U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing

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The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office works with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

Prepared for DOE / EERE's Advanced Manufacturing Office by Energetics Incorporated.

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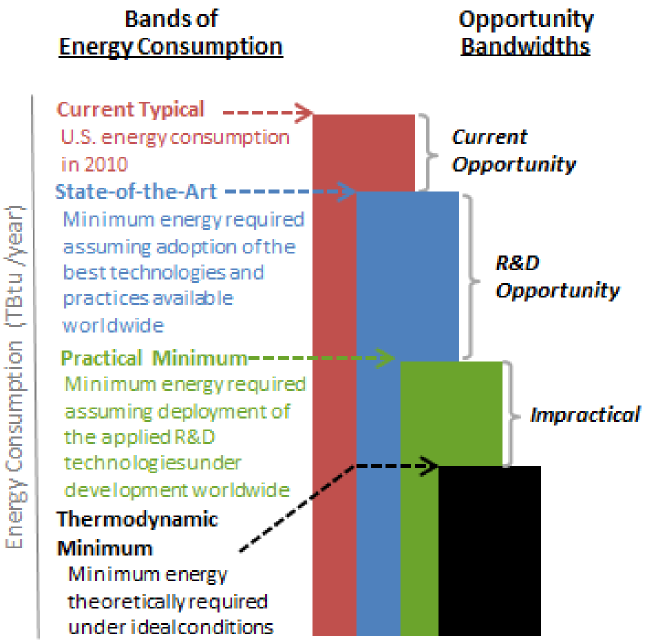
Disclaimer

Preface

Reducing energy consumption through investment in advanced technologies and practices can enhance American manufacturing competitiveness. Energy bandwidth studies of U.S. manufacturing sectors serve as general data references to help understand the range (or *bandwidth*) of potential energy savings opportunities. The U.S. Department of Energy (DOE)'s Advanced Manufacturing Office (AMO) has commissioned a series of bandwidth studies to analyze the processes and products that consume the most energy, and provide hypothetical, technology-based estimates of potential energy savings opportunities. The consistent methodology used in the bandwidth studies provides a framework to evaluate and compare energy savings potentials within and across manufacturing sectors at the macro-scale. Bandwidth studies using the terminology and methodology outlined below were prepared for the Chemicals, Petroleum Refining, Iron and Steel, and Pulp and Paper industry sectors in 2014.[11]



Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

Four different energy *bands* (or measures) are used consistently in this series to describe different levels of onsite energy consumption to manufacture specific products and to compare potential energy savings opportunities in U.S. manufacturing facilities (see figure). **Current typical** (CT) is the energy consumption in 2010; **state of the art** (SOA) is the energy consumption that may be possible through the adoption of existing best technologies and practices available worldwide; **practical minimum** (PM) is the energy consumption that may be possible if applied R&D technologies under development worldwide are deployed; and the **thermodynamic minimum** (TM) is the least amount of energy required under ideal conditions, which typically cannot be attained in commercial applications. CT energy consumption serves as the benchmark of manufacturing energy consumption. TM energy consumption serves as the baseline (or

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[1] The concept of an energy bandwidth, and its use as an analysis tool for identifying potential energy saving opportunities, originated in AMO in 2002 (when it was called the Office of Industrial Technologies). The first two sector studies—Iron and Steel, and Metal Castings—were completed in 2004. That work was followed by Chemicals and Petroleum Refining studies in 2006, and Aluminum, Glass, and Mining in 2007. A Cement Industry analysis was conducted in 2010 and a Pulp and Paper analysis was conducted in 2011.

theoretical minimum) that is used in calculating energy savings potential. Feedstock energy (the nonfuel use of fossil energy) is not included in the energy consumption estimates.

Two onsite energy savings opportunity *bandwidths* are estimated: the ***current opportunity*** spans the bandwidth from CT energy consumption to SOA energy consumption, and the ***R&D opportunity*** spans the bandwidth from SOA energy consumption to PM energy consumption. These bandwidths are estimated for processes and products studied and for all manufacturing within a sector. The difference between PM energy consumption and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities. Significant investment in technology development and implementation would be needed to fully realize the energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.

In each sector studied in the series, the four energy bands are estimated for select individual products or processes, subsectors, and sector-wide. The estimation method compares diverse industry, governmental, and academic data to analyses of reported plant energy consumption data from the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA). MECS is a national sample survey of U.S. manufacturing establishments conducted every four years; information is collected and reported on U.S. manufacturing energy consumption and expenditures.

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In addition, AMO recognizes Joseph Cresko of DOE/AMO who lead the conceptual development and publication of the bandwidth study series with the support of Dr. Alberta Carpenter at the National Renewable Energy Laboratory, as well as the important contributions made by Theresa Miller, Sabine Brueske, and Caroline Kramer of Energetics Incorporated for conducting the majority of the research and analysis and drafting this study.

Executive Summary

The United States was the largest producer of pulp products and second largest producer of paper and paperboard in 2010 (FAOSTAT 2012). This bandwidth study examines energy consumption and potential energy savings opportunities in U.S. pulp and paper manufacturing. Industrial, government, and academic data are used to estimate the energy consumed in six of the most energy intensive pulp and paper manufacturing processes. Three different energy consumption *bands* (or levels) are estimated for these select manufacturing processes based on referenced energy intensities of current, state of the art, and future technologies. A fourth theoretical minimum energy consumption *band* is also estimated. The data from the select processes studied is also used to determine energy consumption for the entire pulp and paper sector. The *bandwidth*—the difference between bands of energy consumption—is used to determine the potential energy savings opportunity. The costs associated with realizing these energy savings was not in the scope of this study.

The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for pulp and paper manufacturing processes and sector-wide. This is a step toward understanding the processes that could most benefit from technology and efficiency improvements to realize energy savings.

Study Organization and Approach: After providing an overview of the methodology (Chapter 1) and energy consumption in pulp and paper manufacturing (Chapter 2), the 2010 production volumes (Chapter 3) and current energy consumption (current typical [CT], Chapter 4) were estimated for six select processes. In addition, the minimum energy consumption for these processes was estimated assuming the adoption of best technologies and practices available worldwide (state of the art [SOA], Chapter 5) and assuming the deployment of the applied research and development (R&D) technologies available worldwide (practical minimum [PM], Chapter 6). The minimum amount of energy theoretically required for these processes assuming ideal conditions was also estimated (thermodynamic minimum [TM)], Chapter 7); in some cases, this is less than zero. The difference between the energy consumption *bands* (CT, SOA, PM, TM) are the estimated energy savings opportunity *bandwidths* (Chapter 8).

The U.S. Energy Information Administration's (EIA) Manufacturing Energy Consumption Survey (MECS) provides a sector-wide estimate of energy consumption for U.S. pulp and paper manufacturing; this data is referenced as sector-wide CT energy consumption. In this study, CT, SOA, PM, and TM energy consumption for six *individual* processes is estimated from multiple referenced sources. In 2010, these six processes corresponded to 52% of the industry's energy consumption.

Study Results: Two energy savings opportunity *bandwidths* – current opportunity and R&D opportunity – are presented in Table ES-1 and Figure ES-1.[1] The current opportunity is the

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[1] The energy estimates presented in this study are for macro-scale consideration; energy intensities and energy consumption values do not represent energy use in any specific facility or any particular region in the United States. The costs associated with achieving energy savings are not considered in this study. All estimates are for onsite

difference between the 2010 CT energy consumption and SOA energy consumption; the R&D opportunity is the difference between SOA energy consumption and PM energy consumption. Potential energy savings opportunities are presented for the six processes studied and for all of U.S. pulp and paper manufacturing. Figure ES-1 also shows the estimated relative current and R&D energy savings opportunities for individual processes.

Table ES-1. Potential Energy Savings Opportunities in the U.S. Pulp and Paper Manufacturing Sector[1]

Opportunity Bandwidths	Estimated Energy Savings Opportunity for Six Select Pulp and Paper Manufacturing Processes (per year)	Estimated Energy Savings Opportunity for All of the U.S. Pulp and Paper Sector (per year)
Current Opportunity – energy savings if the best technologies and practices available are used to upgrade production	273 TBtu[2] (45% energy savings, where TM is the baseline)	465 TBtu[3] (61% energy savings, where TM is the baseline)
R&D Opportunity – additional energy savings if the applied R&D technologies under development worldwide are deployed	121 TBtu[4] (20% energy savings, where TM is the baseline)	147 TBtu[5] (19% energy savings, where TM is the baseline)

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energy use (i.e., energy consumed within the refinery boundary). Energy used as feedstocks (non-fuel inputs) to production is excluded.

