 MtC in 1994, and 25.9 MtC in 2006, indicating a reduction in total carbon emission intensity by 21% (390 kgC/t vs.307 kgC/t).

Table 2. Primary energy, associated carbon emissions, and production in 1994 and 2006.

		Pulp (waste paper pulp)	Paper and paper board	Total paper
1994	Production (Mt)	97.0 (31)	81.0	81.0
2006	Production (Mt)	100.3 (46.6)	84.3	84.3
1994	Primary Energy Use (PJ)	1,316	1,301	2,779*
2006	Primary Energy Use (PJ)	1,093	1,225	2,484*
1994	Primary Energy Intensity (GJ/t)	13.6	16.1	34.3*
2006	Primary Energy Intensity (GJ/t)	10.9	14.5	29.5*
1994	Carbon Emissions (MtC)	15.3	13.0	31.6*
2006	Carbon Emissions (MtC)	12.1	12.5	25.9*

Note: * includes other pulp and paper types not listed in the table.

In this paper, we analyze the potential of energy savings and carbon reduction of energy efficiency measures and their annualized costs based upon the available data for years 1994 and 2006, respectively. The analysis was accomplished by developing cost curves of energy savings and carbon reductions. The sensitivities of cost curves to their determinants are then discussed and evaluated. Based upon the cost curves, the rate of change in the savings potential at a given cost can be further evaluated and be used to estimate future rates of change that can be the input for energy-climate models.

5.1 Development of Cost Curves for Mitigation Measures

In order to develop cost curves for mitigations measures, we adopted the methodology discussed in the previous section to evaluate applicable measures for 1994 and 2006. Cost curves for 41 measures for improving energy efficiency in the pulp and paper sector were evaluated for the year 1994, and cost curves of 101 measures were developed for the year 2006. The data on costs of implementation, energy savings and lifetimes were collected from a variety of sources, including information and data from case studies and experts. These data are included in Appendix A (1994) and Appendix B (2006). In addition, Appendices C and D include descriptions of some of mitigation measures included. . Little data is available for estimating non-energy benefits for the measures included in our study. Therefore, for estimation of other benefits in this study, we only include reduced operation costs due to saved energy from the selected measures.

After each mitigation technology is characterized individually, its applicability to the U.S. pulp and paper industry as a whole was then assessed as well. In principle, in order to estimate the potential for future uptake of each energy efficiency and GHG-emission reduction measure, each measure was characterized by the degree to which implementation of the measure can be applied in the U.S. pulp and paper industry. The potential degree of implementation depends on a number of factors, such as technical limitations on the implementation of the measure in specific processes, cost effectiveness that is acceptable to the market and the degrees of application of competing technologies.

In general, overall data availability limits the accuracies of estimating the potential degree of implementation. It is easier to find data for some measures than other measures. For example, the Energy Information Administration reports the uptake of some energy efficiency measures in the Manufacturing Energy Consumption Survey (MECS), such as crosscutting technologies like process controls, building controls, waste heat recovery or adjustable speed drives (EIA 1997, 2001, 2005, and 2009).

The cost data (U.S. dollars) are obtained in the currency values for the respective reference years (i. e., 1994, or 2006). A direct comparison of costs is made in Figure 6 and Figure 7 by converting the existing reference-year data (e. g., 1994) to a preferred year (i. e., 2006). The conversions can be accomplished by multiplying the existing cost in a reference year by a GDP-based inflation index for the preferred year (BEA 2011).

5.2 Energy Cost Curves in the U.S. Pulp and Paper Industry in 1994 and 2006

Cost curves of conserved energy (in U.S. dollar per GJ energy used) of mitigation measures can be plotted against the specific final energy savings (GJ per tonne of paper) for the U.S. pulp and paper industry in 1994 and 2006.

For calculating the CCE values, we assumed that a real discount rate of 30% is applied, in part reflecting the industry's capital constraints and preference for short payback periods and high internal rates of return. In general, the assumption of higher discount rates (e. g., 30%) can also indirectly account for program costs and various barriers against the adoption of cost-effective energy efficient technologies. It is also clear that such an assumption would mathematically lead to a prediction with higher (e. g., positive) annualized costs of GHG mitigation measures. An energy-climate model that assumes a high discount rate or constrains market penetration of efficient technologies may represent two likely scenarios – the first being that market failures and indirect costs are a reality for implementing efficiency measures; or the second being that cost-effective policies are not implemented while the costs of efficiency measures are positive. In the latter case, however, implementing these policies could possibly lead to negative-costs of GHG mitigation measures and improved market.

Figure 2 and Figure 3 show the cost curves ($/GJ saved) vs. saved final energy (GJ/t) for 1994 and 2006, respectively, using the discount rate of 30%. The scale of ordinate y-axis in both figures is truncated to highlight the major potential of final energy savings.
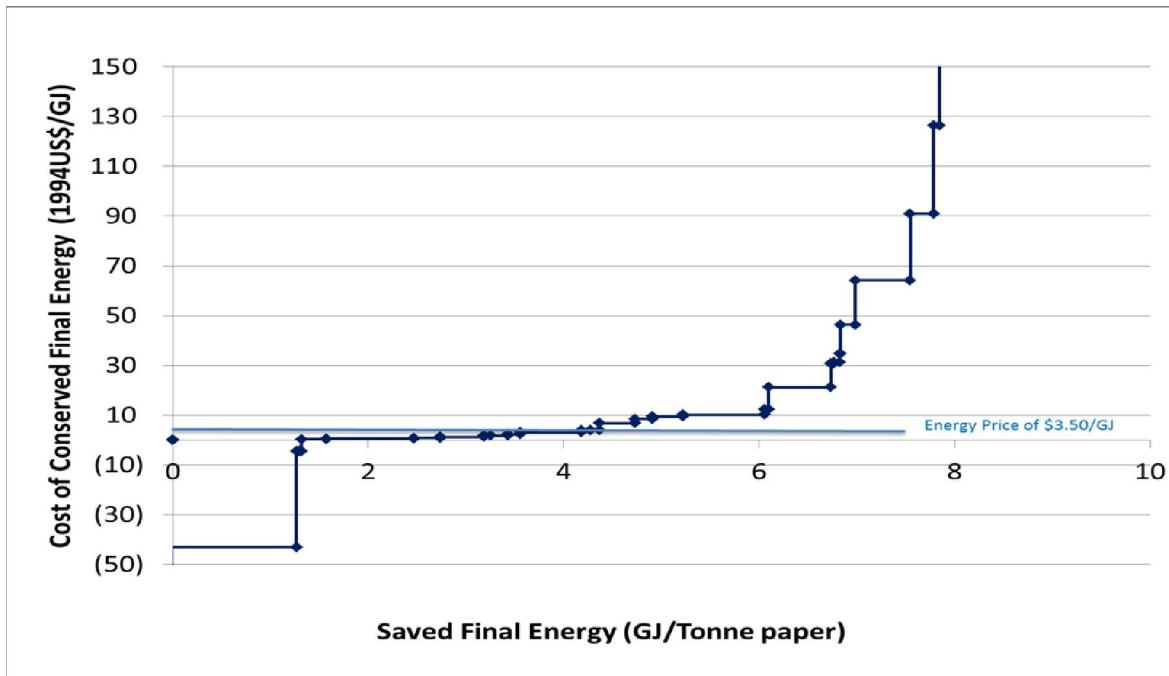
Figure 2. Cost curves for saved energy in U.S. pulp and paper industry in 1994 (discount rate of 30%)
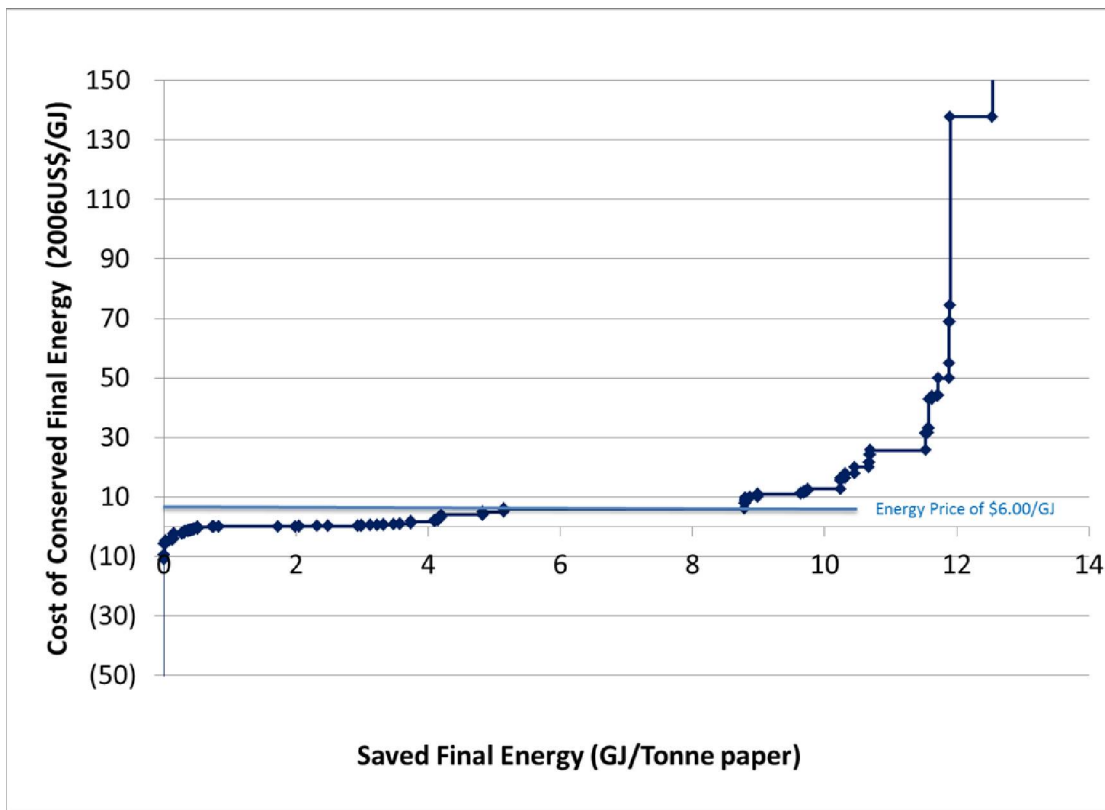
Figure 3. Cost curves for saved energy in U.S. pulp and paper industry in 2006 (discount rate of 30%)

One would expect that a lower discount rate (e. g., 20%) would decrease the total cost of conserved energy for all measures. By changing the discount rates for the estimation, we confirmed this hypothesis with CCE value comparisons for the U.S. pulp and paper industry in 2006. Figure 4 shows increased costs of conserved final energy of mitigation measures at the higher discount rate for year 2006. The Y-axis is truncated at $350/GJ saved in order to better exhibit the cost difference corresponding to the majority of the efficiency measures.
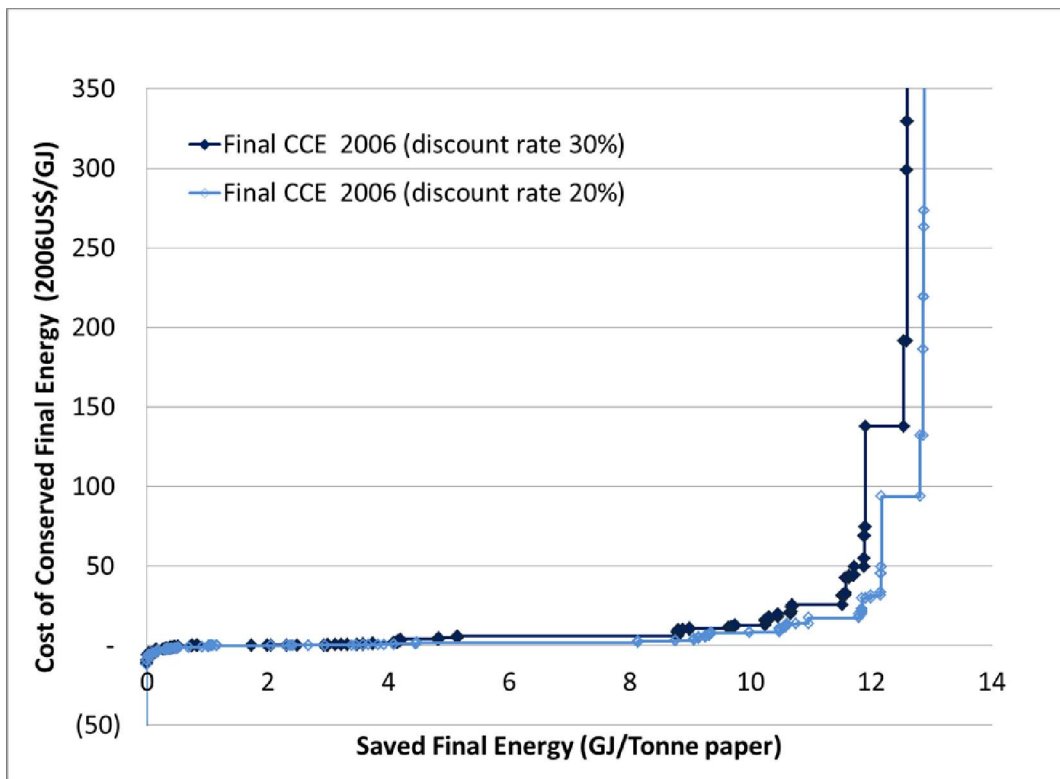
Figure 4. Cost of conserved final energy with different discount rates in 2006

5.3 *Technological Change (Uptake) between 1994 and 2006*

Many factors affect the changes seen in the cost curves: discount rates, energy intensity, production, industry structure (e. g. , amount of waste paper recycle), shares of U.S. production to which the individual measures are applied, additional technologies and measures becoming available from 1994 to 2006, and data availability of the costs, savings, and other benefits. We have identified 41 measures for 1994, and 101 measures for 2006.

Figure 5 shows two cost curves, one that was developed for 1994 and the other for 2006 for the entire U.S. pulp and paper sector. Each of the two curves shows the costs of conserved energy versus energy-savings potential for each year, using 2006 US dollar to compare the cost of conserved energy. In general, the cumulative energy-savings potential in 2006 was larger than that in 1994 when given the same cost of conserved energy (i. e., exhibited by a same Y-value in the chart).

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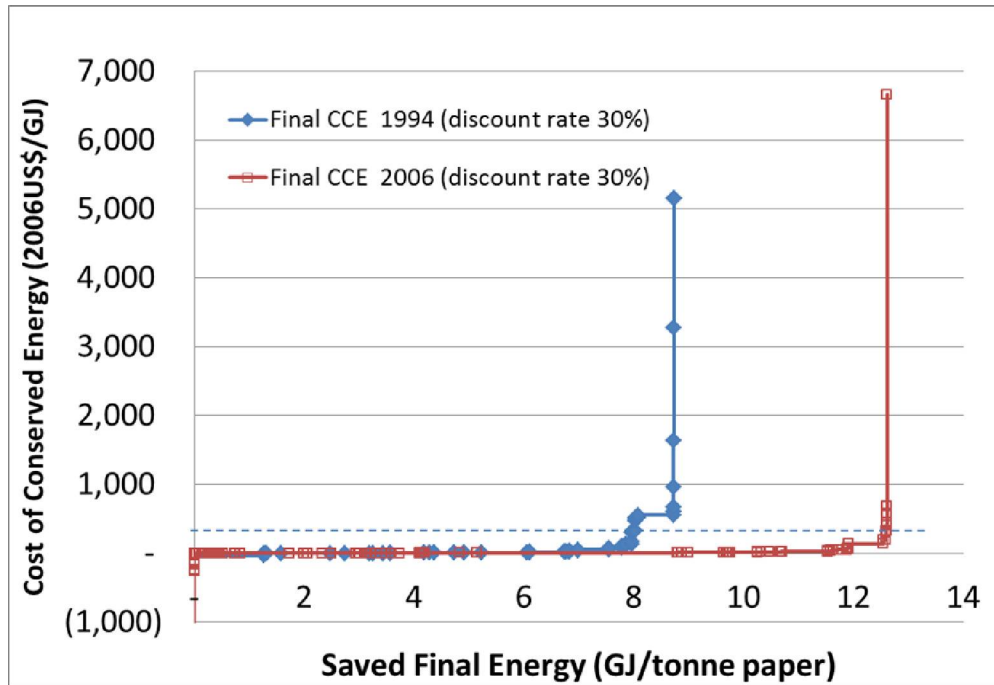
Figure 5. U.S. pulp and paper sector: Changes in energy savings potential between 1994 and 2006 (30% discount rate).
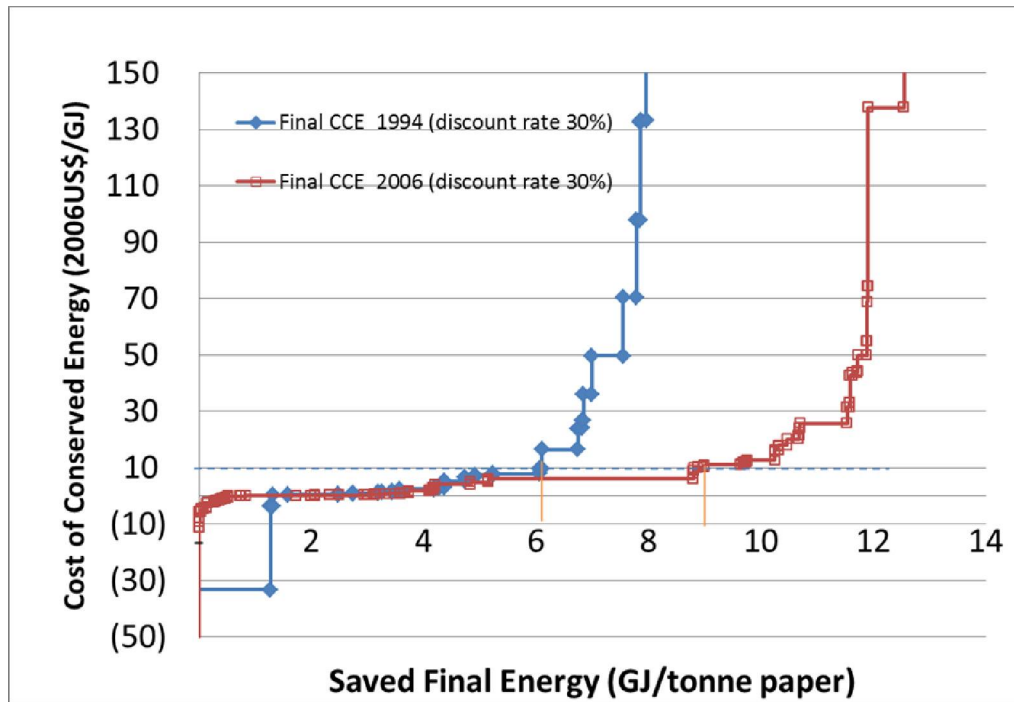
Figure 6. U.S. pulp and paper sector: Changes in energy savings potential between 1994 and 2006 (enlarged cost scale, 30% discount rate).

