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**Environmental Energy
Technologies Division**

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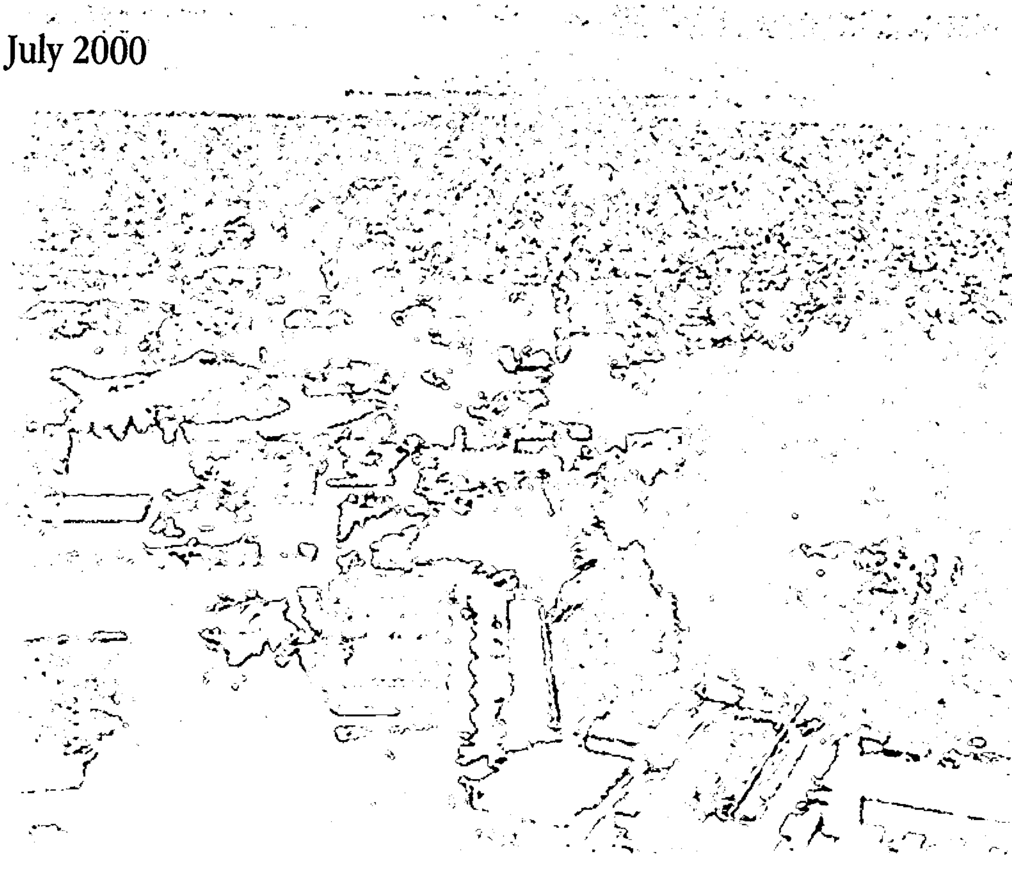

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ABSTRACT

The pulp and paper industry accounts for over 12% of total manufacturing energy use in the U.S. (U.S. EIA 1997a), contributing 9% to total manufacturing carbon dioxide emissions. In the last twenty-five years primary energy intensity in the pulp and paper industry has declined by an average of 1% per year.

However, opportunities still exist to reduce energy use and greenhouse gas emissions in the manufacture of paper in the U.S. This report analyzes the pulp and paper industry (Standard Industrial Code (SIC) 26) and includes a detailed description of the processes involved in the production of paper, providing typical energy use in each process step. We identify over 45 commercially available state-of-the-art technologies and measures to reduce energy use and calculate potential energy savings and carbon dioxide emissions reductions. Given the importance of paper recycling, our analysis examines two cases. *Case A* identifies potential primary energy savings without accounting for an increase in recycling, while *Case B* includes increasing paper recycling. In Case B the production volume of pulp is reduced to account for additional pulp recovered from recycling. We use a discount rate of 30% throughout our analysis to reflect the investment decisions taken in a business context.

Our Case A results indicate that a total technical potential primary energy savings of 31% (1013 PJ) exists. For case A we identified a cost-effective savings potential of 16% (533 PJ). Carbon dioxide emission reductions from the energy savings in Case A are 25% (7.6 MtC) and 14% (4.4 MtC) for technical and cost-effective potential, respectively. When recycling is included in Case B, overall technical potential energy savings increase to 37% (1215 PJ) while cost-effective energy savings potential is 16%. Increasing paper recycling to high levels (Case B) is nearly cost-effective assuming a cut-off for cost-effectiveness of a simple payback period of 3 years. If this measure is included, then the cost-effective energy savings potential in case B increases to 22%.

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I. INTRODUCTION

In 1994[1] the U.S. manufacturing sector consumed 22.8 EJ of primary energy, almost one-quarter of all energy consumed that year in the United States (U.S. EIA 1997a).[2] Within manufacturing, a subset of raw materials transformation industries (pulp and paper, primary metals, cement, chemicals, petroleum refining) require significantly more energy to produce or transform products than most other manufactured products. This report reflects an in-depth analysis of one of these energy-intensive industries – pulp and paper.

The manufacture of paper and paperboard is an important element of a modern economy. It also is a highly capital and energy-intensive process. International comparisons show that U.S. papermaking energy intensities are greater than those in many other countries (Farla et al., 1997). As such, opportunities exist for increasing energy efficiency in the pulp and paper industry in the U.S.

This paper is divided into six sections. After providing an overview of the U.S. pulp and paper industry (*Section II*), we describe the various stages of the pulp and papermaking process (*Section III*). We then present information on the industry's historical energy use and carbon dioxide emissions (*Section IV*). This is followed by a more detailed breakdown of energy use in our base year of analysis (*Section V*). In *Section VI* we describe the various technologies and measures that we assessed in our efficiency analysis, including estimates of costs and energy savings. Finally, we estimate technical and cost-effective potential energy savings and the associated carbon dioxide emissions reductions from the investment in various technologies and measures (*Section VII*) followed by a summary and conclusion (*Section VIII*).

II. OVERVIEW OF THE U.S. PULP AND PAPER INDUSTRY

The health of the U.S. pulp and paper industry in an increasingly competitive global paper market is highly dependent upon an accessible fiber resource base, continuing capital investments, the maintenance of a pool of skilled labor, and demand powered by the growth in the economy. The United States, with its developed economy, growing population income, vast forest resources, large pool of skilled labor and access to capital is the largest producer of pulp and paper in the world. The U.S. pulp and paper industry is made up of three primary types of producers: i) *pulp mills*, which manufacture pulp from wood or other materials, primarily wastepaper; ii) *paper mills*, which manufacture paper from wood pulp and other fiber pulp; and iii) *paperboard mills*, which manufacture paperboard products from wood pulp and other fiber pulp.

There were 190 operating pulp mills and 598 operating paper and paperboard mills in the U.S. in 1996. About 58% of all the paper/paperboard mills are located in the Northeast and the North Central regions, close to final consumers. However, 56% of the paper/paperboard capacity and more than 70% of wood pulp capacity are located in the South Atlantic and the South Central regions, close to the sources of fibers. Mills located in those regions are mostly large integrated pulp and paper mills (Kincaid, 1998). More than 45% of all paper and paperboard and about 60% of all wood pulp are produced by mills with capacity over 450 tonnes per year (tpy). The average capacity of an U.S. paper/paperboard mill in 1995 was about 168 tpy, while the average capacity of a wood pulp mill was about 330 tpy.

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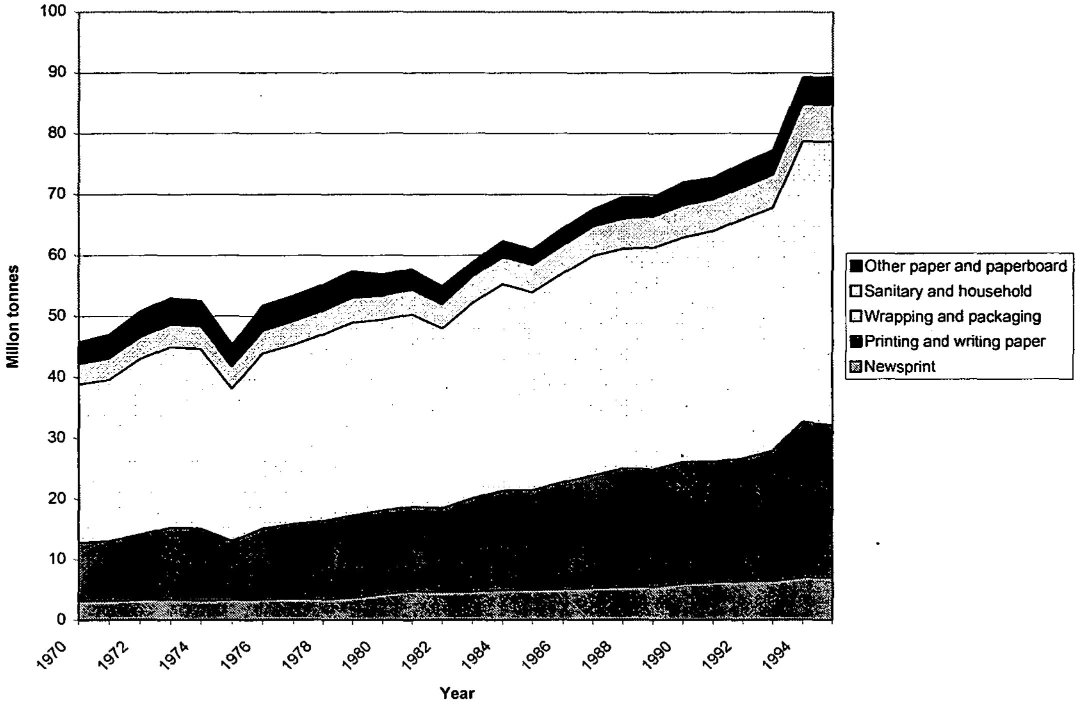
[1] We use a base year of 1994 throughout our analysis since these are the latest available nationally published energy data by the U.S. Energy Information Administration.

[2] Primary energy accounts for losses in electricity transmission and distribution and is calculated using a conversion rate from final to primary electricity of 3.08, reflecting the difference between an average power plant heat rate of 10,500 Btu/kWh and a site rate of 3412 Btu/kWh. To convert from EJ to Quads, from PJ to TBtu, and from GJ to MBtu, multiply by 0.95; to convert from metric tons to short tons, multiply by 1.1; to convert from GJ/metric tonne to MBtu/short ton, multiply by 0.86.

Virgin pulp is used to produce a variety of pulps in the U.S., most importantly chemical pulp, semi-chemical pulp, mechanical pulp, dissolving pulp, and pulp made from non-wood fibers. Total U.S. pulp production increased from 37.9 Mt (Million tonnes) in 1970 to 60.0 Mt in 1994, at a rate of 1.9% per year, though growth has slowed slightly in recent years (UN, 1998). Pulp production increased at a 2.2% average annual rate between 1970 and 1980, decreasing to an average of 1.8% per year between 1980 and 1994. Overall, pulp production increased steadily, with periodic minor decreases. In 1970, chemical pulp accounted for 77% of pulp production, while mechanical and other pulp, accounted for 9.8% and 13.5%, respectively. While total pulp production has increased significantly since 1970, the composition of U.S. pulp production has changed little; chemical pulp production has become more dominant, comprising 82% of total pulp production while mechanical pulp production has fallen to 9%. In addition to the various types of raw pulp, recovered paper is used as a raw material in producing paper products. Recovered paper use has grown from 8.4 Mt in 1961 to 33.3 Mt in 1997, at an average rate of 3.9% per year.

Figure 1. U.S. Paper Production by Process, 1970 to 1994



Source: UN, 1998.

Paper production in the U.S. consists primarily of wrapping and packaging paper, paperboard, and printing and writing paper, which made up about 80% of U.S. paper production in 1994. The remainder is made up of newsprint, household and sanitary paper, and paper and paperboard not elsewhere specified, a catch-all category for such paper products as Kraft paper, blotting paper, and filter paper. Total U.S. paper production increased from 45.81 Mt in 1970 to 82.46 Mt in 1994, an average increase of 2.5% per year. Growth has slowed slightly in recent years, though paper production still increased at 2.2% per year between 1970 and 1980, and 2.7% per year between 1980 and 1994. In 1970 the shares of paper by type were: 57% wrapping and packaging paper, 21% printing and writing paper, 7% household and sanitary paper, 7% newsprint, and 8% paper not elsewhere specified (see Figure 1). Although the share of wrapping and packaging paper fell from

57% to 51% by 1994, and the share of printing and writing paper increased from 21% to 28% there were no other major structural changes. The share of newsprint increased from 7% to 8%, the share of household paper remained the same, and the share of paper not elsewhere specified increased from 4% to 5%. The primary change in the sector over the period was the decline in wrapping and packaging paper and the increase in printing and writing paper.

III. PROCESS DESCRIPTION

The pulp and paper industry converts fibrous raw materials into pulp, paper, and paperboard. The processes involved in papermaking include raw materials preparation, pulping (chemical, semi-chemical, mechanical, or waste paper), bleaching, chemical recovery, pulp drying, and papermaking. A flow diagram of the processes is shown in Figure 2. The most significant energy-consuming processes are pulping and the drying section of papermaking.

Raw Materials Preparation

In 1994 wood pulp accounted for 68% of paper production by weight, with used paper (discussed under pulping) covering the remaining 32% (Kincaid, 1998). The main raw materials preparation operations typically include debarking, chipping, and conveying. Logs are transported to pulping mills where the bark is treated. Several of these logs are then placed in a rotating drum, where rubbing against each other and the edge of the drum removes the bark (Saltman, 1978), which is then used for fuel. In some cases, hydraulic debarking is used, but this is more energy intensive, and requires the bark to be pressed before it can be used for fuel. Debarking requires about 8.5 kWh of electricity per tonne of raw material (Elaahi and Lowitt, 1988; Nilson et al., 1995; Giese, 1989; Giraldo and Hyman, 1994; Jaccard and Willis, 1996). After debarking the logs are chipped, most often in a radial chipper. Energy is used in conveyors to transport chips to the digesters. These processes consume about 30.3 kWh/t raw material (Elaahi and Lowitt, 1988; Nilson et al., 1995; Giese, 1989; Giraldo and Hyman, 1994; Jaccard and Willis, 1996).

Pulping

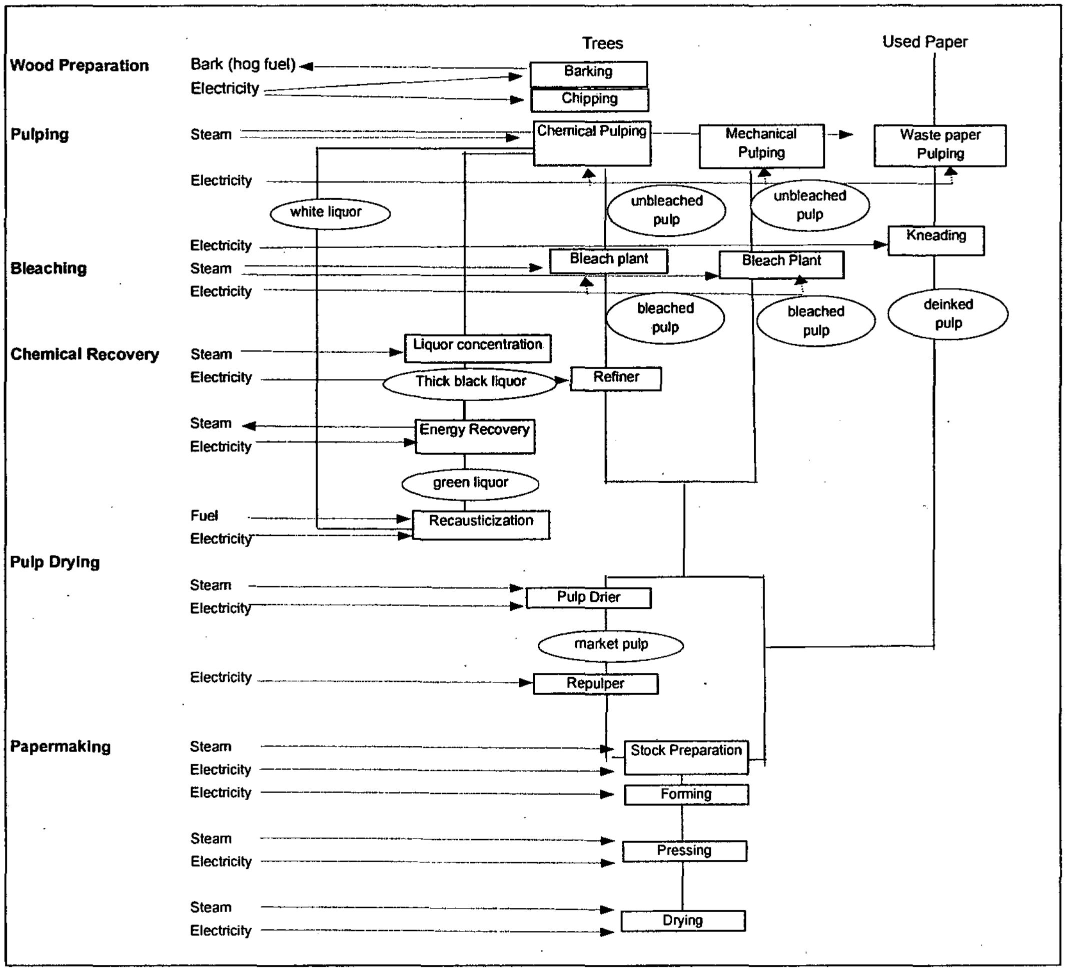
The next stage in the papermaking process is pulping. The primary purpose of pulping is to free the fibers from the lignin that binds the fibers together in wood, and then to suspend the fibers in water. Typical wood consists of about 50% fiber, 20-30% non-fibrous sugars, and 20-30% lignin (Kline, 1991). Pulp with longer fibers and less lignin is considered best, in order to produce the strongest paper with the greatest resistance to aging. There are three main pulping processes: mechanical, chemical, and semi-chemical. Of these, the Kraft chemical pulping process accounts for the majority of U.S. pulp production today (Kincaid, 1998).