[2] 273 TBtu = 1,103 – 829

[3] 465 TBtu = 2,110 – 1,645

[4] 121 TBtu = 829 – 708

[5] 147 TBtu = 1,645 – 1,498

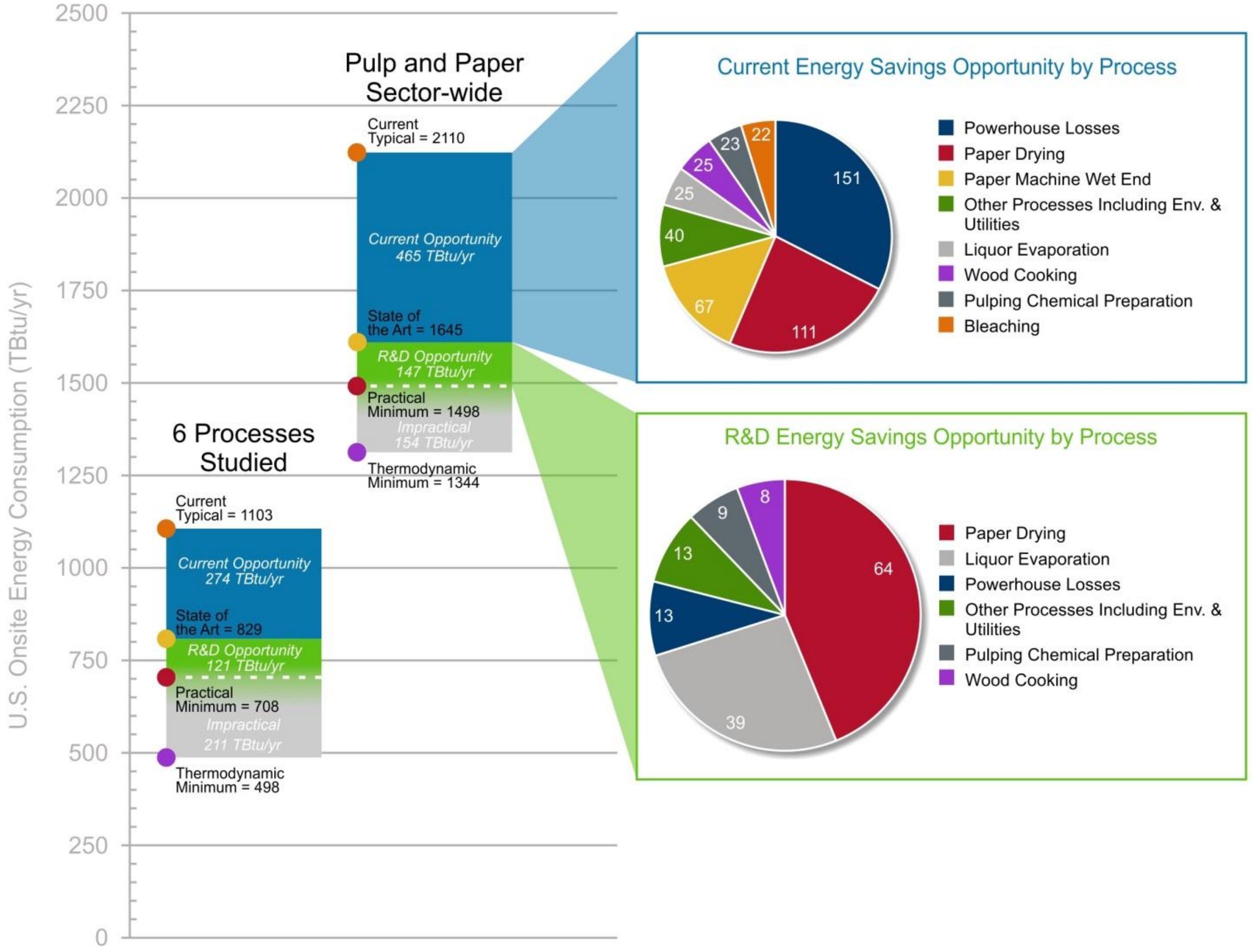

Figure ES-1. Current and R&D Energy Savings Opportunities for the Nine Processes Studied and for Pulp and Paper Sector-wide

The PM energy consumption estimates are speculative because they are based on unproven technologies. The estimates assume deployment of R&D technologies that are under development; where multiple technologies were considered for a similar application, only the most energy efficient technology was considered in the energy savings estimate. The difference between PM and TM is labeled “impractical” because with today’s knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

The results presented show that 273 TBtu of energy could be saved each year if capital investments in the best technologies and practices available worldwide are used to upgrade six pulp and paper manufacturing processes; an additional 121 TBtu could be saved through the adoption of applied R&D technologies under development worldwide.

However, if the energy savings potential is estimated for the U.S. pulp and paper industry as a whole, the current energy savings opportunity is 465 TBtu per year and the R&D opportunity increases to 147 TBtu per year.

The top five Current Energy Savings Opportunities for the processes are as follows:

- Paper drying - 111 TBtu (or 24% of current opportunity)
- Paper machine wet end - 67 TBtu (or 14% of current opportunity)
- All other NAICS 322[1] processes - 4 TBtu (or 9% of the current opportunity)
- Liquor evaporation – 25 TBtu (or 5% of the current opportunity).
- Wood cooking – 25 TBtu (or 5% of the current opportunity).

The top four R&D Energy Saving Opportunities for the processes are as follows:

- Paper drying - 64 TBtu (or 44% of the R&D opportunity)
- Liquor evaporation - 39 TBtu (or 26% of the R&D opportunity)
- All other NAICS 322[2] processes - 13 TBtu (or 9% of the R&D opportunity)
- Pulping chemical preparation- 9 TBtu (or 6% of the R&D opportunity).

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[1] All other NAICS 322 includes all other processes in the pulp and paper sector other than the six processes studied, excluding powerhouse losses.

[2] All other NAICS 322 includes all other processes in the pulp and paper sector other than the six processes studied, excluding powerhouse losses.

List of Acronyms and Abbreviations

admt	Air dried metric ton
adst	Air dried short ton
AMO	Advanced Manufacturing Office
Avg	Average
BAT	Best available technology
BDmt	Bone dried metric ton (same as oven dried below)
BkWh	Billion kilowatt hour
Btu	British Thermal unit
CHP	Combined heat and power
CT	Current typical energy consumption or energy intensity
DOE	U.S. Department of Energy
E/NPS	Electricity to net process steam ratio
EIA	U.S. Energy Information Administration
Fst	Finished short ton (2,000 lb)
GJ	Gigajoules
HW	Hardwood
kg	kilogram
kJ	kilojoule
kWh	Kilowatt hour
MMBtu	Million British thermal units
MOW	Mixed office waste
MECS	Manufacturing Energy Consumption Survey
na	Not applicable
NAICS	North American Industry Classification System
NGL	Natural gas liquids
NSSC	Neutral sulfite semi-chemical
OCC	Old corrugated containers
Odmt	Oven dried metric ton
ONP	Old newsprint
P&W	Printing & writing
PM	Practical minimum energy consumption or energy intensity
R&D	Research & development
SGW	Stone ground wood
SOA	State of the art energy consumption or energy intensity
SW	Softwood
TBtu	Trillion British thermal units
TM	Thermodynamic minimum energy consumption or energy intensity
TMP	Thermo-mechanical pulp
WBLS	Weak black liquor solids

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1. Introduction

1.1. OVERVIEW

This bandwidth study examines energy consumption and potential energy savings opportunities in the U.S. pulp and paper manufacturing sector, as defined by classification 322 of the North American Industry Classification System (NAICS). The purpose of this data analysis is to provide macro-scale estimates of energy savings opportunities for pulp and paper manufacturing processes and pulp and paper sector-wide. In this study, four different energy consumption *bands* (or measures) are estimated. The *bandwidth*—the difference between bands of energy consumption—is the estimated potential energy savings opportunity.

In 2010, the United States was the world's largest producer of pulp (30% of global production) and the second largest producer of paper and paperboard (20% of global production) (FAOSTAT 2012).The four bands of energy consumption estimated in this report include: the onsite energy consumption associated with six pulp and paper manufacturing processes in 2010 (current typical); two hypothetical energy consumption levels with progressively more advanced technologies and practices (state of the art and practical minimum); and one energy consumption level based on the minimum amount of energy needed to theoretically complete a pulp or paper manufacturing process (thermodynamic minimum). The bands of energy consumption are used to calculate *current* and *R&D opportunity* bandwidths for energy savings.

1.2. COMPARISON TO OTHER BANDWIDTH STUDIES

This study builds upon the 2006 DOE bandwidth report *Pulp and Paper Industry Energy Bandwidth Study*. Specifically, this study uses the same methodology to calculate the current typical, current and R&D savings opportunities, and the thermodynamic minimum energy requirements and includes additional analysis of R&D savings potential through analysis of research and development (R&D) projects. This study compares diverse industrial, academic and governmental consumption data to analyses[1] of reported plant energy consumption data in the Manufacturing Energy Consumption Survey (MECS) conducted by the U.S. Energy Information Administration (EIA) for data year 2010. This study also updates energy consumption and production values to the year 2010.