Quantifying or comparing historical changes in the magnitudes of savings potential can be useful for predicting future trend for energy climate modeling. In this case, we quantified the rate of

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change in energy-savings potential at a given cost over this decade (2006 vs.1994) using 1994 as the baseline. For instance, as shown in Figure 6, at the cost of $10/GJ (2006 dollar), the energy-savings potential increased from approximately 6 GJ/tonne to 9 GJ/tonne (by approximately 50%) over this decade. The exact magnitudes of such shifts are influenced by the selection of individual mitigation measures, implementation rates, and the cost level of conserved energy.

There are a number of reasons for which the observed technical potential increased from 1994 to 2006. These included 1) technology uptakes and implementation - more technologies became available for implementation in 2006; and 2) pulp production and structure change, e. g. , higher waste paper recycle in 2006 (in terms of the actual production and its share of the total pulp production). The changes (e. g., structural changes, and technological uptakes) had also collectively affected the percentage applicability of each measure to the whole U.S. pulp and paper industry, thus the total potential of applicable energy savings.

We have identified typical technologies that presented top energy saved per pulp and paper production (saved GJ/tonne of paper) for each year: Oxygen pre-delignification, increased use of recycled paper, bar-type chip screens, screen out thick chips, boiler maintenance, steam trap maintenance, improved process control, automatic steam trap monitoring, leak repair, and continuous digester modifications. In 1994, the top ten technologies if all implemented as appropriate would contribute to energy savings of 6.6 GJ/tonne paper, accounting for three quarters of applicable final energy savings (8.7 GJ/tonne) from implementing all 41 measures. In 2006, the same ten technologies still topped the list, and if all implemented as appropriate, would have contributed to energy savings of 8.9 GJ/tonne paper, accounting for 71% of applicable final energy savings (12.5 GJ/tonne) from implementing all 101 measures.

5.4   *Potential of Technical and Cost-effective Final Energy Savings*

The technical potential for applicable final energy savings are calculated and presented in Table 3. The potential technical savings was 707 PJ from 41 measures in 1994, while it was 1064 PJ for from 101 measures in 2006. Compared to the overall final energy use – 2,218 PJ in 1994 and 1,702 PJ in 2006, the technical potential of applicable energy savings was approximately 32% in 1994 and 62% in 2006.

Table 3. Technical potential for applicable final energy savings in 1994 and 2006.

	Applied Final Energy Savings (PJ)	
Year	Total	Max Applied Technical (%)
1994	707	32%
2006	1,064	62%

Furthermore, based upon the average unit energy price of all energy types, we can identify cost effective measures from the pool of mitigation measures by comparing their CCE values with the average energy price. Note that this is a simplified approach to estimate cost effective energy savings because some efficiency measures will only be operated with a single type of energy source (e.g., electricity). For example, when using average final energy price of $3.50/GJ for 1994 and 6.00/GJ for 2006 (EIA 2009) to select cost-effective measures, we have considered 12 measures in 1994 and 61 measures in 2006 to be cost effective.

We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 339 PJ in 1994 and 434 PJ in 2006, corresponding to 15% and 25% of total annual final energy use in the U.S. pulp and paper industry in 1994 and 2006, respectively.

This is an important finding in that implementing existing cost effective measures can result in significant energy savings for both years relative to the total annual final energy use, and more so compared to their technical potential in energy savings.

Table 4 shows the total potential energy savings from implementing all cost-effective measures.

We estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 339 PJ in 1994 and 434 PJ in 2006, corresponding to 15% and 25% of total annual final energy use in the U.S. pulp and paper industry in 1994 and 2006, respectively. This is an important finding in that implementing existing cost effective measures can result in significant energy savings for both years relative to the total annual final energy use, and more so compared to their technical potential in energy savings.

Table 4. Technical potential for cost-effective final energy savings in 1994 and 2006.

	Cost-effective Final Energy Savings (PJ)	
Year	Total	Max Applied Technical (%)
1994	339	15%
2006	434	25%

6   Estimation of Carbon Reduction and its Costs

As analyzed earlier, the total carbon emissions from the pulp and paper sector in the U.S. were approximately 31.6 MtC in 1994 and 25.9 MtC in 2006. Associated with the energy savings from implementing mitigations measures is the mitigation cost and carbon reduction. In this paper, we consider cost of carbon reduction as the cost of the mitigation measures.

Figure 7shows cost curve of conserved carbon (in U.S. dollar per MtC) of mitigation measures against the carbon reduction (in MtC) with discount rate of 30% for the U.S. pulp and paper industry in 1994.

Figure 8 shows cost curve of conserved carbon (in U.S. dollar per MtC) of mitigation measures against the carbon reduction (in MtC) with discount rate of 30% for the U.S. pulp and paper industry in 2006.
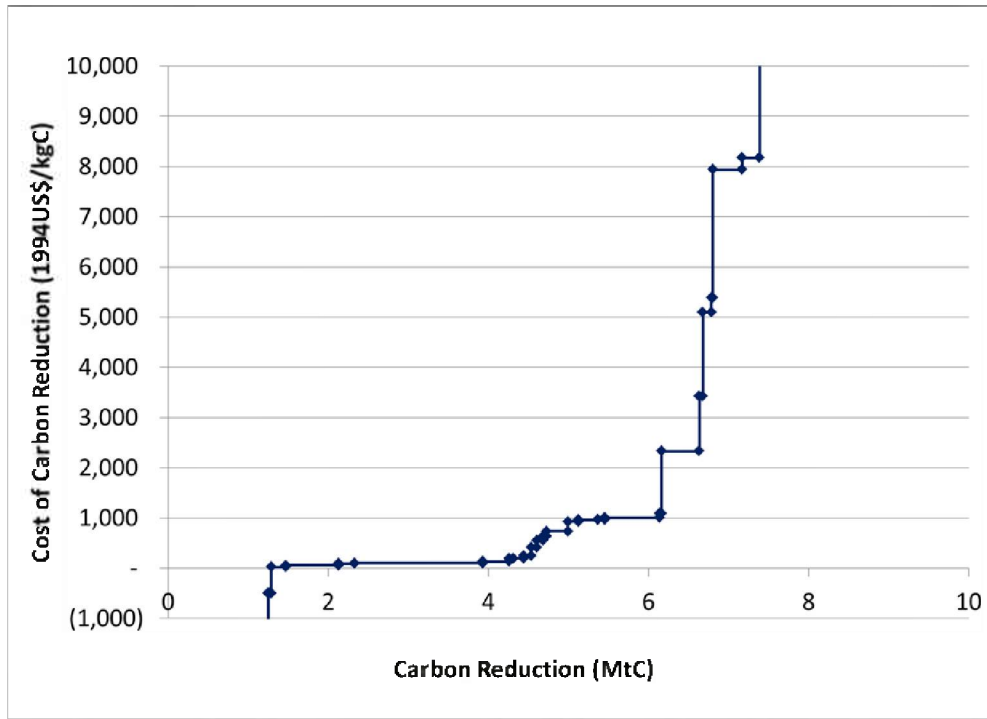
Figure 7. Carbon reduction cost curve for the U.S. pulp and paper sector, 30% discount rate in 1994
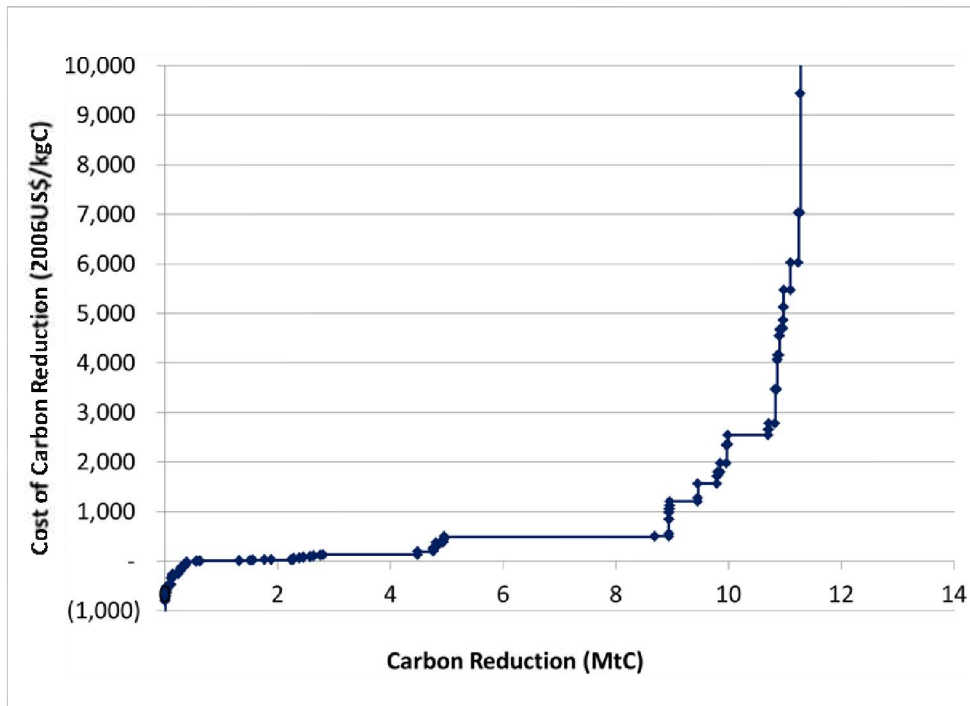
Figure 8. Carbon reduction cost curve for the U.S. pulp and paper sector, 30% discount rate, in 2006

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In addition, Table 5 shows the aggregated numbers for potential carbon reductions.

We estimated that the potential reduction of carbon emissions resulting from applicable mitigations measures was 8.1 MtC in 1994 and 11.8 MtC in 2006, corresponding to 26% and 45% of total annual carbon emissions in the U.S. pulp and paper industry in 1994 and 2006, respectively.

Table 5. Technical potential for carbon reductions in 1994 and 2006.

	Applied Total Carbon Reduction (MtC)	
	Total	Max Applied Carbon Reduction (%)
1994	8.1	26%
2006	11.8	45%

Table 6 shows the potential carbon reductions corresponding to the cost-effective measures identified for each year.

We estimated that the potential reduction of cost effective carbon emissions resulting from applicable mitigations measures was 4.6 MtC in 1994 and approximately 5.1 MtC in 2006, corresponding to 14% and 20% of the total annual carbon emissions associated with energy use in the U.S. pulp and paper industry in 1994 and 2006, respectively. This is an important finding in that implementing existing cost effective measures can result in significant reduction in carbon emissions for each year relative to the total annual carbon emissions in the sector, and more even so when compared to the technical potential reduction in carbon emissions associated with energy use.

Table 6. Technical potential for cost-effective carbon reductions in 1994 and 2006.

	Cost-effective Carbon Reduction (MtC)	
	Total	Carbon Reduction (%)
1994	4.6	14%
2006	5.1	20%

Finally, we performed a parallel analysis to examine the effects of discount rates on the magnitudes of costs of reduced carbon emissions related to the conserved energy and savings potential for individual mitigation measures. For each year, we have found no changes in the magnitudes of collective carbon emission reductions for all rates, while the cumulative costs of conserved energy increase with the increase in discount rates.

In summary, similar to the analysis about energy saving potential, we also analyzed potential reduction in carbon emissions associated with energy use for each year, and have found similar patterns in the cost curves.

7 Conclusions

Pulp and paper appeared to be among the most energy intensive industrial sectors in the U.S. Through characterizing energy-efficiency technology costs and improvement potentials, we have developed and presented energy and carbon reduction cost curves for energy efficiency measures

applicable to the U.S. pulp and paper industry for the years 1994 and 2006. The cost curves can change significantly under various scenarios: the baseline year, discount rate, energy intensity, pulp and paper production, industry structure, efficiency measures, share of pulp and paper production to which the individual measures can be applied.

Important findings in energy savings and carbon reductions in the U.S. pulp and paper industry are included below:

From 1994 to 2006 the primary energy intensity of U.S. paper production changed from 16.1 to 14.5 GJ/t (a reduction of 10%) indicating some change in efficiency technology uptakes. During the same period of time, the energy intensity of U.S. pulp production decreased from 13.6 to 10.9 GJ/t (a reduction of 20%). This reduction benefited from technology uptake as well as increased waste paper recycling replacing wood pulp making. Waste paper pulp accounted for 46% of total pulp in 2006 compared to 32% in 1994. Overall, from 1994 to 2006 the collective primary energy intensity of pulp and paper production has decreased from 34.3 GJ/t to 29.5GJ/t (a reduction of 14%), indicating the collective effect from efficiency technology uptakes and structural change in the U.S. pulp and paper production over the period of time.

We evaluated final energy use in the U.S. pulp and paper sector, and estimated that 2,218 petajoules (PJ) final energy was used in 1994, and 1,702 PJ final energy was used in 2006. The potential savings of final energy use from applying 41 measures was 707 PJ in 1994, while the potential savings of final energy use resulting from applying 101mitigations measures was 1,064 PJ in 2006. Therefore, the technical potential of energy savings was approximately 32% in 1994 and 62% in 2006. We have found that for each year, the top ten technologies would contribute to approximately 70-75% of potential energy savings applicable to the U.S. pulp and paper industry.

We also identified a number of cost-effective mitigation measures for 1994 and 2006 in this study, and estimated that the potential savings of final energy use resulting from cost-effective mitigations measures was 339 PJ in 1994 and 434 PJ in 2006, corresponding to 15% and 25% of total annual final energy use in the U.S. pulp and paper industry in 1994 and 2006, respectively. Implementing cost effective measures can result in significant energy savings relative to the total annual energy use in the sector, and more even so when compared to the technical energy savings potential.

We also estimated overall potentials in carbon-emission reductions due to mitigation measures for both years (1994 and 2006), respectively. The potential reduction of carbon emissions resulting from applicable mitigations measures was estimated as 8.1 million ton of carbon (MtC) in 1994, and 11.8 MtC in 2006, corresponding to 26% and 45% of total annual energy-related carbon emissions in 1994 and 2006, respectively. Applying cost-effective measures would reduce carbon emissions by 4.6 MtC in 1994, and 5.1 MtC in 2006, corresponding to 14% and 20% of annual energy-related carbon emissions in 1994 and 2006 respectively. It is clear that implementing cost effective measures can result in significant carbon-emission reduction relative to the total carbon emissions in the sector, and more even so when compared to the technical potential in carbon-emission reduction.

In this study we have developed cost curves for conserved energy and carbon reduction associated with the measures, and concluded that based upon the cost curves derived from

available information on mitigation measures, the rate of change in the energy-savings or carbon-reduction potential at a given cost can be evaluated and considered in energy-climate models. Such estimation of the rate change may be improved as more comprehensive information on characterizing the mitigation measures becomes available.

In addition, total costs of conserved energy increase with the increases in discount rates. The outcomes from this research provide information on initial technology database that can be accessible to integrated assessment modeling groups seeking to enhance their empirical descriptions of technologies. The report includes tabulated databases on costs of measure implementation, energy savings, carbon-emission reduction, and lifetimes. The appendix section of this report also includes description of the pulp and paper making processes, and the mitigation measures identified in this study.

8   Recommendations for Future Work

The development of concepts and information on costs of conserved energy for the U.S. pulp and paper sector provides a better understanding of costs and carbon impact of energy efficiency measures in the industrial sector. While many energy efficiency technologies have become cost-effective to mitigate long-term climate change, it is important and necessary to incorporate new information on technology characteristics, their evolution and response to energy and carbon price, which can be utilized by integrated assessment modelers who are seeking to enhance their empirical descriptions of technologies.

To date we have completed studies on three U.S. industrial sectors: iron and steel, cement, and pulp and paper sectors. Additional industrial sectors, such as refinery and petrochemicals industries, are also energy intensive. It is important to develop data similar to that produced in these studies for the other sectors. These too will cover information on types of mitigation options that can be readily utilized to improve energy efficiency, their economic potential, and changes that have occurred in the nature of the cost curves including the non-energy benefits.

Future work will be needed to update these industries, and more importantly, to include other business sectors such as commercial and residential buildings and transportation. This is particularly true if comprehensive carbon policies such as carbon offset are to be addressed, given that the building sector possesses largest potential in global carbon reduction.

