OPPORTUNITIES TO IMPROVE ENERGY EFFICIENCY IN THE U.S. PULP AND PAPER INDUSTRY

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Abstract. This paper analyzes the energy efficiency and carbon dioxide emissions reductions potential of the U.S. pulp and paper industry, one of the largest energy users in the U.S. manufacturing sector. We examined over 45 commercially available state-of-the-art technologies and measures. The measures were characterized, and then ordered on the basis of cost-effectiveness. The report indicates that there still exists significant potential for energy savings and carbon dioxide emissions reduction in this industry. The cost-effective potential for energy efficiency improvement is defined as having a simple pay-back period of three years or less. Not including increased recycling the study identifies a cost-effective savings potential of 16% of the primary energy use in 1994. Including increased recycling leads to a higher potential for energy savings, i.e. a range of cost-effective savings between 16% and 24% of primary energy use. Future work is needed to further elaborate on key energy efficiency measures identified in the report including barriers and opportunities for increased recycling of waste paper.

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 (1). 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 paper reports on the 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 (2). As such, opportunities exist for increasing energy efficiency in the pulp and paper industry in the U.S. 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. The most significant energy-consuming processes are pulping and the drying section of papermaking.

In this paper we first discuss the U.S. pulp and paper industry and its energy consumption, followed by a discussion of commercially available technologies to improve the energy efficiency. We assess the cost-effective potential for energy efficiency improvement using current energy prices. This is followed by a brief discussion of the potential energy impact of increased fiber recycling and new emerging technologies currently under development. We end with discussion and conclusions. The paper is based on an extensive study by Martin et al. (3).

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

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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.

skilled labor and access to capital is the largest producer of pulp and paper in the world. 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 (4). 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.

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 Million tonnes (Mt) in 1970 to 60.0 Mt in 1994, at a rate of 1.9% per year, though growth has slowed slightly in recent years (5). 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.

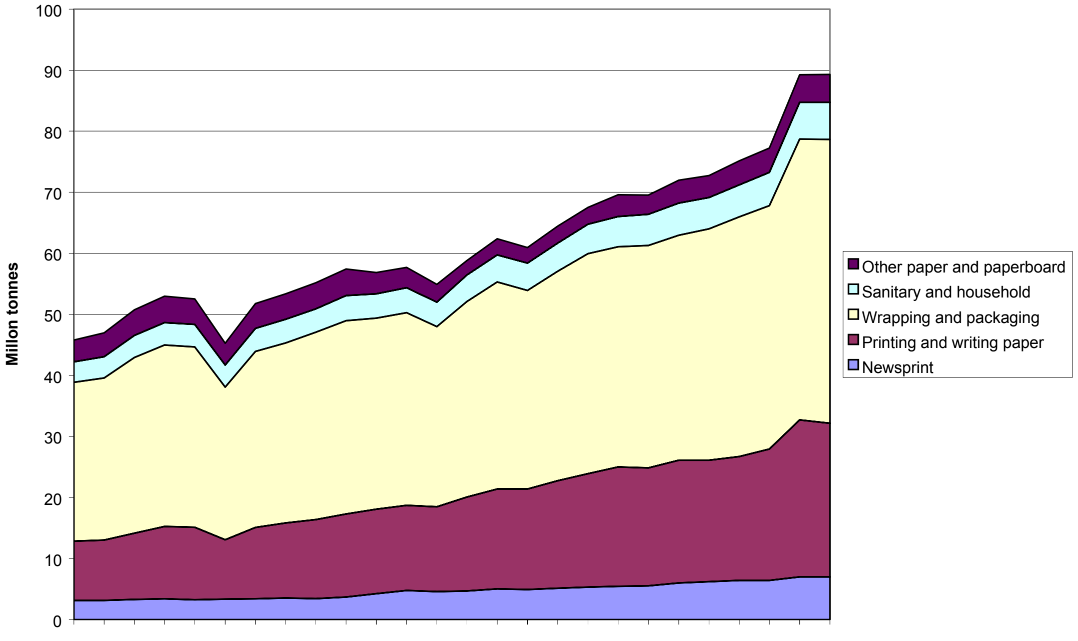

Figure 1. U.S. Paper Production by Process, 1970 to 1994. Source: United Nations (5).

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.