This report is one in a series of bandwidth studies commissioned by DOE's Advanced Manufacturing Office characterizing energy consumption in U.S. manufacturing using a uniform methodology and definitions of energy bands. Other manufacturing sector bandwidth studies include chemicals, petroleum refining, and iron and steel; additional sector studies are under consideration. Collectively, these studies explore the potential energy savings opportunities in

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[1] The relevant analysis was published as the *Manufacturing Energy and Carbon Footprint for the Forest Products Sector* (NAICS 321, 322), based on energy use data from 2010 EIA MECS (with adjustments) in February 2014. Hereafter, this document will be referred to as the "Energy Footprint" and listed in the References section as DOE 2014.

manufacturing that are available through existing technology and with investment in research and development (R&D) technologies.

1.3. DEFINITIONS OF ENERGY CONSUMPTION BANDS AND OPPORTUNITY BANDWIDTHS

There are four energy consumption bands referenced throughout this report: current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM) energy consumption. These bands describe different levels of energy consumption for pulp and paper manufacturing processes.

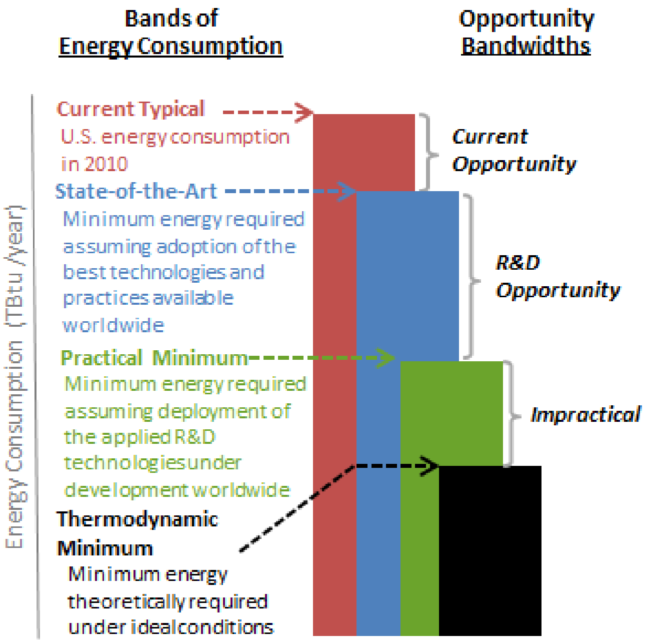

Figure 1-1. Energy Consumption Bands and Opportunity Bandwidths Estimated in this Study

As shown in Figure 1-1, the bands progress from higher to lower levels of energy consumption, reflecting the use of increasingly more efficient manufacturing technologies and practices. The upper bound is set by a mix of new and older technologies and practices in current use (the current typical level of energy consumption). The lower bound is defined by the theoretical minimum energy requirement assuming ideal conditions and zero energy losses (the thermodynamic minimum level of energy consumption).

Each of these two bounds defining the extremes of energy consumption can be compared to hypothetical measures in the middle of this range. If manufacturers use the most efficient technologies and practices available in the world, energy consumption could decrease from the current typical to the level defined by the state of the art. Since these state of the art technologies already exist, the difference between the current typical and the state of the art energy consumption levels defines the *current opportunity* to decrease energy consumption. Given that this is an evaluation of technical potential, fully realizing the current opportunity would require investments in capital that may or not be economically viable for any given facility.

Widespread deployment of future advanced technologies and practices under investigation by researchers around the globe could help manufacturers attain the practical minimum level of energy consumption. The difference between state of the art and practical minimum levels of energy consumption defines the *R&D opportunity* for energy savings.

Definitions of the four energy bands are provided in the inset (box at right). Definitions of the two opportunity bandwidths are provided below:

The *current opportunity* is the energy savings that is potentially attainable through capital investments in the best technologies and practices available worldwide. It is the difference between CT and SOA energy consumption.

The *R&D opportunity* is the energy savings that is potentially attainable through the applied R&D technologies under development. It is the difference between SOA and PM energy consumption. To attain this energy savings, pulp and paper mills would need to manufacture products in new ways with technologies that are not commercially available.

Definitions of Energy Bands Used in the Bandwidth Studies

The following definitions are used to describe different levels of U.S. energy consumption for a *specific manufacturing process industry-wide*:

Current Typical (CT) energy consumption:
U.S. energy consumption in 2010.

State of the Art (SOA) energy consumption:
The minimum amount of energy required assuming the adoption of the best technologies and practices available worldwide.

Practical Minimum (PM) energy consumption:
The minimum amount of energy required assuming the deployment of the best applied R&D technologies under development worldwide.

This measure is expressed as a range to reflect the speculative nature of the energy impacts of the unproven technologies considered.

Thermodynamic Minimum (TM) energy consumption:
The minimum amount of energy theoretically required assuming ideal conditions typically unachievable in real-world applications.

The difference between PM and TM energy consumption is labeled as *impractical*. The term *impractical* is used because with today's knowledge of technologies in R&D, further investment may no longer lead to incremental energy savings and thermodynamic limitations impede technology opportunities.

1.4. BANDWIDTH ANALYSIS METHOD

This Section describes the method used in this bandwidth study to estimate the four bands of energy consumption and the two corresponding energy savings opportunity bandwidths. This section can also be used as a guide to understanding the structure and content of this report.

In this study, U.S. energy consumption is labeled as either "onsite energy" or "primary energy" and defined as follows:

- **Onsite energy** (sometimes referred to as site or end use energy) is the energy consumed within the manufacturing plant boundary (i.e., within the plant gates). Non-fuel feedstock energy is *not* included in the onsite energy consumption values presented in this study.
- **Primary energy** (sometimes referred to as source energy) includes energy that is consumed both offsite and onsite during the manufacturing process. Offsite energy consumption includes generation and transmission losses associated with bringing electricity and steam to the plant boundary. Non-fuel feedstock energy is not included in

the primary energy values. Primary energy is frequently referenced by governmental organizations when comparing energy consumption across sectors.

Four bands of energy consumption are quantified for select individual processes and pulp and paper manufacturing sector-wide. **The bands of energy consumption and the opportunity bandwidths presented herein consider onsite energy consumption; feedstocks[2] are excluded.** To determine the total annual onsite CT, SOA, PM, and TM energy consumption values of the processes studied (TBtu per year), energy intensity values per unit weight (Btu per pound or ton of product) are estimated and multiplied by the production volumes (pounds or tons per year of product). The year 2010 is used as a base year since it is the most recent year for which consistent sector-wide energy consumption data are available. Unless otherwise noted, 2010 production data is used.

The estimates presented are for macro-scale consideration of energy use in pulp and paper manufacturing. The estimates reported herein are representative of average U.S. pulp and paper manufacturing; they do not represent energy use in any specific facility or any particular region in the United States or the world.

Significant investment in technology development and implementation would be needed to fully realize the potential energy savings opportunities estimated. The costs associated with achieving SOA and PM energy consumption are not considered in this report; a techno-economic analysis of the costs and benefits of future technologies was not in the scope of this study.

The calculated energy consumption values in this report are based on an examination of referenced data and extrapolation to sector-wide energy savings opportunities. The references, methodology, and assumptions employed are presented with the data in each chapter and were peer reviewed.

Overview of energy use in pulp and paper manufacturing: Chapter 2 provides an **overview** of the U.S. pulp and paper sector and how energy is used in pulp and paper manufacturing (how much, what type, and for what end uses).

Estimating production volumes for select processes: Chapter 3 presents the relevant **production volumes** for the six processes (tons per year) in 2010 and the rationale for how the six processes were selected.

Estimating CT energy consumption: Chapter 4 presents the calculated onsite **CT energy consumption** (TBtu per year) for the six processes individually and sector-wide (along with references for the CT energy intensity data and assumptions). The CT energy consumption data is calculated based on this energy intensity data and the production volumes (identified in

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[2] Feedstock energy is the nonfuel use of combustible energy. Feedstocks are converted to products (not used as a fuel); MECS values reported as “feedstocks” exclude feedstocks converted to other energy products.

Chapter 3). The boundary assumptions for the industrial processes considered in this bandwidth study are presented.

MECS provides onsite CT energy consumption data sector-wide for 2010 (See Table 2-3). However, MECS does not provide CT energy consumption data for individual processes. The percent coverage of the processes studied (compared to MECS sector-wide data) is presented and used in calculations discussed later in this report.

Primary CT energy consumption (TBtu per year) estimates are calculated, which include offsite generation and transmission losses associated with bringing electricity and steam to manufacturing facilities. Primary energy consumption estimates are not provided for SOA, PM, or TM because they were outside the scope of this study.

***Estimating SOA energy consumption*:** Chapter 5 presents the estimated onsite **SOA energy consumption** for the six processes (along with the references for the SOA energy intensity data and assumptions). The sector-wide SOA energy consumption is estimated based on an extrapolation of the SOA energy consumption for the six processes studied. The *current opportunity* bandwidth, the difference between CT energy consumption and SOA energy consumption (also called the SOA energy savings), is presented along with the SOA energy savings percent.