9   Acknowledgements

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Appendix A Cost Curve Data for the U.S. Pulp and Paper Sector for 1994 (1994 US$)

1994 Baseline	Applied Carbon Savings (kgC/t)	Applied Final Energy Savings (GJ/t)	Cost of Measure (US$/t)	O&M Cost Change (US$/t)	Measure Lifetime (years)	Applied Carbon Savings (MtC)	Final CCR US$/tC	Final CCE (US$/GJ)	Capital Recovery Factor
Raw Materials Preparation									
Ring style debarker	0.21	0.01	0.59	(0.00)	30	0.02	5,388	171.2	0.30
Cradle Debarker	0.35	0.01	11.55	-	30	0.03	66,311	2,107.6	0.30
Enzyme-assisted debarker	0.29	0.01	1.76	-	30	0.02	12,081	384.0	0.30
Bar-type chip screens	0.24	0.03	0.11	(0.05)	15	0.02	(499)	(4.5)	0.31
Screen out thick chips	0.24	0.03	0.11	(0.05)	15	0.02	(499)	(4.5)	0.31
Pulping Mechanical									
Refiner Improvements	0.01	0.00	0.00	0.00	20	0.00	24,253	770.8	0.30
Biopulping	0.05	0.00	0.02	0.01	22	0.00	22,201	869.7	0.30
Pulping Thermomechanical	-	-	-	-	-	-	-	-	-
RTS	0.01	0.00	0.02	-	25	0.00	39,213	1,246.3	0.30
Pressurized groundwood pulping -Super	0.01	0.00	0.03	(0.00)	15	0.00	209,344	6,653.5	0.31
Heat recovery in thermomechanical pulping	0.01	0.00	0.01	0.00	20	0.00	88,958	612.3	0.30
Pulping Chemical									
Continuous digesters	4.54	0.56	18.26	-	20	0.37	7,942	64.2	0.30
Continuous digester modifications	1.65	0.18	0.23	0.03	20	0.13	199	1.8	0.30
Batch digester modifications	1.63	0.18	0.37	0.03	20	0.13	931	8.5	0.30
Chemical Recovery									
Falling film black liquor evaporation	1.64	0.10	11.65	-	20	0.13	10,888	172.0	0.30
Lime kiln modifications	0.89	0.04	0.22	-	30	0.07	551	12.4	0.30
Extended Delignification and Bleaching									
Ozone bleaching	0.01	0.00	4.99	(0.07)	20	0.00	1,373,496	43,653.6	0.30
Brownstock washing	0.03	0.00	1.01	(0.05)	20	0.00	152,545	4,223.7	0.30
Washing presses (post delignification)	0.07	0.01	0.34	(0.01)	20	0.01	24,161	219.9	0.30
Papermaking									
Gap forming	1.64	0.05	24.49	0.25	20	0.13	13,319	423.3	0.30
High consistency forming	2.67	0.24	11.94	0.12	20	0.22	8,172	90.9	0.30
Extended nip press (shoe press)	5.82	0.64	15.02	0.90	20	0.47	2,330	21.2	0.30
Hot Pressing	0.56	0.06	2.57	-	20	0.05	13,875	126.3	0.30
Direct drying cylinder firing	0.48	0.05	5.56	0.07	20	0.04	72,817	662.6	0.30
Reduced air requirements (closing hoods and optimizing ventilation)	3.04	0.31	3.80	0.03	20	0.25	964	9.4	0.30
Waste heat recovery	1.36	0.15	5.28	0.49	20	0.11	5,094	46.4	0.30
Condebelt drying	8.44	0.84	14.08	-	20	0.68	1,006	10.1	0.30
Infrared profiling	0.58	0.09	0.19	-	20	0.05	641	4.0	0.30
Dry sheet forming	3.25	0.64	225.54	-	20	0.26	139,555	711.3	0.30
General Measures									
Pinch Analysis	3.27	0.36	1.60	-	20	0.26	738	6.7	0.30
Optimization of regular equipment	1.03	0.03	-	0.30	15	0.08	968	30.8	0.31
Energy-efficient lighting	0.33	0.01	0.25	(0.00)	15	0.03	1,093	34.7	0.31
Efficient motors	19.77	0.62	6.00	-	10	1.60	98	3.1	0.32
Steam Production and Efficiency									
Boiler maintenance	2.30	0.25	-	0.01	25	0.19	27	0.3	0.30
Improved Process Control	2.45	0.27	0.21	0.04	10	0.20	90	0.8	0.32
Flue Gas Heat Recovery	1.15	0.13	0.33	0.05	15	0.09	255	2.3	0.31
Blowdown Steam Recovery	0.87	0.10	0.34	0.05	15	0.07	421	3.8	0.31
Steam trap maintenance	8.17	0.90	0.63	0.03	10	0.66	57	0.5	0.32
Automatic Steam Trap Monitoring	4.09	0.45	0.62	0.08	10	0.33	138	1.3	0.32
Leak Repair	0.59	0.06	0.03	0.00	25	0.05	187	1.7	0.30
Condensate Return	0.49	0.05	0.08	0.01	25	0.04	3,424	31.2	0.30
Fiber Substitution									
Increased use of recycled paper	15.45	1.27	40.04	(6.10)	25	1.25	3,451	41.8	0.30
Oxygen predelignification	0.22	(0.01)	5.72	(0.59)	20	0.02	47,425	(1,386.6)	0.30

Appendix B Cost Curve Data for the U.S. Pulp and Paper Sector for 2006 (2006 US$)

2006 Baseline	Applied Site Electricity Savings GJ/tonne	Applied Carbon Savings (kgC/t)	Applied Final Energy Savings (GJ/t)	Cost of Measure (US$/t)	O&M Cost Change (US$/t)	Measure Lifetime (years)	Applied Carbon Savings (MtC)	Final CCR US$/tC	Final CCE US$/GJ	Capital Recovery Factor
Raw Materials Preparation	-									
Ring style debarker	0.00	0.14	0.00	0.48	(0.00)	30	0.01	1,044	33.2	0.30
Cradle Debarker	0.01	0.21	0.01	8.79	-	30	0.02	12,845	408.3	0.30
Enzyme-assisted debarker	0.01	0.19	0.01	1.45	-	30	0.02	2,340	74.4	0.30
Bar-type chip screens	-	0.21	0.02	0.13	(0.06)	15	0.02	(126)	(1.1)	0.31
Screen out thick chips	-	0.21	0.02	0.13	(0.06)	15	0.02	(126)	(1.1)	0.31
Replace pneumatic chip conveyors with belt conveyors	-	0.03	0.00	0.79	(0.08)	23	0.00	4,859	44.2	0.30
Use secondary heat instead of steam in debarking	-	0.11	0.01	0.21	(0.06)	23	0.01	39	0.4	0.30
Pulping Mechanical	-									
Refiner Improvements	0.00	0.00	0.00	0.00	0.00	20	0.00	251	8.0	0.30
Biopulping	0.00	0.04	0.00	0.02	0.01	22	0.00	203	7.9	0.30
Replace the conventional groundwood process with pressurized groundwood operation	0.00	0.00	0.00	2.13	(0.07)	21	0.00	209,685	6,664.4	0.30
Install mid-consistency drum pulpers	0.02	0.50	0.02	0.70	(0.02)	21	0.04	379	12.1	0.30
Recover heat from the de-ink effluent	-	0.00	0.00	0.03	(0.01)	21	0.00	(585)	(5.3)	0.30
Reduce operating temperatures in de-inking plant pulpers	-	0.00	0.00	0.00	(0.02)	21	0.00	(4,689)	(42.7)	0.30
Replace pump impellers in Pressurized De-inking Modules (PDM)	0.00	0.03	0.00	0.02	(0.01)	21	0.00	(45)	(1.4)	0.30
Install drum pulpers	0.00	0.06	0.00	3.97	(0.05)	21	0.01	18,203	578.5	0.30
Pulping Thermomechanical	-									
RTS	0.00	0.01	0.00	0.02	-	25	0.00	554	17.6	0.30
Pressurized groundwood pulping -Super	0.00	0.01	0.00	0.03	(0.00)	15	0.00	986	31.3	0.31
Heat recovery in thermomechanical pulping	(0.00)	0.01	0.00	0.01	0.00	20	0.00	838	5.8	0.30
Use load management in refining	0.00	0.01	0.00	0.13	(0.04)	16	0.00	(465)	(14.8)	0.30
Eliminate secondary screen feed pump	0.00	0.00	0.00	0.00	(0.00)	17	0.00	(766)	(24.3)	0.30
Implement Advanced Quality Control (AQC)	0.00	0.00	0.00	0.03	(0.05)	17	0.00	(49,939)	(1,587.2)	0.30
TPM (tissue paper making) combustion air preheating	-	0.00	0.00	0.02	(0.00)	17	0.00	48,412	440.5	0.30
Increase rotational speed of TMP refiners	0.00	0.00	0.00	-	(0.01)	17	0.00	(152,725)	(4,854.0)	0.30
Minimize steam blowthrough in TMP refining	-	0.00	0.00	-	(0.01)	17	0.00	(17,559)	(159.8)	0.30
Implement heat recovery from TMP process to steam and water	(0.00)	0.00	0.00	0.24	(0.04)	17	0.00	28,771	68.8	0.30
Add third refining to the TMP plant	(0.00)	0.00	0.00	0.24	(0.01)	17	0.00	75,053	682.6	0.30
Recover heat from latency chest vent	-	0.00	0.00	0.00	(0.00)	17	0.00	(6,489)	(59.0)	0.30
Use heat recovery to generate hot water	-	0.00	0.00	0.00	(0.02)	17	0.00	(15,409)	(140.2)	0.30
Pulping Chemical	-									
Continuous digesters	(0.02)	4.03	0.50	20.93	-	20	0.34	1,566	12.7	0.30
Continuous digester modifications	-	1.47	0.16	0.27	0.03	20	0.12	78	0.7	0.30
Batch digester modifications	-	1.45	0.16	0.42	0.03	20	0.12	110	1.0	0.30
White-water heating	-	0.33	0.04	0.80	(0.32)	20	0.03	(221)	(2.0)	0.30
Vapor take-off	-	0.07	0.01	0.32	(0.07)	20	0.01	445	4.0	0.30
Install blow heat (batch digester) or flash heat (continuous digester) evaporators	-	0.41	0.05	5.45	(0.22)	20	0.03	3,466	31.5	0.30
Replace conventional batch digesters with cold blow systems	-	1.48	0.16	30.70	(1.17)	20	0.12	5,474	49.8	0.30
Use two pressure level steaming of batch digester to maximize backpressure power generation	-	0.09	0.01	-	-	20	0.01	-	-	0.30
Use flash heat in a continuous digester to preheat chips	(0.01)	0.08	0.03	1.06	(0.21)	20	0.01	1,276	3.1	0.30
Use evaporator condensates on decker showers	(0.00)	0.03	0.01	0.39	(0.08)	20	0.00	1,123	2.7	0.30
Convert evaporation to seven-effect operation	(0.02)	0.17	0.07	4.11	(0.54)	20	0.01	4,065	9.8	0.30
Chemical Recovery	-									
Falling film black liquor evaporation	0.00	1.35	0.09	12.42	-	20	0.11	2,771	43.8	0.30
Lime kiln modifications	-	0.74	0.03	0.23	-	30	0.06	94	2.1	0.30
Teriary and quaternary combustion air	-	0.00	0.00	0.17	(0.19)	23	0.00	(2,334,086)	(21,240)	0.30
High solids firing of black liquor in recovery boiler	-	0.14	0.02	1.60	(0.15)	23	0.01	2,356	21.4	0.30
High temperature video monitors	-	0.00	0.00	0.02	(0.02)	23	0.00	(741,375)	(6,746.5)	0.30
Perform evaporator boilout with weak black liquor	(0.00)	0.15	0.02	0.21	(0.08)	23	0.01	(92)	(0.8)	0.30

Measure										
Extended Delignification and Bleaching	-									
Ozone bleaching	0.00	0.01	0.00	5.72	(0.08)	20	0.00	(7,524)	(239.1)	0.30
Brownstock washing	0.00	0.03	0.00	1.15	(0.05)	20	0.00	10,798	299.0	0.30
Washing presses (post delignification)	-	0.06	0.01	0.39	(0.01)	20	0.01	1,710	15.6	0.30
Heat recovery from bleach plant effluents	-	0.43	0.05	0.17	(0.26)	20	0.04	(479)	(4.4)	0.30
ClO2 filtrate heating	-	0.03	0.00	0.08	(0.03)	20	0.00	(93)	(0.8)	0.30
Lime kiln oxygen enrichment	-	0.16	0.02	-	-	20	0.01	-	-	0.30
Reline lime kiln using high performance	-	0.07	0.01	0.01	(0.08)	20	0.01	(1,035)	(9.4)	0.30
Efficient bleaching chemical mixing in the pulp	0.00	0.00	0.00	-	(0.03)	20	0.00	(8,006)	(254.5)	0.30
Optimize the dillution factor control	(0.00)	0.05	0.01	0.16	(0.06)	20	0.00	(315)	(1.3)	0.30
Optimize the filtrate recycling concept for optimium chemical and energy use	(0.00)	0.14	0.03	0.57	(0.12)	20	0.01	385	2.0	0.30
Preheat ClO2 before it enters the mixer	(0.00)	0.06	0.01	0.14	(0.09)	20	0.01	(806)	(4.1)	0.30
Use oxygen based chemicals to reduce use of ClO2	0.01	0.39	0.01	9.49	(0.14)	20	0.03	7,037	329.4	0.30
Implement an energy efficient lime kiln	-	0.10	0.01	1.26	(0.12)	20	0.01	2,656	24.2	0.30
Replace lime kiln scrubber with an electrostatic precipitator	(0.00)	0.03	0.01	1.14	(0.06)	20	0.00	9,428	54.9	0.30
Papermaking	-									
Gap forming	0.05	1.64	0.05	31.63	0.32	20	0.14	6,020	191.3	0.30
High consistency forming	0.02	2.27	0.20	13.11	0.13	20	0.19	1,801	20.0	0.30
Extended nip press (shoe press)	-	5.82	0.64	19.40	1.16	20	0.49	1,204	11.0	0.30
Hot Pressing	-	0.56	0.06	3.32	-	20	0.05	1,792	16.3	0.30
Direct drying cylinder firing	-	0.48	0.05	7.18	0.09	20	0.04	4,702	42.8	0.30
Reduced air requirements (closing hoods and optimizing ventilation)	0.01	3.04	0.31	4.91	0.04	20	0.26	498	4.9	0.30
Waste heat recovery	-	1.36	0.15	6.82	0.64	20	0.12	1,973	18.0	0.30
Condebelt drying	0.04	8.44	0.84	18.18	-	20	0.71	2,542	25.6	0.30
Infrared profiling	(0.01)	0.58	0.09	0.24	-	20	0.05	124	0.8	0.30
Dry sheet forming	(0.11)	3.25	0.64	291.26	-	20	0.27	27,033	137.8	0.30
Heat water shower for paper machines	-	2.00	0.22	2.01	(0.63)	20	0.17	(13)	(0.1)	0.30
Recover heat from Uhle box effluent	-	1.03	0.11	0.44	(0.40)	20	0.09	(260)	(2.4)	0.30
Use dryers bars and stationary siphons in rimming dryers	-	0.43	0.05	0.45	(0.17)	20	0.04	(82)	(0.8)	0.30
Use a dryer management system	-	0.22	0.02	0.15	(0.09)	20	0.02	(189)	(1.7)	0.30
Operate pockets ventilation between 180-195F	-	0.13	0.01	-	(0.02)	20	0.01	(157)	(1.4)	0.30
Use of shoe press in the press section	-	1.49	0.16	2.24	(0.64)	20	0.13	24	0.2	0.30
Heat felt water	-	0.48	0.05	0.35	(0.35)	20	0.04	(517)	(4.7)	0.30
Paper machine hood heat recovery	-	0.65	0.07	-	-	20	0.05	-	-	0.30
Enclose the machine hood (if applicable) and install air-to-air-to-water heat recovery	(0.03)	0.29	0.12	5.59	(0.49)	20	0.02	4,160	10.1	0.30
Install properly sized white water and broke systems to minimize white water losses	(0.02)	0.13	0.05	2.67	(0.22)	20	0.01	4,550	11.3	0.30
Implement hood exhaust moisture controls to minimize air heating and maximize heat recovery	(0.00)	0.03	0.01	0.71	(0.06)	20	0.00	5,121	12.2	0.30
Implement efficient control systems for the machine steam and condensate systems to eliminate excessive blowthrough and steam venting during machine breaks	(0.00)	0.02	0.01	2.15	(0.04)	20	0.00	28,617	68.9	0.30
Eliminate steam use in the wire pit by providing hot water from heat recovery and by reducing water use on the machine	(0.03)	0.24	0.10	1.36	(0.35)	20	0.02	256	0.6	0.30
General Measures	-									
Pinch Analysis	-	3.27	0.36	2.07	-	20	0.28	191	1.7	0.30
Optimization of regular equipment	0.03	1.03	0.03	-	0.39	15	0.09	375	11.9	0.31
Energy-efficient lighting	0.01	0.33	0.01	0.32	(0.00)	15	0.03	282	9.0	0.31
Efficient motors	0.62	19.77	0.62	7.75	-	10	1.67	127	4.0	0.32
Steam Production and Efficiency	-									
Boiler maintenance	-	2.30	0.25	-	0.02	25	0.19	7	0.1	0.30
Improved Process Control	-	2.45	0.27	0.27	0.05	10	0.21	22	0.2	0.32
Flue Gas Heat Recovery	-	1.15	0.13	0.43	0.06	15	0.10	51	0.5	0.31
Blowdown Steam Recovery	-	0.87	0.10	0.44	0.06	15	0.07	70	0.6	0.31
Steam trap maintenance	-	8.17	0.90	0.81	0.04	10	0.69	5	0.0	0.32
Automatic Steam Trap Monitoring	-	4.09	0.45	0.80	0.10	10	0.34	26	0.2	0.32
Leak Repair	-	0.59	0.06	0.04	0.00	25	0.05	7	0.1	0.30
Condensate Return	-	0.49	0.05	0.10	0.01	25	0.04	28	0.3	0.30
Fiber Substitution	-									
Increased use of recycled paper	0.49	44.24	3.65	148.09	(22.55)	25	3.73	496	6.0	0.30
Oxygen predelignification	0.01	0.25	(0.01)	8.49	(0.88)	20	0.02	4,667	(136.4)	0.30
Other	-									
Demineralized water heating	-	0.20	0.02	0.11	(0.16)	15	0.02	(635)	(5.8)	0.31
Add water/glycol for heating building and process	-	0.14	0.02	-	(0.04)	15	0.01	(275)	(2.5)	0.31
Reduce fresh water consumption	-	0.00	0.00	0.20	(0.20)	15	0.00	(213,388)	(1,941.8)	0.31
Integrate condensate stripping to evaporation	(0.01)	0.11	0.04	0.26	(0.15)	15	0.01	(700)	(1.7)	0.31
Motor Idle mode	0.01	0.24	0.01	0.06	(0.11)	16	0.02	(351)	(11.2)	0.30

Appendix C Description of Pulp and Paper Subsectors and Processes

The North America Industry Classification System (NAICS) codes associated with these three industry sub-sectors are summarized in Table 7, along with some of the key products that are manufactured by each sub-sector. The paper mill sub-sector (NAICS 32212) is further subdivided into paper mills that make newsprint (NAICS 322122) and paper mills that manufacture all other paper products (NAICS 322121).