Mechanical Pulping

Mechanical pulping is the original form of pulping and although it has been largely replaced by chemical pulping, it is still used for lower grade papers such as newsprint and is the only process used for recycled paper. The main subdivisions of this method are stone groundwood pulping, refiner pulping, thermomechanical pulping (TMP), and recycled paper pulping. Mechanical pulp accounted for 9% of production in 1994 (Kincaid, 1998). The principle behind all mechanical pulping is to take a raw material and grind it down into individual fibers. The advantage of mechanical pulping is that it produces much higher yields than chemical pulping (90-95% of the wood ends up as usable pulp). However, a problem with leaving impurities in the pulp is that it produces a weaker paper with less resistance to aging. The weakening effect is compounded by the fact that the grinding action of mechanical pulping produces shorter fibers (Kincaid, 1988).

Stone groundwood pulping is the oldest and least energy-intensive mechanical pulping process, using approximately 1650 kWh/t pulp (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996). This process takes small logs and grinds them against artificial bonded stones made of silicon carbide or aluminium 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 this method is its very high yield. The disadvantages are that the fibers produced are very short and often must be combined with strong but expensive chemical fibers to be strong enough to pass through the paper machine, coaters and printing processes.

Figure 2. Schematic of the Pulp and Papermaking Process



Refiner pulping keeps the high yield advantages of stone groundwood, while producing somewhat longer fibers with greater strength. RPM (refiner-mechanical pulping) was introduced in order to use wood in chip rather than in log form. In this process, wood chips are ground between two grooved discs. The fibers produced permit lighter weight paper to be used for printing, thus delivering more print media area per tonne. Estimates of the energy consumption of this process vary widely throughout the published sources depending upon furnish species and desired freeness. In this analysis we estimate an average electricity consumption of about 1972 kWh/t pulp (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996).

Thermomechanical pulping produces the highest grade of pulp from mechanical pulping and over the past fifteen years has become the most common process used, despite some drawbacks (i.e. high-energy intensive process, production of darker pulp more costly to bleach). This process steams wood chips to soften them before putting them through the same machine that is used in the refiner process. Yields are nearly as high as other mechanical processes. Average steam consumption for this process is estimated at 0.9 GJ/t pulp while electricity consumption is estimated to be about 2041 kWh/t pulp (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996; Pulp and Paper, 1998).

Chemi-thermomechanical pulp (CTMP) process entails application of chemicals to the chips prior to refining. The process begins with an impregnation of sodium sulfite and chelating agents. The mixture is then preheated at 120-130 °C and refining follows. The chemical pre-treatment of the chips permits less destructive separation of fibers from the wood, resulting in a higher, longer fiber content and a much lower shive content[3]. Other advantages of CTMP over TMP are that CTMP delivers more flexible fibers (providing higher sheet density and higher burst and tensile strength) and provides a higher brightness before bleaching. When compared to bleached softwood kraft, CTMP has a better opacity and tear strength but it still has problems of color reversion. The major drawback remains the high-energy demand of the process which was reported in 1985 to run 26.8 GJ/t (Elaahi and Lowitt, 1988; Kincaid, 1998).

Pulp generated from recovered paper accounted for 32% of the pulp consumed in 1994 (Kincaid, 1998). The machine that is responsible for most recycled paper pulping is called the Hydrapulper. Paper is dumped into the top of the hydrapulper and is pulped in a manner similar to a blender by producing slurry. The pulp exits the bottom of the machine, while the impurities exit out the side. Objects that float and heavy objects like nuts and bolts also exit out the side. The ragger pulls large contaminants out of the bath (Anonymous, 1995b). Since recovered paper can use considerably less energy in pulp production than wood-based pulp, making secondary fibers competitive with virgin ones can save significant energy in the mill. Modern techniques for removing contaminants from secondary fibers have made them competitive in all papers, except for the highest grade of papers where long fibers are essential. We assume an energy consumption of 392 kWh/t for waste paper pulping.

Chemical Pulping

Chemical pulping is by far the most common method for pulping wood in the U.S. Chemical processes have a low yield (40-55%) but the pulp produced is of very high quality. These high quality pulps are mainly used for higher quality paper production, such as office paper. Chemical processes accounted for 82% of the wood pulp produced in the U.S. in 1994 (AFPA, 1998).

The *Kraft, or sulfate, process* is the most common of the chemical processes, accounting for over 95% of the chemical pulp produced in 1994 (Kincaid, 1998). In this process, the wood chips are first pre-steamed to soften them and force out any trapped air. Then they are combined with a highly alkaline solution, called white liquor, which contains sodium hydroxide (NaOH), and sodium sulfide (Na_2S). All these ingredients are mixed together in a digester, where they are pressurized

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

and heated to 160-170°C. Over several hours, the liquid permeates the chips, and eventually dissolves most of non-fibrous materials in the wood. After being cooked in this fashion, the chips are separated into individual fibers by being blown into low-pressure tanks. The spent liquor and dissolved contaminants, now called black liquor, are washed away and the fibers move on to the bleaching phase. This process consumes about 4.4 GJ/t pulp of steam and around 406 kWh/t pulp of electricity (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson *et al.*, 1995; Giraldo and Hyman, 1994). The black liquor can be concentrated and burned to provide the heat required for the process. After burning, the pulping chemicals can be extracted and reused (Elaahi and Lowitt, 1988).

The other main type of chemical pulping is called the *sulfite process*. The two chemical processes use very similar kinds of wood and produce a similar type of paper, but each still has its advantages and disadvantages. The Kraft process produces pulp with longer fibers, while sulfite pulp, using lower process temperatures, produces more white pulp with shorter fibers. The disadvantages of sulfite pulping are the production of slightly lower strength paper and the relative difficulty of recovering spent chemicals. The solvent, sulfite liquor, is produced by burning sulfur and mixing the resulting gasses with a basic solution. Similar to the Kraft process, the sulfite process allows for burning of the used liquor, allowing the pulping chemicals to be reused in the majority of mills. Due to the disadvantage of the sulfite pulping, it is only used when special kinds of fibers are desired, i.e. in very smooth papers (Elaahi and Lowitt, 1988). Estimates of energy consumption for this process are 4.2 GJ/t pulp of steam consumption and 572 kWh/t pulp electricity consumption (Jaccard and Willis, 1996; Elaahi and Lowitt, 1988).

Semi-Chemical Pulping

The last form of pulping is a combination of chemical and mechanical pulping: semi-chemical or chemi-mechanical pulping. In both of these systems, the wood chips are chemically pre-treated before they are mechanically pulped. Whether it is called chemi-mechanical or semi-chemical depends on whether the chemical or mechanical parts of the process are performing the largest part of the pulping. These methods are primarily used for hardwoods, which have short narrow fibers. This type of fiber does fill in areas between softwood fibers, making a smoother, denser, and more opaque sheet of paper. This process accounted for 6% of U.S. wood pulp production in 1994 and consumes approx. 5.3 GJ/t pulp of thermal energy and approximately 505 kWh/t of electricity (Kincaid, 1998).

Chemical Recovery

Extraction and reuse of the pulping chemicals following chemical pulping consists of three stages: black liquor concentration, energy recovery, and recaustization of the remaining liquor. The concentration usually takes place in Multiple Effect Evaporators (MEEs) and Direct Contact Evaporators (DCEs). The MEEs use steam to evaporate water from the black liquor, concentrating the black liquor to about 50% solids. A DCE uses the exhaust gases from the recovery boiler to drive up the final concentration to 70-80%. Advances in this area have focused on producing MEE systems that can handle higher solids content, thus reducing or eliminating the need for the less efficient DCEs. Higher solids content makes the recovery boiler process more efficient. Concentration requires about 4.4 GJ of steam/t of pulp and 25 kWh of electricity/t pulp (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson *et al.*, 1995).

The black liquor is sprayed into the recovery boiler where the remaining water evaporates. The organic components of the solids burn, thereby releasing the heat that dries the liquor transferring heat to boiler tubes for heat generation. The heat of this combustion smelts the remaining inorganic chemicals, which flow from the furnace and are ready for recaustization. The recovery boiler consumes an estimated 1.1 GJ/t pulp of supplementary fuel and 58 kWh of electricity/t pulp for furnace auxiliaries (Elaahi and Lowitt, 1988; Nilsson *et al.*, 1995). The boiler also produces between 10 and 17 GJ/t pulp of useable heat, that is used to create steam for other parts of the process (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson *et al.*, 1995). This large range is explained by the fact that there have been great strides in efficiency since the invention of the recovery boiler.

Most of the sulfur is reduced via chemical reaction to form one of the principal pulping chemical components contained in the smelt. The smelt from the recovery boiler is mixed with some weak white liquor to form green liquor. This green liquor consists mostly of sodium carbonate (Na_2CO_3) and sodium sulfide (Na_2S). The green liquor is recausticized by the addition of calcium hydroxide ($Ca(OH)_2$) under controlled temperature and agitation. This recaustization converts the sodium carbonate back to sodium hydroxide ($NaOH$) and leaves a precipitate of calcium carbonate ($CaCO_3$). The precipitate is removed, and what is left is white liquor that can be reused to pulp more wood. The calcium carbonate precipitate also feeds back into the process in to the lime kiln, where it is heated to produce lime (CaO). The lime is then dissolved in water to produce the calcium hydroxide used in recaustization. The lime kiln is usually fuelled by oil or gas, and requires on average 2.3 GJ/t pulp fuel and 15 kWh/t pulp electricity (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson et al., 1995).

Extended Delignification

Extended delignification is the modification of the pulping equipment that provides a more uniform reaction of chips in the pulping process and results in greater delignification. Several alternative technologies are available which could be applied depending on the age, type and condition of the existing equipment and associated recovery operations at the mill site. Mills with continuous digesters can choose for example from Modified Continuous Cooking (MCC), Extended Modified Continuous Cooking (EMCC) from Ahlstrom and Isothermal Cooking (ITC) from Kvaerner. The batch digester options are Rapid Dispersion Heating (RDH) from Beloit, Enerbatch from Ingersoll-Rand, and Super Batch from Sunds Defibrator[4]. Oxygen delignification, kraft pulping additives and alternative pulping chemistry can further extend the delignification process and reduce the use of bleaching chemicals (Pulliam, 1995).

Bleaching

The removal of the remaining lignin (after chemical pulping) that is still closely bonded to the pulp occurs through a series of bleaching stages. Prior to the late 1980s, elemental chlorine was commonly used in the first stage of bleaching. Environmental concerns, however, have lead to increasing use of alternative chemicals such as ozone, hydrogen peroxide, enzymes, and chlorine dioxide. Not all the alternative bleaching chemicals are applicable to all types of pulp bleaching and the selection of chemicals is also driven by cost considerations. Bleaching is used for different types of paper, varying from unbleached pulps, to brightened newsprint, to highly white printing paper. The selection of one technology among the others and the mill specific case may make the consumption of energy vary, i.e. in the refining section. For our analysis we assume an average energy consumption of 4.3 GJ/t pulp steam consumption and 159 kWh/t pulp electricity consumption for Kraft pulp bleaching (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson et al., 1995). A typical bleaching sequence for Kraft pulp includes several towers, known as stages, where the pulp is mixed with different chemicals. In between stages, the chemical is removed, and the pulp is washed. One example of a bleaching system begins with an elemental chlorine stage, which acidifies the lignin. The next stage is the extraction phase where a strong alkaline solution of sodium hydroxide extracts the lignin acid. Finally, the pulp is whitened by some combination of the

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[4] These processes claim to reduce Kappa numbers 30-50% lower than conventional pulping without significant loss in pulp yield or strength (Pulliam, 1995). Kappa numbers are defined as percentage share of lignin in total pulp.

following: sodium hypochlorite[5], chlorine dioxide, or hydrogen peroxide. The conditions vary in each stage, but all stages take place between 25° and 80°C at 3-43% consistencies (Kline, 1991). Increasingly stringent effluent limitations have meant increasing interest in ECF (Elemental Chlorine Free), TCF (Totally Chlorine Free), and TEF (Totally Effluent Free) bleaching processes. These processes are very diverse, but all seek to reduce chlorine use or make the bleaching chemicals recoverable. By 1998, about 60% of North American pulp mills had converted to have the ability to produce elemental chlorine free pulp, and about 50% of the pulp produced in the U.S. is ECF (Ferguson, 1998). After bleaching, pure chemical pulps must be briefly refined (see refiner pulping description).

Recent developments in the bleaching processes in the U.S. are mainly driven by the EPA Cluster Rulemakings that requires pulp and paper industry to switch from chlorine gas as a bleaching agent to chlorine dioxide (ECF) and even to chlorine-free (TCF) chemicals for sulfite pulp. For new sources in bleached papergrade kraft and soda sub-category ECF+, oxygen delignification is required (Dean, 1998). Under the EPA's incentive-based best available technology (BAT) Tier I option it is required that only pulps of Kappa numbers of 20 or less are sent to the bleach plant. At this Kappa number, the effluent quality from ECF bleaching is the same as that from TCF (Parthasarathy, 1997).

TCF pulps tend to have lower brightness and reduced strength properties compared with ECF pulps. The bleaching yield in TCF pulps is generally lower compared with ECF bleaching process, starting from the same Kappa level number (Panchapakesan et al., 1995). In all the bleaching stages, bleaching chemicals consumption in the first-stage is directly proportional to the incoming Kappa number (Parthasarathy, 1997). Bleaching costs of TCF bleaching are on par with the cost of ECF bleaching at a Kappa number of around 20 (Södra, 1998). Total operating costs (wood, power, chemicals) are higher for TCF pulps. ECF adds $5-$10/t of total production cost above chlorine bleaching, while TCF adds $40-60/t, including capital expenditures (Pulliam, 1995).

The amount of elemental chlorine consumed in 1994 was 790 thousand tonnes (Kincaid, 1998). The amount of bleached pulp produced by ECF bleaching was 33% (NCASI, 1998). It is estimated that the conversion of all U.S. bleached kraft mills to ECF bleaching will require 20 PJ/year for generation of chlorine dioxide. Reductions of 13.7 PJ/year in energy use will be achieved from chlorine elimination and improvements in pulp washing and spill control practices. This will result in additional 6.3 PJ/year of energy requirements (NCASI, 1998).

Pulp Drying

In situations where the pulp and paper mills are not located in the same place or when a temporary imbalance between pulp production and paper machine requirements occurs, the pulp must be dried. Market pulp is dried on average to 20% water. Once the pulp is dried, it can be shipped to a paper mill, where it is re-pulped using a machine similar to the kind used for pulping recycled paper. Pulp drying is energy intensive and not essential to the papermaking process, therefore large savings might be achieved through co-locating the pulp and paper mills. Pulp drying consumes about 4.5 GJ of steam per tonne of pulp and 155 kWh/t pulp electricity (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson *et al.*, 1995).

Papermaking

After bleaching, the pulp is ready to enter the final stage: papermaking. The process can be divided into three basic steps –stock preparation, sheet formation and finishing (pressing and drying). Stock preparation consists of blending pulps and additives to form a uniform and continuous slurry (Elaahi and Lowitt, 1988). Next, the paper web is formed (sheet formation). By far the most

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[5] The use of sodium hypochlorite in bleaching is decreasing, mainly due to the effect of the effluent limitation guidelines.

common forming machines are the Fourdrinier machines for thin sheets and the twin wire formers and cylinder board machines for thick or multilayered sheets. Both of these machines spray low consistency pulp (~1% pulp) onto a moving wire mesh, which allows water to drain away. We estimate that stock preparation consumes about 274 kWh/t paper electricity and 0.7 GJ/t paper steam (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996).

Once the fibers have been sufficiently dewatered that they begin to bond to form paper, they move on to the press section. Here the paper is pressed to remove water, and promote further bonding between fibers. As it moves through the press section, the paper is held together by felts, which are actually woven materials that allows water to pass through. The pressing section is the target of many of the energy efficiency improvements in papermaking because the drier the paper is leaving the press section, the less energy it consumes in the drying section. Together forming and pressing consume about 238 kWh/t paper electricity (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996).

Lastly, the paper moves to the drying section, where steam filled rollers dry the paper through evaporation. This section consumes the bulk of energy in papermaking. 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 last stage in the papermaking process is the Calendar stack, which is a series of carefully spaced rollers that control the thickness and smoothness of the final paper. Energy consumption in the drying section is relatively high. We estimate consumption at 10 GJ/t paper steam and 21 kWh/t paper electricity (Elaahi and Lowitt, 1988; Jaccard and Willis, 1996, Nilsson *et al.*, 1995).

IV. HISTORICAL ENERGY USE AND CARBON DIOXIDE EMISSIONS IN THE U.S. PULP AND PAPER INDUSTRY

Primary energy consumption[6] in the U.S. pulp and paper industry increased steadily between 1960 and 1994 from 1495 PJ[9] to 3267 PJ equivalent to an increase of 2.3% per year. Final energy consumption (not accounting for electricity generation and distribution losses) grew at a rate of 2.1% per year. Primary energy consumption growth has slowed in recent years, evidenced by a 1.5% annual energy consumption growth rate between 1970 and 1994, and a 1.3% annual growth rate between 1980 and 1994 (see Figure 3 for primary energy consumption). The composition of the fuel mix has changed substantially over the period. Biomass and electricity grew more rapidly, increasing their shares from 35% and 5% in 1970 to 43% and 7.2% in 1994, respectively. Use of coal and coke, along with oil, decreased most rapidly in the paper sector, as coal and coke fell from 21% to 11%, and oil fell from 11.4% to 7%, between 1970 and 1994.