Estimating PM energy consumption: Chapter 6 presents the estimated onsite **PM energy consumption** for the six processes (along with the references for PM energy intensity data and assumptions). The range of potentially applicable applied R&D technologies to consider in the PM analysis worldwide is vast. The technologies that were considered are sorted by process and described in Appendix A3. The technologies that are considered crosscutting throughout all of pulp and paper manufacturing along with the most energy-saving, process-specific R&D technologies were used to determine PM energy consumption for each process. A weighting method that includes factors such as technology readiness, cost, and environmental impact was developed for all technologies considered; the weighting analysis methodology and summary table provided in Appendix A4 is intended to serve as a resource for continued consideration of all identified R&D opportunities.

The sector-wide PM energy consumption is estimated based on an extrapolation of the PM energy consumption for the six processes studied. The *R&D opportunity* bandwidth, the difference between SOA energy consumption and PM energy consumption, is presented along with the PM energy savings percent. PM energy savings is the sum of *current* and *R&D opportunity*.

The technologies considered in the PM analysis are unproven on a commercial scale. As a result, the PM energy consumption is expressed as a range. The upper limit is assumed to be the SOA energy consumption; the lower limit is estimated and shown as a dashed line with color fading in the summary figures because the PM is speculative and depends on unproven R&D technologies.

Furthermore, the potential energy savings opportunity could be greater if additional unproven technologies were considered.

Estimating TM energy consumption: Chapter 7 presents the estimated onsite **TM energy consumption** for the six processes (along with the references for the TM energy intensity data and assumptions). The TM energy intensities are based on the commercial process pathways. TM energy consumption assumes all of the energy is used productively and there are no energy losses. TM is the minimum amount of energy required; in some cases it is less than zero.

To determine the available potential energy savings opportunities in this bandwidth study, TM energy consumption was used as the baseline for calculating the energy savings potentials for each process studied (not zero, as is typically the case in considering energy savings opportunities). The rationale for using TM as the baseline is explained in Chapter 7.

Estimating the energy savings opportunities: Chapter 8 presents the energy savings **opportunity bandwidths** for the processes and sector-wide. The analyses used to derive these values are explained in Chapters 3 to 7.

2. U.S. Pulp and Paper Manufacturing Sector Overview

This Chapter presents an overview of the U.S. pulp and paper manufacturing sector, including its impact on the economy and jobs, number of establishments, types of energy consumed, and the end uses of the energy. The convention for reporting energy consumption as either onsite versus primary energy is explained. The data and information in this Chapter provide the basis for understanding the energy consumption estimates.

2.1. U.S. PULP AND PAPER MANUFACTURING ECONOMIC OVERVIEW

The United States pulp and paper industry (NAICS Code 322) is comprised of pulp mills, dedicated paper mills and paperboard mills, and integrated mills that include both pulp processing and paper manufacturing.

The paper manufacturing sector is an integral part of the economy. In 2010, the industry shipped manufactured paper products valued at more than $170 billion while employing more than 360,000 people (AFPA 2011). Globally, the U.S. is the second largest producer of paper and paperboard products (19%) and the world's largest producer of virgin wood pulp (30%) (LBNL 2013).

A worldwide trend in the pulp and paper industry is the increasing use of recovered paper in paper production. In 2010, 63.5% of the paper consumed in the U.S. was recovered for recycling compared to 48.2% in 2002 (AFPA 2011). Recovered paper that had been sorted or processed in the U.S. in 2010 had a market value of $8.9 billion (AFPA 2012). The value of U.S. recovered paper exports totaled $3.3 billion with 80% of the export supplying the Asian pulp and paper industry (AFPA 2011). It should be noted that not all types of recovered paper can be used as recycled pulp and certain types of paper require higher percentages of virgin pulp (IEA 2007).

2.2. U.S. PULP AND PAPER MANUFACTURING PRODUCTS, ESTABLISHMENTS, AND PROCESSES

Table 2-1 lists the regional and state distribution of paper and paperboard production across the United States. More than half of the production is located in the South with the remaining production almost evenly distributed among the Northeast, North Central and Western regions of the United State. There are an estimated 386 pulp and/or paper mills in the U.S. (EPA 2010) with paper mills located in 41 states (IRC 2013). The following states do not have paper mills: Alaska, Colorado, North Dakota, Nebraska, Nevada, Rhode Island, South Dakota, Utah, and Wyoming (IRC 2013).

The pulp and paper industry produces various types of pulp that are subsequently processed into paper products in either integrated or non-integrated mills. At an integrated mill, pulping and papermaking processes are integrated at one production site. Non-integrated mills either manufacture pulp that is then sold on the market or purchase pulp for their paper production (LBNL 2012).

Table 2-1. Paper and Paperboard Production by Region and State, 2010

Region		State	State Total (1,000 tons)	Regional Total (1,000 tons)	Percent of Total
New England	New England	Maine	3,370	4,682	5.6%
		New Hampshire	121		
		Vermont	170		
		Massachusetts	360		
		Connecticut	661		
	Mid Atlantic	New York	2,578	4,846	5.8%
		Pennsylvania	2,268		
North Central	East North Central	Ohio	1,784	11,147	13.4%
		Indiana	683		
		Illinois	287		
		Michigan	3,055		
		Wisconsin	5,338		
	West North Central	Minnesota	2,441	2,441	2.9%
South	South Atlantic	Virginia	3,736	19,875	24.0%
		North Carolina	1,704		
		South Carolina	4,502		
		Georgia	7,106		
		Florida	2,827		
	East South Central	Kentucky	1,754	14,201	17.1%
		Tennessee	2,826		
		Alabama	7,747		
		Mississippi	1,874		
	West South Central	Arkansas	2,957	12,293	14.8%
		Louisiana	6,894		
		Texas	2,442		
West	Mountain	Arizona, Idaho, Montana, New Mexico		1,289	1.6%
	Pacific	Washington	4,226	7,947	9.6%
		Oregon	2,574		
		California	1,147		
States Not Disclosing State level Data: Iowa, Kansas, Maryland, New Jersey, West Virginia				1,842	2.2%
			Subtotal	80,563	97.0%
			Amount Not Attributed to State/Region	2,397	3.0%
			Total	82,960	100.0%

Source: AFPA 2011

Figure 2-1 shows a flow diagram of the pulping and papermaking process. The actual manufacturing process in a pulp or paper mill will vary depending on the raw materials used and the paper products produced. However, the basic principle of pulping and papermaking remains the same.