Table 7 NAICS codes and key products of the U.S. pulp and paper industry

NAICS Code	Sub-sector description	Key products
32211	Pulp mills	Deinked recovered paper, groundwood pulp, pulp manufacturing (i. e. , chemical, mechanical, or semichemical processes)
32212	Paper mills	
322121	Paper (except newsprint) mills	Bond paper, book paper, cigarette paper, diapers, facial tissues, napkins, sanitary paper, office paper, writing paper, paper towels
322122	Newsprint mills	Groundwood paper products (e. g. , publication and printing paper, tablet stock, wallpaper base), newsprint
32213	Paperboard mills	Binder's board, cardboard stock, container board, folding boxboard stock, milk carton board

Pulp and paper mills

Pulp mills are primarily engaged in manufacturing pulp without manufacturing paper or paperboard. The pulp is made by separating cellulose fibers from other components in wood using chemical, semi-chemical, or mechanical pulping processes. Pulp is also commonly manufactured using recovered wastepaper as a raw material. Less commonly, pulp can also be manufactured from other fibrous materials such as used or recycled rags, linters, scrap paper, and straw.

Pulp mills produce "market pulp," which is sold on the open market for the production of paper at separate facilities. Only approximately 15% of the pulp currently produced in the United States is market pulp (Li et al. 2004). The majority of U.S. pulp production occurs at integrated mills that produce both pulp and paper products.

In 2006, there were 44 pulp mills in operation in the United States, which generated roughly $5.6 billion in product shipments (U.S. Census Bureau 2008a, 2008b). The pulp mill sub-sector currently accounts for approximately 5% of industry employment and approximately 7% of industry value of product shipments (U.S. Census Bureau 2008a).

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Paper mills are engaged in the manufacture of paper products from pulp. An integrated paper mill is one that manufactures its own pulp in house; however, paper mills may also purchase market pulp. Some paper mills may also convert the paper that they make into final products (e. g., boxes or bags). Paper mills are further classified by the U.S. Census Bureau as newsprint mills (NAICS 322122) and paper mills that make all other paper types (NAICS 322121).

Newsprint mills

Newsprint mills are paper mills whose production is limited to newsprint and uncoated groundwood paper from pulp. Newsprint mills represent the smallest sub-sector of the U.S. pulp and paper industry. In 2006, there were 23 newsprint mills in operation in the United States with an annual value of product shipments of approximately $4.1 billion, newsprint mills account for roughly 5% of U.S. pulp and paper mill shipments (U.S. Census Bureau 2008a).

Paper (except newsprint) mills

Paper mills that make all other paper types besides newsprint and uncoated groundwood sheet are classified as paper (except newsprint) mills. Paper (except newsprint) mills manufacture a wide variety of products, including paper for books and cigarettes, writing paper, office paper, napkins, paper towels, tissues, sanitary paper, and diapers. Paper mills of this type represent the largest sub-sector of the U.S. pulp and paper industry by a significant margin. There were 325 paper mills in operation in the United States in 2006, with a total employment of over 88,000 and $46.6 billion in product shipments (U.S. Census Bureau 2008a, 2008b). This industry sub-sector accounts for roughly 60% of total industry employment and product shipments, and nearly 55% of its shipment values from operating mills.

Paperboard mills

Paperboard mills are primarily engaged in the manufacture of paperboard from pulp. Major paperboard products produced in the United States include cardboard stock, container board, Kraft liner board, and milk carton board. Many paperboard mills manufacture their own pulp, but some may purchase market pulp. Paperboard mills are the second largest sub-sector in the U.S. pulp and paper industry.

There were 205 paperboard mills in operation in the United States in 2006 (U.S. Census Bureau 2008b). Nearly 38,000 people were employed at these mills, which generated approximately $23 billion in product shipments (U.S. Census Bureau 2008a).

Overview of Pulp, Paper and Paperboard Processing

The pulp and paper industry converts fibrous raw materials into pulp, paper, and paperboard products. Pulp mills manufacture only pulp, which is then sold and transported to paper and paperboard mills. A paper and paperboard mill may purchase pulp or manufacture its own pulp in house; in the latter case, such mills are referred to as integrated mills.

The major processes employed in the pulp and paper industry include raw materials preparation, pulping (chemical, semi-chemical, mechanical, and waste paper), bleaching, chemical recovery, pulp drying, and paper making. Figure 9 provides a flow diagram of these processes and typical energy use such as fuels, steam, and electricity.

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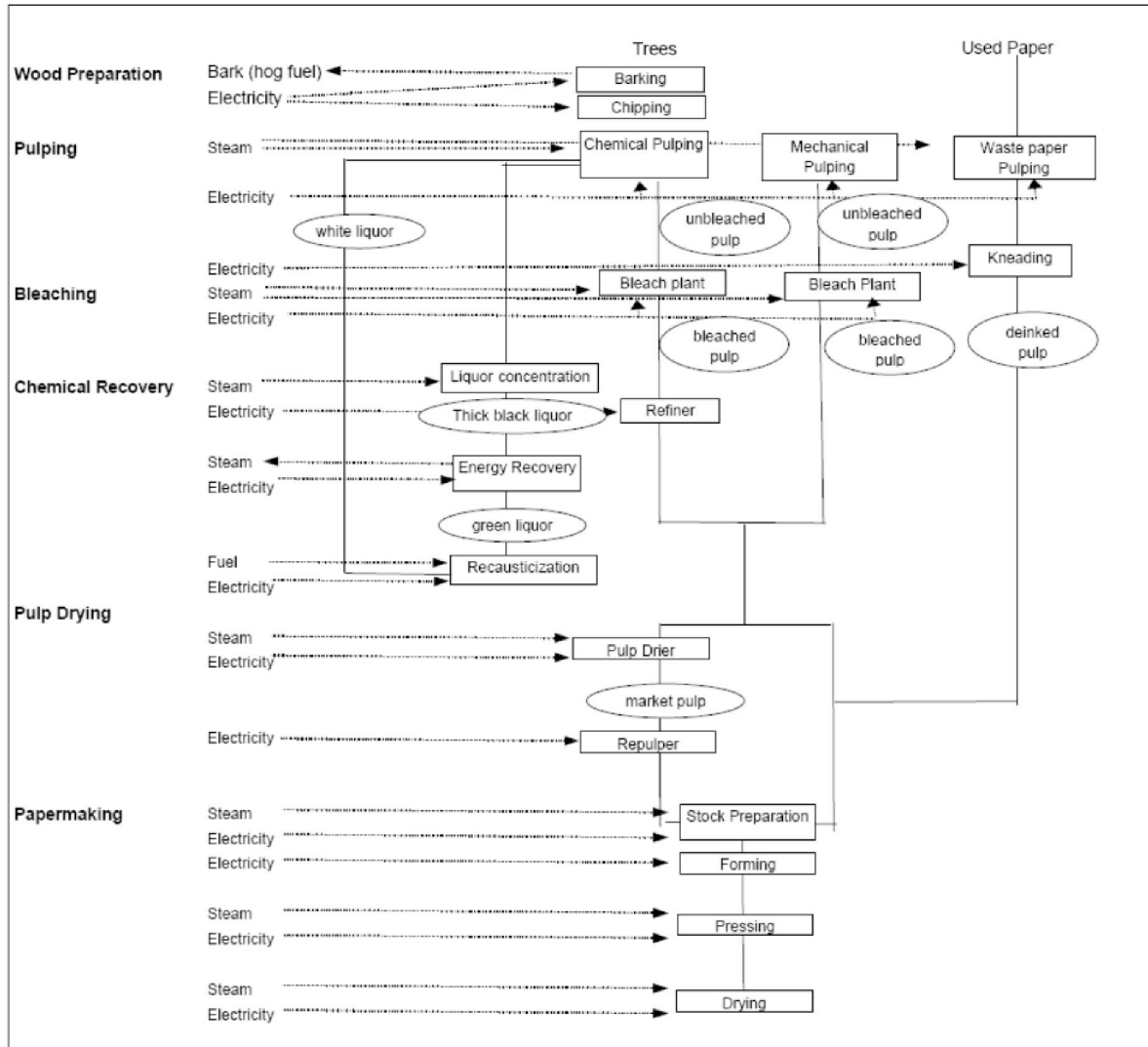
Figure 9. Schematic of major pulp and paper manufacturing processes

C.1 Raw Materials Preparation

Wood is the primary source of fiber in the production of paper products, and is typically delivered to the mill in the form of logs or wood chips. Both softwoods and hardwoods are used in the production of wood pulp. The primary processes used to convert logs into a size and shape suitable for pulping are size reduction, debarking, chipping, and screening. Wood chips are normally free of bark and are often only subjected to screening.

Logs typically arrive at the mill on trucks or rail cars. For ease of handling, large logs are sometimes sent to a slasher deck for size reduction prior to debarking.

Because bark is a contaminant in the pulping process, debarkers are used to remove bark from logs prior to chipping. Drum debarkers are primarily used in larger whole log chipping applications. Bark is removed from logs by placing them in a large rotating steel drum, where the logs rub against one another and the bark is removed by friction (Saltman 1978). Such a rotating

steel drum is a mechanical debarker. In addition, ring debarkers are primarily used in high speed softwood sawmill applications. On a ring debarker, logs or stems are fed linearly into the debarking system. In some cases, hydraulic debarkers are used, in which high-pressure water jets blast bark from the surface of the log. However, hydraulic debarkers are more energy-intensive than mechanical debarkers; they also require the bark to be dried and pressed before it can be used as a fuel (Martin et al. 2000). As a result, hydraulic debarkers are being phased out of operation in the United States (U.S. DOE 2005).

After debarking, the logs are sent to a chipping machine (most commonly a radial chipper). These machines produce wood chips of manageable sizes and shapes to maximize the efficiency of the pulping process. The optimal size of wood chip depends on the species of wood and method of pulping to be employed (e. g., chemical or mechanical). Wood chips are then passed over a series of vibrating screens to remove chips that are either oversized or undersized. Chips that are too small—often called "fines"—can be subsequently used as "hog fuel" to generate thermal energy such as steam. Chips that are too large are typically recovered for further size reduction. The chips are then transported via belt conveyors to the pulping stage (Martin et al. 2000).

Wood provides roughly 72% of the fiber used for paper production in the United States. The majority of remaining fiber (i. e., secondary fiber) comes from waste paper and paperboard (U.S. DOE 2005). According to the American Forest and Paper Association (AFPA), approximately 80% of U.S. pulp and paper manufacturers use some secondary fiber in the production of pulp, and approximately 40% of U.S. mills rely exclusively on secondary fibers to produce pulp (AFPA 1999a, U.S. EPA 2002).

Because waste paper products can contain inks and other contaminants, they are often used as pulping feedstock for low-purity paper and paperboard products, such as corrugating paper used to produce corrugated cardboard (U.S. EPA 2002). However, deinking and other contaminant removal technologies exist, which allow the U.S. pulp and paper industry to recycle waste paper products into high-quality paper and paperboard.

C.2 Pulping

The primary goals of pulping are to free fibers in wood from the lignin that binds these fibers together, and then to suspend the fibers in water into slurry, which will be ready for paper making. Typical North American wood consists of approximately 60%-65% cellulose and hemicelluloses, which are the key fibrous ingredients in paper. The remaining materials mass consists primarily of lignin, with small amounts of extractives (e. g., terpenes) and ash (U.S. DOE 2005; Biermann 1996). Pulp with longer fibers and less lignin can produce papers with higher strength and greater resistance to aging using the same process.

The three main processes for producing wood pulp are mechanical pulping, chemical pulping, and semi-chemical pulping. Of these, the Kraft chemical pulping process accounts for the majority of U.S. wood pulp production (Kincaid 1998). Also significant is recycled or secondary fiber pulping, which is primarily a mechanical pulping process with heat and chemicals added for contaminant removal and paper dissolution (U.S. EPA 2002).

The type of pulping process that is employed depends on a number of different factors, including the wood source (hardwood or softwood), the desired pulp properties (e. g., fiber length, strength, and purity), and the paper products to be manufactured (e. g., newsprint, packaging, or writing paper). Table 8 summarizes the major attributes of each pulping process. Each of these processes is described following the table.

Table 8 Summary of pulping process characteristics

Pulping Process	Primary Fiber Separation Mechanism	Yield (mass of pulp/mass of original fiber source)	Pulp Properties	Typical Products
Mechanical	Mechanical energy	High (85-95%) lignin not removed	Short, weak, unstable, high opacity fibers; good print quality	Newsprint, magazines, books, container board
Chemical	Chemicals and heat	Lower (45-50% for bleachable/bleached pulp; 70% for brown papers)	Long, strong, stable fibers	Kraft: bags, wrapping, linerboard, newsprint Sulfite: fine paper, tissue, glassine, newsprint
Semi-chemical	Combination of chemical and mechanical treatments	Intermediate (55-85%)	"Intermediate" pulp properties	Corrugated board, food packaging, newsprint, magazines
Recycled	Mechanical energy with some heat and chemicals	Depends on waste paper source. Up to 95% for waste packaging and as low as 60% for waste hygienic papers.	Mixture of fiber grades; properties depend on waste paper source	Newsprint, writing paper, tissue, packaging

Source: Adapted from U.S. DOE 2005

Mechanical Pulping

Mechanical pulping is the oldest form of pulping. The process employs mechanical energy to weaken and separate fibers from wood and waste paper feedstock via a grinding action. The advantage to mechanical pulping is that it produces much higher yields than chemical pulping processes (up to 95%). However, because this process does not dissolve lignin, the fiber strength and age resistance of the resulting pulp are low (U.S. DOE 2005). The weakness of the resulting pulp is compounded by the fact that the mechanical grinding process also produces shorter fibers (Kincaid 1998). As a result, most mechanical pulp is used for lower grade papers such as newsprint, magazines, and catalogues (Biermann 1996). Mechanical pulping also requires more raw materials screening to remove contaminants such as dirt, shives,[1] and knots than chemical pulping processes (U.S. DOE 2005).

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[1]Shives are small bundles of fibers that are not fully separated in the pulping operation.

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As of 2006, mechanical pulp accounted for roughly 8% of U.S. wood pulp production (FAO 2011). There are four primary types of mechanical pulping: (1) stone groundwood pulping, (2) refiner mechanical pulping, (3) thermomechanical pulping, and (4) chemi-thermomechanical pulping.

Stone groundwood pulping (SGW) is the oldest and least energy-intensive mechanical pulping process (Martin et al. 2000). In the SGW process, small logs are ground against artificial bonded stones made of silicon carbide or aluminum oxide grits. These stones can be submerged (pit grinding) or sprayed with water to keep them cool while maintaining grinding performance and fiber quality. The advantage of the SGW process is its very high yield. However, the fibers produced by the SGW process can be very short and often must be combined with expensive chemical fibers to be strong enough to pass through the paper machine and subsequent coating and printing processes.

Refiner mechanical pulping (RMP) keeps the high yield advantages of the SGW process, while producing somewhat longer fibers with greater strength. The RMP process was introduced to allow the use of wood feedstock other than logs, such as wood scraps and sawdust from lumber mills (U.S. DOE 2005). Wood feedstock is ground between two grooved discs. The RMP process produces longer and stronger fibers that permit lighter weight paper to be used for printing and result in more print media per ton of feedstock.

In the *thermomechanical pulping (TMP)* process, wood chips are first steamed to soften them before being ground in the same manner as the RMP process. The TMP process generates the highest grade mechanical pulp but is also a high energy intensity process due to its steam use. This process can also produce a darker pulp that is more costly to bleach (Martin et al. 2000). Despite these drawbacks, TMP is the most common mechanical process in use today.

Chemi-thermomechanical pulping (CTMP) involves the application of chemicals to wood chips prior to refiner pulping. The process begins with an impregnation of sodium sulfite and chelating agents. The mixture is then preheated to 120-130 °C and ground in the refiner. The chemical pre-treatment of wood chips allows for less destructive separation of fibers from the feedstock, resulting in longer fibers, higher fiber content, and far fewer shives. The CTMP process also produces more flexible fibers (which provide higher sheet density, burst strength, and tensile strength) and higher pulp brightness than the TMP process. Its primary drawback, like TMP, is that the energy intensity of the process is higher (Martin et al. 2000).

Chemical Pulping

Chemical pulping is by far the most common method of producing wood pulp in the United States. As of 2006, nearly 85% of U.S. wood pulp was produced by chemical pulping processes (FAO 2011). Chemical pulping processes have low yields but generate pulp with strong and stable fibers for high quality products such as office paper.

Chemical pulping separates the fibers in wood feedstock by dissolving the lignin bonds that hold these fibers together, often at elevated temperatures and pressures. There are two primary forms of chemical pulping: (1) Kraft (or sulfate) pulping process, and (2) sulfite pulping process. According to the American Forest and Paper Association (AFPA), approximately 98% of today's U.S. chemical pulping capacity uses the Kraft process (AFPA 2002).

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In a Kraft pulping process, wood chips are first steamed to soften them and to force out any trapped air. The wood chips are then combined with a highly alkaline solution – called white liquor – which contains sodium hydroxide (NaOH), and sodium sulfide (Na_2S). These ingredients are pressurized and cooked at 160-170°C in a digester over several hours, which allows the liquid to permeate the wood chips and dissolve most of the non-fibrous constituents in the wood.

There are two primary types of digesters— batch digesters and continuous digesters—which cook wood chips on batch and continuous bases, respectively. Batch digesters offer lower capital costs and more product flexibility. Continuous digesters are more space efficient and less labor intensive; because they reuse process steam, they are also more energy efficient (DOE 2005; Biermann 1996).

After digestion, hot pulp and spent liquor are discharged into low-pressure blow tanks, which separate the wood chips into fibers. The spent liquor and its dissolved contaminants—referred to as "black liquor'—are washed away and sent to the chemical recovery process for use as boiler fuel and to regenerate white liquor. The resulting Kraft pulp is dark brown and can be used to make unbleached cardboard products and grocery bags. For Kraft pulp that is used for white products, the next step in the process is the bleaching phase.

A sulfite pulping process uses a mixture of sulfurous acid (H_2SO_3) and bisulfate ion (HSO_3^-) as its solvent, which is produced by burning sulfur and mixing the resulting gases with a basic solution (U.S. DOE 2005; Martin et al. 2000). Similar to the Kraft pulping process, the sulfite process allows the pulping chemicals to be reused for energy recovery and solvent regeneration. The sulfite pulping process is used on a much smaller scale in the United States, and accounts for approximately two percent of U.S. chemical pulping capacity (AFPA 2002).