Energy Consumption Trends in the U.S. Pulp and Paper Industry

Primary energy consumption[2] 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. 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. 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.

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. (1,5). This energy intensity decline is due to process efficiency improvements and increased combined heat and power capacity.

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 (6). 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 (1). 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 (7).

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, a significant increase in the share of biomass fuels, resulting in lower carbon emissions per unit of energy consumed. Secondly, there has also been a significant increase in the use of recycled fiber, growing to 28 Mt in 1994. 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.

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[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 11.1 MJ/kWh (HHV) and a site rate of 3.6 MJ/kWh

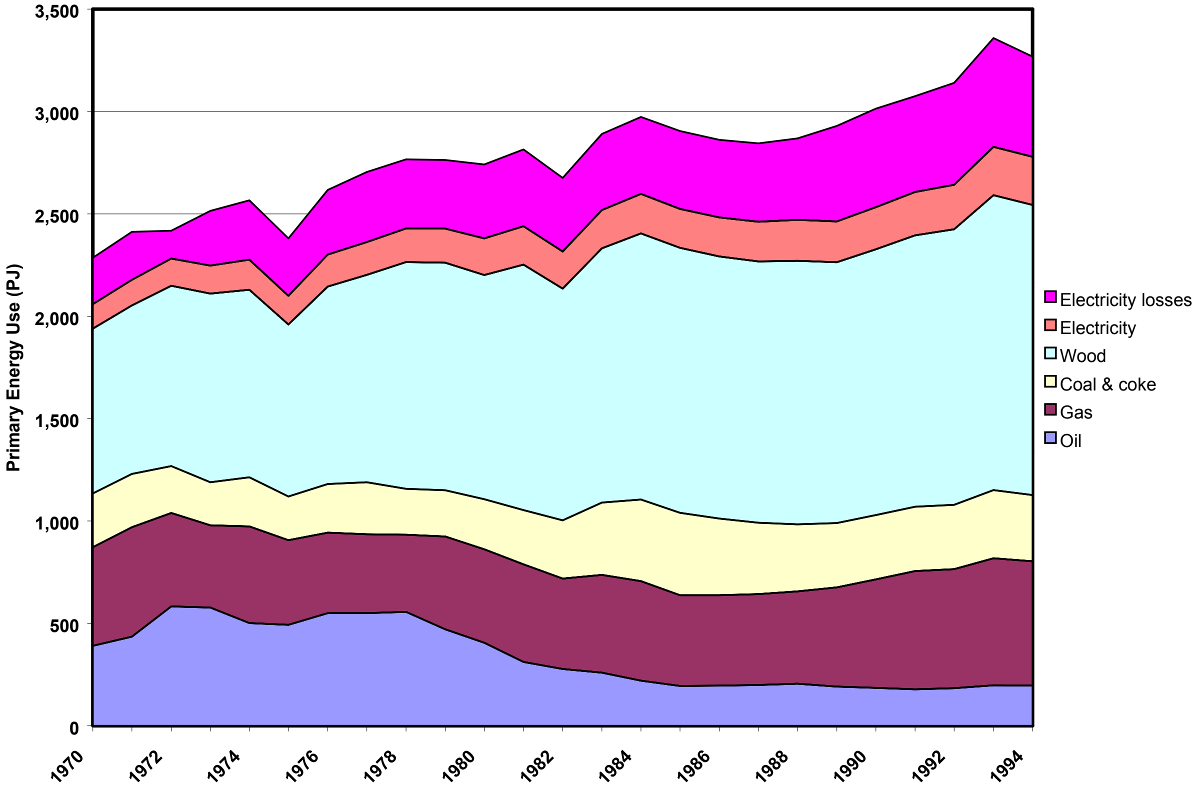

Figure 2. Primary Energy Use in U.S. Paper Production. Source: U.S. Department of Commerce, U.S. Department of Energy.

1994 Energy Balance for the U.S. Pulp and Paper Industry

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 (1,8). Table 1 provides an estimate 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 Table 1 indicates, most of the commercial and bio-fuels are used to first produce steam, which is used in various processes and for electricity generation. The estimate of steam, fuels, and electricity consumption by process was based on average unit consumption estimates found in the literature (4, 6, 9, 10, 11).