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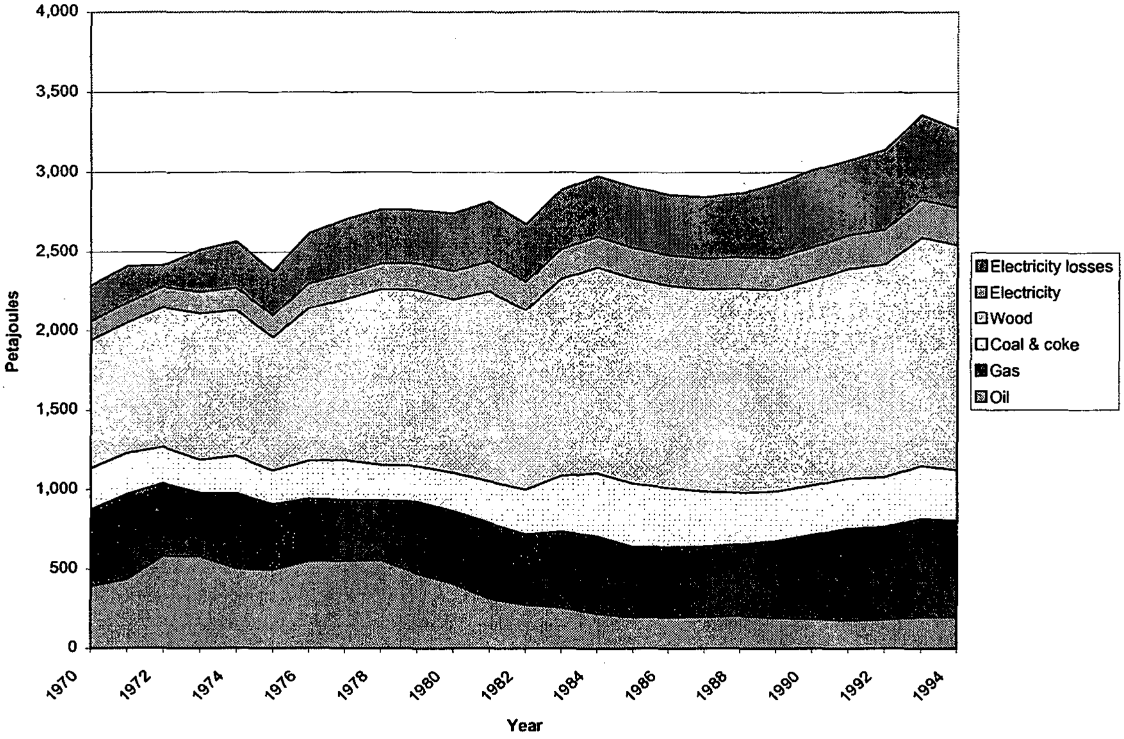
[6] Primary energy accounts for losses in electricity transmission and distribution and is calculated using a conversion rate from final to primary electricity of 3.08, reflecting the difference between an average power plant heat rate of 10,500 Btu/kWh and a site rate of 3412 Btu/kWh.

Figure 3. Primary Energy Use in U.S. Paper Production



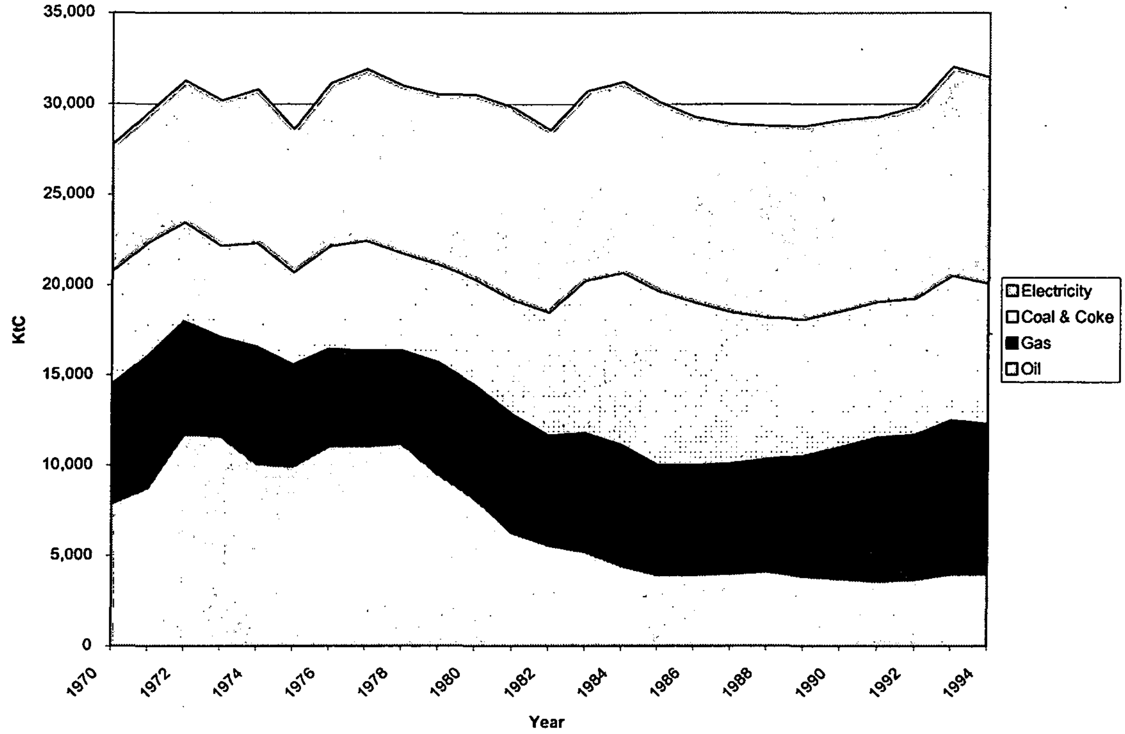
Source: U.S. DOC, various years; U.S. DOE, 1988, 1991, 1994, and 1997.

The OPEC oil embargo of 1973 (otherwise known as the oil crisis) had a significant impact on the U.S. paper industry. Since the oil crisis, the industry has been trying to reduce its dependence on oil, by changing the fuel mix away from oil as well as reducing the energy intensity of the mills. Between 1970 and 1994 industry reduced its primary energy consumption per tonne of paper and paperboard produced by 27%, from 49.9 to 39.6 GJ/tonne, at a rate of 1% per year. (Kincaid, 1998; U.S. EIA 1997a). This energy intensity decline reflects process efficiency investment and increased combined heat and power capacity additions over the period.

The leveling off of energy prices in the mid-1980s has appeared to reduce the rate of efficiency improvement, although there still are continuing improvements (Nilsson et. al., 1995). In particular, there is a strong interest in reducing the amount of purchased electricity which currently represents about 45% of total energy costs in the industry (EIA, 1997). Some of this improvement will be the result of upgrading old power boiler systems (about 80% of the operating boilers in the industry, both power boilers and recovery boilers, were installed prior to 1980) as well as through investment in combined heat and power (Cadmus, 1998).

The paper industry's carbon dioxide emissions increased overall between 1960 and 1994 from 27.7 Mt to 31.5 Mt, at a rate of 1.4% per year, less than the rate of increase of primary energy consumption which increased 2.3% per year over the same period. Since 1970, the rate of growth of carbon dioxide emissions has been more gradual, 0.5%/year. This slower growth is due primarily to two major changes in the industry. First, as noted earlier, there has been a significant increase in the share of biomass fuels over the past few decades. This results in lower carbon emissions per unit of energy consumed on an industry-wide basis. Secondly, there has also been a significant increase in the use of waste paper or recycled pulp which grew from 10.8 Mt to 28 Mt in 1994. Recycled pulp production is significantly less energy intensive, thereby contributing to reductions in energy intensity as well to reductions in carbon dioxide emissions. Carbon intensity, as measured by emissions per tonne of product, has declined rapidly (3% per year) from 0.6 tC/t of paper in 1970 to 0.4 tC/t of paper in 1994. This decline reflects the fuel and product shifts discussed above.

Figure 4. Carbon Dioxide Emissions from Fuel Consumption in U.S. Paper Production



Source: U.S. DOC, various years, U.S. DOE, 1988, 1991, 1994, 1997, IPCC, 1995.

V. 1994 BASELINE ENERGY USE AND CARBON DIOXIDE EMISSIONS

Energy Consumption

In 1994, the U.S. pulp and paper industry, excluding converting industry, consumed 2779 PJ of final energy, accounting for about 12% of total U.S. manufacturing energy use. The industry (SIC 26) emitted 31.5 MtC that contributed about 9% to total U.S. manufacturing carbon dioxide emissions (U.S. EIA, 1997a; U.S. EIA, 1997b). The fact that carbon emissions are lower than the share of energy use is mainly due to the assumption of biomass neutrality in carbon dioxide emissions accounting. Table 1 and Figure 5 provide an estimate and a better understanding of 1994 U.S. baseline energy consumption and carbon dioxide emissions by process for pulp, paper and paperboard production, excluding the paper and paperboard converting industry (SIC 27). This analysis does not include the amount of carbon sequestered in forests as well as industry's products and wastes. As the table indicates, most of the commercial and bio-fuels are used to first produce steam which is then used in various processes and to generate electricity. The estimate of steam, fuels, and electricity consumption by process was based on average unit consumption estimates found existing literature especially (Elaahi and Lowitt, 1988; Nillson et al., 1995; Jaccard and Willis, 1996; Giraldo and Hyman, 1994; Kincaid, 1998; and EIA, 1997)

Table 1. 1994 Energy Consumption and Specific Energy Intensity in the U.S. Pulp and Paper Industry by Process

Process Stage	**Steam Used**[1]	**Commercial Fuel**	**Bio-fuels**	**Electricity**	**Final Energy**	**Tonnes of throughput**	**Steam or Fuel/Bio-fuel SEC**	**Electricity SEC**	**Carbon Dioxide Emissions from Energy Use**
	-a-	**-b-**	**-c-**	**-d-**	**e=a+b+c+d**	**-f-**	**$g=\frac{a+b+c}{f}$**	**h=d/f**	**I=[SCF•a+FCF•b+OCF•c+ECF*d]/1000**
	PJ	PJ	PJ	PJ	PJ	Mt throughput	GJ/t paper	GJ/t paper	MtC
Wood Preparation	0.00	0.00	0.00	33.70	33.70	241.46	0.00	0.41	1.06
Pulping									
Chemical	240.22	0.00	0.00	79.58	319.8	53.41	2.91	0.97	4.71
Mechanical	2.67	0.00	0.00	67.59	70.26	5.34	0.03	0.82	2.15
Wastepaper						27.82			
Other	16.80	0.00	0.00	2.33	19.14	5.25	0.20	0.03	0.23
Bleaching	132.76	0.00	0.00	18.22	150.98	34.92	1.61	0.22	1.78
Chemical Recovery	300.32	110.67	0.00	6.92	417.91	53.41	4.98	0.08	4.93
Pulp Drying	34.23	0.00	0.00	4.24	38.47	7.61	0.42	0.05	0.44
Papermaking	880.28	0.00	0.00	157.93	1038.20	82.46	10.68	1.92	12.97
Other	0.00	61.50	0.00	24.94	86.44	82.46	0.75	0.30	1.88
Total Process Energy –A-	*1607*	*172*	*0*	*395.4*	*2175*	*82.5*	*21.6*	*4.8*	*30.1*
Total Non-Process Energy –B-				*43.2*	*43.21*				*1.3*

Secondary Energy Production	**Output Steam**	**Input Steam**	**Input Fuel**	**Input Bio-fuel**	**Electricity**	**Final Energy**		**Carbon Dioxide Emissions from Energy Use**
	-j-[3]	-k-	-l-	-m-	-n-			-o-[3]
	PJ	PJ	PJ	PJ	PJ	PJ		MtC
CHP & non CHP onsite energy production[2]	-437	688	106	69	-203			0.00
Boiler Plant Facilities	-1858		848	1348				0.00
Total balance for Onsite Energy Production	*-2296*	*688*	*955*	*1417*	*-203*			*0.0*
Total Energy Required/produced/bought (CO2 emissions)	**-688**	**688**	**1127**	**1417**	**235**[4]	**2779**		**31.5**

Notes: Excludes paper and paperboard converting sector (SIC 27).

SEC – specific energy consumption

SCF – steam carbon factor equal to 9 ktC/PJ, which reflects the average carbon factor of all the fuel inputs into on-site steam generation, including biomass

ECF - electricity carbon factor of 32 ktC/PJ, which reflects the average of purchased and on-site generated electricity carbon factor

FCF - fuel carbon factor of 17.8 ktC/PJ, which reflects the average carbon factor of all the fuel inputs into on-site thermal power generation, excluding biomass

OCF – other carbon factor of 0 ktC/PJ, i.e. average other (biomass) carbon factor

[1] Includes steam purchased from utility and non-utility suppliers

[2] Includes ~ 9 PJ hydroelectric production for non-CHP on-site generation

[3] See Figure 5 for all the other assumptions

[4] This number represents the balance between the overall electricity required by the sector and the onsite production (see Figure 5, item: "Electricity from the grid")

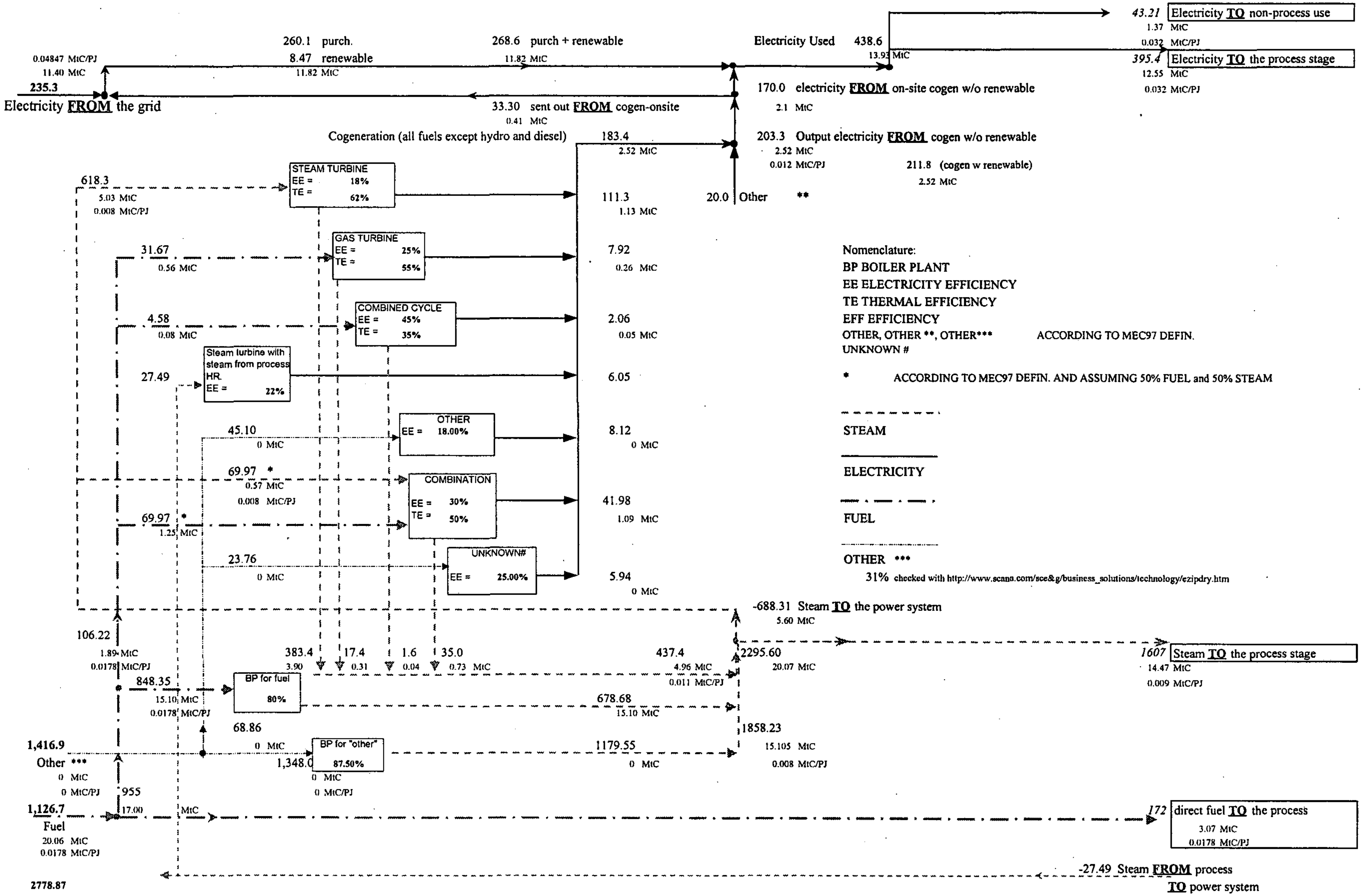


Figure 5: Estimate of Energy Flow (PJ) and Carbon Dioxide Emissions (MtC) in the U.S. Pulp and Paper Industry -1994

Carbon Dioxide Emissions Baseline

Table 2 below shows 1994 energy consumption by fuel type for the pulp and paper industry (SIC 26) and the respective carbon emissions by fuel. The data for 1994 carbon coefficients for the various commercial fuels come from the U.S. Energy Information Administration database (U.S. EIA, 1997b). A carbon emissions factor of 48.5 ktC/PJ is used for purchased electricity, reflecting the average carbon intensity in 1994 of U.S. public electricity production.

Table 2. Energy Consumption, Carbon Emissions Coefficients, and Carbon Emissions from Energy Consumption for the U.S. Pulp and Paper Industry (SIC 26) in 1994

Energy – Related Carbon Dioxide Emissions			
Fuel	**Energy Use (PJ)**	**Carbon Emissions Coefficient (ktC/PJ)**	**Carbon Emissions (MtC)**
Electricity (Purchased)	235.3	48.5	11.4
Residual Fuel Oil	182.5	20.4	3.7
Distillate Fuel Oil	9.5	18.9	0.2
Natural Gas	605.6	13.7	8.3
LPG	5.3	16.1	0.1
Coal	323.9	24.3	7.7
Other (biomass & steam)	1416.9	0.0	0.0
Total Energy	2,779	-N.A.-	31.5

Sources: U.S. EIA, 1996; U.S. EIA, 1997; UNEP et al., 1996.