Kraft and sulfite pulping processes can be used to produce similar types of paper. However, the Kraft process dominates U.S. chemical pulp production due to several key advantages over the sulfite process. Such advantages include its applicability to a wider variety of tree species, its superior fiber strength, its ability to tolerate wood contaminants, its high lignin removal rates (up to 90%), and the high efficiency of its chemical recovery process (U.S. EPA 2002; U.S. DOE 2005). In contrast, the sulfite process produces a pulp with shorter fiber length and its chemical recovery process is inefficient. As a result, the sulfite process is mostly used for specialty product applications such as very smooth papers (Elaahi and Lowitt 1988).

Extended delignification and oxygen delignification are two process modifications that can be employed to reduce the lignin content of chemical pulp even further. Both methods can reduce the amount of chemicals required during the bleaching phase, while extended delignification can also reduce cooking liquor consumption by 5-10% (U.S. DOE 2005).

Semi-Chemical Pulping

Semi-chemical pulping uses a combination of chemical and mechanical pulping processes whereby wood chips are subjected to a mild chemical digestion process before they are mechanically pulped. This pulping method is primarily used for hardwoods, which have short narrow fibers that can be used to make a smoother, denser, and more opaque sheet of paper (Martin et al. 2000). The major differences between semi-chemical and chemical digestion

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processes are that semi-chemical digestion uses lower temperatures, more dilute cooking liquors, and shorter cooking times (U.S. EPA 2002). Semi-chemical pulping processes generate a pulp yield higher than chemical pulping processes due to higher lignin content, but lower than the yields achievable with mechanical pulping. Approximately 6% of U.S. wood pulp production is from semi-chemical pulping processes (U.S. EPA 2002).

Recycled/Secondary Fiber Pulping

The use of recovered paper as feedstock in the U.S. pulp and paper industry has grown significantly over the last 30 years. According to the AFPA, nearly 200 U.S. mills rely exclusively on recovered paper for pulp production, and roughly 80% of U.S. mills use recovered paper in some fashion. The main types of recovered paper include post-consumer (or "old") corrugated cardboard (OCC) boxes, newspapers, and miscellaneous mixed papers such as office paper. Nearly half of recovered paper fiber is in the form of OCC (U.S. DOE 2005).

The typical process for generating pulp from recovered paper feedstock involves blending the feedstock with water in a large tank. Pulping chemicals and heat are sometimes added to the process to aid in the production of fibrous slurry (U.S. EPA 2002). Large contaminants and contaminants that float are removed from the slurry with a ragger mechanism, while heavy objects such as nuts and bolts exit the process via a chute at the lower end of the pulping tank (Martin et al. 2000; Biermann 1996). Inks and other fiber contaminants can be removed during the process using chemical surfactants. The combined application of heat, dissolution of chemical bonds, and mechanical shear action liberates fibers and produces a pulp with desired properties and consistency (U.S. EPA 2002).

Producing pulp from recycled and secondary fibers typically requires less energy than mechanical or chemical pulping processes. However, the energy intensity of the process can vary significantly depending on the extent and types of contamination and final pulp yields. Moreover, the availability of recycled and secondary fiber inputs is also an issue, since supplies can fluctuate over time. Still, modern contaminant removal techniques have made recycled pulp a competitive option for many types of paper, excluding only the highest grades of papers for which long fiber length is essential (Martin et al. 2000).

C.3 Bleaching

Raw pulp can range in color from brown to crème due to the remaining lignin that was not removed during the pulping process. For paper products for which brightness and resistance to color reversion are important, such as office and printing paper, the pulp must be whitened by a bleaching process prior to the paper making phase. According to the AFPA, approximately 50% of the pulp produced in the United States is bleached pulp (U.S. EPA 2002). Unbleached pulp is typically used to make products such as corrugated boxes and grocery bags for which brightness is not required.

Bleaching can be defined as any process that chemically alters pulp to increase its brightness (U.S. EPA 2002). The pulping process (i. e., chemical or mechanical) is a major driver of the type of bleaching that is required. Mechanical and semi-chemical pulping process will generate pulps with high lignin content, which requires a chemical-intensive bleaching process to decolorize the remaining lignin. The bleaching process for chemical pulps—which have low

lignin content—focuses on the removal of remaining lignin from the pulp (U.S. DOE 2005; U.S. EPA 2002).

Mechanical pulp is often bleached using hydrogen peroxide and/or sodium hydrosulfite. Bleaching chemicals can be added into the mechanical pulping process, or added to the pulp in multi-stage reactions which occur in a series of post-pulping bleaching towers. The number of bleaching reactions employed depends on the brightness requirements of the final paper product.

The bleaching of chemical pulp comprises multiple stages that alternate between washing the pulp and treating it with chemicals in bleaching towers (U.S. DOE 2005). In the past, elemental chlorine was commonly used as a bleaching agent in this process. Increasingly stringent effluent limitations have led to the adoption of elemental chlorine free (ECF) bleaching processes at most U.S. pulp and paper mills. Today, over 95% of bleached chemical pulp production in the United States uses ECF processes (AFPA 2005). The totally chlorine free (TCF) process eliminates the use of chlorine altogether. As of 2001, TCF processes accounted for roughly 1% of U.S. bleached pulp production (U.S. EPA 2002).

The specific chemicals that are applied in bleaching processes for chemical pulp, and the number of stages, vary by mill and depend on a number of factors including local environmental regulations, costs, and desired pulp properties (U.S. DOE 2005). The most common chemicals employed in ECF and TCF processes in the United States are summarized in Table 9, along with a description of their primary purpose.

Table 9Common ECF and TCF bleaching chemicals

Bleaching Chemical	Chemical Formula	Primary Purpose
Chlorine dioxide	ClO_2	An oxidizer that selectively destroys lignin without extensive damage to pulp fibers
Ozone	O_3	A chlorine free oxidizer used to destroy lignin. Less selective to lignin than chlorine compounds, and must be used in low charges to prevent pulp strength loss.
Hypochlorite	HClO, NaOCl, $Ca(OCl)_2$	An oxidizer used to destroy lignin that is typically used for sulfite pulps. Hypochlorite is being phased out due to increasing environmental concerns related to chloroform formation.
Sodium hydroxide	NaOH	An alkali that is mixed with oxidized pulp and steam to displace lignin that was made soluble during oxidation so that lignin can be extracted from the pulp.
Oxygen	O_2	Used under pressure in combination with an alkali to enhance lignin extraction
Hydrogen peroxide	H_2O_2	Can be used to bleach lignin fibers in mechanical pulp or as a delignification agent for chemical pulp to reinforce alkaline extraction

Source: U.S. EPA 2002 and U.S. DOE 2005

C.4 Chemical Recovery

The primary purpose of the chemical recovery process is to recover pulping chemicals from spent cooking liquor (i. e., black liquor) for reuse in subsequent pulping processes. Chemical recovery allows a mill to regenerate pulping chemicals at a rate of up to 98% (U.S. EPA 2002), which significantly reduces the costs of purchased process chemicals. An added benefit is that chemical recovery allows a mill to generate a significant portion of its steam requirements by combusting the pulp residue contained in black liquor as part of the refining process. The chemical recovery process for Kraft pulping consists of four key stages: (1) black liquor concentration, (2) black liquor combustion (recovery boiler), (3) recausticizing, and (4) calcining (lime burning).

Black liquor concentration is the process of evaporating water from black liquor to increase its solids content, which makes the recovery boiler combustion process far more efficient. Most mills employ multiple effect evaporators to concentrate black liquor using indirect heat from steam. Some mills may also use direct contact evaporators, which use the exhaust gases from the recovery boiler to drive up the final solids concentration. Evaporation is the single largest use of steam in the production of Kraft pulp. Multiple effect evaporators can maximize the efficiency of this steam use; the use of seven effects is currently considered industry best practice. Further, much of this steam can be reused in the form of condensate or hot water in other facility applications (U.S. DOE 2005).

After concentration, black liquor will typically have a fuel value between 6,000 Btu/lb. and 7,000 Btu/lb. (Biermann 1996). It is then combusted in a *recovery boiler* to produce steam for mill process heating applications and/or electricity generation. During combustion, organic constituents burn to generate useful heat while the inorganic process chemicals are reduced to a molten smelt. This smelt is removed from the bottom of the boiler for further refining in the recausticizing stage (U.S. DOE 2005). Recovery boilers typically have a thermal efficiency of approximately 65%; steam generation typically increases by 2% for each 5% increase in solids content above 65% (Gullichsen 1999; Smook 1992).

In the *recausticizing* process, the smelt from the recovery boiler is first mixed with weak white liquor to form an intermediate solution known as green liquor. This green liquor consists mostly of sodium carbonate (Na_2CO_3) and sodium sulfide (Na_2S). The green liquor is then recausticized by adding calcium hydroxide $Ca(OH)_2$ under controlled temperature and agitation. The recausticizing process converts the sodium carbonate in the green liquor into sodium hydroxide (NaOH) and a calcium carbonate ($CaCO_3$) precipitate. The calcium carbonate precipitate—also known as lime mud—is then removed, leaving behind white liquor (i. e., NaOH and Na_2S) that can be reused in the pulping process.

The lime mud is then sent to the *calcining* process, where it is heated in a kiln to produce lime (CaO) with carbon dioxide (CO_2) as a by-product. The lime is then dissolved in water to produce the calcium hydroxide $Ca(OH)_2$ that is used in the mill's recausticizing process.

C.5 Pulp Drying

In situations where pulping and papermaking operations are not located at the same facility, or when a temporary imbalance between pulp production and paper machine requirements exists, pulp is dried to reduce its moisture content. On average, market pulp is dried to approximately 10% water before being shipped to a paper mill. The process for re-pulping of dried pulp at a

paper mill is similar to that employed for pulping recovered paper. Pulp drying is energy intensive (about 4.2 MMBtu of steam per ton of pulp) (Martin et al. 2000) and is not essential to the papermaking process. Thus, significant energy savings are realized by co-locating pulping and paper making operations at one facility.

C.6 Papermaking

The papermaking process can be divided into three basic stages :(1) stock preparation, (2) "wet end" processing where sheet formation occurs, and (3) "dry end" processing where sheets are dried and finished.

The purpose of stock preparation is to process the pulp into homogenous slurry with properties suitable for introduction into the paper machine. Stock preparation involves the following processes: mechanical homogenization of pulp, dispersion in water, fiber declustering, and introduction of wet additives, blending, and contaminant screening (U.S. DOE 2005, U.S. EPA 2002). The purpose of wet additives is to provide the final paper product with specific desirable properties (such as color and water repellence) and to improve the quality and efficiency of the paper making process.

The slurry is then fed into the so-called wet end of the papermaking machine where a paper web (i. e., sheet) is formed. Fourdrinier machines are the most common type of papermaking machines in use today. In a Fourdrinier machine, the slurry first enters a headbox, which creates a uniform layer of slurry and deposits this layer onto a moving fabric (also called wire or forming fabric). This fabric forms the fibers into a continuous web while allowing water removal via gravity and the application of vacuum pressure.

Once the fibers have been sufficiently dewatered that they begin to bond to form paper, they move on to the press section of the paper machine. Here the paper is pressed to remove water, which promotes further bonding between fibers. As it moves through the press section, the paper is supported by rolls and press fabrics which absorb water from the sheet at the press nips. The bonded and dewatered sheet then proceeds to the so-called dry end of the paper machine for further drying and finishing operations. The press section has historically been the target of many energy efficiency improvements in papermaking, because the drier the paper is leaving the press section, the less energy it consumes in the drying section.

Dry end processes include drying, calendering, and reeling. In the drying section, steam heated rollers compress and further dry the sheet through evaporation, which facilitates additional bonding of fibers. The drying section represents the largest user of energy in the papermaking stage. In the middle of this section is the size press, which can apply coating to the paper. The size press must be placed so that the paper can continue drying after coating because the coating itself must dry as well. The next step is calendering, which involves a series of carefully spaced rollers that control the thickness and smoothness of the final paper. After calendering, the finished paper is wound on a large reel for storage and transportation.

Appendix D Typical Mitigation Technologies

41 and 101 mitigation measures for improving energy efficiency in the pulp and paper sector were evaluated in this study for the year 1994 and 2006, respectively. Data on costs of implementation, energy savings and lifetimes were collected and compiled. After each measure

was characterized individually, its applicability to the US industry as a whole was assessed. The potential degree of implementation depends on a number of factors, of which the most important are the technical limitations on the implementation of the measure, the degree of application of competing technologies and the current degree of implementation of the measure. Appendices A and B list the selection of the mitigation technologies and their corresponding benefits for the pulp and paper industry.

Data availability limits the accurateness of estimating the potential degree of implementation. For some measures it is easier to find data than others; for others, more information is documented in statistics or other sources. For example, the Energy Information Administration reports the uptake of some energy efficiency measures in the Manufacturing Energy Consumption Survey such as cross-cutting technologies like process controls, building controls, waste heat recovery or adjustable speed drives (EIA 1997, 2001, 2005, and 2009). Even though the MECS results are only an indication, they serve as a relative gauge for the penetration of those measures.

The following descriptions include typical efficiency measures enlisted in Appendix A and Appendix B. Because some of the measures enlisted were self-explanatory, the following section is not intended to correspond one-on-one with the measures enlisted.

D.1 Energy Efficiency Measures for Raw Material Preparation

The processes associated with raw materials preparation are estimated to consume roughly 10% of the electricity use and 3% of the steam use in U.S. pulp manufacturing operations (Jacobs and IPST 2006). Available efficiency measures are described in the following.

Ring-style debarker. Debarkers are utilized to remove the bark from logs or stems prior to sawing or chipping. Ring-style debarkers consist of a ring of cutting heads or knives that are mounted on a series of arms in a circular position. The rings have a variable pressure capacity for relaxing and constricting while rotating around the log to adapt to the difference in contour and diameter of each log. Ring-style debarker with the features on cleaning debarking, steady and reliable logs supplement, high value softwood or hardwood production, are becoming the popular choice for some mills (Nicholson Manufacturing Co. 2000).

Cradle debarker. The cradle debarker is designed to remove bark from de-limbed logs in a manner that reduces debarking energy use by up to 33% (U.S. DOE 2002b). According to the U.S. DOE, a cradle debarker works in the following manner: Logs are loaded into a long trough that contains a series of horizontal and vertical conveyor chains, which are oriented at a slight angle to the path of the logs. The chains lift and drop the logs as they move along the trough; this action loosens and removes bark via compressive and shear forces that are generated between the logs in the trough (U.S. DOE 2002b). Additional reported benefits include less damage to logs leading to a greater wood recovery rate, decreased transportation costs through elimination of off-site debarking, and greater process control. The U.S. DOE reported that the cradle debarker can save a mill $30 per ton of wood in debarking costs (U.S. DOE 2007a).

Replace pneumatic chip conveyors with belt conveyors. Two common methods of transporting wood chips within a mill are pneumatic conveyors and mechanical (belt) conveyors. Of these, belt conveyors are typically far more energy efficient (Martin et al. 2000). An analysis

by the National Council for Air and Steam Improvement (NCASI 2001) illustrates the possible savings of replacing pneumatic conveyors with belt conveyors at a typical mill. For a mill operating at 1,000 tons per day, it was assumed that an 18.2 kWh/ton pneumatic conveyor from the chip pile to screening could be replaced by a 1 kWh/ton belt conveyor. The resulting energy savings were estimated at 17,200 kWh per day, or $210,000 per year in electricity costs (NCASI 2001). Belt conveyors can also reduce fine and chip pin losses, which can improve yield by about 1.6% (Martin et al. 2000). However, installation and maintenance costs associated with belt conveyors can be significant.

Use secondary heat instead of steam in debarking. In some parts of the country, logs can freeze during the winter season and require defrosting prior to debarking operations. Defrosting is commonly done by steam thawing, hot water sprinklers, or hot ponds (NCASI 2001). When feasible, hot water and/or steam for use in defrosting can be generated from waste heat recovered from other sources in the mill. According to an analysis by NCASI (2001), the typical steam use associated with defrosting (northern conditions) was approximately 0.5 MMBtu per air dried ton (ADT) of pulp. Replacing this steam use by recovered heat was estimated to save over $150,000 per year in energy costs (NCASI 2001), although energy savings will vary based on boiler fuel type and costs. Capital investments were estimated at $110,000 primarily for piping.

Automatic chip handling and thickness screening. Automated chip handling is based on the "first in, first out" inventory principle to maintain more consistent wood chip aging. Improved screening processes that allow for a more even size distribution of wood chips entering the digester will reduce steam consumption in both the digester and the evaporator in chemical pulping (Elaahi and Lowitt 1988). Combined, automated chip handling and thickness screening can result in reduced cooking energy, higher pulp yields, higher by-product yields, and less chip damage due to handling. Published estimates suggested that digester yield can be increased by approximately 5% to 10% (which is offset somewhat by raw material screened out as undersized), which can reduce raw materials input (which also reduced raw materials transportation requirements) and save hundreds of thousands of dollars in energy costs per year (Focus on Energy 2006a). It is estimated that the return on investment is about 15% to 20% for this measure.

Bar-type chip screens. The design of a bar screen is different from the majority of the installed disc and V-type screens in the United States. Due to the design, the life-time of a bar-screen is longer than that of conventional screens. Maintenance costs in bar screens are lower, and working energy consumed is minimal (Strakes 1995). Martin et al. (2000) estimated energy savings from bar-type screen installations at 0.33MMBtu/ton chemical pulp, due to about 2% increase in yield. Operation and maintenance cost savings due to improved yield were estimated at $0.70/ton pulp (Kincaid 1998). Capital costs required for new bar-type screens were approximately the same as for other screening equipment (U.S. EPA 1993).

Chip conditioning. Chip conditioners prepare chips for efficient delignification by making cracks along their grains, unlike chip slicers that fractionate chips (Henry and Strakes 1993). According to Martin et al. (2000), chip conditioning generated fewer fines, achieved an average reduction of 1.2% in rejects, and required less maintenance than slicing equipment. Energy savings from replacing chip slicers with chip conditioners had been estimated at 0.19MMBtu/ton

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chemical pulp, and savings in operations and maintenance costs from improved yield had been estimated at $0.40/t chemical pulp (Kincaid 1998; Martin et al. 2000).

Screen out thick chips. Chip size and uniformity directly influence the amount of specific energy required, motor load stability, refiner performance and pulp quality (J&L Fiber Service, Technical Group 1989). Chip thickness screening is to remove pins and fines and the re-direction of oversize chips for further processing in pulp mill operations, can reduce costs, improving productivity, yield and overall operational efficiency (Acrowood Corporation 2007).