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
Pulping - Mechanical	2.67	0.00	0.00	67.59	70.26	5.34	0.03	0.82	2.15
Pulping - Wastepaper						27.82			
Pulping - 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**
	-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 Onsite Energy Production	*-2296*	*688*	*955*	*1417*	*-203*			*0.0*
Total Energy Required/produced/bought	**-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”)

Table 2 shows 1994 energy consumption by fuel type for the pulp and paper industry (SIC 26) and the respective carbon dioxide emissions by fuel. The data for 1994 carbon coefficients for various commercial fuels come from the U.S. Energy Information Administration database (8). 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: Energy Information Administration, U.S. Department of Energy (1, 8).

Energy-Efficient Technologies and Practices for the U.S. Pulp and Paper Industry

A number of technologies and measures exist that can reduce energy intensity of the various processes in pulp and paper production. Table 3 lists the technologies and measures that have been analyzed for this study. These technologies can be divided into two categories: current state-of-the-art technologies and emerging technologies. Current state-of-the-art technologies are technologies currently implemented in the pulp and paper mills world-wide, while emerging technologies are currently used only in pilot plants or are in early stages of commercialization. Emerging technologies are not included in the analysis of the potential for energy efficiency improvement.

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. The savings and costs for each process step are converted to savings and costs *per tonne of paper,* by multiplying each value by the ratio of process step throughput to total paper produced. Finally, based on a variety of information sources and expert judgment, we estimate the potential penetration rate for each technology that can be attained by the year 2010, and project this estimate on the 1994 baseline to estimate the potential energy efficiency improvements.

Table 3 shows fuels, electricity, and primary energy savings per tonne (t) of production, retrofit capital costs[3] and O&M costs per tonne of production, the percentage of production to which the measure can be applied nationally and the associated carbon dioxide emission reductions. A detailed description of each technology is provided in the underlying report (3).

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[3] 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 3. 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%

Assessing the Potential for Energy Efficiency Improvement

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 (12). 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 (13). Ranking investments according to supply curve methodology is consistent with micro-economic 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 (14). The CCE of a particular measure is calculated as:

$$\text{CCE} = \frac{\text{Annualized Investment} + \text{Annual Change in O\&M Costs}}{\text{Annual Energy Savings}} \qquad [1]$$

The Annualized Investment is calculated as:

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

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 (1).

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.[4]

The energy conservation supply curve shown in Figure 3 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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[4] For examples of conservation supply curves, see e.g. Meier et al. (12), Interlaboratory Working Group (15), National Academy of Sciences, (16), Worrell (17) and Worrell et al. (18).