VI. ENERGY EFFICIENCY TECHNOLOGIES AND MEASURES FOR THE U.S. PULP AND PAPER INDUSTRY

A large number of technologies and measures exist that can reduce energy intensity (i.e., the electricity or fuel consumption per unit of output) of the various process stages of pulp and paper production. This section provides estimates on the technologies and measures and their costs and potential for implementation in the U.S. Table 3 lists the technologies and measures that have been analyzed for this study. These technologies can be divided into two general categories: current state-of-the-art technologies and advanced technologies. Current state-of-the-art technologies are technologies currently implemented in the pulp and paper mills world-wide, while advanced technologies are technologies that are currently used only in pilot plants or are at an early stage of commercialization. Advanced technologies are not included in the analysis of measures for energy intensity reductions, but are shown in Table 3 for general information.

Several technologies and measures are analyzed by means of an extensive literature review and discussions with industry specialists. For each technology and measure, we have estimated energy savings and/or carbon dioxide emissions reductions per tonne of product produced in 1994. We have also calculated the capital investments needed and the change in operation and maintenance costs (O&M) associated with the implementation of these technologies and measures per annual tonne of product. The analysis mostly focuses on retrofit measures. A further conversion from energy savings, carbon dioxide emissions reductions and associated costs, expressed in *per tonne of product,* to values expressed in *per tonne of paper* is given. This is assessed multiplying each value by the ratio of throughput (production from a specific process) to total paper produced. Finally, based on a variety of information sources and expert judgment, the authors provide an estimate of the potential penetration rate for each technology and measure that can be attained by the year 2010, and project this estimate on the 1994 baseline to estimate the potential energy efficiency improvements in that year.

Table 4 provides the summary of the input data and assumptions for the scenarios. The table shows fuels, electricity, and primary energy savings per tonne (t) of production, retrofit capital costs[7] and O&M costs per tonne of production, the percentage of production to which the measure can be applied nationally (by 2010), and the associated carbon dioxide emissions reductions. A detailed description of each technology and measure and estimates of associated energy savings and costs is provided below.

Table 3. Energy-Efficient Technologies and Measures for the U.S. Pulp and Paper Industry.

Process	Technology/Measure	Process	Technology/Measure
Raw Materials Preparation	Ring style debarker	**Papermaking (continued)**	Hot Pressing
	Cradle debarker		Direct drying cylinder firing
	Enzyme-assisted debarker		Reduced air requirements (closing hoods and optimizing ventilation)
	Bar-type chip screens		Waste heat recovery
	Chip conditioners		Condebelt drying
	Improved screening processes		Infrared profiling
	Belt conveyor		Dry sheet forming
	Fine slotted wedge wire baskets		
Pulping: Mechanical	Refiner improvements	**General Measures**	Optimization of regular equipment
	Biopulping		Energy-efficient lighting
Pulping: Thermo-Mechanical	RTS (short Residence Time, elevated temperature, high speed)		Efficient motors
	LCR (low consistency refining)		Pinch Analysis
	Thermopulp	**Efficient Steam Production and Distribution**	Boiler maintenance
	Super Pressurized groundwood pulping		Improved process control
	Heat recovery in thermomechanical pulping		Flue gas heat recovery
	Improvements in Chemi- thermomechanical Pulping		Blowdown steam Recovery
Pulping: Chemical	Continuous digesters		Steam trap maintenance
	Continuous digester modifications		Automatic steam trap monitoring
	Batch digester modifications		Leak repair
Chemical Recovery	Falling film black liquor evaporation		Condensate return
	Tampella recovery system	**Other Measures**	Increased use of recycled paper
	Lime kiln modifications		Combined heat and power systems**
Bleaching	Extended cooking (delignification)	**Advanced Technologies - Pulping**	Alcohol based solvent pulping
	Oxygen predelignification		Black liquor gasifier+gas turbines
	Ozone bleaching		Pre-treatment of incoming pulp into drying section
	Oxidative extraction		Direct alkali recovery system
	Biobleaching	**Advanced Technologies - Papermaking**	Infrared drying*
	Improved brownstock washing		Impulse drying
	Washing presses (post delignification)		Airless drying
Papermaking	Gap forming		Press drying
	High consistency forming		Air impingement drying
	Extended nip press (shoe press)		Steam impingement drying

Notes:

* Technologies that provide energy savings, but increase carbon dioxide emissions.

** The CHP systems (combined heat and power) have not been included in the analysis because use those systems should be evaluated separately from and in comparison with other technologies, as their installation significantly alter the heat-to-power ratio of the facilities. The CHP potential for the pulp and paper industry has been covered in separate studies (Khrushch, et al., 1999; NCASI, 1999).

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[7] All capital costs are calculated in dollars per tonne per year ($-yr/t). For the sake of brevity, we have listed the values in the table as $/t. We do not deflate dollar values to a standard year but our internal analysis indicates that this does not adversely affect the results.

Table 4. Energy Savings, Costs, and Carbon Dioxide Emissions Reductions for Energy-Efficient Technologies and Measures Applied to the U.S. Pulp and Paper Industry in 1994.

	Production	Fuel Savings	Electricity Savings	Primary Energy Savings	Carbon Savings	Retrofit Cost of Measure	Annual Operating Cost Change	Applicable Share of Production
Measure	(Mt)	(GJ/t)	(GJ/t)	(GJ/t)	(kgC/t)	(US$/t)	(US$/t)	%
Raw Materials Preparation								
Ring style debarker	241.5	0.00	0.02	0.03	0.5	1.3	-0.01	15%
Cradle debarker	241.5	0.00	0.03	0.05	0.8	25.8	0.0	15%
Enzyme-assisted debarker	241.5	0.00	0.02	0.04	0.7	3.9	0.0	15%
Bar-type chip screens	49.5	0.35	0.00	0.50	3.1	1.5	-0.7	20%
Chip conditioners	49.5	0.21	0.00	0.30	1.9	N/A	-0.4	30%
Improved screening processes	49.5	0.35	0.00	0.50	3.1	1.5	-0.7	20%
Belt conveyors	239.4	0.00	0.02	0.04	0.7	N/A	-0.5	20%
Fine-slotted wedge wire baskets	5.3	0.00	0.61	1.24	19.4	N/A	N/A	10%
Pulping: Mechanical								
Refiner Improvements	3.2	0.00	0.81	1.63	25.6	7.7	2.6	20%
Biopulping	5.3	-0.50	2.04	3.41	60.1	27.0	9.4	20%
Pulping: Thermomechanical (TMP)								
RTS	3.0	0.00	1.10	2.23	35.0	50.0	0.0	30%
LCR	3.0	0.00	0.51	1.04	16.3	N/A	0.0	5%
Thermopulping	3.0	0.00	1.10	2.20	35.0	226.7	N/A	15%
Super Pressurized groundwood	3.0	0.00	2.67	5.40	84.7	220.0	-2.6	10%
Heat recovery in TMP	3.0	6.05	-0.54	7.52	37.4	21.0	18.0	20%
Improvements in Chemi-TMP	3.0	0.00	1.10	2.23	35.0	300.0	N/A	20%
Pulping: Chemical								
Continuous digesters	49.5	6.30	-0.27	8.40	48.1	196.0	0.0	25%
Continuous digester modifications	49.5	0.97	0.00	1.39	8.8	1.3	0.2	50%
Batch digester modifications	49.5	3.20	0.00	4.55	28.8	6.6	0.5	15%
Chemical Recovery								
Falling film black liquor evaporation	53.2	0.80	0.001	1.14	10.1	90.00	0.00	30%
Tampella recovery system	53.2	2.90	0.0	4.13	23.9	N/A	N/A	1%
Lime kiln modifications	53.2	0.46	0.0	0.46	7.82	2.50	N/A	20%
Extended Delignification and Bleaching								
Ozone bleaching	29.6	0.00	0.01	0.02	0.3	149.5	-2.0	25%
Brownstock washing	29.6	0.01	0.05	0.11	1.5	50.0	-2.3	15%
Washing presses (post-delignification)	29.6	0.39	0.00	0.55	3.5	17.0	-0.5	15%
Papermaking								
Gap forming	82.5	0.00	0.15	0.30	4.7	70.0	0.7	35%
High consistency forming	70.6	1.50	0.15	2.43	18.2	70.0	0.7	20%
Extended nip press (shoe press)	82.5	1.60	0.00	2.28	14.4	37.6	2.2	40%
Hot pressing	82.5	0.61	0.00	0.87	5.5	25.7	0.0	10%
Direct drying cylinder firing	82.5	1.05	0.00	1.50	9.5	111.2	1.4	5%
Reduced air requirements	82.5	0.76	0.02	1.12	7.5	9.5	0.1	40%
Waste heat recovery	82.5	0.50	0.00	0.71	4.5	17.6	1.6	30%
Condebelt drying	82.5	1.60	0.07	2.43	16.7	28.2	0.0	50%
Infrared profiling	82.5	0.70	-0.08	0.84	3.8	1.2	0.0	15%
Dry sheet forming	82.5	5.00	-0.75	5.59	21.2	1504.0	0.0	15%
General Measures								
Optimization of regular equipment	82.5	0.00	0.10	0.20	3.4	N/A	1.0	30%
Energy-efficient lighting	82.5	0.00	0.05	0.10	1.6	1.20	-0.01	20%
Efficient motor systems	82.5	0.00	0.62	1.25	19.6	6.00	0.0	100%
Pinch analysis	82.5	1.79	0.00	2.54	16.1	8.00	0.0	20%
Efficient Steam Production and Distribution								
Boiler maintenance	82.5	1.26	0.00	1.79	11.3	0.0	0.06	20%
Improved process control	82.5	0.54	0.00	0.76	4.8	0.4	0.08	50%
Flue has heat recovery	82.5	0.25	0.00	0.36	2.3	0.7	0.09	50%
Blowdown steam recovery	82.5	0.23	0.00	0.33	2.1	0.8	0.11	41%
Steam trap maintenance	82.5	1.79	0.00	2.54	16.1	1.2	0.09	50%
Automatic steam trap monitoring	82.5	0.89	0.00	1.27	8.0	1.2	0.16	50%
Leak repair	82.5	0.54	0.00	0.76	4.8	0.3	0.03	12%
Condensate return	82.5	2.68	0.00	3.81	24.1	3.8	0.54	2%
Fiber Substitution								
Increase use of recycled paper	60	13.4	2.1	22.4	186	485	-73.9	15%

Raw Materials Preparation

Ring style debarkers

Wet debarkers remove bark by rotating logs in a pool of water and knocking the logs against the drum. Dry debarkers eliminate the use of about 7-11 tonnes of water per tonne of wood, thus reducing water and energy use (EPA, 1993). Dry debarkers dominate the industry. However we estimate that dry debarkers can still replace wet debarkers for about 15% of pulpwood debarking. Wet debarkers use approximately 0.04 GJ/t of debarked logs of energy, while ring style debarkers use approx. 0.025 GJ/t of debarked logs (Jaccard, Willis, 1996). We estimate investment costs of $1.3/t of woodpulp, and savings in O&M costs of $0.01/t of woodpulp.

Cradle Debarker

The Cradle Debarker marketed by Dieter Bryce Co. (U.S.) has an electricity load 90 kW of energy and can debark about 120 cords of pulpwood per hour (Anonymous, 1995c, Dieter Bryce, 1999). The price of the Cradle Debarker is about 70% of a regular drum debarker (Dieter Bryce, 1999). We estimate energy savings of 0.025 GJ/t of debarked logs, and apply this measure to 15% of debarked logs throughput. Estimated investments are of $25.8/t of woodpulp, and O&M costs are same as for regular drum debarker.

Enzyme-assisted debarker

Enzyme-assisted debarking is based on enzyme pretreatment of logs for debarking that reduces energy consumption in the process. Investment costs for a enzyme-assisted debarker are about $CAN 1.4 million (1990) for an 800 tpd plant, while O&M costs are the same as for other dry debarkers (Jaccard, Willis, 1996). Enzyme-assisted debarkers use about 0.01 GJ/t of debarked logs of electricity (Jaccard, Willis, 1996). We estimate energy savings of 0.021 GJ/t of debarked logs of electricity from enzyme-assisted debarker, and apply this measure to 15% of debarked logs throughput. The necessary capital investments are of $3.9/t of woodpulp. The energy associated with the production of enzymes is not included.

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 U.S. 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). Energy savings from bar-type screen installations are estimated at 0.35 GJ/t chemical pulp, due to about 2% increase in yield. O&M cost savings due to improved yield are $0.7/t pulp (Kincaid, 1998). Capital costs required for new bar-type screens are approximately the same as for other screening equipment (EPA, 1993). We apply this measure to 20% of chemical pulp throughput.

Chip conditioners

Chip conditioners prepare chips for efficient delignification by making cracks along their grains, unlike chip slicers that fractionate chips (Henry, Strakes, 1993). Chip conditioning generates less fines, achieves an average reduction of 1.2% in rejects, and requires less maintenance than slicing equipment. Rader's Dyna Yield Chip Conditioner is powered by two 150-hp motors and can condition about 73 tonnes of chips per hour (Henry and Strakes, 1993). We estimate energy savings from replacing chip slicers with chip conditioners as 0.2 GJ/t chemical pulp, and savings in O&M costs from improved yield of $0.4/t chemical pulp (Kincaid, 1998). We apply this measure to 30% of raw materials throughput.

Improved Screening Processes –Screen out thick chips

Elahi and Lowitt (1988) note that 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. Energy savings from this measure are estimated to be 0.35

GJ/t pulp assuming an increase of 2% in quality chip yield (Elahi and Lowitt, 1988). Costs for screening equipment for a greenfield installation are estimated to be $1.1/t chemical pulp. The retrofit option has higher investment costs, and is estimated at $1.5/t pulp (EPA, 1993). O&M cost savings from improved yield are $0.7/t pulp (Kincaid, 1998). We apply this to 20% of chemical pulp throughput.

Belt conveyers
In the woodyard of some mills chips are conveyed by pneumatic chip-blowing systems that are intensive energy users. The more efficient bark and chip handling systems are belt conveyors. Belt conveyors use about 15% of power required for pneumatic conveyors. Belt conveyors reduce fine and chip pin losses, which improves yield by about 1.6% (Hamid, 1993, Young, 1994). Estimated electricity savings from replacing pneumatic systems with belt conveyors are 0.021 GJ/t raw material handled (Hamid, 1993) or 5.8 kWh/t. We estimate reduction in O&M costs of $0.53/t of raw materials handled from reduction in fines and pin chip losses. Currently, pneumatic conveyors, as they wear out, are being replaced by belt conveyors. However, potential for replacement still exists. We apply this measure to 20% of raw materials throughput.

Fine-slotted wedge wire baskets
This kind of technology can yield significant improvement in shive removal, enhancement of physical pulp properties, and, in some cases, reduction of electrical power. It has already been implemented in many European mills (Cannell, 1999). A prerequisite is a chip supply with low dirt/bark content and an efficient chip wash system. Cannell (1999) also claims lower capital costs than the traditional screening systems, in some cases, and less O&M costs because pipes' diameters and pump sizes can be reduced and sometimes the TMP mainline cleaners can be shut down. Estimated electricity savings in mechanical pulping is roughly 9% in refiner energy consumption that is 169 kWh/t of mechanical pulp (Cannell, 1999). The technology has lower capital costs than the traditional screening systems, because of the reduced pipe diameters and pump sizes are reduced. The main drawback is that the wedge wire baskets are mechanically weaker than conventional baskets and prone to failure. We apply this measure to 10% of mechanical pulp throughput, due to high level of mechanical failures at the current stage of development of this technology.

Pulping

Mechanical Pulping

Refiner Improvements
Several improvements are possible with the refiner section of a mill, which can reduce electricity consumption in mechanical pulping. A newsprint mill in Quebec, Canada recently implemented a refiner control strategy to minimize variations in the freeness of ultra-high-yield sulfite pulps and saved 51.3 kWh/t 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 to 15% electricity savings are possible in TMP and RMP (Alami, 1997). Based on these measures, we assume an electricity savings potential of 11% or 305 kWh/t for mechanical refining improvements and a capital cost of $7.7/t pulp (Caddet, 1990). An increase in the O&M costs of $2.6/t of pulp has been taken into account by switching from one to two refining stages (Caddett, 1990; Jaccard and Willis 1996). We apply this measure to 20% of mechanical pulping.

Biopulping
Biopulping consists of pretreating the wood chips with biological agents to degrade the lignin. These agents can consist of fungi containing a variety of enzymes (or isolated enzymes) that break

down the lignin. The physical process begins after the pulpwood has been chipped and screened for oversize chips. At this point the chips are briefly heated to 100 °C to kill off anything that might compete with the lignin-degrading fungus. The chips are then air-cooled and the fungus and the nutrients are added. The treated chips are placed in a pile for the next 1 to 4 weeks: climatic and seasonal factors are very important for the effectiveness of the treatment. The fact that up to 4 weeks worth of chips must be stored may be a problem for mill sites with space constraints. This system is not yet commercial, but has been demonstrated in large-scale tests (Scott et al., 1998). Experts agree that many unresolved issues still need to be deepened. Electricity savings from biopulping have been estimated at 25-40% compared to mechanical refining. (Scott et al., 1998). However, there are some additional steam requirements. We therefore assume savings of 30% or 565 kWh/t pulp and additional steam consumption of 0.5 GJ/t. This process may extend machine life and improve product quality. Scott and Swaney (1998.) report a cost investment of $6M for a 600 ton/day output. We therefore assume a cost of $27/t pulp. Operations and maintenance costs are expected to increase with this process. We assume an increase of $9.4/t based on (Scott and Swaney, 1998). Given that this technology is used for smaller sized mills, we assume that 20% of all mechanical pulp mills less than 600 tpd are retrofitted with biopulping technology.

Thermo-Mechanical Pulping

RTS (short Residence time, elevated Temperature, high Speed)

The RTS process has been commercialized in 1996. 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. 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; Fergusson, 1997; Patrick, 1999). The pulp produced with low-retention/high-pressure/high-speed conditions demonstrated approximately 15% lower specific energy requirements than the pulp produced with a traditional refining system. This reflects a savings of 306 kWh/t in TMP with an investment cost of $50/t pulp. This pulp has slightly higher strength properties and comparable optical properties to TMP pulps. There are five RTS installations in operation at 1999 in the world. We assume a potential penetration of 30% in remaining thermomechanical pulping, as it is becoming more and more common in TMP mills.