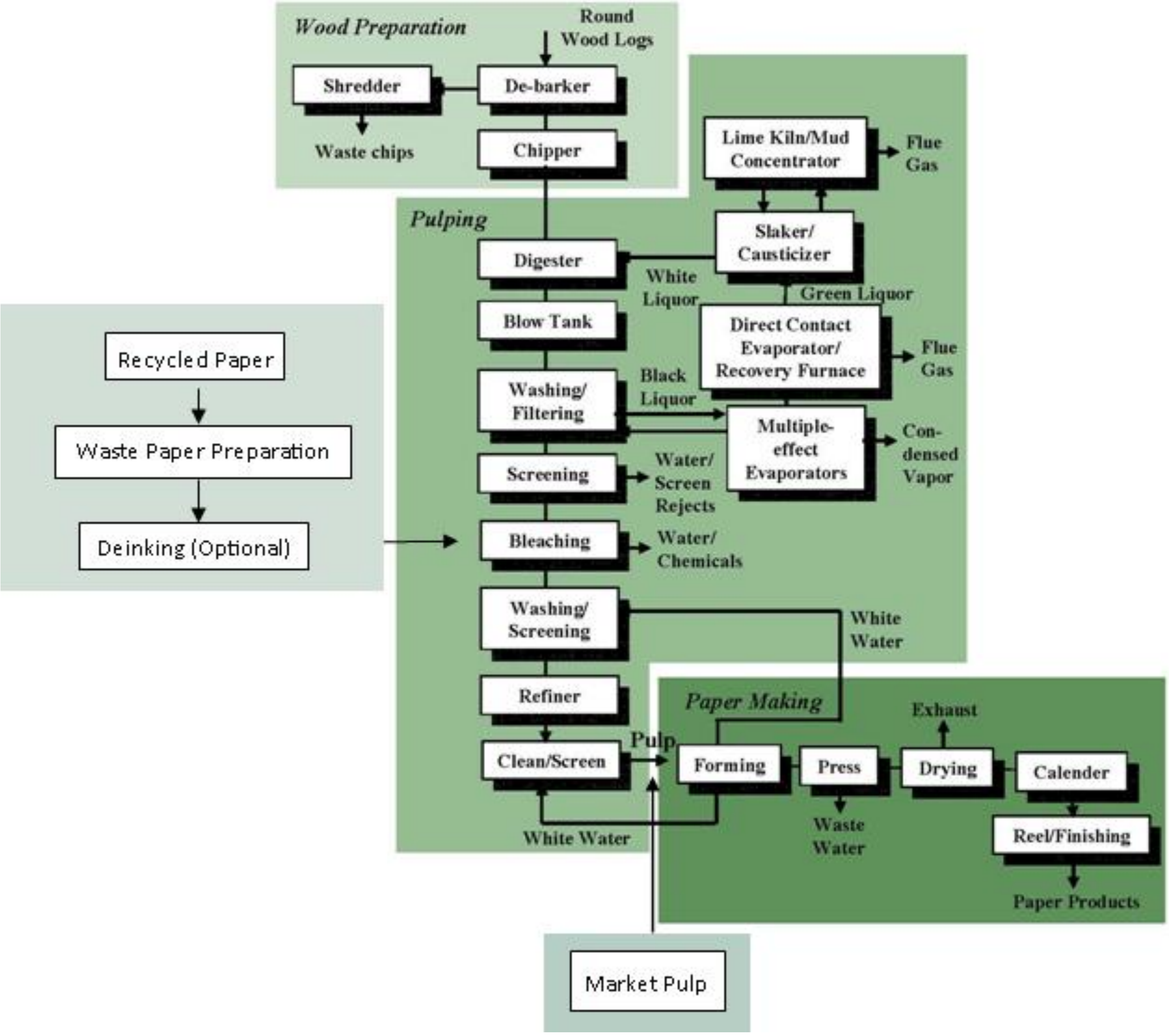


Figure 2-1. Flow diagram of Pulping and Papermaking Process *(adapted from DOE 2005)*

This study is production weighted – the energy consumed is based on the tons of pulp and paper produced by type (kraft pulp, thermo-mechanical pulp (TMP), printing & writing paper, linerboard, etc.) multiplied by the energy intensity for the various large process areas within a mill. Examples of large process areas are: pulping, bleaching, liquor evaporation, stock preparation, paper drying, etc. This report focuses on the large blocks of energy consumed by the U.S. pulp and paper industry rather than the large process units with relatively little impact on the industry's total energy consumption. The six major consumers of energy by area within pulp and paper manufacturing selected for this study are liquor evaporation, pulping chemical prep, wood cooking, and bleaching in pulp manufacturing and paper drying and paper machine wet end in paper manufacturing and are shown in Table 2-2.

Table 2-2. Pulp and Paper Processes Selected for Bandwidth Analysis

Subsector	Process Areas
Pulp Manufacturing	Liquor Evaporation
	Pulping Chemical Preparation
	Wood Cooking
	Bleaching
Paper Manufacturing	Paper Drying
	Paper Machine Wet End

Paper drying and bleaching are self-explanatory. Paper machine wet end is the stock preparation ahead of the paper machine and includes refining, cleaning and screening, pumping of stocks, forming and pressing, etc. Liquor evaporation is the energy consumed as steam to concentrate the weak liquor solids generated during washing of chemical pulp to that required for firing in a recovery boiler. Pulping chemical preparation is the energy used in the pulp mill for chemical preparation, such as white liquor, and includes energy consumed in the lime kiln. Wood cooking is the energy consumed in the cooking of chemical pulps (sulfite, kraft, and neutral sulfite semi-chemical (NSSC)) and does not include the energy used for refining and grinding in the preparation of mechanicals pulps such as thermo-mechanical (TMP) or stone groundwood (SGW) pulp.

2.3. U.S. PULP AND PAPER MANUFACTURING ENERGY CONSUMPTION

Onsite energy and primary energy for the U.S. pulp and paper sector are provided in Table 2-3. EIA MECS provides onsite energy consumption data by end use, including onsite fuel and electricity consumption, as well as feedstock energy. Primary energy includes assumptions for offsite losses (DOE 2014).

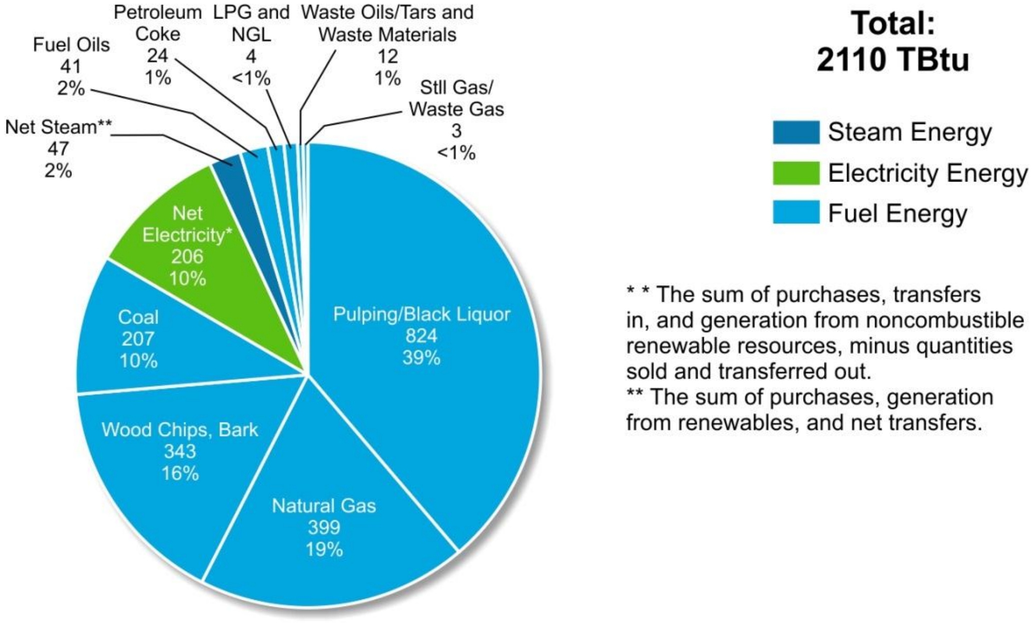
Table 2-3. U.S. Pulp and Paper Manufacturing Energy Consumption Sector-Wide, 2010

Onsite Energy Consumption (includes electricity, steam, and fuel energy used onsite at the facility)	2,559 TBtu
Primary Energy Consumption (includes onsite energy consumption, and offsite energy losses associated with generating electricity and steam offsite and delivering to the facility)	2,110 TBtu

Source: DOE 2014

Pulp and paper manufacturing is the 3rd largest consumer of energy in U.S. manufacturing (after chemical manufacturing and petroleum refining), accounting for 2,559 TBtu (13%) of the 19,237 TBtu of total primary manufacturing energy consumption in 2010 (DOE 2014). Offsite electricity and steam generation and transmission losses in pulp and paper manufacturing totaled 449 TBtu in 2010; onsite energy consumed within the boundaries of U.S. pulp and paper mills totaled 2,110 TBtu.

Figure 2-2 shows the total onsite energy *entering* U.S. pulp and paper mills; most of the energy entering is in the form of fuel. Nearly all (90%) of this fuel is used onsite in boilers and combined heat and power (CHP) to generate additional electricity and steam (DOE 2014). In contrast, Figure 2-3 shows the total onsite energy at the *point of end use*. Electricity and steam from both offsite and onsite generation are included in Figure 2-3 along with the portion of energy loss that occurs in onsite generation. The data provided in Table 2-3, Figure 2-2, and Figure 2-3 are based on MECS with adjustments to account for withheld and unreported data (DOE 2014).



* * The sum of purchases, transfers in, and generation from noncombustible renewable resources, minus quantities sold and transferred out.
** The sum of purchases, generation from renewables, and net transfers.

Figure 2-2. Onsite Energy Entering U.S. Pulp and Paper Mills, 2010 *(DOE 2014)*

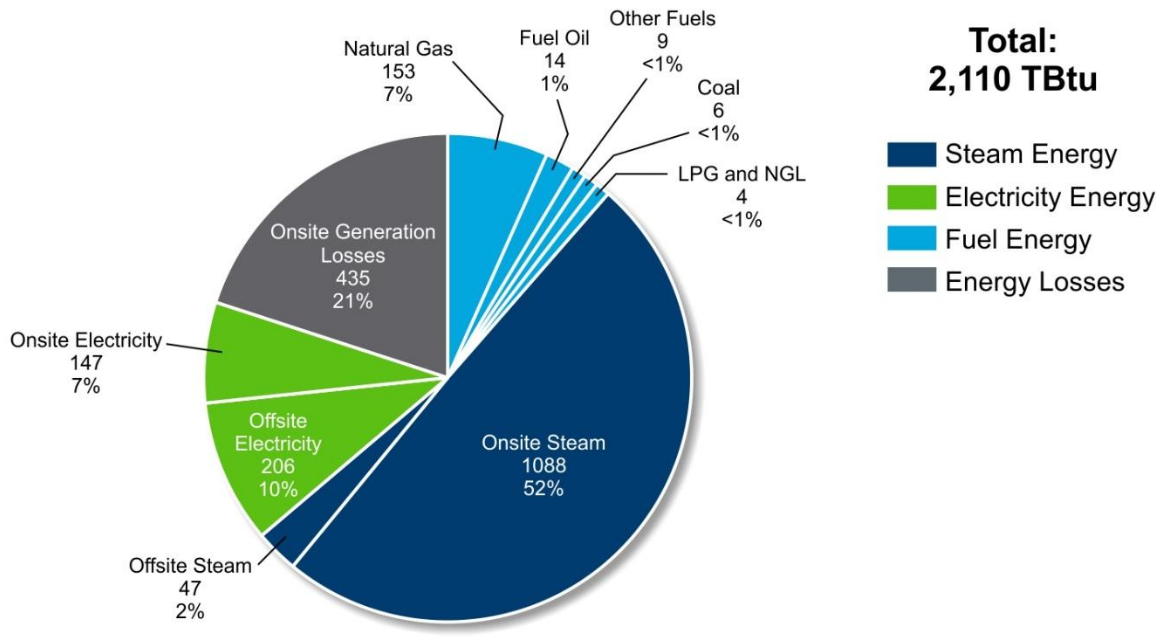


Figure 2-3. Onsite Energy Consumption at Point of End Use in
U.S. Pulp and Paper Mills, 2010 *(DOE 2014)*