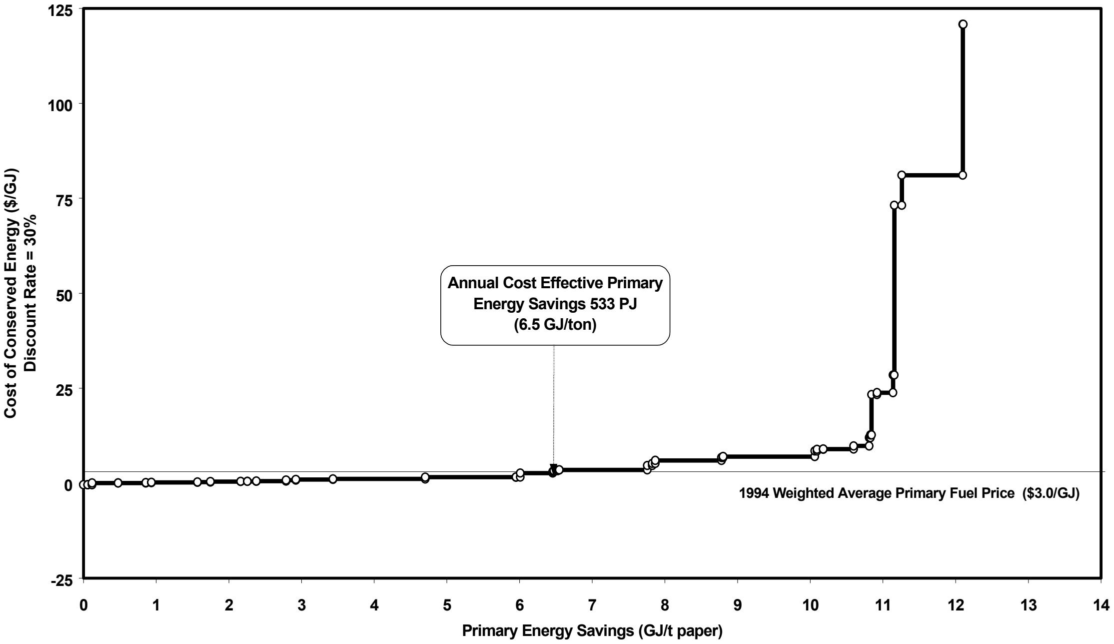

Figure 3. Case A: Energy Conservation Supply Curve for U.S. Pulp and Paper Industry (excluding increased recycling of waste fibers) using a discount rate of 30%.

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 Energy Consumption Survey (1). Using different methods of averaging we calculated a range of prices from $2.7/GJ to $3.4/GJ. Using the lower prices, energy savings are still 13-14% of total primary energy consumption.

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.

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 4 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 4. Cost of Conserved Energy for Energy Efficiency Measures in U.S. Pulp and Paper Industry (excluding increased fiber recycling).

	Primary CCE $/GJ	**Primary Energy savings** GJ/t	**Cumulative primary energy savings** GJ/t	**$3/GJ Internal rate of return** %	**Simple payback time** years	**Carbon Emissions Reduced** 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

Increased Use of Recycled Fiber

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 (19). 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 de-inking is the current best practice in this area (20). 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 (21). 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.

In a scenario assuming increased use of recycled fibers 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. The total technical potential for energy savings in the industry is approximately 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 energy saving and cost assumptions in both scenarios but do vary the throughput of materials at the various process stages to account for an increase in recovered paper.

We identify cost-effective potential as those technologies and measures that have a CCE less than the average price of energy. In the Recycling Scenario, 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). While the amount of energy savings in the scenario without increased recycling was not sensitive to the range of average energy prices examined in this analysis (a variation of only 1% primary energy savings) in the Recycling Scenario the sensitivity is greater. In the recycled paper scenario, the savings vary between energy prices of $2.6/GJ and $3.4/GJ range from 16-22%.The CCE, IRR, and payback period for increased use of recycled paper are $3.2/GJ, 29%, and 3.4 years respectively.

Emerging Technologies

The emerging technologies described below are not included in our assessment of cost effective potential, but we include the selected descriptions for informational purposes, based on recent study by LBNL and ACEEE (22). The study assessed the future potential of selected technologies specific fir the pulp and paper industry (7 technologies) as well as cross-cutting technologies that can also be applied in the pulp and paper industry (18 technologies, including advanced electric motor technologies). The study found that various technologies may have an important impact on the future of the U.S. pulp and paper industry, especially black liquor gasification and new drying technologies like Impulse and Condebelt drying. Other technologies assessed include dry sheet forming, high consistency forming, electrolytic causticizing, advanced adjustable speed drives, advanced gas turbines, low-NOx high efficiency boiler designs, and membrane technology for waste water treatment.

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 (6,23) by means a standard combined cycle power generation system. This could produce up to 2000 kWh/tonne of pulp, resulting in primary energy savings of 23% for chemical pulping. This technology will make a pulping plant an electricity exporter. Currently, the first gasifiers are demonstrated, and by 2015 gasifiers may replace up to 15% of the Tomlinson boiler capacity.

New drying technologies involve 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 (impulse drying) or in a drying chamber in contact with a continuous hot steel band (Condebelt drying). In impulse drying the pressure is about 10 times higher than that in press and Condebelt drying (22, 24). Impulse drying tremendously increases the drying rate of paper although there may be problems with the paper delaminating or sticking to the roll. Energy savings are estimated at 15% compared to current paper machines.

Discussion 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 increased recycling of waste fiber). 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 (corresponding to 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 (25).

The difference between the two scenarios 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. Furthermore, emerging technologies have not been included in either scenario. Future technologies represent opportunities for further energy savings beyond the potential identified in this study. Further refinement and improvement of cost estimates and benefits of energy efficient investments would be desired. Finally, often so-called non-energy benefits, e.g. productivity increases, accompany the investment in new technology. We believe that a careful investigation into these benefits will further strengthen the case for selected energy efficiency investments in the pulp and paper industry.

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