LCR (Low Consistency Refining)

Installation of LCR (it functions as a third stage refiner) is justified based on energy savings and/or an increase in production rate (from 4% to 12%) (Cannell, 1999). The reduction in specific energy is due to the difference in the refining response for LCR versus high consistency refining for a particular freeness range and is assessed being about 7% less than TMP energy requirements (Cannell, 1999). Energy savings of 142 kWh/t of thermomechanical pulp can be achieved. We apply this measure to a small portion (5%) of thermomechanical pulp production (i.e. technology applications limited to low freeness TMP).

Thermopulp

Thermopulping is a variation of the TMP process whereby pulp from the primary stage refiner is subject 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. Commercial development of this process is ongoing in 6 mills, reporting savings in the range of 10% to 20% (Cannell, 1999). Based on these measures, we assume an energy saving potential of approx. 306 kWh/t (15% savings) for mechanical refining improvements. One drawback in this process was reported at the Ortviken mill. Mill tests experienced an increase of peroxide, in the bleaching section, ranging from 1.35 to 3.6 kg/t of pulp, depending on the number of stages in the TMP process before switching to Thermopulp (Höglund, 1997). We assume a cost of $226 tpy of pulp (Anonymous, 1997) for a new installation and a potential penetration of 15% in the TMP pulp production. We keep the penetration limited because the average mill size of many mills in North America doesn't not allow use of thermopulping.

Super Pressurized GroundWood

Pressurized groundwood pulping was first developed in Scandinavia in the 1970s. In a pressurized groundwood system, grinding takes place under pressure where water temperature is high (more than 95 °C), thereby allowing for higher grinding temperatures without steam flashing (P&P Staff report, 1989). The technical literature claims a 36% saving in electricity (~ 740 kWh/t) compared with TMP (Caddett, 1992). Costs for system installations are estimated at $220/t as well as a $2.6/t saving for O&M costs (Sutton, 1989). With the Super pressurised groundwood technology better smoothness and opacity of paper is achieved (EPA, 1994). One of the reasons that may attract mills to adopt this technology is also a better handling of lower fiber coarseness (SC paper grades). We assume a potential application for 10% of 1994 thermomechanical pulping. The strength properties of PGW-s improve by 30-50% compared to atmospheric grinding and 15-20% compared to conventional PGW without using any more energy.

Heat recovery in thermomechanical pulping

A vast amount of steam is produced as by-product of thermo-mechanical pulping. Most of this energy (about 60-70%) can be recovered as low pressure steam in an evaporator/reboiler system (Franko 1989; Lahner, 1989; Engstrom 1989, Komppa 1993.). This recovery can also be accomplished by other technologies such as: MVR[8] (Tistad 1989; Engstrom 1989; Ryham 1989) for integrated mills, where all the steam available can be used in the paper machine dryer section, ejectors[9] (Engstrom 1989) and cyclotherm systems+ heat pump[10] (Engstrom 1989; Klass 1989). The steam must be at about 0.27 MPa to be suitable for use in other processes such as the paper machine dryer section. The TMP process generates 2-3 kg of steam per kg of refined pulp. The amount varies with pulp production rate, refining fiber consistency, dilution water temperature, and power input rate (Rockhill, 1989). Heat recovery systems can be expected to save between 3.2 to 5.5 GJ/t of pulp (Tistad, 1989) while electricity consumption is expected to increase up to 149 kWh/t pulp. Installation costs may greatly change depending on the system. Klass (1989), Rockhill (1989), Jaccard *et at.* (1996) report a wide range of installation costs. According to this last reference, we assume an installation cost of $21/t of pulp and a significant increase in the O&M costs of approx. $18/t of pulp, if compared to a traditional cyclotherm system. We assume a potential penetration of 20% in remaining thermomechanical pulping.

Improvements in Chemi-ThermoMechanical Pulping

First developed in Scandinavia during late 1970s, chemi-thermomechanical pulping entails application of chemicals to the chips prior refining. The process begins with an impregnation of 2% to 5% of sodium sulfite and chelating agents at a pH of 9 to 12. The mixture is preheated for 2 to 5 minutes at 120°C to 130 °C and refined. Depending on the raw materials and amount of chemicals used, yields for unbleached softwood CTMP are in the range of 86% to 90% (Kincaid, 1998). Pre-steaming is done to remove air from the woodchips and stabilise the chip temperature (Grossman

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[8] Mechanical vapor recompression: clean steam is produced recovering heat from dirty steam or heat that comes from the refiner. If the pressure is too low to be directly used in the drying section, a compressor is needed to increase its enthalpy content.

[9] in Ejectors or TVR (thermal vapor recompression): high-pressure steam from boilers is used to transport the rejected steam into the ejector, thus converting the velocity of the mixture to pressure a diffuser.

[10] Cyclotherm and heat pump is a system using heat from dirty steam in an inverse-Carnot cycle. The difference with MVR is that an intermediate fluid is used to be compressed and not directly the steam.

and Salmen, 1997). The chemical pre-treatment of the chips permits less destructive separation of fibers from the wood resulting in a higher longer fiber content and a much lower shive content than thermomechanical pulp (Stationwala, 1994). CTMP proved a higher brightness before bleaching and is better suited for absorbent grades and food packaging. Typically, newsgrade quality CTMP from black spruce requires 9.3-10 GJ/t of refining energy. However, increasing the first stage refiner speed and decreasing the pH of the sulfite liquor can allow this process to operate at 6.5-8.3 GJ/t (Stationwala, 1994). We assume savings of 15% or 283 kWh/t (Grossman and Salmen, 1997). An increase in waste treatment requirements, caused by the added dissolved materials, may be experienced. Though the applicability and costs of CTMP are species specific, installation costs for this technology have been estimated on average of \$300/t pulp, including chip washing impregnation, refiners, heat recovery system, wash presses and motors. Improvements in CTMP are still in progress. We assume a potential technical penetration of 20% for thermomechanical pulping (Meadow, 1998).

Chemical Pulping

Continuous digesters

Continuous digesters are a more efficient technology than the cheaper batch digesters. In a continuous digester the wood chips are pre-steamed and cooked in pulping liquor at 160°C. As opposed to a batch process, there is a continuous stream of chips into the digester and a continuous exit stream of pulp. The continuous flow within the digester allows recovery of heat from one part of the process to heat another. (Kline, 1991). Although continuous digesters require about 0.27 GJ/t pulp of additional electricity (+75 kWh/t), this is compensated by reduced steam requirements. We estimate average steam savings of 6.3 GJ/t pulp (Elahi and Lowitt, 1988, Jaccard, and Willis, 1996). Continuous digesters can be easily adapted for computer control, have lower labor requirements, have reduced digester corrosion, and produce higher strength product (Elahi and Lowitt, 1988). Installation of continuous digesters will require replacement of the whole pulp line, which includes technology for bleaching and chemical recovery. Estimates of such replacements run \$100-400 million for a 450 tpd mill (Anonymous, 1993b; Anonymous, 1994b; Elahi and Lowitt, 1988). For the digester portion alone we estimate a cost of \$50 million, or \$196/t pulp (Anonymous, 1998). O&M costs are anyway assumed the same as for batch digester, because of an increased number of pumps and fans. As of 1988, 50% of chemical pulp in the U.S. was produced using continuous digesters. We assume that an additional 25% penetration, starting from 1994 data, is possible.

Continuous digester modifications

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 (Elahi and Lowitt, 1988). Increased indirect heating as a result of these modifications also can improve pulp uniformity, strength, and yield. We assume energy savings of 0.97 GJ/t pulp (Jaccard, and Willis, 1996). Costs may vary depending on the specific modification. We assume a cost of \$1.25 /t pulp for computer control modifications, and increase in O&M costs of \$0.16/t pulp (Jaccard, and Willis, 1996). We assume that continuous digester modifications can be made to 50% of throughput.

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 are several approaches to reduce energy consumption in batch digesters, such as the use of indirect heating and cold blow. 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. Savings are estimated to amount to 3.2 GJ/t (Elaahi and Lowitt). There are however some additional maintenance costs with this system including maintaining the heat exchangers (Elahi and Lowitt, 1988). We estimate an increase in O&M costs of $0.49/t pulp, and the necessary investment for equipment modifications of about $6.6/t pulp (Jaccard, and Willis, 1996). We apply this measure to 15% of digester throughput, given the preponderance of continuous digesters in our technical potential scenario.

Chemical Recovery

Falling film black liquor evaporation

A tube type falling film evaporator effect operates almost exactly the same way as a more traditional rising film effect, except that the black liquor flow is reversed. The falling film effect is more resistant to fouling because the liquor is flowing faster and the bubbles flow in the opposite direction of the liquor. This resistance to fouling allows the evaporator to produce black liquor with considerably higher solids content (up to 70% solids rather than the traditional 50%) thus eliminating the need for a final concentrator. (Nilsson et al., 1995). We estimate steam savings of 0.8 GJ/t pulp with no change in electricity consumption (Elaahi and Lowitt, 1988). Cost for evaporator systems are estimated at $90/t pulp (Minton, 1986). Most new mills already install this system. We apply this therefore to 30% of integrated kraft (Elahi and Lowitt, 1988).

Tampella recovery system

The Tampella recovery system recovers the chemicals and energy from the sulfite process spent liquor to produce chemicals for the sulfite process. It is one of the few operational systems that is able to recausticize sulfite liquor for reuse in the pulping operation. The recovery process begins the same way as the Kraft process, with a recovery boiler producing green liquor consisting of an aqueous solution of Na_2CO_3 and Na_2S. CO_2 from scrubbed flue gasses is pumped into the solution, allowing these chemicals to react with it and the surrounding water. The H_2S gas leaving during the stripping process is burned to form SO_2 which is pumped into the solution of Na_2CO_3 to form the sulfite cooking liquor. Since sulfite liquors are not usually recovered, the use of this process could save considerable energy (Ingruber et al., 1985.). Energy savings are estimated at 2.9 GJ/t (Elahi and Lowitt, 1988). The Tampella recovery is fairly common in Japan but not in the U.S. (Ingruber et. al, 1985). We assume that 50% of 1994 sulfite pulping capacity could still implement the system.

Lime kiln modifications

The lime kiln calcines the calcium carbonate ($CaCO_3$) in lime mud to produce quicklime (CaO). Several modifications are possible to reduce energy consumption in the kiln. 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 or chains to increase heat transfer in the kiln. Heat can also be captured from the lime and from kiln exhaust gases to pre-heat incoming lime and combustion air. We calculate that the average savings achieved by these measures is approximately 0.46 GJ/t pulp (Elahi and Lowitt, 1988; Grace et al., 1989; Byrne and Larsen, 1997; Lewko, 1996; Pearson and Dion, 1999; Martin, Worrell, Price, 1999). These improvements can also improve the rate of recovery of lime from green liquor, thus reducing the plant's requirement for additional purchased lime. Based on a detailed analysis of kiln modifications in cement production we assume an investment cost of $2.5/t pulp (Martin *et al.,* 1999). We assume that such modifications are applicable to 20% of the existing lime kilns.

Extended Delignification

Extended Cooking in Continuous Digesters

MCC (Modified Continuous Cooking) and EMCC (Extended MCC) allow to extend cooking times without loss in pulp quality or yield by maintaining a more even alkali charge than conventional cooking. This measure results in significant reductions of bleaching chemicals. However, we did not find a corresponding energy savings on site, and therefore do not include this measure in our technical potential scenario.

Oxygen delignification

Oxygen delignification is a bleaching process where oxygen is mixed with pulp, is allowed to react with the lignin, and is washed away. This process can be beneficial for selectivity, pulp quality and environmental impact. We did not however find significant energy savings and therefore do not include this measure in our technical potential scenario.

Bleaching

Ozone bleaching

Ozone bleaching is an alternative bleaching process that can produce pulp of equal brightness to either ECF or TCF. Ozone is a very effective delignifying agent, but its usage has been limited due to high investment costs and increased energy consumption, approximately 10 kWh/kg of O_3 (Korhonen, 1993). Laboratory tests showed that the least expensive option for adding ozone (Z) is to add it to the first chlorine dioxide (D) bleaching stage. In this case ozone serves as a replacement chemical for chlorine dioxide[11] (Chirat, Lachenal, 1998, Finchem 1998). Used in the right combination of stages, ozone bleachng can save on capital costs, reduce consumption of chlorine dioxide, and eliminate one washing stage (Finchem, 1998).

Another process, the EnZone being developed at the University of Georgia combines oxygen and enzymatic delignification of hardwood pulps with ozone treatment and a final hydrogen peroxide bleaching stage (Eriksson and Alophson, 1997). The use of ozone has proven to be effective with and without oxygen delignification, and employs much of the existing bleach plant equipment, thereby minimizing capital costs for the installation (Ferguson, 1998). Further optimization of ozone bleaching focuses on low pulp consistency bleaching (3-4%) rather than medium pulp consistency bleaching, and demonstration projects have been tested in this area (Ferguson, 1998).

Union Camp has developed a C-Free ozone bleaching process for Kraft pulping, which uses very little energy. This process can be used with ECF as well as with TCF sequences, and uses oxygen for bleaching before the ozone bleaching (Union Camp, 1998, Ferguson, 1998). The first cost for the installation was cited at $113 million for a 900 tpd plant which reflected the construction of all new bleaching facilities (Ferguson, 1993). The systems capital costs (for the ECF line) are 25-30% higher than that of a traditional chlorine system, but its operating costs are lower -- bleaching costs have been reduced by 30-40%. Consolidated papers reported an investment of $34 million for a 650 tpd plant retrofit, which reflected investments in dewatering elements, ozone reactor and generation equipement, but no oxygen generation equipment. (Bergin, 2000) Others claim that ozonation systems can be cost effective for new bleaching plants, however they are unlikely to be used as retrofit, due to high capital costs (Lamarre, 1997).

Ozone systems are likely to gain more interest as new extended cooking and oxygen delignification systems, which are prerequisites for successful ozone bleaching, come online. Ozone will also gain more interest as a low cost partial substitute for expensive chlorine dioxide (EPA, 1993). We

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[11] Chlorine (C) and ozone (O_3) are the most effective bleaching chemicals available, capable of reacting with all types of aromatic structures in residual lignin. Chlorine dioxide (D) and oxygen (O) react primarily with free phenolic groups in lignin, and are not as efficient as far as delignification is concerned (Chirat, Lachenal, 1998).

assume 1:2.3 substitution of chlorine dioxide with ozone, which result in 3 kWh/t of pulping energy savings. Although chemical costs are higher than in a conventional DC sequence, they are smaller than in a chlorine dioxide stage. Combined wood and chemical costs are about $2/t lower (Finchem, 1998). For our analysis we assume a retrofit capital investment of $149.5/t throughput. We apply this measure to 25% of bleached chemical pulp throughput.

Oxidative extraction

The addition of gaseous oxygen in the first caustic extraction stage can enhance the removal of lignin and reduce the requirements for chlorine and chlorine dioxide. This measure results in significant reductions of bleaching chemicals. However, we did not find a corresponding energy savings on site, and therefore do not include this measure in our technical potential scenario.

Biobleaching (Enzyme Bleaching)

Enzymes are biological catalysts that break bonds between lignin and hemicelluloses after cooking. The use of enzymes in the bleaching process reduces bleaching chemical requirements such as hypochlorite and chlorine dioxide. However, we did not find a corresponding energy savings on site, and therefore do not include this measure in our technical potential scenario.

Improved brownstock washing

Conventional brownstock washing technology consists of 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, while washing systems replace the vacuum pressure units with pressure diffusion or wash presses (belt washers are less common). These systems remove solids more efficiently, require less electric power and/or steam and less bleaching chemicals.

Table 5 shows operating costs and energy savings/losses for three washing systems. Capital costs for all three systems range from $10.2 to $12.3 million for a hypothetical mill (EPA, 1993). We assume capital costs of $12 million for a drum displacer, O&M non-energy cost savings of $2.3/t, steam savings of 0.01 GJ/t, and electricity savings of 12.6 kWh/t. We apply this measure to 15% of chemical pulp throughput.

Table 5. Annual operating costs saved for three modern alternative washing systems

	Units	Chemi-Washer	CB Filters	Drum Displacer
Power at $0.0525/kWh	Thous. $US	$12	($12)	$158
Electricity consumption	kWh/t	0.96	-0.96	12.61
Steam at $7/t	Thous. $US	$1,555	$370	$88
Steam consumption	GJ/t	0.013	0.003	0.001
Total energy savings	GJ	3837	-106	11005
Defoamer at $1/kg	$0.45	$118	$236	$297
Maintenance – labor and materials for facewire change	Thous. $US	($60)	$15	$15
O&M non-energy cost savings	$/t	$0.2	$1.1	$1.3
Total annual savings	Thous. $US	$1,225	$609	$558
Savings per t	$US	$5.14	$2.55	$2.34

Source: modified from EPA, 1993.

Washing presses

In a conventional bleach plant that has four bleaching stages using an ECF process it is difficult to achieve low water consumption without excessive increase in the bleaching chemical consumption. Relatively low water consumption can be achieved through recycling bleach plant filtrates for dilution and washer showers without excessive increase in chemical consumption. When a high degree of bleaching plant closure is required, a different type of washing equipment is needed for successful D(EOP)DD bleaching. Pulp washing on presses (with a washing efficiency of 70-85%)

instead of filters (with a washing efficiency of 65%) is better suited for such an application (Germg et al., 1994). The press is a significantly better pulp washer than a filter, but has larger capital costs. However, lower building costs and smaller filtrate tanks can compensate or even outweigh higher capital cost requirements of press washing. Savings in steam and chemicals consumption provide additional benefits. Therefore, a press-bleach plant may be a competitive alternative for a new pulp mill. Sunds Defibrator applies dewatering presses for washing and dewatering to high solids content. Washing is carried out counter-current to the refining process to ensure maximum removal of dissolved material using a minimum of fresh water while preparing the pulp for the bleaching sequence. We estimate energy savings from reduced steam consumption of 0.38 GJ/t pulp (Germg et al., 1994). Operating cost savings from lower chemicals use will amount to $0.53/t pulp. Capital cost of the pre- and post-delignification washing equipment of a 900 tpd are listed at $6 million (Parthasarathy, 1997), equivalent to $17/t throughput. Therefore, for greenfield capacities and for retrofitting plants we assume that capital costs for both filters are the same. Press washers can also be considered as a good alternative for mill retrofits and additional washing stages, since they have very small space requirements (Panchapakesan et al., 1993). We apply this measure to 15% of bleached chemical pulp.