Enzyme-assisted debarker. For fossil energy consumption and potential environmental impacts reduction, in the pulping process, the logs are pretreated with enzyme before debarking. Enzyme assisted debarking is one of the main available technologies for debarking wood entering the plant (Clark et al. 2007; Martin et al. 2000).

D.2 Energy Efficiency Measures for Chemical Pulping

The majority (85%) of U.S. wood pulp is produced by chemical pulping processes. Similarly, chemical (i. e., Kraft) pulping and its associated chemical recovery account for the vast majority of steam, electricity, and direct fuel used by the industry in the manufacture of pulp. Efficiency improvements to the chemical pulping process can therefore lead to significant energy savings across the industry. This section briefly discusses some of the most significant energy saving measures for Kraft pulping, bleaching, and chemical recovery.

Use of pulping aids to increase yields. Advanced chemical pulping aids can be added to the pulping process to increase liquor penetration and promote more even cooking. This can increase pulp yields and lead to reduced energy consumption per ton of pulp, reduced raw material inputs, and improved productivity. The financial viability of this measure is typically determined by comparing the costs of chemicals to the projected fiber savings; some studies have suggested savings of approximately $20 per ton of bleached pulp after the cost of chemicals have been considered (Focus on Energy 2006a). Anthraquinone compounds are commonly used as chemical pulping aids, but new alternatives are emerging.

For example, with help of U.S. DOE the application of the chemical ChemStone OAE-11 was investigated. Reportedly, this chemical can be applied at both hardwood and softwood pulps and also protects fine fibers from over processing (U.S. DOE 2008). It was estimated that the reduction of cooking time can lead to energy savings of 125,000 Btu per ton of processed wood chips. Other reported benefits included an increase in yield of 2-5% per ton of wood, reductions in rejected pulp, less use of bleaching chemicals, and reductions of sulfur-based emissions (U.S. DOE 2008; Ronneberg and Jennings 2007).

Phosphonate is another emerging chemical pulping aid. Preliminary results of a U.S. DOE project suggested that adding phosphonate to Kraft cooking liquor increases lignin removal, improves yield and bleached brightness, and conserves pulp viscosity (U.S. DOE 2006b). Energy savings of phosphanate addition were estimated at 8-10%, and yield increases were estimated at 4-6% (U.S. DOE 2006a). Additional reported benefits were an expected reduction in pulping chemical use and a corresponding reduction in effluent.

Optimize the dilution factor control. Organic solids and spent cooking chemicals can be washed from the pulp with brown stock, resulting in a higher level of chemical recovery while

minimizing dilution of black liquor. According to NCASI, optimizing the dilution factor control will lower the average amount of water that must be evaporated from weak black liquor, thereby reducing steam consumption in the evaporators (NCASI 2001). The dilution factor can be optimized by controlling shower water flow on the last washing stage to an optimum level that can be determined by considering the cost of steam, the cost of bleaching chemicals, the impact on effluent quality, and other process variables (NCASI 2001).

At an assessment of a Weyerhaeuser pulp and paper mill in Longview, Washington, a project was identified to improve digester washing and to reduce the dilution factor. It was estimated that these improvements would save 200 gallons of water per minute, and 310,000 MMBtu of natural gas annually (U.S. DOE 2004a). The projected annual cost savings associated with these measures was $580,000.

Continuous digester control systems. Improving digester performance can significantly reduce production losses, operating costs, and negative environmental effects while increasing paper quantity and quality (U.S. DOE 2008, 2007b). Control systems can optimize the process based on key mechanical, chemical, and thermal process parameters. For example, a computer model sponsored by the U.S. DOE allows for material, energy balance, and diffusion simulations to be calculated as various-origin chips pass through a continuous digester, which can help identify process improvements. The model's first commercial application in a Texas mill allowed the temperature to be reduced in part of the pulping process, thereby saving 1% of the process energy (U.S. DOE 2008, 2007b).

Batch digester modification. For smaller mills, it may not be operationally efficient to switch to larger batch digesters in the digesting operation. Additionally, specialty mills or mills that need to be able to produce a variety of pulp types are less suited for continuous digesters. There were several approaches to reduce energy consumption in batch digesters, such as the use of indirect heating and cold blows (Martin et al. 2000).

In indirect heating, cooking liquor is withdrawn from the digester through a center pipe, pumped through an external heat exchanger, and returned into the digester at two separate locations in the vessel, thereby reducing direct steam loads (Martin et al. 2000). Energy savings were estimated to amount to 3 MMBtu/ton; however, there were some additional maintenance costs with this system including maintaining the heat exchangers (Elaahi and Lowitt 1988).

In cold blow systems, hot spent pulping liquor is displaced from the digester contents using brown stock washer filtrate at the end of the cooking cycle. Heat is thereby recovered from the spent liquor for heating subsequent cooks, leading to reduced steam requirements for heating the digester contents (NCASI 2001). Recovered black liquor can be used for preheating and impregnating incoming wood chips or for the heating of other process inputs, such as white liquor or process water. An analysis by NCASI estimated that for a typical 1,000 ton per day mill, annual energy savings would be approximately $2 million (NCASI 2001). However, capital costs for additional equipment (i. e., additional pumps and accumulators for the recovered black liquor) are quite high for this measure.

Digester blow/flash heat recovery. In the Kraft chemical pulping process, steam is produced when hot pulp and cooking liquor is reduced to atmospheric pressure at the end of the cooking cycle. In batch digesters, steam is typically stored as hot water in an accumulator tank. In

continuous digesters, extracted black liquor flows to a tank where it is flashed (NCASI 2001). Recovered heat from these processes can be used in other facility applications, such as chip pre-steaming, facility water heating, or black liquor evaporation (NCASI 2001; Focus on Energy 2006a).

For black liquor evaporation, flash steam from batch digester blow (created by flashing from the hot water accumulator) or black liquor flash from a continuous digester can used for thermal energy in a multi-stage evaporator. This thermal energy will offset the need for steam generated by a boiler for black liquor evaporation (NCASI 2001).

In chip steaming, the black liquor that is flashed in stages from continuous digesters can be used in two ways. Flash vapor from the first stage is normally used to heat the chips in the steaming vessel, while the flash vapor of the second stage can be used instead of live steam in the chip bin (NCASI 2001). Reportedly, the use of flash steam in the chip bin been proven out at several North American mills; however, U.S. regulations state that the vent from the chip bin has to be collected and treated if flash steam is used for chip preheating (NCASI 2001).

A plant-wide energy audit of Georgia-Pacific's mill in Crossett, Arkansas, recommended improving blow heat recovery from the mill's two parallel batch digester lines. At the time of the audit, a cooling tower was used to remove excess heat from the blow steam accumulator and a steam heater was used to generate hot water for the bleach plant (U.S. DOE 2003). The audit team recommended installing new heat exchangers and rerouting water lines such that the cooling tower and steam heater could be shut down. It was estimated that this project would save 940,000 MMBtu of fuel, 705,000 MMBtu of natural gas, and $2,350,000 in costs each year with a payback period of approximately one year (U.S. DOE 2003).

At the Weyerhaeuser pulp and paper mill in Longview, Washington, the proposed addition of a digester heat recovery system was expected to result in annual natural gas savings of 130,000 MMBtu, leading to $280,000 per year in cost savings (U.S. DOE 2004b).

Continuous digester modifications. Continuous digesters reuses process steam, which are more space efficient, energy efficient and more product flexibility than batch digesters (Kramer et al. 2009). Modifications of the continuous digesters focus on reducing the amount of material that must be heated and increasing the level of heat recovery. Measures involve minimizing the liquor to wood ratio, improving the recycling of waste heat, use of heat exchangers, improved steam recovery, and increased insulation (Elaahi and Lowitt 1988). Increased indirect heating as a result of these modifications also can improve pulp uniformity, strength, and yield (Martin et al. 2000).

White-water heating. White water is filtered to separate fibers, fines and filler materials to provide a clean source of reusable water meeting operational and ecological requirements. Whitewater heating brings about benefits of speedy start-up, efficient heat transfer, elimination of recirculation pump, and low maintenance from the direct steam injection technology.

Vapor take-off. Evaporation is the largest use of steam in the Kraft pulp production, the efficiency of this steam usage can be maximized by multiple effect evaporators, and much of this steam can be reused in the form of condensate or hot water in other facility application (Kramer et al. 2009).

Install blow heat (batch digester) or flash heat. The batch digester and continuous digester are two types of pulp digesters. The decision on installing one or the other system is based on the mill basis and the factors such as product mix, environmental constraints, energy costs, future expansion and capital and operating costs (Fuller 1987).

Replace conventional batch digesters with cold blow system. Conventional batch digesters continue to be replaced by modern displacement batch digesters as mills are modernized (Shackford 2003). The upgrade results in higher yield screen, more uniform cook, less kappa variation, less energy consumption in the evaporator and better pulp quality. Cold-blow batch digesters feature liquor circulation through sidearm, electrical heating in circulation line, basket inserts to hold chips, and piping configuration permits chemical profiling during cook.

Use two pressure levels of streaming in batch digester. The digester controls including heating, cooking, blowing, relieving, turnover, shakeup and blow-back control. The high pressure feeder is for getting the chips into the digester, while the low pressure (or reduced pressure) is for a rapid decrease in temperature but enough to separate the fibers from the chips. Using two level pressures in steam power balance is to increasing the flow of high pressure stream through the high efficiency turbine connected to the electrical generator and reducing steam flows through low efficiency mechanical drive turbines or zero efficiency pressure reducing stations.

Use flash heat in a continuous digester to preheat (NCASI 2001). Continuous digesters, which are capable of processing the woodchips in a continuous stream, are at about 40% lower energy consumption than for batch digesters (Thielsch and Cone 1994; Fuller 2003).

Use evaporator condensates on decker showers. According to EPA Cluster Rules, the methanol removing on selected foul condensate streams from digesters and evaporators is required. Evaporator condensates may be segregated using external liquor heaters, secondary condensate, internal baffles or by simply removing condensates from individual effects, and be sent to existing effluent treatment system are reused as wash water on decker (Mittet et al. 1999). Gu and Edwards (2001) predicted that the total fiber line methanol air emissions will be 1/3 lower than that time's emission.

Convert evaporation to seven-effect operation. Evaporation is the single largest use of stream in the production of Kraft pulp. Multiple effect evaporators can maximize the efficiency of this steam use and the use of seven effects is currently considered industry best practice.

Heat recovery from bleach plant effluents. Bleach plant effluents can contain a large amount of heat, which will be wasted if the effluents are discharged without heat recovery. Heat exchangers can be installed to recover some of this heat for other beneficial uses around the mill, including hot water heating.

At Georgia-Pacific's mill in Crossett, Arkansas, an audit uncovered an opportunity for installing heat exchangers to recover heat from bleach plant effluent for the generation of hot water for the mill's paper machine. Estimated energy savings were 890,000 MMBtu per year, with annual cost savings of approximately $2.4 million (U.S. DOE 2003). With an estimated capital investment of $1.6 million, the expected payback period was only 0.7 years (U.S. DOE 2003).

Improved brown stock washing. Conventional brown stock washing technology consists of a series of three to four drum washers where a fiber mat under vacuum pressure is sprayed with water to dissolve solids. State-of-the-art washing systems replace the vacuum pressure units with pressure diffusion or wash presses. These systems reportedly remove solids more efficiently; require less electric power and/or steam and less bleaching chemicals (Martin et al. 2000). In particular, wash presses have demonstrated improved efficiency and their adoption is becoming widespread in the industry. Published estimates suggested steam savings associated with state-of-the-art washing systems of approximately 9,500 Btu per ton of production, and electricity savings of approximately 12 kWh per ton of production (Martin et al. 2000).

Chlorine dioxide (ClO$_2$) heat exchange. Solutions of ClO$_2$ are normally chilled to maximize ClO$_2$ concentration prior to use in the bleach plant. However, preheating of ClO$_2$ before it enters the mixer will reduce steam demand in the bleach plant, and is therefore an important energy conservation measure (NCASI 2001). Pre-heating can be accomplished using secondary heat sources by installing heat exchangers in the ClO$_2$ feed circuit.

For example, at a Georgia-Pacific mill in Crossett, Arkansas, a U.S. DOE sponsored audit identified an opportunity to pre-heat ClO$_2$ using chiller feed water. The mill operates two chillers to provide cold water for the ClO$_2$ plant; each chiller takes well water at 70F and chills it down to 45F. A proposed prechiller would utilize 50F ClO$_2$ solution from the bleach plant to cool the incoming well water while simultaneously preheating the ClO$_2$ solution, thereby reducing bleach plant steam demand. Annual savings in fuel, electricity, and steam were estimated at $61,000 while capital costs were estimated at $124,000 (U.S. DOE 2003). The payback period of this measure was therefore around 2 years, which is similar to estimated payback periods elsewhere in the literature (NCASI 2001).

Ozone bleaching. Ozone bleaching is an alternative bleaching process that can produce pulp of equal brightness to either ECF or TCF (Martin et al. 2000). Used in the right combination of stages, ozone bleaching can save capital costs, reduce consumption of chlorine dioxide, and eliminate one washing stage (Finchem 1998). The use of ozone was proven to be effective with and without oxygen delignification, and employed much of the existing bleach plant equipment, thereby minimizing capital costs for the installation (Ferguson 1997).

Washing press (post delignification). Lower water consumption can be achieved through recycling bleach plant filtrates for dilution and washer showers without excessive increase in chemical consumption (Martin et al. 2000). Pulp washing on presses (with a washing efficiency of 70-85%) instead of filters (with a washing efficiency of 65%) is a significantly better pulp washer than a filter, but has higher equipment capital costs. However, lower building costs and smaller filtrate tanks associated with washing press can compensate or even outweigh the increased equipment capital cost of press washer. Savings in steam and chemicals consumption provide additional benefits. Therefore, a press-bleach plant may be a competitive alternative for a new pulp mill, for green field capacities and for retrofitting plants. Martin et al. (2000) assumed that capital costs for both filters were the same. Press washers can also be considered as a good alternative for mill retrofits and additional washing stages, since they had very small space requirements (Panchapakesan et al. 1993).

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ClO$_2$ filtrate heating. Solutions of chlorine dioxide (ClO$_2$) are normally chilled to maximize ClO$_2$ concentration prior to use in the bleach plant (Kramer et al. 2009). Preheating of ClO$_2$ before it enters the mixer is an energy conservation measure due to its effect on reduced steam demand in the bleach plant.

Reline lime kiln using high performance. Relining a lime is a routinely improved maintenance event. This is a new practice with empirical information in the pulp mills, with an estimated energy savings about $250,000 in a typical mill annually as well as the fossil fuel savings. The difference in costs between standard and high performance was less than $20,000 for a typical kiln, while the return on investment was in excess of 100% (Focus on Energy 2006a).

Efficient bleaching chemical mixing in the pulp. Improving efficiency of bleaching chemical mixing can reduce energy use, chemical use, and waste water treatment (Focus on Energy 2006a).

Optimize the dilution factor control. Organic solids and spent cooking chemicals can be washed from the pulp with brown stock, resulting in a higher level of chemical recovery while minimizing dilution of black liquor. According to NCASI, optimizing the dilution factor control will lower the average amount of water that must be evaporated from weak black liquor, thereby reducing steam consumption in the evaporators (NCASI 2001). The dilution factor can be optimized by controlling shower water flow on the last washing stage to an optimum level that can be determined by considering the cost of steam, the cost of bleaching chemicals, the impact on effluent quality, and other process variables (NCASI 2001).

Lime kiln oxygen enrichment. Oxygen enrichment is an established technology for increasing the efficiency of combustion, and has been adopted in various forms by a number of industries with high-temperature combustion processes (e. g., glass manufacturing). Oxygen enrichment of lime kilns can reduce fuel requirements by approximately 7-12% (Focus on Energy 2006a). Reportedly, capital investments for oxygen enrichment are low, with only feed piping, an injection lance, and controls required (McCubbin 1996). Payback periods have been estimated between roughly one and three years (Focus on Energy 2006a).

Lime kiln modification. Several modifications are possible to reduce energy consumption in lime kilns. High efficiency filters can be installed to reduce the water content of the kiln inputs, thereby reducing evaporation energy. Higher efficiency refractory insulation brick can be installed to decrease radiation heat losses from the kiln. For example, one published estimate suggests that newer high-performance refractory can lead to lime kiln energy savings of up to 5% (Focus on Energy 2006a). Heat can also be captured from the lime and from kiln exhaust gases to pre-heat incoming lime and combustion air. Martin et al. (2000) estimated that the energy savings achievable through the combined application of the above measures was approximately 0.47 MMBtu per ton of production. Furthermore, such improvements may also improve the rate of recovery of lime from green liquor, thus reducing a mill's requirement for additional purchased lime (Martin et al. 2000)

Lime kiln electrostatic precipitators. Electrostatic precipitators can replace wet scrubbers on lime kilns and lead to energy and water savings. Electrostatic precipitators can collect kiln dust as a dry material, and return it directly to the kiln feed without unnecessarily loading the lime mud filter (NCASI 2001). In contrast, wet scrubbers require effluent recycling via the lime mud

filter and are significant consumers of water (Focus on Energy 2006a). One published estimate suggests that for every 1% reduction in lime mud feed moisture content (through the addition of dry dust), lime kiln energy consumption is reduced by approximately 46 MMBtu (Focus on Energy 2006a). An analysis by NCASI suggested increasing mud dryness from 70% to 75% would reduce fuel consumption by 0.4 MMBtu per ton of lime (NCASI 2001).

Black liquor solids concentration. Black liquor concentrators are designed to increase the solids content of black liquor prior to combustion in a recovery boiler. Increased solids content means less water must be evaporated in the recovery boiler, which can increase the efficiency of steam generation substantially. There are two primary types in use today: submerged tube concentrators and falling film concentrators.

In a submerged tube concentrator, black liquor is circulated in submerged tubes where it is heated but not evaporated; the liquor is then flashed to the concentrator vapor space, causing evaporation (NCASI 2001). An analysis by NCASI suggests that for a 1,000 ton per day pulp plant, increasing the solid content in black liquor from 66% to 80% would lead to fuel savings of 30 MMBtu/hour, or roughly $550,000 (NCASI 2001). Capital costs of the high solids concentrator will include concentrator bodies, piping for liquor and steam supplies, and pumps (NCASI 2001).