2.3.1. Fuel and Feedstocks

As shown in Figure 2-2, onsite fuel consumption amounted to 1,857 TBtu in 2010, or about 77% of total onsite energy entering pulp and paper mills (EIA 2013). A significant majority of the purchased fuel that was provided by offsite sources includes natural gas and coal. Coal is used as a fuel in conventional boilers and CHP while natural gas is used in the lime kilns in pulp manufacturing and for process heating and machine drive.

Figure 2-4 provides a breakdown of fuel consumption in the pulp and paper sector by end use in 2010. The categories of end use are reported by EIA in MECS. A significant portion of fuel (90%) is used indirectly in boilers and CHP to generate additional onsite electricity and steam (DOE 2014). Fuel is directly used for other end uses—the majority of the remainder is used in process heating.

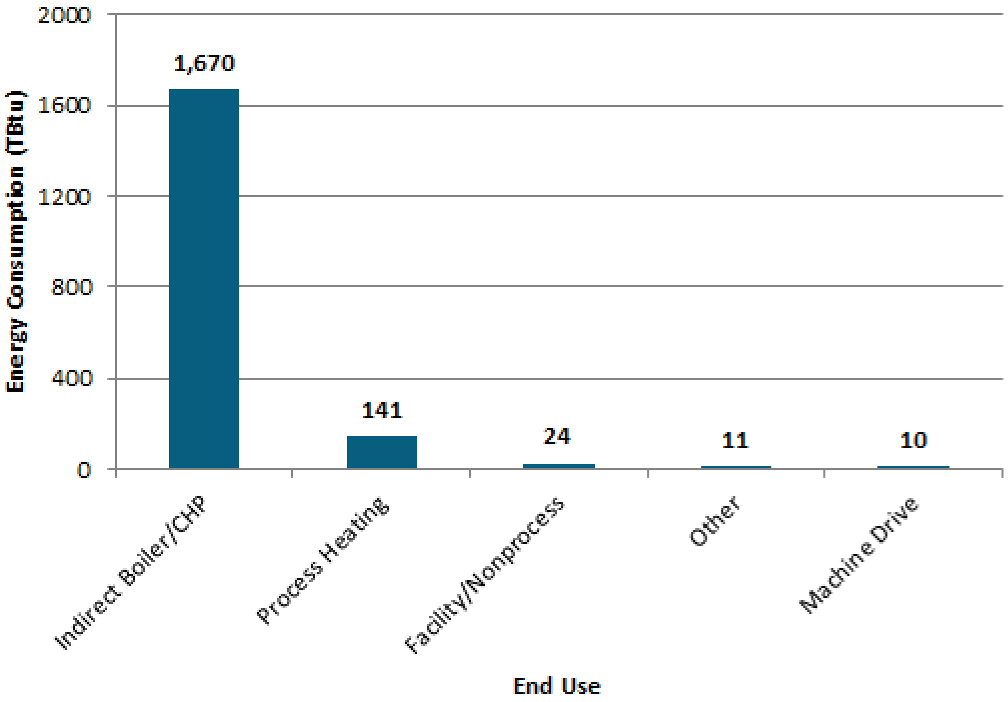


Figure 2-4. Fuel Consumption in the Pulp and Paper Sector by End Use, 2010 *(DOE 2014)*

Feedstock energy is the nonfuel use of combustible energy. For pulp and paper manufacturing, feedstock energy is relatively minor, accounting for only 3 TBtu of the total 6,104 TBtu of feedstock energy use for all manufacturing.

Feedstock energy is a significant portion of energy consumption in U.S. manufacturing, but is minor for pulp and paper manufacturing. **Feedstock energy is not included in the onsite energy data in the energy consumption bands in this study**. Feedstock energy is excluded in order to be consistent with previous bandwidth studies and because the relative amount of feedstock energy versus fuel energy used in manufacturing is not readily available for individual processes.

2.3.1.1. Pulping Liquor

Increasingly, coal, natural gas, and fuel oils are being displaced by pulping liquor, wood, and bark for energy use. In 2002, pulping liquors and wood/bark accounted for 48% of the total energy consumed, increasing to 55% in 2010. These fuels are significant contributors to CHP/cogeneration.

When current and R&D energy savings technologies are taken into consideration, it is expected that the decrease in energy demand will primarily allow the industry to continue to maximize the energy output from black liquor while reducing the use of other energy sources. Future economics may also allow some or all of the black liquor to be diverted to new processes such as isolating lignin for sell or to make lignin-based chemicals. The business plan of an individual facility will likely dictate the best use of this resource; however, a comprehensive economic analysis quantifying the likely application of these options is outside the scope of this study.

2.3.2. Electricity

Figure 2-2 shows that onsite net electricity entering pulp and paper mills totaled 206 TBtu in 2010. The data presented is the *net amount*, which is the sum of purchases and transfers from offsite sources as well as generation from non-combustion renewable resources (e.g., hydroelectric, geothermal, solar, or wind energy) less the amount of electricity that is sold or transferred out of the plant. Figure 2-3 shows that 353 TBtu of total electricity is consumed at the point of end use and includes 147 TBtu of electricity generated onsite.

In Figure 2-5, the breakdown of the 353 TBtu of electricity is shown by end use in 2010 (DOE 2014). There are numerous uses for electricity in pulp and paper manufacturing; the most common use is for machine driven equipment (i.e., motor-driven systems such as compressors, fans, pumps, and materials handling and processing equipment). Motors used for cooling water circulation pumps and fans, however, are accounted for in process cooling end use. Other end uses of electricity for pulp and paper manufacturing are less significant, but include nonprocess facility related end uses (e.g., facility heating, ventilation, and air conditioning (HVAC), facility lighting, cooking, office equipment, etc.) and other end uses.

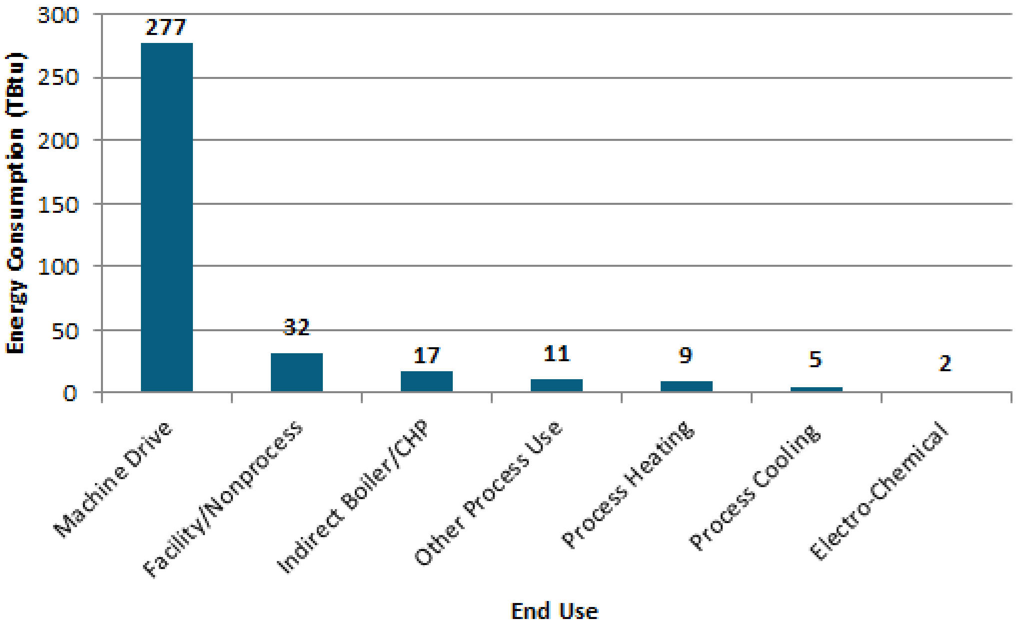


Figure 2-5. Electricity Consumption in the Pulp and Paper Sector by End Use, 2010 *(DOE 2014)*

2.3.3. Steam

Figure 2-2 shows 47 TBtu of net steam entering pulp and paper mills in 2010. The data presented is the *net amount*, which is the sum of purchases, generation from renewables, and net transfers. A larger amount of steam is generated onsite. , Figure 2-3 shows that 1,135 TBtu of steam is consumed at the point of end use, including 1,088 TBtu of steam generated onsite (227 TBtu of purchased and generated steam is lost through distribution to end uses) (DOE 2014).