Papermaking

Stock preparation and sheet formation

Gap forming

The most common papermaking machines are based on the Fourdrinier design, but they are being replaced by both twin wire former and gap former designs. Gap formers are categorized as blade formers, roll formers, and roll-blade formers (Kincaid *et al.*, 1998; Buehler and Guggemos, 1995). Gap formers receive furnish (processed pulp) which is injected into the head box through a gap of air onto a twin wire unit. 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 . Rolls, blades, or vacuums facilitate the removal of excess water from the web, known as dewatering. (Kincaid *et al.*, 1998). Some new top wire formers have been shown to achieve formation equivalent to gap formers (Gustafson and Duchesne, 1996). The forming sections on both former types are very short and the formation takes place in a fraction of the time it takes for a Fourdrinier machine. 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% (Kincaid et al., 1998; Paulapuro, 1993; Elenz and Schaible, 1995)[12]. Nevertheless, retrofitting a gap former may increase retention losses. Energy savings from gap formers come from reduced electricity consumption (Kline, 1982). The technology also may improve quality. We assume electricity savings of 41 kWh/t of paper (Jaccard & Willis, 1996). Based on (AF&PA, 1999) installation costs including the head box for a gap former is approximately $75,750 per inch of width, as opposed to $30,750 for a fourdrinier with head box. We assume a capital cost of $70/t of paper with an additional maintenance cost of $0.72/t (Jaccard & Willis, 1996). Gap formers are becoming a standard technology for new machines. As from 1994 to 1998 the penetration in the paper production has been of approximately 26% (AF&PA, 1999). We assume a penetration of 35% of paper production in our analysis.

High consistency forming

In high consistency forming, the furnish (process pulp) which enters at the forming stage has more than double the consistency (3%) than normal furnish. This measure increases forming speed, and reduces dewatering and vacuum power requirements (Elahi and Lowitt, 1988). Application of this

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[12] Note that Anon., 1996 discusses the use of top wire formers for mini-fourdrinier and Bristol Super Formers.

technology is limited to specific paper grades, especially low-basis weight grades such as tissue, toweling, and newsprint. Electricity savings are estimated at 8% that is about 41 kWh/t of paper. (Elahi and Lowitt, 1988; de Beer et al., 1993). High consistency formers are expected to cost $70/t of paper with an additional maintenance cost of $0.72/t (Jaccard & Willis, 1996), also assuming that new paper machine wet ends are similarly costly. We apply this measure to 20% of current paper production with exclusion to light grade.

Extended nip press (Shoe 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. The additional pressing area 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). Since this technology reduces the load on the dryer, it allows plants to increase capacity up to 25% in cases where the plant was dryer limited. Extended nip pressing also increases wet tensile strength (Lange and Radtke, 1996). In our analysis, we assume steam savings in the drying section of 16% or 1.6 GJ/t paper (de Beer et al., 1994). Although there are additional electricity requirements, we have already included them in our total energy savings estimate. We assume investment costs of $38/t of paper and additional maintenance costs of $2.24/t (deBeer et al., 1994). According to Jaccard & Willis (1996) this technology has been implemented in almost half the Canadian mills. We assume an additional penetration of 40% in the U.S industry.

Hot pressing

Pre-heating the water in the paper sheet before pressing can reduce the evaporation load. In hot pressing a steam shower is used to heat the water in the sheet to 80°C or more, which lowers the viscosity of the water and softens the structure of the sheet to improve water flow (Elahi 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 (Elahi and Lowitt, 1988). Use of steam showers has been estimated to reduce the steam requirement by 1 kg of steam per kg paper. We estimate steam energy savings of 0.61 GJ/t paper through hot pressing. Costs for hot pressing technology are 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

Instead of heating the drying cylinders in a standard drying section of a paper machine with steam, direct drying cylinder firing heats the cylinders using natural gas or other petroleum products thereby reducing the intermediate step of steam production. This technology can achieve significant fuel savings of 1.1 GJ/t paper[13] (average for the paper grades examined) but does require additional operation and maintenance. We estimate additional O&M costs at $1.4/t paper (Jaccard and Willis, 1996). Retrofit costs are high, $111/t paper (Jaccard and Willis, 1996), since the cylinder system requires significant modification. We therefore estimate a penetration rate of 5% (EIA, 1997).

Reduced air requirements (closing hoods and optimizing ventilation)

Air to air heat recovery systems on existing machines recover only about 15% of the energy contained in the hood exhaust air. This percentage could be increased to 60-70% for most installations with proper maintenance and extensions of the systems (Maltais –ABB Industrial drying 1993). Paper machines with enclosed hoods require about one-half the amount of air per tonne of water evaporated that paper machines with a canopy hoods require. Enclosing the paper machine reduces thermal energy demands since a smaller volume of air is heated. Electricity requirements in the exhaust fan are also reduced (Elaahi and Lowitt, 1988). We assume steam

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[13] Based on eliminating losses in steam distribution

savings of 0.76 GJ/t paper and electricity savings of 6.3 kWh/t paper by installing a closed hood and an optimized ventilation system (CADDET, 1994). Investment costs for this measure are moderate : about \$9.5/t paper and additional O&M costs are estimated at \$0.07/t paper (CADDET, 1994). Since the drying sections often oversized, we assume a potential share of 40% in the pulp and paper U.S industry (Elaahi and Lowitt, 1988).

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 0.89 GJ/t due to improved drying efficiency, with an operation cost savings of \$25,000 (\$0.045/t) (Morris, 1998). A second system used mechanical vapour recompression in a pilot facility to reuse superheated steam into the drying process (Van Deventer 1997). Steam savings for this approach were up to 5 GJ/t (50%) with additional electricity consumption of 160 kWh/t (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 (Abrahamsson et al., 1997). The heat can also be recuperated from the ventilation air of the drying section and used for heating of the facilities (de Beer *et al.*, 1994). We assume steam energy savings of 0.5 GJ/t paper through the installation of heat recovery systems at the mill (de Beer *et al.*, 1994). Costs for the installation of a heat recover system are estimated to be \$17.6/t paper (de Beer *et al.*, 1994). However, because the heat exchangers require frequent cleaning, the additional O&M costs will amount to \$1.6/t paper. We apply this measure to 30% of U.S. paper production.

Condebelt drying

The first commercial Condebelt dryers were installed in Finland in 1996, and in Korea 1999 (Valmet Press releases, 1997, 1999). 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. (deBeer 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 (Lehtinen, 1993). On the other hand, condebelt drying is not suited for high basis weight papers, and thus we apply this measure to 50% to the U.S. paper production. For large machines savings of 10-20% steam are possible (Anon., 1996b; deBeer, 1998). We assume savings of 15% in steam consumption (1.6 GJ/t of paper) and a slight reduction in electricity consumption (20 kWh/t of paper). Capital costs are considered to be high, although the size of the drying area can be reduced. We assume investment costs of \$28/t paper for the retrofitting and \$110/t for a greenfield plant (deBeer, 1998; Atlas, 1996a).

Infrared profiling

Moisture profiling on fine paper machines can greatly reduce moisture variation while allowing for production increases (Elahi and Lowitt, 1988). Cross directional (CD) profiling at the head box is a recent technology which combines sensors and controls to adjust the relative moisture content of the incoming sheet, allowing more independent optimization of basis weight and fiber orientation while reducing variations in CD basis weight (Anon., 1996b). A Concept IV-MH head box installed at Bowater's Catawba (SC, USA) mill provides 168 zones using tray water for CD weight control, and improves weight profiles (Pantaleo and Wilson, 1995). Infrarödteknik, Sweden (Mitchell, 1994) and Compact Engineering, UK (Compact Engineering, 1999) are marketing infrared profiling systems to control the moisture profile of the web. Currently it is applied to fine paper and heavy paperboard production. Relative thermal energy savings, given production increases, are estimated at 7%, with an increase in electricity requirements (Mitchell, 1994, Elaahi, Lowitt, 1988). We estimate 0.7 GJ/t paper of energy savings and additional electricity requirements of 0.08 GJ/t paper (approx. 22 kWh/t paper). Compact Engineering claims that on all the applications the infrared systems have paid of themselves within one year, taking into account the incremental production increases, too (Compact Engineering, 1999). Assuming that the only cost benefits achieved from infrared profiling are from reduced energy costs, we estimate capital investments of $1.12/t paper (Elaahi, Lowitt, 1988). We assume a penetration rate of 15%.

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. We estimate energy savings of 5 GJ/t with an increase in electricity requirements of 208 kWh/t (de Beer, 1998). In Germany a new dry-formed paper machine with a capacity of 25000 t/y for $37.6 million was scheduled to start up in 1997. An installation cost of $1500/t has been assumed (Pulp & Paper Online, 1995).

General Measures

Pinch Analysis

Pinch analysis has been used successfully in many energy-intensive industries to better optimize thermal energy flows throughout the plant. This analysis technique identifies heat flows between cold streams (operations that require heat) and hot streams (operations that lose heat), and then optimizes the stream flows. The Augusta Newsprint Company identified overall steam savings of 42% at a cost of $7.15/t paper (EPRI, 1997). Kimberly Clarke's Coosa Pines facility in Alabama also undertook a pinch analysis in 1996. After implementing the projects, mill staff were able to achieve energy savings of 22% at a cost of $15.4/t paper. A recent analysis of the potential for pinch analysis/process integration in Canada found a cost-effective energy savings potential of 8% (Bruce, 1999). A pinch analysis of an ALCELL plant in New Brunswick, Canada found steam savings of 15% (Ronan et al., 1994) with a payback period of 4 years. In our analysis we assume a thermal saving potential of 10% (1.8 GJ/t) at a cost of $8/t paper. We do not assume any additional operations and maintenance costs for the measure. We apply the savings to 20% of the industry.

Optimization of regular equipment

Opportunities often exist to improve operations equipment, such as boilers and paper machines. Future systems, such as smart systems, will be able to increasingly incorporate real-time diagnostics to improve performance (Hill *et al.*, 1998). DeBeer *et al.* (1994) estimates that, although most paper machines are 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) noted that optimizing the lubrication of bearings to reduce heat loss and wear and tear has achieved savings up to 30% of oil consumption, or 0.7 GJ/t paper at costs of less than $1.1/t paper. And the project also reduced plant down time. McNicol (1999) noted a case of several plants that focused on optimizing the waste treatment systems of pulp and paper mill effluents. Using and optimizing submerged aeration systems for this purpose can save up to 40% of energy use, with an average savings of 0.12-0.3 GJ/t paper (McNicol, 1999). We estimate electricity savings of approx. 27 kWh/t paper (De Beer, 1994) and a potential penetration rate of 30%.

Energy-efficient lighting

Factory buildings often use high-pressure mercury lamps for lighting. The use of electronic ballasts and flourescent tubes in depots and offices as well as other technologies can result in electricity savings (deBeer et al., 1994; Maillet, 1992). A detailed 1991 study by Maillet (1992) on lighting in the paper mills assessed the replacement of existing lighting with high- pressure sodium lamps in various sections of the paper mill. Maillet found lighting energy savings ranging from 30-75% depending on the retrofit area. We assume savings of 40% of lighting energy use, or 14 kWh/t paper. Investment costs for this measure are estimated at $1.2/t paper, and a decline of $0.01/t paper in O&M costs is expected (DeBeer et al., 1994). We apply this measure to 20% of the industry.

Efficient motor systems

Motors are used throughout the pulp and paper industry to operate equipment such as fans and pump 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, 1998). In addition to motor efficiency improvement, motor system improvements include upgrading fan systems, air compressors, and other motor end-uses and adjustable speed drives, too. A recent study by Xenergy (1998) found a total savings potential of 14% of total motor energy use (13,942 GWh/yr). This results in a 1994 energy savings of 171 kWh/t paper. Costs estimate for motor improvements are approximately $6/t paper based on motor replacement cost given in Motor Master+ software (Washington State University, 1998) and (Caddett, 1993). We assume a penetration rate of XX%.

Efficient Steam Production and Distribution

Boiler maintenance

A simple maintenance program to ensure that all components of the boiler are operating at peak performance can result in substantial savings. In the absence of a good maintenance system, the burners and condensate return systems can wear or get out of adjustment. These factors can end up costing a steam system up to 20-30% of initial efficiency over 2-3 years (OIT, 1998). We estimate a 10% possible energy savings (OIT, 1998) over 20% of all boilers (IAC, 1999). This measure can be accomplished for an additional operating cost of $0.06/tonne paper with no additional start-up cost[14].

Improved process control

Using flue gas monitors to analyze the composition of exhaust from boiler combustion makes it possible to maintain optimum flame temperature, and monitor CO, oxygen and smoke. The oxygen content of the exhaust gas is a combination of excess air (which is deliberately introduced to improve safety or reduce emissions) and air infiltration (air leaking into the boiler). By combining an oxygen monitor with an intake airflow monitor, it is possible to detect even small leaks. A small 1% air infiltration will result in 20% higher oxygen readings. A higher CO or smoke content in the exhaust gas is a sign that there is insufficient air to complete the fuel burning. Using a combination of CO and oxygen readings, it is possible to optimize the fuel/air mixture for high flame temperature (and thus the best energy efficiency) and low emissions. We assume that this measure can easily be applied to most big boilers (50% of total boiler capacity)[15] because of its $0.42/tpy capital cost (IAC, 1999), but small boilers will not apply this measure because they will not make up the initial capital cost as easily. Three percent of boiler fuel use could be saved by this measure (Zeitz, 1997) with an estimated additional operating cost of $0.08/tonne paper.

Flue gas heat recovery

In this measure, heat from boiler flue gasses 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. 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). Traditionally this has been done by keeping the flue gasses exiting the economizer at a temperature significantly above the acid dew point. In fact, the economizer wall temperature is much more dependent on the feed water temperature than flue gas temperature because of the high heat transfer coefficient of water. As a result, it makes more sense to preheat the feed water to close to the acid dew point before it enters the economizer. This allows the economizer to be designed so that the flue gas exiting the economizer is just barely above the

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[14] Unreferenced operating cost changes are based on an industry-wide estimate of maintenance costs as a percentage of capital costs.

[15] All boilers greater than 100MMBtu/hr. Based on GRI, 1996

acid dew point. One percent of fuel use is saved for every 25°C reduction in exhaust gas temperature. (Ganapathy, 1994). Since exhaust gas temperatures are already quite low, we assume a 2% savings across half of all boilers, with a capital cost of \$0.66/tpy (IAC, 1999). Operating expenses are expected to increase by \$0.09/tonne paper.

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 used for space heating and feed water preheating. We assume that this measure can save 1.3% of boiler fuel use[16] across all small boilers (41% of total boiler capacity)[17] with a capital cost of \$0.82/tpy (IAC, 1999). Operating expenses will increase slightly, estimated at \$0.11/tonne paper.

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. Energy savings for a regular system of steam trap checks and follow-up maintenance is conservatively estimated at 10% (OIT, 1998; Jones 1997; Bloss, 1997) with an initial cost of \$1.24/tpy (IAC, 1999). This measure offers a quick payback but is often not implemented because maintenance and energy costs are separately budgeted. We estimate that this can be applied in an additional 50% of steam systems and will cost an additional \$0.06/tonne paper to fund the program.

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. Using automatic monitoring is conservatively estimated to give an additional 5% energy savings over steam trap maintenance alone with a capital cost of \$1.23/tpy[18] (Johnston, 1995; Jones, 1997; Climate Wise, 1996). Systems which are able to implement steam trap maintenance are also likely to be able to implement automatic monitoring, so we estimate an additional 50% of systems can implement this measure. Maintaining the automatic monitors is estimated to cost an additional \$0.16/tonne paper.

Leak repair

As with steam traps, the distribution pipes themselves often have leaks that go unnoticed without a program of regular inspection and maintenance. 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. (OIT, 1998; Climate Wise, 1996). We estimate that this is applicable to an additional 12% of industry[19] with an initial cost of \$0.27/tpy (IAC, 1999). Funding an ongoing program is estimated to cost \$0.03/tonne paper.

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

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[16] Based on the following assumptions: 10% of boiler water is blown down (OIT, 1998) and 13% of the energy can be recovered from this (Johnston, 1995).

[17] All boilers less than 100MMBtu/hr. Based on GRI, 1996

[18] Calculated based on a UK payback of 0.75 years (accounts for lower U.S. energy prices)

[19] This estimate is based on the percentage of IAC heat system projects where leak repairs were implemented.

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, however, already been implemented in most of the places where it is easy to accomplish. We assume a 15% energy savings (OIT, 1998) with a capital cost of \$3.77/tpy for an additional 2% of the boiler population (IAC, 1999). Maintaining a condensate return system is estimated to cost \$0.54/tonne paper.

Other Measures

Increased use of recycled pulp (only included in Case B)

The energy and carbon emissions impacts of this measure may vary greatly depending on furnish and final product types. In 1994, 28 Mt of wastepaper pulp was used in the pulp and paper industry (AFPA, 1998). This accounted for 32% of all pulp. In its collaborative research work with the U.S. Department of energy, the U.S. pulp and paper industry has discussed increasing the use of recycled pulp to further reduce energy use associated with virgin pulping processes. Recycled pulp does produce sludge that presents a disposal difficulty. Flotation deinking is the current best practice in this area (McKinney, 1998). In our analysis, we assume that additional technical capacity exists to increase recycled pulp production to 15% of the existing production mix. Given the existing 1994 pulping production mix, this increase would result in energy savings of 13.4 GJ/t steam and 2.06 GJ/t electricity. Additional costs for the construction of recycled pulp processing facilities are estimated at \$485/t pulp, and depending on the price of waste paper versus virgin pulp this may result up to \$73.9/t pulp in O&M cost savings (O'Brien, 1996).