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% solids rather than the traditional 50%), thus eliminating the need for a final concentrator (Nilsson et al. 1995). Martin et al. (2000) estimated a steam savings of 0.76 MMBtu per ton of pulp (Elaahi and Lowitt 1988).

A U.S. pulp and paper mill with 900 ton paper production per day installed a liquor concentrator to increase its solids content from 73% to 80%. This increase results in annual energy savings of about 110,000 MMBtu. Costs saving were about $900,000/year, leading to an estimated period of payback of 4 years (Kramer et al. 2009).

Improved composite tubes for recovery boilers. Recovery boilers consist of tubes that circulate pressurized water to permit steam generation. These tubes are normally made out of carbon steel, but severe corrosion thinning and occasional tube failure has led to the search for more advanced tube alloys. Research sponsored by the U.S. DOE led to the development of new weld overlay and co-extruded tubing alloys. These advanced alloys make it possible to use black liquor with higher dry solids content, leading to an increase in boiler thermal efficiency, as well as to a decrease in the number of shutdowns. Improved composite tubes have been installed in more than 18 Kraft recovery boilers in the United States, leading to a cumulative energy savings of 4.6 TBtu since their commercialization in 1996 (U.S. DOE 2007b).

Recovery boiler deposition monitoring. Better control of deposits on heat transfer surfaces in recovery boilers can lead to higher operating efficiencies, reduced downtime (due to avoidance of plugging), and more predictable shutdown schedules. A handheld infrared inspection system has been developed that can provide early detection of defective fixtures (tube leaks or damaged soot blower) and slag formation, preventing impact damage and enabling cleaning before

deposits harden (U.S. DOE 2007b). The system can reportedly provide clear images in highly particle-laden boiler interiors, and enable inspection anywhere in the combustion chamber. As of 2005, 69 units were in use in the United States, generating 1.4 TBtu in energy savings since their introduction in 2002 (energy savings are attributable to reduced soot blower steam use) (U.S. DOE 2007b).

Quaternary air injection. According to Focus on Energy (2006a), most recovery boilers in the United States have three stages of air injection, but utilize the third stage in a limited fashion. By fully utilizing the third stage and adding a fourth air injection port, carry over and tube fouling can be reduced. This can reduce the frequency of recovery boiler washing, which will lead to energy savings because boiler shut downs and reheat can be reduced. Focus on Energy (2006a) estimated that each boiler reheat-cycle will consume approximately 10 MMBtu at a cost of approximately $50,000. Capital costs for this measure were estimated at $300,000 to $500,000 (Focus on Energy 2006a).

Falling film black liquor evaporation. The falling film effect is more resistant to fouling because the liquor is flowing faster and allows the evaporator to produce black liquor with relatively higher solids content (Martin et al. 2000), up to 70% solids rather than the traditional 50% thus eliminating the need for a final concentrator without the need of a final concentrator (Martin et al. 2000; Nilsson et al. 1995).

D.3 Energy Efficiency Measures for Mechanical Pulping

Although less common than chemical pulping, mechanical pulping operations still account for approximately 8% of wood pulp production in the United States. Mechanical pulping is also the primary method used in the manufacture of pulp from recycled and secondary fibers. This chapter discusses some key energy saving measures for various aspects of mechanical pulping operations.

Refiner improvements. Several improvements are possible within the refiner section of a mill, which can reduce electricity consumption in mechanical pulping. For example, a newsprint mill in Quebec, Canada implemented a refiner control strategy to minimize variations in the freeness of ultra-high-yield sulfite pulps and saved 51.3 kWh per ton of production due to reduced motor load (Tessier et al. 1997). Another option in refining is the switch to conical refiners rather than disk refiners. By decreasing the consistency of pulping to about 30% from 50%, a 7-15% electricity savings were possible in TMP and RMP processes (Alami 1997). Martin et al. (2000) estimated an electricity savings potential of 11% due to such mechanical refining improvements, at a capital cost of approximately $7.7 per ton of pulp production.

Refiner optimization for overall energy use. Fibers (either from waste paper or virgin pulp) are refined to optimize fiber properties. However, refining also leads to higher water retention in the fiber, which leads to lower dewatering on the wire and hence increased steam consumption in the dryer. The increased water retention can potentially lead to additional energy costs of $30-$40 per ton of paper (Westenbroek and Dekker 2006). Hence, in refiner operation it is important to include water retention in the optimization strategy. Alternatively, it is important to optimize the refiner effect on steam consumption by improved pulp selection.

Pressurized groundwood. Pressurized groundwood pulping was first developed in Scandinavia in the 1970s. In a pressurized groundwood system, grinding takes place under compressed air pressure where water temperature is high (more than 95 ℃), thereby allowing for higher grinding temperatures without steam flashing (Martin et al. 2000). The higher temperature promotes softening of the lignin, which improves fiber separation and reduces specific energy consumption (NCASI 2001). The technical literature claimed approximately 20-36% saving in electricity compared with atmospheric mechanical pulping processes (Martin et al. 2000; NCASI 2001). So-called super pressurized groundwood technology—which operated at higher temperatures and pressures than pressurized groundwood technology—provided better smoothness and opacity of paper (U.S. EPA 1993).

Continuous repulping. The repulping process for purchased market pulp involves blending the dried pulp feedstock with water in a large tank to produce fibrous slurry. Typically this is done as a batch process, but converting to a continuous process can lead to energy savings due to improved process efficiency. Focus on Energy (2006a) estimated that energy savings of up to 40% are possible, in the form of reduced pulping motor power requirements. If the existing repulper can be retrofitted, capital costs were estimated approximately $100,000 (Focus on Energy 2006a).

Efficient repulping rotors. Newer repulper rotor designs have been optimized for power consumption using computational fluid dynamics simulations to study the interaction of rotors with pulping slurries. Reportedly, replacing an existing rotor with a new rotor that is optimized for efficiency can reduce rotor motor consumption by anywhere from 10% to 30% (Focus on Energy 2006a). Payback periods for this measure have been estimated at one to two years (Focus on Energy 2005a).

Wausau Paper installed and tested a new 500HP high efficiency repulper rotor in its mill in Rhinelander, Wisconsin. Reportedly, the high efficiency rotor reduced re-pulping electricity consumption by 23%, while producing a pulp furnish with similar defibering time and fiber quality as their conventional repulper rotor (Focus on Energy 2005b).

In another example, Canfor's Northwood Kraft Pulp Mill in Prince George, British Columbia tested a new high capacity, aerodynamic, variable speed pulping rotor. The design of the rotor allows operation at lows speeds while still effectively cleaning the pulper screen apertures (BC Hydro 2006). Reportedly, the new rotor reduced electricity consumption by more than 50%, while producing the same or higher tonnage with similar removal efficiency. Projected annual energy savings amounted to approximately 3.6 GWh, or about $193,000 in electricity costs (BC Hydro 2006).

Drum pulper. Drum pulpers are applicable to mills that generate pulp from recovered paper and paperboard products. A drum pulper is essentially a rotating, inclined drum with baffles that is used to mix recovered fiber sources, water, and (in de-inking applications) de-inking chemicals. The more gentle mechanical action of drum depulpers allows contaminants to remain intact while the paper is defibered (Focus on Energy 2006a; NCASI 2001). Drum pulpers have lower energy requirements than conventional mechanical pulpers, can use less water, and reduce fiber shortening (Focus on Energy 2006a; APPW 2004). However, when drum pulpers are used in brown fiber applications, the rapid wetting of furnish and the incomplete removal of bailing wire can reportedly cause problems (APPW 2004). An analysis by NCASI suggests that replacing a

vat type batch pulper with a continuous drum pulper in de-inking operations can reduce specific pulping energy by over 25% (NCASI 2001).

Increased use of recycled pulp. The production of recycled pulps consumes, on average, significantly less energy than that required to produce mechanical or chemical wood pulps. According to the AFPA, nearly 200 U.S. mills relied exclusively on recovered paper for pulp production, and roughly 80% of U.S. mills used recovered paper in some fashion (U. S. EPA 2002). In its collaborative research work with the U.S. DOE, the U.S. pulp and paper industry was pursuing an increased use of recycled pulp to further reduce energy use associated with virgin pulping processes (Martin et al. 2000). Martin et al. (2000) estimated that costs for the construction of recycled pulp processing capacity in the United States were approximately $485 per ton of pulp; however, depending on the price of waste paper versus virgin pulp this might result in up to $73.9 per ton of pulp in operations and maintenance cost savings (O'Brien 1996). However, recycled pulp produces sludge that can present a disposal difficulty.

Heat recovery from de-inking effluent. De-inking effluents are often discharged at elevated temperatures and represent a possible source of low-grade heat recovery in a typical recycled fiber pulping mill. The installation of heat exchangers in the effluent circuit can recover some of this heat for other beneficial uses, such as facility water heating.

For example, a U.S. DOE sponsored energy assessment (U.S. DOE 2004c) at the Blue Heron Paper Company mill in Oregon City, Oregon, revealed a cost-effective opportunity for effluent heat recovery. The mill produces newsprint and specialty paper products on three paper machines, using about 60% recycled fiber from old newsprint and magazines. The mill's combined effluent streams were at approximately 120°F with a flow rate of 600 gallons per minute. A proposed heat exchanger would generate warm filtered shower water for the mill's paper machines, which would offset some of the mill's steam demand. Annual boiler fuel savings of 37,000 MMBtu were estimated, which would lead to annual cost savings of $125,000 (U.S. DOE 2004c). Capital costs were estimated at $375,000; the resulting payback period would be approximately 3 years.

Fractionation of recycled fiber. Andritz (Austria) has tested the potential of separating the long fibers and short fibers in a deinking line. This enables a simplification of the deinking line (with a capital reduction of 13-22% compared to traditional DIP-lines), and a reduction electricity by 11-13% and thermal energy of 40% (Hertl 2008). This setup is now being implemented and tested at the newsprint mill of PerlenPapier in Switzerland.

Thermopulping. Thermo-pulping is a variation of the TMP process whereby pulp from the primary stage refiner is subjected to a high temperature treatment for a short time in a thermo-mixer and in the subsequent secondary refiner. Temperatures in the primary stage are below the lignin softening temperature. The higher operating pressures in the secondary refiner reduce the volumetric flow of generated steam. An advantage is that in contrast with other energy savings technologies this process can be turned on and off as desired by mill personnel. A drawback is a small brightness loss and a slight reduction in the tear index (Martin et al. 2000; Miotti 2001). Published estimates suggested that thermo-pulping can reduce specific energy consumption compared to TMP by up to 20% (Miotti 2001; Ola et al. 1998).

RTS pulping. RTS stands for short residence time, elevated temperature, high speed pulping. In the RTS process, energy consumption is reduced by increasing the rotational speed of the primary refiner. This leads to reduced residence time, smaller plate gaps, and higher refining intensity. Chips are subjected to elevated temperatures for a short residence time prior to high speed primary stage refining. (Martin et al. 2000). Temperatures of approximately 165 °C are used, resulting in a reduction in specific energy consumption with no loss of pulp quality and a one-point brightness improvement (Cannell 1999; Ferguson 1997; Patrick 1999). Published estimates for the energy savings achievable with RTS pulping varied. Martin et al. (2000) estimated that RTS pulp can be produced with approximately 15% lower specific energy requirements than pulp produced with a traditional refining system. Data from Miotti (2001) suggested that the specific energy of RTS pulping is approximately 20% lower than TMP processes. Focus on Energy (2006a) estimated that the effect of increasing rotational speed on TMP refiners would reduce energy use by anywhere from 15-30%, depending on plate type and refiner mode. Reportedly, RTS pulp has slightly higher strength properties and comparable optical properties to TMP pulps.

Heat recovery in TMP. A vast amount of steam is produced as by-product of thermo mechanical pulping. This low-pressure steam is often contaminated, but most of the energy can be reclaimed for use in other mill processes through heat recovery equipment. Heat recovery options include: (1) mechanical vapor recompression (Tistad and Asklund 1989; Martin et al. 2000) for integrated mills, where the clean steam generated can be used in the paper machine dryer section (Martin et al. 2000), (2) direct contact heat exchangers for generating hot water for use in paper machines and as boiler makeup water and clean process steam (Focus on Energy 2006a), (3) re-boilers for producing clean process steam (NCASI 2001), and (4) other devices such as thermo vapor recompression and cyclo-therm plus heat pump systems (Martin et al. 2000; Klass 1999). According to NCASI (2001), TMP heat recovery is applicable to any mill that uses pressurized refining and currently does not use heat recovery (which usually means older mills, because most modern TMP mills are designed with heat recovery systems). Focus on Energy (2006a) estimated that typical heat recovery systems for pressurized refiners can generate 1.1 to 1.9 tons of clean steam at dryer can pressure per ton of pulp. Payback periods varied widely depending on capital costs, but can be as low as a few months (Focus on Energy 2006a; NCASI 2001; Martin et al. 2000). Martin et al. (2000) estimated average installation costs of $21 per ton of pulp with significant increases in operations and maintenance costs. Jaccard et al. (1996) reported a wide range of installation costs.

Biopulping. Biopulping is defined as the treatment process of wood chips or other lignocellulosics with a natural lignin-degrading fungus which containing a variety of enzymes (or isolated enzymes) that break down the lignin prior to pulping. The primary economic advantage of biopulping is led by significantly improved strength of the biomechanical pulp fibers as a substitution for expensive chemical pulp produces large savings (Swaney et al. 2003). The reduction in pitch content of chips and the elimination of other spore are the two major sources of savings.

Replace the conventional groundwood process with pressurized groundwood (PGW) operation. Pressurized groundwood pulping was first developed in Scandinavia in the 1970s. In a pressurized groundwood system, grinding takes place under compressed air pressure where water temperature is high (more than 95 °C), thereby allowing for higher grinding temperatures

without steam flashing (Martin et al. 2000). The higher temperature promotes softening of the lignin, which improves fiber separation and reduces specific energy consumption (NCASI 2001). The technical literature claimed around 20-36% saving in electricity compared with atmospheric mechanical pulping processes (Martin et al. 2000; NCASI 2001). So-called super pressurized groundwood technology—which operated at higher temperatures and pressures than pressurized groundwood technology—provided better smoothness and opacity of paper (U.S. EPA 1993).

Reduce operating temperature in de-inking plant. De-inking is the industrial process of removing printing ink from paper fibers of recycled paper to making deinked pulp. The key in the deinking process is the ability to detach ink from the fibers, which is achieved by a combination of mechanical action and chemical means. The de-inking plant currently uses live steam to heat water in the pulper supply tank to a temperature of 125°F. The energy in the steam input varies from 9 MMBtu/hr. in summer to 16 MMBtu/hr. in winter. Almost all of this heat is added to the mill effluent. De-ink operation practices to reduce temperatures by 5° could save about 4 MMBtu/hr. of steam use. Considerable analysis would be required before implementation, because temperature changes could negatively impact the quality of pulp produced (DOE, OIT 2003).

Replace pump impellers in pressurized de-inking. The pressurized de-inking module (PDM) removes ink and other materials from the pulp. Optimized pump impellers used in de-inking modules can effectively lower the horsepower requirements.

D.4 Energy Efficiency Measures for Papermaking

Papermaking process accounts for about half of the total steam, electricity, and direct fuel used by the U.S. pulp and paper industry. In particular, the drying stage of the paper machine accounts for the vast majority of thermal energy use in papermaking. Most energy saving opportunities for papermaking are therefore related to improving the efficiency of the drying process and recovering its waste heat for beneficial use. This chapter discusses several key energy saving measures that can help reduce the energy use of papermaking (TAPPI 2003). Combined, such measures for improving the efficiency of papermaking can add up to big energy and cost savings.

For example, one two-machine mill reduced annual energy costs by $ 1 million by implementing several paper machine efficiency improvements. These improvements included adjusting dryer differential pressures to reduce steam venting to the condenser, reducing rewet after the last press, lowering whitewater temperatures, modifying the dry end pulper so one agitator could be shut down when the sheet was on the reel, lowering pocket ventilation supply air temperatures, and upgrading paper machine clothing designs.

In another example, Procter & Gamble won a Wisconsin Governor's 2008 Pulp and Paper Energy Efficiency Award for the development of a new energy efficient tissue paper machine at their Green Bay location (Wroblewski 2009). The new paper machine uses 19% less natural gas and electricity than the most recent similar machine installed in 2004 that makes a similar paper grade (normalized for production schedule differences). The machine design is customized, and has a blend of commonly accepted design practices, including efficient lighting, premium efficiency motors, and low-NOx burners, as well as uncommon features such as cascade heat uses. Reportedly, the new paper machine will save 20,000 metric tons of CO_2 per year, while reducing other air emissions.

Advanced dryer controls. Control systems are a well-known way to optimize process variables and thereby reduce energy consumption, increase productivity, and improve the quality of industrial processes. One example of a control system for dryers is Dryer Management System^{TM} control software, which reportedly offers advanced control of dryer system set points and process parameters to reduce steam use and improve productivity (Focus on Energy 2006a, 2006b, 2006c; Reese 2005). Several case studies of this technology are available in the literature.

Focus on Energy (2006b) described a pilot of the Dryer Management System software at a Stora Enso mill in Steven's Point, Wisconsin. The mill's paper machine was metered to determine energy savings, which were deemed quite significant: 4,500 pounds of steam per hour, which were estimated to lead to $360,000 in annual energy cost savings (Focus on Energy 2006b). Additionally, the company reportedly experienced significant improvement with product quality and throughput. The payback period was estimated at less than 3 years based on energy savings alone (i. e., no consideration of productivity benefits).

Reese (2005) described results from another Stora Enso installation of Dryer Management System software, this time on a Voith lightweight coated machine with two on-machine coaters. Reportedly, annual savings of $263,000 were observed due to reduced energy consumption, lower maintenance cost, and higher production. The reported payback period was seven months.

Control of dew point. The water vapor dew point (in the dryer hood) determines the heat exchange efficiency, but is affected by the setting of ventilation fans. The dew point levels in paper drying hoods should be measured and controlled to optimize the drying process (Mulder 2008). Optimizing the operation of the dryer hood provides greater quality control, which leads to a more consistent product.

Optimization of water removal in forming and pressing. Water is removed in three successive steps in a paper machine in the wire, press, and dryer sections. A rule of thumb is that five times as much energy is required to remove a pound of water in the press section compared to removing a pound of water in the forming section, and that up to 25 times as much energy is required to remove a pound of water in the dryer section compared to removing a pound of water in the forming section. Thus, the energy benefits of removing as much water prior to the dryer section are self-evident.