Figure 2-6 shows the breakdown of 908 TBtu of steam by end use in 2010 (DOE 2014). A majority of the offsite- and onsite-generated steam is used for process heating; other end uses for steam in pulp and paper manufacturing include machine driven equipment (i.e., steam turbines), facility heating, ventilation, and air conditioning (HVAC), and other processes and nonprocesses. Unlike fuel and electricity end use, steam end use is not reported in MECS. The end use distribution shown here was determined in the Energy Footprint analysis (DOE 2014) based on input from an industry-led working group.

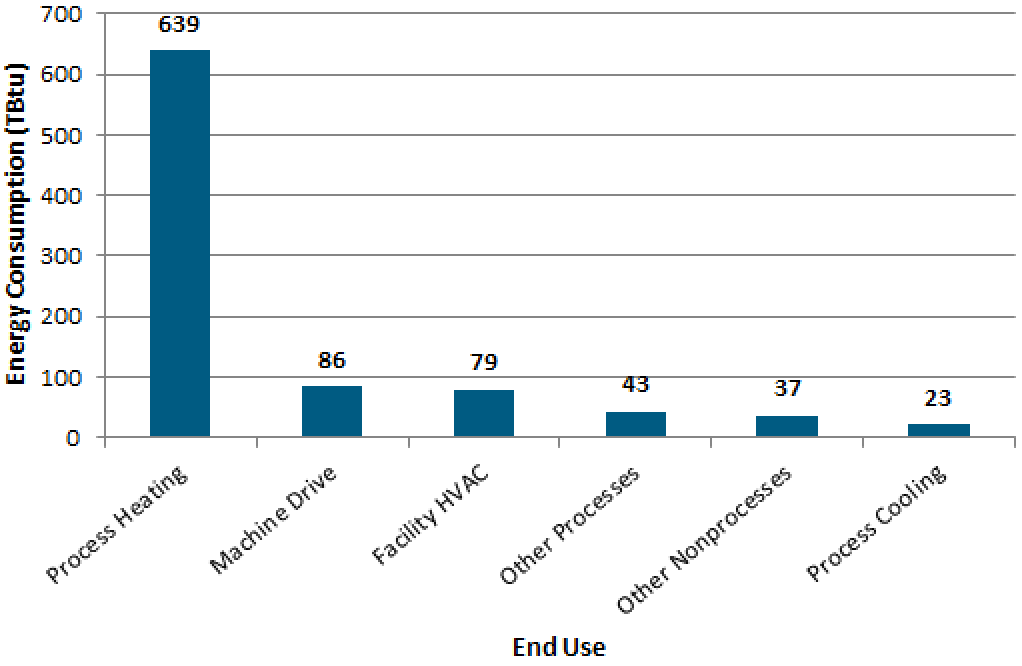


Figure 2-6. Steam Consumption in the Pulp and Paper Sector by End Use, 2010 *(DOE 2014)*

3. Production Volumes in U.S. Pulp and Paper Manufacturing

In this bandwidth study, six pulp and paper processes were selected for individual analysis. The most energy intensive processes were selected for this study. In general, the selection of processes was largely dependent on the availability of current production and energy consumption data.

The year 2010 was used for production values to correspond with the latest MECS data, which is also for 2010. Pulp and paper production data was gathered from the *2010 Statistical Summary: Paper, Paperboard, Pulp* prepared by the American Forest & Paper Association (AFPA 2011). AFPA production data provides production data by paper and paperboard grade and by type of pulp. Note that all tonnage units in this report are short tons (2,000 lb/ton) unless otherwise indicated.

As mentioned, this study is production weighted; the energy consumed is dependent upon the amount of pulp and paper produced by type (e.g., kraft pulp, thermo-mechanical pulp (TMP), printing & writing paper, linerboard, etc.).

3.1. PULP PRODUCTION

Figure 3-1 and Table 3-1 provide production data and relative percentages for the different types of pulp produced in the United States in 2010. As indicated in Table 3-1, kraft pulp (bleached and unbleached) accounts for 58% of total pulp production. For this study, 68% of the total pulp used is wood pulp and 32% is pulp from recovered paper. Production of bleached kraft softwood (SW) and bleached kraft hardwood (HW) was estimated based on their production capacity relative to the total production capacity for bleached kraft pulp (49.7% versus 50.3% respectively). Total bleached kraft production was 26.470 million tons in 2010.

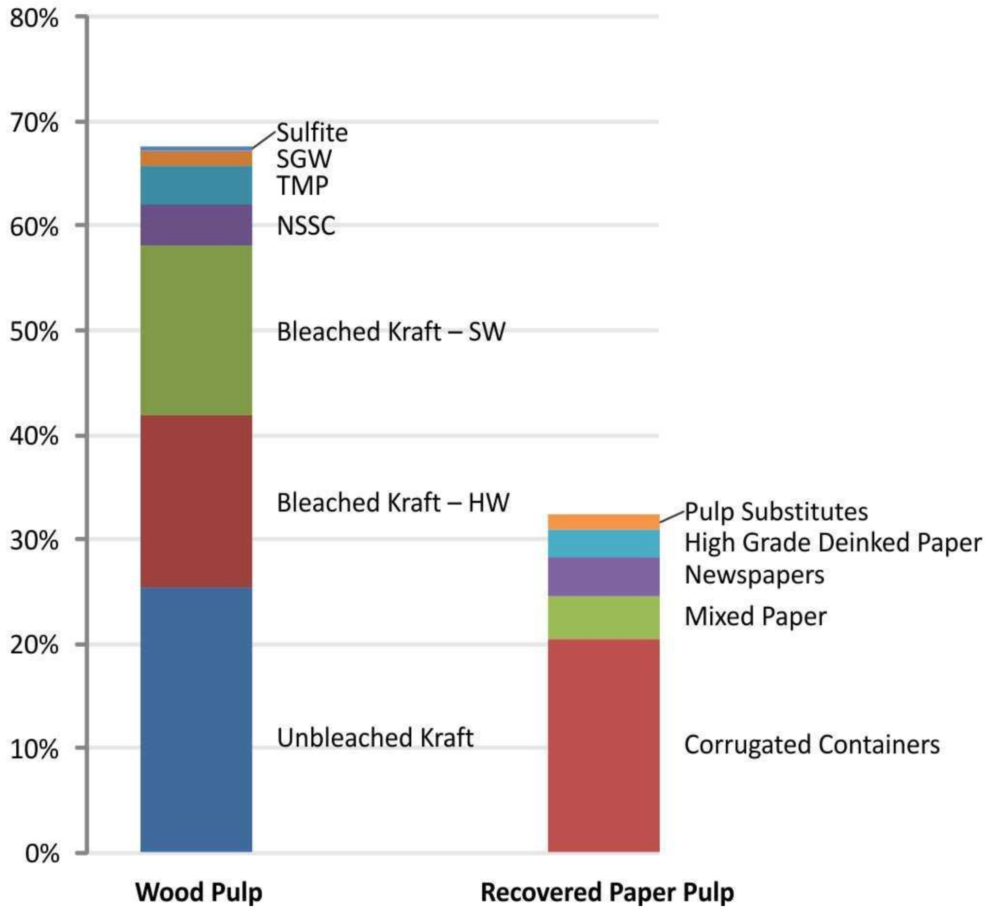


Figure 3-1. U.S. Pulp Production, 2010

Table 3-1. U.S. Pulp Production, 2010

Type		Production (1,000 tons)	% of Total
Wood Pulp	Sulfite	326	0.4%
	Bleached Kraft – softwood (SW)	13,156	16.3%
	Bleached Kraft – hardwood (HW)	13,314	16.6%
	Unbleached Kraft	20,338	25.3%
	Stone ground wood (SGW)	1,185	1.5%
	Thermo-mechanical pulp (TMP)	2,904	3.6%
	Neutral sulfite semi-chemical (NSSC)	3,121	3.9%
Recovered Paper Pulp	Mixed Paper	3,278	4.1%
	Newspapers	3,109	3.9%
	Corrugated Containers	16,428	20.4%
	High Grade Deinked Paper	2,031	2.5%
	Pulp Substitutes	1,260	1.6%
Total		**80,450**	**100.0%**

Source: AFPA 2011

3.2. PAPER AND PAPERBOARD PRODUCT PRODUCTION

Figure 3-2 shows the primary types of paper and paperboard produced in the U.S. in 2010 along with the cumulative percent of total production. Linerboard and corrugating material represent slightly more than 40% of total paper and paperboard production. Containerboard is a subset of paperboard; it encompasses both linerboard and corrugating material that are widely used in the manufacture of corrugated boxes. Table 3-2 provides the corresponding production information for paper and paperboard products for the U.S. in 2010, as well as market pulp.