Increased combined heat and power

A recent study done by LBNL estimates about 17.8 GW of remaining technical potential for combined heat and power systems (CHP) installations (Khrushch, *et.al.*, 1999). This potential can result in about 89-150 TWh/y electricity and 456-767 GJ/y steam generated on-site. This will result in about 600-1000 GJ/y primary energy savings in comparison to generating the same amount of electricity and steam by conventional systems[20]. Respectively, primary energy savings per tonne of output will be 7-11 GJ/t paper. This will amount to about \$24-\$53/t of paper of savings on purchased electricity. The needed capital investments will run between \$140-168/t of paper for new installations and \$103-150/t of paper for retrofit (Khrushch, et al., 1999). We estimate that this measure can be applied to about 50% of paper throughput. The combined heat and power systems usually change the thermal and electric load in pulp and paper facilities. Therefore, we do not include this technology in our supply curve.

Advanced Technologies

The advanced technologies described below are not included in our assessment of cost effective potential, but we include the descriptions for informational purposes.

Alcohol based solvent pulping

Alcohol based solvent pulping offers a potential advantage to traditional Kraft pulping in that it can produce high yield high quality pulps in shorter cooking times. The process also produces a sulfur-free lignin that is extracted at a much faster rate than the Kraft process. Wood chips and the ethanol-water solution is processed in a batch digester at 200°C and 392 psi (Elahi and Lowitt, 1988). The combination of alcohol and high temperature releases about 75% of the lignin; most of the

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[20] In a conventional system electricity is generated by the utility and than sold to the pulp and paper company, and steam is produced by industrial boiler on-site.

remaining lignin is removed with secondary extraction liquor and recycled alcohol-water. Steam stripping is used to recover residual alcohol from the pulp (Elahi and Lowitt, 1988). Lignin is recovered from the black liquor in a proprietary process. A drawback is the high cost of solvents that can be cost prohibitive. One source estimates a small amount of additional fuel input requirements of 0.9 GJ/t pulp with electricity savings of 273 kWh/t (Elahi and Lowitt, 1988). A 142 ktonne test plant considered in 1994 had an installation cost of $21.1/t (Anonymous, 1994a).

Black liquor gasification with gas turbine

Black liquor gasification is used to produce gas from spent pulping liquor. This gas can be used in a traditional boiler, or may in the future be used in conjunction with gas turbines. There are two major types of black liquor gasification: low temperature/solid phase and high temperature/smelt phase. Today, black liquor gasifiers are used as an incremental addition in chemical recovery capacity in situations where the recovery boiler is a process bottleneck. In the future, gasifiers may be able to provide fuel for gas turbines and lime kilns (Nilsson et al., 1995; Lienhard and Bierbach, 1991) by means a standard combined cycle power generation system (the system is made up of gas turbine, heat recovery systems, steam turbine and electricity generators). The success of turbine based technology depends on making a turbine that can use low energy gas (produced by an air blown gasifier) or the creation of a more efficient oxygen blown gasifier. We assume the improved turbine and thus respective fuel savings of 1.6 GJ/t pulp for a complete gasification and combined cycle system (Gilbreath, 1995). We expect this technology to cost $320/t production for a turnkey installation. It will also cost $6.9/t pulp more in operation and maintenance costs21. This technology is relatively new. There is one commercially operating mill in New Bern mill, North Carolina and one in Sweden though recently shut down (McCubbin, 1996; Finchem, 1997.). According to European sources this technology is expected to interest a wide share of chemical mills, the expectation is for approx. 80% of the chemical pulp (Atlas, 1996b)

Impulse drying

Impulse drying involves pressing the paper between one very hot rotating roll (150-500°C) and a static concave press (the nip) with a very short contact time. The pressure is about 10 times higher than that in press and Condebelt drying (deBeer, 1998; Boerner and Orloff, 1994). Impulse drying tremendously increases the drying rate of paper although there may be problems with the paper delaminating or sticking to the roll (Boerner and Orloff, 1994). Energy savings can be significant. DeBeer (1998) assumes potential savings steam consumption of 50-75%. Another description of impulse drying claims energy savings of about 18-20% or 2.1 GJ/t paper (Lockie, 1998, CADDET EEproject 1993). Electricity requirements do increase however, by 5-10%. (deBeer, 1998). Jaccard (and Associates, 1996) report an average installation cost of $74/t paper for linerboard. Impulse drying subjects the paper web to very high temperatures at the press nip in order to drive moisture out of the web. The technology promises to bring reduced capital costs, increased machine productivity, reduced fibre use, reduced energy use and improved physical properties in the paper. But it is still a technology to be proved on a commercial scale, due to difficulties in controlling the physical aspects of the web under the intense condition.

Infrared drying

Short-wave infrared drying provides better heat transfer capabilities and compactness (Infrarödteknik, 1999). Infrared drying improves system's moisture evaporation rate by directing more of the heat (at higher temperatures) onto the web itself. Along with improved energy efficiency, it increases the drying power output. Infrared dryers are powered by electricity, and require about 4.08 GJ of electricity/t paper versus 8.16 GJ of steam/t paper for conventional steam dryers (Jaccard, Willis, 1996). We therefore estimate primary energy savings of 3.3 GJ/t paper. Investment costs for infrared dryer installation are $120/t paper and additional O&M costs

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[21] The costs and savings are based on a comparison of the following articles: Consonni, et al. July, 1998. Kreutz et al., 1998. Larson *et al.*, 1998a. Larson, *et al.*, 1998b. Lorson, *et al.*, December 1997. Nasholm et al., 1997.

requirements are $0.92/t paper (Jaccard, Willis, 1996). As being this technology mostly suitable for drying high-quality coated paper, we estimate that it can be applied to about 15% of total paper produced.

Pre-treatment of incoming pulp into drying section

Boise Cascade and Weyerhauser have combined efforts to explore the potential of pre-soaking the never dried pulp in a sodium carbonate solution. This solution replaces some of the water in the pulp fiber micropores and thereby reduces drying energy use. Energy savings for this process have been estimated at 16% of steam, or 1.7 GJ/t paper (Allan et al.,1997).

Air impingement drying

Air impingement drying involves blowing hot air (300°C) in gas burners at high velocity against the wet paper sheet. This technology can be combined with existing technologies. (deBeer *et al.*, 1998). Heat input requirements have been modelled at 3 MJ/kg evaporated water, or a 10-40% savings in steam requirements. Electricity requirements are expected to increase by 0-5%.

Steam impingement drying

In steam impingement drying superheated steam (300°C, 1.1 bar) rather than hot air is used as the drying medium (deBeer, 1998). The steam is blown onto the sheet. Steam requirements are estimated at 4.5 GJ/t paper with additional savings available if the latent heat from the purge steam is captured. (DeBeer, 1998) estimates a savings of 10-15%, with a slightly lower reduction in electricity requirements (5-10%).

Airless drying

Airless drying uses the latent heat of the evaporated moisture and requires an airtight and well-insulated hood around the drying section of the paper machine. The paper is still dried by steam heated cylinders, as in conventional drying, but the steam is produced by compressing the evaporated water. This condensed water vapor can provide 60-80% of the total amount of thermal energy needed for drying, achieving a 70-90% reduction in thermal energy requirements (deBeer, 1998). Electricity requirements increase (15-20%) due to increased ventilation requirements (deBeer, 1998).

Press drying

In press drying, the sheet is pressed between two hot surfaces or pressing cylinders at a temperature of 100-250°C. In most cases these cylinders are installed in between the conventional pressing section and the drying section of the machine. The drying rate can be 2-10 times faster than conventional drying (deBeer, 1998). Energy savings have been estimated at 5-30%. This technology is near commercialization.

VII. ENERGY EFFICIENCY AND CARBON DIOXIDE EMISSIONS REDUCTION POTENTIAL FOR PULP AND PAPERMAKING IN THE U.S.

Supply Curve Methodology

In the 1970s, energy conservation supply curves were developed by energy analysts as a means of ranking energy conservation investments alongside investments in energy supply in order to assess the least cost approach to meeting energy service needs (Meier et al, 1983). Energy saving technologies and measures can be ranked by calculating the Cost of Conserved Energy (CCE), which accounts for both the costs associated with implementing and maintaining a particular technology or measure and the energy savings associated with that option over its lifetime (Koomey et al., 1991). Ranking investments according to supply curve methodology is consistent with microeconomic theory which posits that a firm will invest in energy conservation up to the point where the marginal costs equal the marginal benefits, or the value of one unit energy saved or the price of energy. When all options are then ranked according to their cost effectiveness, one can develop a curve ranking the lowest cost to the highest cost options (Velthuijsen, 1995). The CCE of a particular measure is calculated as:

$$\text{CCE} = \frac{\text{Annualized Investment} + \text{Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \qquad \text{(eq. 1)}$$

The Annualized Investment is calculated as:

$$\text{AI} = \text{Capital Cost x } d/(1-(1+d)^{-n}) \qquad \text{(eq.2)}$$

where d is the discount rate and n is the lifetime of the conservation measure. For this analysis, a 30% real discount rate is used, reflecting the capital constraints and preference for short payback periods and high internal rates of return in the pulp and paper industry. In order to calculate the current cost of energy, the industry average fuel cost based on energy consumption data and energy price data for the industry in 1994 is used as reference (U.S. DOE, EIA, 1997).

CCEs are calculated for each measure that can be applied in the pulp and papermaking. The CCEs are plotted in ascending order to create a conservation supply curve. The width of each option or measure (plotted on the x-axis) represents the annual energy saved by that option. The height (plotted on the y-axis) shows the option's CCE. All measures that fall below the average-weighted price of energy for the pulp and papermaking industry can be defined as cost-effective.[22]

Similarly, the specific carbon emissions reduction costs – Cost of Avoided Carbon (CAC) –will be defined as total net annual costs divided by the annual emissions avoided, due to implemented energy efficiency measures:

$$\text{CAC} = \frac{\text{Annualized Investment} + \text{Annual Change in O\&M Costs}}{\text{Annual Carbon Avoided}} \qquad \text{(eq.3)}$$

Case A: Cost-Effective Energy and Carbon Savings without Recycling

The energy conservation supply curve shown in Figure 6 is a snapshot of the total annualized cost of investment for all of the efficiency measures being considered at that point in time. The technical potential for energy savings reflects the total area under the curve represented by all the measures examined in this analysis. The total technical potential for energy savings in the industry is approximately 1013 PJ representing about 31% of the 1994 primary energy consumption in the pulp and paper industry.

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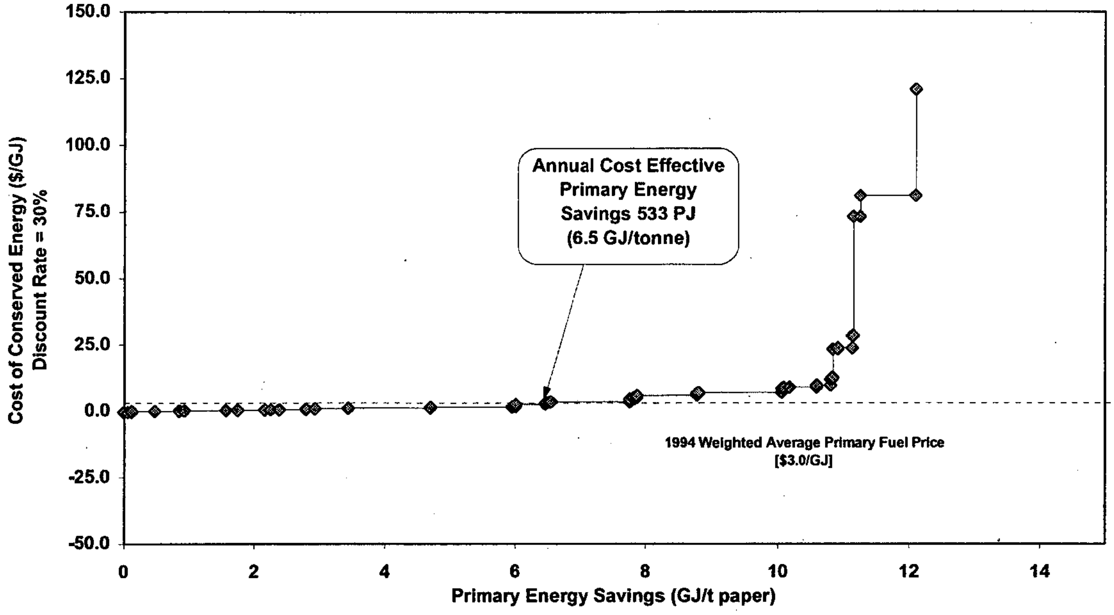
[22] For examples of conservation supply curves in the buildings, transportation, and industrial sectors, see Meier et al., 1983; Ross, 1987; Ledbetter and Ross, 1989; Difiglio et al., 1990; EPRI, 1990; Ross, 1990; Block et al., 1993; Interlaboratory Working Group, 1997; Koomey et al., 1991; Krause et al., 1995; Rosenfeld et al., 1991; DeBeer et al., 1996; National Academy of Sciences, 1992; Worrell, 1994, Worrell et al., 1999.

Figure 6. Case A: Energy Conservation Supply Curve for U.S. Pulp and Paper Industry (Excluding increased recyling of waste paper)



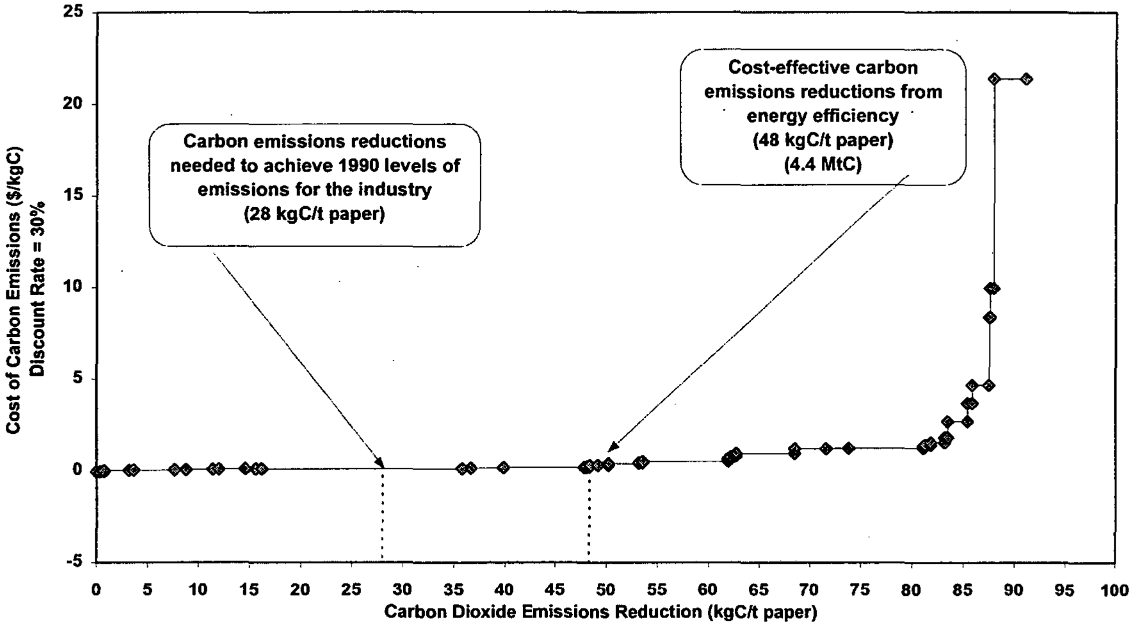
The cost-effective potential reflects those efficiency investments which have a CCE lower than the average price of energy ($3/GJ). We identify a cost-effective energy savings potential of 533 PJ, or 16% of 1994 primary energy consumption. The actual cost-effective energy savings may be higher, since not all of the energy-saving technologies and measures mentioned are included due to a lack of available data on investment and O&M costs of these technologies.

The calculation of average energy prices was based on data from the U.S. Manufacturing Consumption Survey (U.S. EIA, 1997a). Using different methods of averaging we calculated a range of prices from $2.7/GJ to $3.4/GJ. However, even using the lower and upper bound prices, energy savings are still 13-14% of total primary energy consumption. About 10 PJ of primary energy savings can be achieved at negative cost.

Carbon dioxide emission reductions associated with the implementation of all identified measures was estimated at 7.6 MtC, reducing carbon dioxide emissions from the 1994 level by nearly 25%. Most of the reductions are due to measures that reduce fuel or steam use by the various processes. Some of the largest technical potential savings identified are in chemical pulping (especially new digester technology), papermaking (new drying technologies) general plant-wide measures, and boiler efficiency measures. As indicated by the term technical potential, not all of the measures identified can be achieved cost effectively at the current energy prices.

Following the methodology for the energy conservation supply curve, the authors constructed carbon dioxide emission reduction supply curve for the pulp and paper industry (see Figure 7). Similar to the conservation supply curve for energy savings, the cost-effective potential for carbon dioxide emissions can be determined. The difference between the two curves is determined by the crabon intensity of the fuel mix. Due to the large share of biomass in the fuel mix, the relative effect of the energy efficiency measures on emission reduction will be lower compared to that for energy use. Using the average energy prices the cost effective level of carbon dioxide emissions reductions was where the cost of conserved carbon fell below $0.25/kgC. As figure 7 indicates, 1994 cost-effective carbon dioxide emissions reductions were estimated at 4.4 MtC. This value is 14% below the 1994 baseline emissions of 31.5 MtC (US EIA, 1997). Estimated carbon emissions for the pulp and paper industry in 1990 were 29.1 MtC (28 kg/t paper). The cost effective energy efficiency measures would reduce the paper industry's emissions to 7% below 1990 levels.

Figure 7. Case A: Carbon Dioxide Emission Reduction Supply Curve for U.S. Pulp and Paper Industry



In order to rate the cost effectiveness of the energy efficiency investments, the internal rate of return (IRR) and simple payback period (PBP) of each technology and measure are provided. The IRR shows the value of the discount rate to make the net benefits cash flows equal to the initial investment, while the PBP gives the number of years it takes before the forecasted cash flows equal the initial investment. Industry executives in making investment decisions commonly use these indicators. Table 6 provides the list of measures ranked by their cost of conserved energy, and gives their internal-rate-of-return, and simple payback period based on an average fuel cost of $3/GJ.