Many paper machines operate with less than ideal water removal in the forming section. There are many reasons for this, including equipment limitations, and inadequate and/or poorly maintained instrumentation and controls in the low and high vacuum dewatering elements. On older paper machines, there is often an excessive quantity of high vacuum elements which add to the vacuum system operating power as well as increasing the forming fabric drag load and associated drive power.

An issue is the potential for rewetting of the paper after the wire and press sections, which increases the energy use in the drying section. As grades change on a paper machine, it is hence important to optimize the choice of felt. It is also important to optimize the geometry of the web path and the felt paths such that the two are separated as early as possible to minimize rewetting (Rollinson 2008). The "double doctor" approach may be an effective option for couch rolls and suction rolls to reduce rewetting when leaving the Fourdrinier and press nips.

As with the forming section, press optimization can help to improve water removal prior to the dryer section. Press water balances will provide valuable information which points to where the sheet water is extracted within the press. However, many paper machines lack the proper equipment required to make water measurement possible from uhle boxes and press nips. There are many variables to pressing and there is not a single set of parameters to set up the press for maximum water removal on all grades. Press nip loadings need to be maximized within design limits. Also, analysis of roll coverings (soft to hard) and surface patterns (drilled, grooved, and hybrids of these) should be part of the entire press section study. Additionally, felt design changes should be considered and will require some trial and error as each step in the optimization process is taken. Typically, sheet temperature is reduced as it passes through the press, so efforts should be made to maintain, or even increase the sheet temperature as it exits the press. An 18°F increase in sheet temperature leaving the press provides a 4% decrease in dryer steam. Additionally, higher pressing temperatures can improve water extraction from the sheet which further reduces dryer steam requirements. Increasing sheet temperature can be achieved with significantly increasing press shower water temperature (over 130° F) and/or adding steam showers at the uhle boxes, where the steam is pulled into the felt at the vacuum slot. Finally, sheet rewetting within the press should be addressed to be sure it does not exist, or is minimized.

Reduction of blow-through losses. Modern high speed paper machines use stationary siphons. The amount of blow through steam depends upon the siphon differential pressure required for efficient evacuation. The lower the differential pressure, the lower the blow through steam use. At initial commissioning these were set at reasonable values. However, during operation these set points may have increased and were not re-set to the original values but are only needed in exceptional circumstances. This results in increased blow-through steam use, which can be reduced by sticking to the original set points (Duller 2008).

Reduced air requirements. Air to air heat recovery systems on existing machines recover only about 15% of the energy contained in the hood exhaust air (Martin et al. 2000). This percentage could be increased to 60-70% for most installations with proper maintenance and extensions of the systems (Martin et al. 2000). Paper machines with enclosed hoods require about one-half the amount of air per ton of water evaporated compared to paper machines with a canopy hoods. Enclosing the paper machine reduces thermal energy demands since a smaller volume of air is heated. Electricity requirements in the exhaust fan were also reduced (Elaahi and Lowitt 1988). Published estimates suggested steam savings of 0.72 MMBtu per ton of paper and electricity savings of 6.3 kWh per ton of paper by installing a closed hood and an optimized ventilation system. Investment costs and operations and maintenances costs were reported at $9.5/ton paper and $0.07/ton paper, respectively (Martin et al. 2000).

Optimizing pocket ventilation temperature. Mill operators often monitor the operating air temperature of pocket ventilation systems, but when such systems operate at greater air temperatures than the minimum required for proper operation, energy can be wasted. Focus on Energy (2006a) estimated that when the temperature of the pocket ventilation system can be decreased to between 180-195F, the overall use of steam can also be decreased by about 1,000 to 2,000 lbs. per hour in a typical mill. Paybacks are immediate since this measure involves improved operations and control rather than capital investments.

Waste heat recovery. In the paper drying process, several opportunities exist to recover thermal energy from steam and waste heat. One mill replaced the dryers with stationary siphons in their paper machine and was able to achieve energy savings of 0.85 MMBtu/ton due to improved drying efficiency, with an operation cost savings of $25,000 ($0.045/ton) (Morris 1998). A second system used mechanical vapor recompression in a pilot facility to reuse superheated steam into the drying process (Van Deventer 1997). Steam savings for this approach were up to 4.7 MMBtu/ton (50%) with additional electricity consumption of 160 kWh/ton (Van Deventer 1997). A third system noted in the literature was the use of heat pump systems to recover waste heat in the drying section (Abrahamson et al. 1997). Martin et al. (2000) estimated steam energy savings of approximately 0.4 MMBtu/ton of paper are achievable through paper machine heat recovery, with installation costs of approximately $18 per ton of paper. However, the installation of heat recovery systems will lead to more maintenance since heat exchangers require periodic cleaning.

Heat can also be recovered from the ventilation air of the drying section and used for heating of the facilities (de Beer et al. 1994). For example, a mill-wide energy assessment Appleton Paper's mill in West Carrollton, Ohio, found that the recovery of paper machine vent heat could be used for heating the plant in winter months. It was recommended that cross-flow heat exchangers be installed to generate hot air for plant heating from recovered heat in the paper machine vent exhaust gas. The estimated annual cost savings were about $1,000,000. With investment costs of about $1,500,000 the payback period was estimated at only 1.5 years (U.S. DOE 2002a)

For direct-fired air dryer hoods, which are mainly used on tissue and toweling machines, several opportunities for waste heat recovery exist (Marin 2008). Hood exhaust air can be recovered and used to preheat the air entering the combustion chamber, thereby reducing hood fuel demand. A cascade system can be employed, which uses the hood exhaust air to feed the supply fan of the wet section, which will reduce the fuel demand for wet section burners. Lastly, an economizer can be installed to reclaim heat from hood exhaust air and use it to heat fresh water for high pressure showers of the paper machine felt and wires.

Shoe (extended nip) press. After paper is formed, it is pressed to remove as much water as possible. Normally, pressing occurs between two felt liners pressed between two rotating cylinders. Extended nip presses use a large concave shoe instead of one of the rotating cylinders (Martin et al. 2000). The additional pressing area adds dwell time in the nip and allows for greater water extraction (about 5-7% more water removal) to a level of 35-50% dryness (Elaahi and Lowitt 1988; Miller Freeman 1998; Lange and Radtke 1996). Greater water extraction leads to decreased energy requirements in the dryer, which leads to reductions in steam demand. Furthermore, reduced dryer loads allow plants to increase capacity up to 25% in cases where production is dryer limited (Martin et al. 2000). Extended nip pressing also increases wet tensile strength (Lange and Radtke 1996). Published estimates for the steam savings achievable through the installation of extended nip presses range from 2% to approximately 15%, depending on product and plant configuration (Martin et al. 2000; Focus on Energy 2006a). The application of the X-NIP T shoe press in tissue plants was estimated to reduce drying energy use by 15% (Baubock and Anzel 2007). Capital costs had been estimated at $38 per ton of paper and additional maintenance costs had been estimated at $2.24 per ton of paper (deBeer et al. 1994).

Paper machine vacuum system optimization. Vacuum pumps and a vacuum system exist on every paper machine. There is approximately the same horsepower associated with the vacuum system as is used to drive the entire paper machine. However, inefficiencies within the vacuum system increase the electrical and/or steam energy requirements of water removal, and therefore represent an important energy efficiency improvement opportunity.

For example, following an audit of 14 paper machines owned by a Canadian manufacturer, a potential of 3.5 MW of electrical power demand could be saved following system modifications, operational changes, and even removal of some vacuum pumps. The 14 paper machines had a total of 50,000 horsepower connected to the vacuum pump systems and were operating with a combined demand of 45,000 horsepower by the drive motors. Cost to achieve the first MW of savings was considered negligible with minor piping or operational changes. Total annual cost savings was approximately $400,000 per year.

The situation of excess vacuum capacity sometimes exists because significant operational changes have occurred since the system was new, which can impact the performance and requirements of the vacuum system. Over time, changes in furnish, chemistry, headbox consistency, retention, and forming and press fabrics can have an effect on the needs and performance of the vacuum system. In one recent example, a survey of a newly rebuilt paper machine with a new press found many problems with improper vacuum control and excess vacuum capacity. Furthermore, there was a total potential of removing 700HP from the vacuum system by removing or slowing down some of the vacuum pumps (Kramer et al. 2009).

Gap forming. Gap formers are an alternative to the Fourdrinier paper machine. They can be categorized as blade formers, roll formers, and roll-blade formers (Buehler and Guggemos 1995). This technology takes the pulp suspension from the headbox and injects it, via individual nozzles across the width of the paper machine directly between two wires. As the furnish passes between the wires, moisture is removed from the fibers through the wires forming a paper web between the wires from the pulp (Martin et al. 2000). Rolls, blades, or vacuums facilitate the removal of excess water from the web, known as dewatering. The forming sections are very short and the formation takes place in a fraction of the time it takes for a Fourdrinier machine (Martin et al. 2000). The gap former produces a paper of equal and uniform quality at a higher rate of speed. Coupling the former with a press section rebuild or an improvement in the drying capacity increases production capacity by as much as 30% (Paulapuro 1993; Elenz and Schaible 1995). Nevertheless, retrofitting a gap former may increase retention losses. Energy savings from gap formers come from reduced electricity consumption (Kline 1991). The technology also may improve quality. Published estimates for electricity savings are approximately 40 kWh/ton of paper (Jaccard and Willis 1996). Based on (AFPA 1999b) installation costs including the head box for a gap former amount to approximately $75,750 per inch of width, as opposed to $30,750 for a Fourdrinier with head box.

CondeBelt drying. The first commercial CondeBelt dryers were installed in Finland in 1996, and in Korea 1999 (Martin et al. 2000). In CondeBelt drying the paper is dried in a drying chamber by contact with a continuous hot steel band, heated by either steam or hot gas. The water from the paper is evaporated by the heat from this metal band. (De Beer et al. 1998) This drying technique has the potential to completely replace the drying section of a conventional paper machine, with a drying rate 5-15 times higher than conventional steam drying (Martin et

al. 2000). However, CondeBelt drying is not suited for high basis weight papers (Martin et al. 2000) and has seen limited application in the United States to date (although it is operating in mills in Europe and Korea) (Jacobs and IPST 2006). Capital costs are considered to be high, although the size of the drying area can be reduced. Martin et al. (2000) estimated savings of 15% in steam consumption (1.5MMBtu/ton of paper) and a slight reduction in electricity consumption (20 kWh/ton of paper), with investment costs of $28/ton paper for retrofit installations (De Beer 1998).

Air impingement drying. Air impingement drying involves blowing hot air (at 300C) in gas burners at high velocity against the wet paper sheet. Air impingement drying leads to less steam use and slightly higher electricity use (Martin et al. 2000). This technology is mostly applicable to coating drying, but is also gaining acceptance for general paper drying in place of traditional steam cylinders (Focus on Energy 2006a). Published estimates suggest that impingement drying can lead to steam savings of 10-40% compared to conventional gas-fired or infrared drying technologies, but with an increased electricity use of up to 5% (Martin et al. 2000; Focus on Energy 2006a). Given that this measure involves a tradeoff between thermal and electrical energy use, and the extent of this tradeoff may vary by installation, it is important that net energy savings be verified on a facility by facility basis.

High consistency forming. In high consistency forming process pulp that enters at the forming stage has more than double the consistency (3%) than normal furnish (Martin et al. 2000). This measure increases forming speed, and reduces dewatering and vacuum power requirements (Elaahi and Lowitt 1988). Application of this technology is limited to specific paper grades, especially low-basis weight grades such as tissue, toweling, and newsprint.

Hot pressing. Pre-heating the water in the paper sheet before pressing can reduce the evaporation load (Martin et al. 2000). In hot pressing, a steam shower is used to heat the water in the sheet to 80°C or higher temperature, which lowers the viscosity of the water and softens the structure of the sheet to improve water flow (Elaahi and Lowitt 1988). Steam showers can reduce dryer loads and increase machine speed and overall production. This technology reduces residence time in the nip and therefore counteracts some of the benefits of the extended nip press (Elaahi and Lowitt 1988). Use of steam showers has been estimated to reduce the steam requirement by 1 kg of steam per kg paper. Martin et al. (2000) estimated steam energy savings of 0.61 GJ/t paper through hot pressing. Costs for hot pressing technology were estimated to be $26.7/t paper. The potential share of 10% in the U.S market is mainly due to the fact that this measure is already near its maximum potential implementation.

Direct drying cylinder firing. Direct drying cylinder firing heats the cylinders using natural gas or other petroleum products, reducing the intermediate step of steam production. This technology can achieve significant fuel savings of 1.1 GJ/t paper (average for the paper grades examined) but does require additional operation and maintenance. Martin et al. (2000) estimated additional O&M costs at $1.4/t paper (Jaccard and Willis 1996). Retrofit costs were high, $111/t paper (Jaccard and Willis 1996), since the cylinder system required significant modifications.

Infrared profiling. Moisture profiling on fine paper machines can greatly reduce moisture variation while allowing for production increases (Elaahi and Lowitt 1988). Infrared profiling systems to control the moisture profile of the web applied to fine paper and heavy paperboard

production for relative thermal energy savings (Mitchell 1994; Elaahi and Lowitt 1988). Martin et al. (2000) estimated 0.7 GJ/t paper of energy savings and additional electricity requirements of 0.08 GJ/t paper (approx. 22 kWh/t paper).

Dry sheet forming. The principle behind dry sheet forming is the production of paper without the addition of water. The fibers can be dispersed either through carding (mechanical disbursement) or air laying techniques. In the air laying technique, the fibers are suspended in air and the paper is formed in this suspension. Resins are sprayed on the sheet and are then polymerized to help forming the web. Few plants are in operation but significant savings are possible. Martin et al. (2000) estimated energy savings with an increase in electricity requirements.

Recover heat from Uhle box effluent. Uhle boxes help removing water from the forming felt as it travels from the forming section toward the dryer section. The Uhle box downstream and in the proximity of the steam box removes a combination of shower water and water from the sheet. The water's temperature is between 115°F and 120°F. This type of recovering heat appears to be economical and technical. Heat recovery is more practical when applied to the Uhle box stream coming off the felt (U.S. DOE 2004c).

General Measures
Pinch Analysis. Pinch analysis, identifies heat flows between cold streams and hot streams, and then optimizes the stream flows. It has been used successfully in many energy-intensive industries to better optimize thermal energy flows throughout the plant (Martin et al. 2000). An analysis of the potential for pinch analysis/process integration in Canada found a cost-effective energy savings potential of 8% (Bruce 1999).

Optimization of regular equipment. The operations of equipment such as boilers and paper machine are always under improvement or real-time diagnostics for improving performance. DeBeer et al. (1994) estimated that, although most paper machines were already equipped with a process computer, an additional 2% reduction on energy demand can be achieved by the optimization of the control equipment. Williams (1996), McNicol (1997) respectively noted that optimizing the lubrication system, waste water system had saved considerable oil consumption and energy use.

Energy-efficient lighting. Factory buildings often use high-pressure mercury lamps for lighting (Martin et al. 2000). The use of electronic ballasts and fluorescent tubes in depots and offices as well as other technologies can result in electricity savings.
Efficient motor systems. As a percentage of total electricity use, motors in the pulp and paper industry rank the highest of any U.S. industrial sector (Xenergy Inc. 1998). In addition to motor efficiency improvement, motor system improvements include upgrading fan systems, air compressors, and other motor end-uses and adjustable speed drive.

Boiler maintenance. Maintaining all components to ensure the boiler are operating at peak performance is a way for substantial savings. In the absence of a good maintenance system, the burners and condensate return systems can wear or get out of adjustment (Martin et al. 2000). These factors can end up costing a steam system up to 20-30% of initial efficiency over 2-3 years

(DOE, OIT 1998). This measure would be accomplished for an additional operating cost of $0.06/tonne paper with no additional start-up cost.

Flue gas heat recovery. Heat from boiler flue gas can be used to preheat boiler feed water in an economizer. While this measure is fairly common in large boilers, there is often still room for more heat recovery (Martin et al. 2000). The limiting factor for flue gas heat recovery is that one must ensure that the economizer wall temperature does not drop below the dew point of acids in the flue gas (such as sulfuric acid in sulfur containing fossil fuels).

Blowdown steam recovery. Water is periodically blown from the boiler to remove accumulated impurities. When the water is blown from the high pressure boiler tank to remove impurities, the pressure reduction often produces substantial amounts of steam. This steam is low grade, but can be recovered for use of space heating and feed water preheating (Martin et al. 2000).

Steam trap maintenance. Steam traps have the function of removing condensed steam and non-condensable gases without losing any live steam. As these traps can vent significant amounts of steam if not properly monitored, a simple inspection and maintenance program can save significant amounts of energy for very little money. If the steam traps are not regularly monitored, 15-20% of the traps can be malfunctioning (Martin et al. 2000).

Automatic steam trap monitoring. Attaching automated monitors to steam traps in conjunction with a maintenance program can save even more energy, without significant added cost. This system is an improvement over steam trap maintenance alone, because it gives quicker notice of steam trap failure, and can detect when a steam trap is not performing at peak efficiency. Systems which are able to implement steam trap maintenance are also likely to be able to implement automatic monitoring, Martin et al. (2000) estimated an additional 50% of systems can implement this measure.

Leak repair. As with steam traps, the distribution pipes themselves often have leaks that go unnoticed without a program of regular inspection and maintenance (Martin et al. 2000). In addition to saving 3% of energy costs (0.5 GJ/t) having such a program can reduce the likelihood of having to repair major leaks (U.S. DOE OIT 1998; EPA 1996).

Condensate return. Reusing the hot condensate in the boiler saves energy and reduces the need for treated boiler feed water. Usually fresh water must be treated to remove solids that might accumulate in the boiler, and returning condensate can substantially reduce the amount of purchased chemical required to accomplish this treatment. The fact that this measure can save substantial energy costs and purchased chemicals costs makes building a return piping system attractive. This measure has already been implemented in most of the places where it is easy to accomplish. Maintaining a condensate return system was estimated to cost $0.54/tonne paper (Martin et al. 2000).

Increased use of recycled paper. The energy and carbon emissions impacts of this measure may vary greatly depending on furnish and final product types (Martin et al. 2000). Large amount of wastepaper pulp was used in the pulp and paper industry (AFPA 1998). Increasing the use of recycled pulp reduces energy use associated with virgin pulping processes.

Appendix E   Additional References

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