Table 6. Case A: Cost of Conserved Energy for Selected Measures in U.S. Pulp and Paper Industry

	Primary CCE	Primary Energy savings	Cumulative primary energy savings	$3/GJ Internal rate of return	Simple payback time	Carbon Emissions Reduced
	$/GJ	GJ/t	GJ/t	%	years	kgC/t
Bar-type chip screens	-0.39	0.06	0.06	142%	0.7	0.38
Screen out thick chips	-0.39	0.06	0.12	--	0.7	0.38
Boiler maintenance	0.04	0.36	0.48	>500%	0.0	2.26
Improved Process Control	0.04	0.38	0.86	292%	0.2	2.41
Condensate Return	0.14	0.08	0.93	299%	0.3	0.48
Automatic Steam Trap Monitoring	0.19	0.63	1.57	152%	0.3	4.02
Flue Gas Heat Recovery	0.29	0.18	1.75	324%	0.7	1.13
Continuous digester modifications	0.39	0.42	2.16	>500%	0.3	2.63
Leak Repair	0.44	0.09	2.25	205%	0.1	0.58
Infrared profiling	0.45	0.13	2.38	201%	0.5	0.57
Batch digester modifications	0.55	0.41	2.79	111%	0.5	2.59
Blowdown Steam Recovery	0.82	0.14	2.92	95%	0.9	0.86
Pinch Analysis	0.95	0.51	3.43	>500%	1.0	3.22
Steam trap maintenance	1.10	1.27	4.70	63%	0.2	8.04
Efficient motors	1.55	1.25	5.95	83%	1.6	19.57
Lime kiln modifications	1.63	0.06	6.01	28%	1.8	1.01
Reduced air requirements	2.61	0.45	6.46	85%	2.9	3.01
Refiner Improvements	3.05	0.01	6.47	17%	3.4	0.20
Heat recovery in thermomechanical pulping	3.27	0.05	6.53	23%	4.7	0.27
Energy-efficient lighting	3.43	0.02	6.55	15%	3.7	0.33
Condebelt drying	3.50	1.21	7.76	82%	3.8	8.37
Optimization of regular equipment	4.60	0.07	7.82	--	0.0	1.02
Biopulping	5.16	0.04	7.87	-7%	30.1	0.78
Extended nip press (shoe press)	5.96	0.91	8.78	47%	8.1	5.76
RTS	6.73	0.02	8.80	-4%	7.4	0.38
Continuous digesters	7.02	1.26	10.06	49%	7.7	7.21
Washing presses	8.47	0.03	10.09	3%	7.8	0.19
Hot Pressing	8.88	0.09	10.18	-2%	9.7	0.55
High consistency forming	8.97	0.42	10.60	10%	10.5	3.11
Waste heat recovery	9.77	0.21	10.81	12%	34.4	1.35
Pressurized groundwood pulping -Super	11.97	0.02	10.83	5%	11.6	0.30
Ring style debarker	12.68	0.01	10.84	--	13.1	0.21
Direct drying cylinder firing	23.29	0.08	10.92	--	35.3	0.47
Falling film black liquor evaporation	23.81	0.22	11.14	16%	26.1	1.95
Enzyme-assisted debarker	28.43	0.02	11.16	--	31.3	0.29
Gap forming	73.14	0.10	11.26	--	376.5	1.64
Dry sheet forming	81.07	0.84	12.10	26%	88.7	3.18
Brownstock washing	120.78	0.01	12.11	--	18.9	0.08
Cradle Debarker	156.05	0.02	12.13	--	171.6	0.34
Ozone bleaching	1968.70	0.00	12.13	--	72.3	0.03
Chip conditioners	--	0.05	12.18	--	--	0.34
Belt conveyors	--	0.02	12.21	--	--	0.39
Fine-slotted wedge wire baskets	--	0.01	12.22	--	--	0.13
LCR	--	0.00	12.22	--	--	0.03
Thermopulp	--	0.01	12.23	--	--	0.19
Improvements in CTMP	--	0.02	12.24	--	--	0.25
Tampella recovery system	--	0.04	12.28	--	--	0.21

Scenario with waste paper recycling: Case B

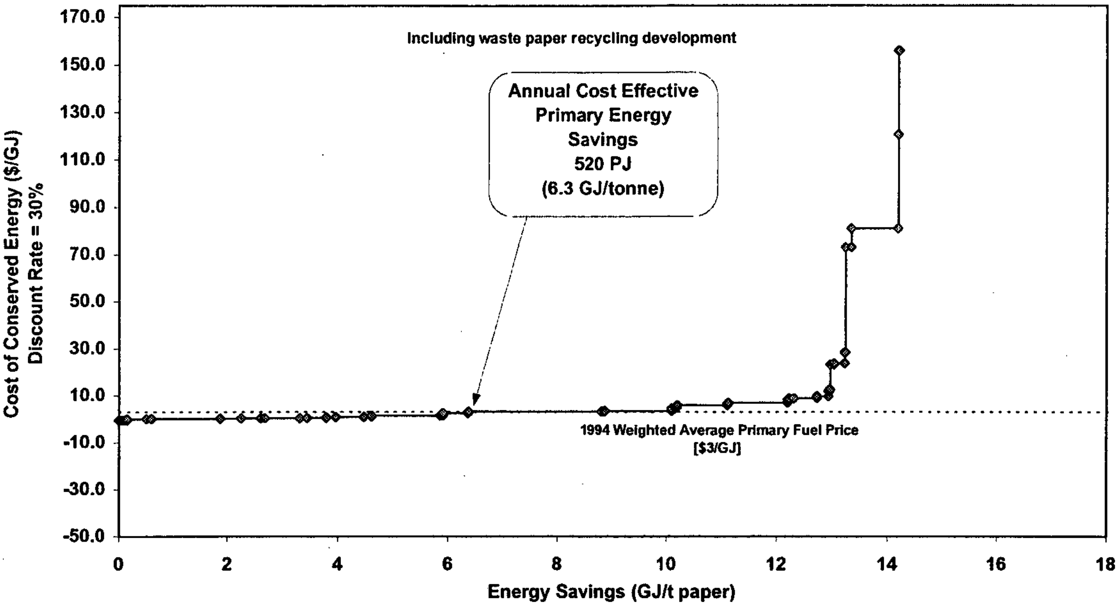
In Case B, we increased the tonnage throughput of recovered paper in pulp and paper mills, thereby lowering the amount of virgin pulp. The authors understand that the economic recovery of fibers is very product, site and time dependent but felt it important to include as a scenario. This scenario lowers the effective national energy efficiency potential from process conservation measures in the pulping mills since there is less throughput of wood and chemical pulps. However, the energy efficiency potential of the paper sector overall is increased since a larger share of the paper production is replaced with recovered paper. (As the energy savings in Table 4 indicates, the energy requirements to produce paper from recovered or recycled paper are significantly lower than the requirements of producing paper from virgin pulp.) The total technical potential for energy savings in the industry is approx. 1215 PJ representing about 37% of the 1994 primary energy consumption in the pulp and paper industry. Carbon dioxide emission reductions associated with the primary energy savings are about 9.1 MtC, reducing carbon dioxide emissions from the 1994 level by over 29%. We use the same costs energy saving and cost assumptions in both scenarios (see Table 4) but do vary the throughput of materials at the various process stages to account for an increase in recovered paper.

Case B: Cost-Effective Energy and Carbon Savings with Recycling

As in Case A, we identify cost-effective potential as those technologies and measures which have a cost of conserved energy (CCE) less than the average price of energy. In Case B, we identify a cost-effective energy savings potential of 520 PJ or 16% of primary energy consumption. The equivalent carbon dioxide emissions reductions are 4.3 MtC (14% below 1994 levels). While the technical energy efficiency potential is greater in the case of increasing recovered paper (37% as compared to 31% in scenario A), the *cost-effective potential is lower.*

The primary reason for the lower cost-effective energy savings is that the recycled paper measure, which has a cost of conserved energy of $3.2/GJ is *just slightly above the average price of energy* ($3.0/GJ) (see Figure 8). While the amount of energy savings in scenario A was not sensitive to the range of average energy prices examined in this analysis (a variation of only 1% primary energy savings) in Case B the sensitivity is greater. In the recycled paper scenario, the savings between energy prices of $2.6/GJ and $3.4/GJ range from 16-22%.

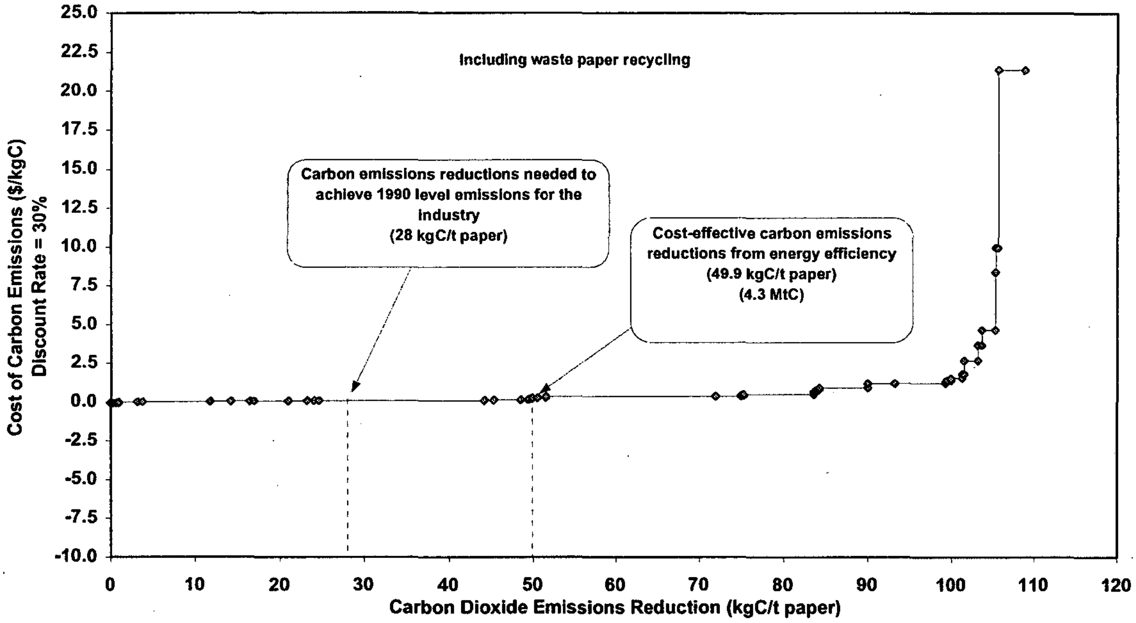
Figure 8. Case B: Energy Conservation Supply Curve for U.S. Pulp and Paper Industry (Including increased recycling of waste paper)



The cost effectiveness of the various technologies and measures shown in Table 5 (cost of conserved energy (CCE), internal rate of return (IRR), payback period) remains the same for both scenarios. The CCE, IRR, and payback period for increased use of recycled paper are $3.2/GJ, 29%, and 3.4 years respectively.

The total carbon savings of the measures do change in scenario B since the throughput of pulp is reduced to account for increased use of recycled paper. Figure 9 ranks all measures and technologies in a carbon reduction supply curve for the pulp and paper industry for scenario B. This curve ranks the measures in terms of the amount of carbon emissions reductions that can be achieved at various investment costs. As the figure indicates, cost-effective carbon dioxide reductions amount to 2.8 MtC (32 kgC/t paper), or 1% below 1990 levels. If the recycled paper measure were included (as it can be considered cost-effective in certain price regimes), cost-effective carbon dioxide emission reductions would be 7% below 1990 levels.

Figure 9. Case B: Carbon Dioxide Emission Reduction Supply Curve for U.S. Pulp and Paper Industry



VIII. SUMMARY AND CONCLUSIONS

Although the U.S. pulp and paper sector has reduced its primary energy intensity by 27% over the past 25 years (1970-1994), a large technical potential still exists to further reduce energy intensity. This analysis of U.S. pulp and paper industry reviews more than 45 specific energy-efficiency technologies and measures, and assesses energy savings, carbon dioxide savings, investments costs and operation and maintenance costs according to two scenarios (with and without development of the recycled paper use). Using a conservation supply curve methodology, we identify a total cost-effective reduction of 6.3-6.5 GJ/t of paper. This is equivalent to an achievable energy savings of 16% of 1994 U.S. pulp and paper primary energy use and 14% of U.S. pulp and paper carbon dioxide emissions (correspondingto a reduction of almost 48-49 kgC/t of paper). If one includes the expansion of recycled paper production as cost-effective, then potential cost-effective energy savings increase to 22% of primary energy use in 1994. These results are consistent with other recent studies that have also examined potentials in the pulp and paper industry (Ruth et al, 2000,

IX. FUTURE AREAS OF RESEARCH

The difference between case A and case B highlights the importance of recycling. The potential for increased use of recovered fiber is product, site, and time-dependent, and given the complexity of the issue, a better assessment of the technical and policy requirements for removing the barriers and identifying opportunities to increase waste paper recovery and recycling is necessary. As can be seen from the write up in Section V, we derived our cost data and energy savings data primarily from a thorough literature review from existing trade publications. There was, however, limited information on some of the measures. Further refinement and improvement of cost estimates and benefits of energy efficient investments would be desired. Finally, it is often the case that certain non-energy, productivity benefits accompany the investment in updated technology. We believe that a careful investigation into this area could further strengthen the case for selected energy efficiency investment in this sector.

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APPENDIX A. NATIONAL ENERGY SAVINGS AND CARBON DIOXIDE EMISSIONS REDUCTIONS RESULTS

Table A-1 National Energy Savings And Carbon Dioxide Emissions Reductions

	CASE A (Excluding increased use of recycled paper)			**CASE B (Including incrased use of recylced paper)**		
	Throughput	**Primary Energy Savings**	**Carbon Savings**	**Throughput**	**Primary Energy Savings**	**Carbon Savings**
	Mt	PJ	MtC	Mt	PJ	Mtc
Raw Materials Preparation						
Ring style debarker	241.5	1.1	0.02	205.2	0.9	0.01
Cradle Debarker	241.5	1.8	0.03	205.2	1.5	0.02
Enzyme-assisted debarker	241.5	1.5	0.02	205.2	1.3	0.02
Bar-type chip screens	49.5	4.9	0.03	42.0	4.2	0.03
Chip conditioners	49.5	4.4	0.03	42.0	3.8	0.02
Screen out thick chips	49.5	4.9	0.03	42.0	4.2	0.03
Belt conveyors	239.4	2.0	0.03	203.5	1.7	0.03
Fine-slotted wedge wire baskets	5.3	0.7	0.01	4.5	0.6	0.01
Pulping Mechanical						
Refiner Improvements	3.2	1.1	0.02	2.8	0.9	0.01
Biopulping	5.3	3.6	0.06	4.5	3.1	0.05
Pulping Thermomechanical						
RTS	3.0	2.0	0.03	2.5	1.7	0.03
LCR	3.0	0.2	0.00	2.5	0.1	0.00
Thermopulp	3.0	1.0	0.02	2.5	0.8	0.01
Pressurized groundwood	3.0	1.6	0.02	2.5	1.4	0.02
Heat recovery in TMP	3.0	4.4	0.02	2.5	3.8	0.02
Improvements in CTMP	3.0	1.3	0.02	2.5	1.1	0.02
Pulping Chemical						
Continuous digesters	49.5	103.9	0.59	42.0	88.3	0.51
Continuous digester modifications	49.5	34.3	0.22	42.0	29.1	0.18
Batch digester modifications	49.5	33.8	0.21	42.0	28.7	0.18
Chemical Recovery						
Falling film black liquor evaporation	53.2	18.2	0.16	45.2	15.5	0.14
Tampella recovery system	53.2	3.0	0.02	45.2	2.5	0.01
Lime kiln modifications	53.2	4.9	0.08	45.2	4.2	0.07
Bleaching						
Ozone bleaching	29.6	0.2	0.00	25.1	0.1	0.00
Brownstock washing	29.6	0.5	0.01	25.1	0.4	0.01
Washing presses	29.6	2.4	0.02	25.1	2.1	0.01
Papermaking						
Gap forming	82.5	8.6	0.13	82.5	8.6	0.13
High consistency forming	70.6	34.3	0.26	70.6	34.3	0.26
Extended nip press (shoe press)	82.5	75.1	0.48	82.5	75.1	0.48
Hot Pressing	82.5	7.2	0.05	82.5	7.2	0.05
Direct drying cylinder firing	82.5	6.2	0.04	82.5	6.2	0.04
Reduced air requirements (closing hoods and optimizing ventilation)	82.5	37.0	0.25	82.5	37.0	0.25
Waste heat recovery	82.5	17.6	0.11	82.5	17.6	0.11
Condebelt drying	82.5	100.0	0.69	82.5	100.0	0.69
Infrared profiling	82.5	10.4	0.05	82.5	10.4	0.05
Dry sheet forming	82.5	69.2	0.26	82.5	69.2	0.26
General Measures						
Pinch Analysis	82.5	41.9	0.27	82.5	41.9	0.27
Optimization of regular equipment	82.5	5.4	0.08	82.5	5.4	0.08
Energy-efficient lighting	82.5	1.7	0.03	82.5	1.7	0.03
Efficient motors	82.5	103.0	1.61	82.5	103.0	1.61
Steam Production and Efficiency						
Boiler maintenance	82.5	29.4	0.19	82.5	29.4	0.19
Improved Process Control	82.5	31.4	0.20	82.5	31.4	0.20
Flue Gas Heat Recovery	82.5	14.7	0.09	82.5	14.7	0.09
Blowdown Steam Recovery	82.5	11.2	0.07	82.5	11.2	0.07
Steam trap maintenance	82.5	104.7	0.66	82.5	104.7	0.66
Automatic Steam Trap Monitoring	82.5	52.4	0.33	82.5	52.4	0.33
Leak Repair	82.5	7.5	0.05	82.5	7.5	0.05
Condensate Return	82.5	6.3	0.04	82.5	6.3	0.04
Fiber Substitution						
Increased use of recycled paper	60.0	202.0	1.67	60.0	202.0	1.67

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