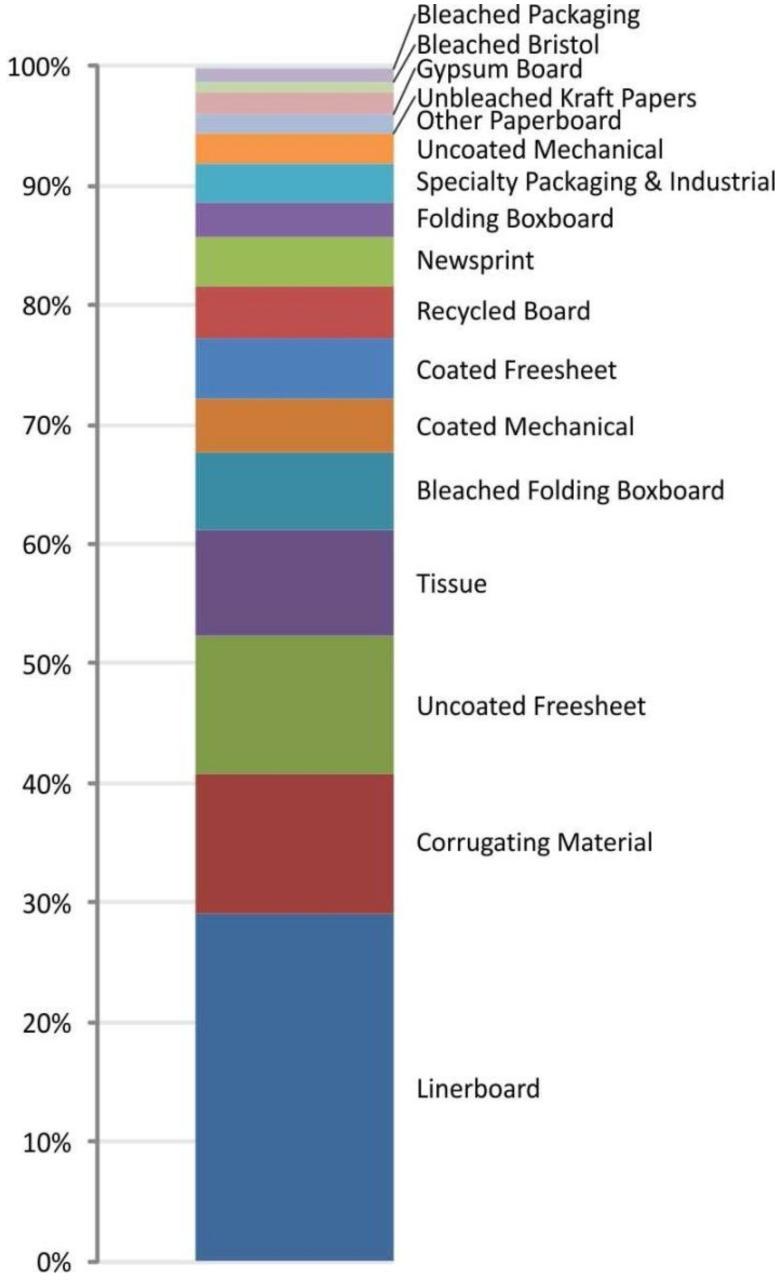


Figure 3-2. U.S. Paper and Paperboard Production, 2010

Table 3-2. 2010 Shipments of Paper, Paperboard, Market Pulp

Paper & Paperboard Product	**Production** (1,000 tons)	**% of Total**
Corrugating Material	9,786	10.7%
Linerboard	24,119	26.3%
Recycled Board	3,601	3.9%
Gypsum Board	865	0.9%
Folding Boxboard	2,421	2.6%
Bleached Folding Boxboard/ Milk & Food	5,378	5.9%
Other Paperboard	1,288	1.4%
Unbleached Kraft Papers	1,427	1.6%
Specialty Packaging & Industrial	2,683	2.9%
Newsprint	3,429	3.7%
Uncoated Mechanical	2,130	2.3%
Coated Mechanical	3,765	4.1%
Bleached Packaging	185	0.2%
Bleached Bristol	848	0.9%
Uncoated Freesheet	9,556	10.4%
Coated Freesheet	4,146	4.5%
Other Specialties (cotton fiber)	23	0.0%
Tissue	7,309	8.0%
Subtotal	**82,959**	**90.4%**
Market Pulp		
Kraft Pulp, bleached & semibleached	8,508	9.3%
Kraft Pulp, unbleached	N/A	N/A
Sulfite Pulp	N/A	N/A
Recycled Pulp	N/A	N/A
Other Pulp/Dissolving Pulp	261	0.3%
Subtotal	**8,769**	**9.6%**
Total	**91,728**	**100.0%**

Source: AFPA 2011

3.3. UTILIZING RECOVERED PAPER

The *2010 Statistical Summary: Paper, Paperboard, Pulp* (AFPA 2011) includes information on the various types of recovered paper. However, the total includes not only recovered paper used for construction grade paper and paperboard manufacture, but also the recovered paper consumed for molded pulp products. Therefore, a percentage of each type of recovered paper was used and included in the total pulp production in Table 3-1. The percentage of each type of recovered paper used is listed in 3, and is the same as that used in the previous bandwidth study (DOE 2006a).

Table 3-3. Recovered Paper in the U.S. in 2010

Type	Amount Used (1,000 tons)	Percent Used of Total Available in 2010
Mixed Paper	3,278	75%
Newspapers	3,109	80%
Corrugated Containers	16,428	85%
High Grade Deinked Paper	2,031	75%
Pulp Substitutes	1,260	100%
Total	**26,106**	**82.7%**

Source: AFPA 2011

4. Current Typical Energy Consumption for U.S. Pulp and Paper Manufacturing

This Chapter presents the energy consumption data for individual pulp and paper manufacturing processes and sector-wide in 2010. Energy consumption in a manufacturing process can vary for diverse reasons. The energy intensity estimates reported herein are representative of average U.S. pulp and paper manufacturing; they do not represent energy consumption in any specific facility or any particular region in the United States.

4.1. BOUNDARIES OF THE PULP AND PAPER BANDWIDTH STUDY

Estimating energy requirements for an industrial process depends on the boundary assumptions; this is especially true in the pulp and paper industry. The key focus of this bandwidth study is energy consumption within the plant boundary, which is the *onsite* use of process energy (including purchased energy and onsite generated steam and electricity) that is directly applied to pulp and paper manufacturing.

This study does not consider lifecycle energy consumed during raw material extraction, off-site treatment, and transportation of materials. Upstream energy, such as the energy required for processing and handling materials outside of the plant is also not included. To be consistent with previous bandwidth studies, feedstock energy and the energy associated with delivering feedstocks to the plant gate (e.g., producing, conditioning, and transporting feedstocks) are *excluded* from the energy consumption bands in this analysis.

4.2. ESTIMATED ENERGY INTENSITY FOR INDIVIDUAL PROCESSES

Energy intensity data are needed to calculate bands of energy consumption in this study. This Section presents the estimated energy intensities of the six processes studied.

The specific energy needed to make one ton of product can vary significantly between processes, and also between facilities. Energy intensity is a common measure of energy performance in manufacturing. Energy intensity is reported in units of energy consumption (typically Btu) per unit of manufactured product (typically short tons, tons, or metric tons) and, therefore, reported as million Btu per short ton (MMBtu/ton). Energy intensity estimates are available for specific equipment performance, process unit performance, or even plant-wide performance. Energy intensity can be estimated by process, both in the United States and other global regions, based on average, representative process and plant performance.

Appendix A1 presents the CT energy intensities and energy consumption for the six processes studied. Table 4-1 presents a summary of the references consulted to identify CT energy intensity by process. Appendix A2 provides the references used for each process. Appendix A3 provides detailed CT energy intensity by pulp or paper type.

Current typical energy intensities for pulp and papermaking processes in the U.S. were derived from the *Pulp and Paper Industry Energy Bandwidth Study* published in 2006 (DOE 2006a). Energy intensity values are available for electricity, steam, and direct fuel where applicable. The authors of DOE 2006a used a wide variety of sources to determine the most representative values for the industry, including benchmarking studies, and are the best available data for the current study.

Each pulp and paper facility is unique and pulp and paper produced in different scales and by different processes; thus, it is difficult to ascertain an exact amount of energy necessary to produce a certain volume of a product. Plant size can also impact operating practices and energy efficiency. Higher efficiency is often easier to achieve in larger plants. Consequently, the values for energy intensity provided should be regarded as estimates based on the best available information.

Table 4-1. Published Sources Reviewed to Identify Current Typical Energy Intensities for Processes Studied

Source	Description
DOE 2006a	The *Pulp and Paper Industry Energy Bandwidth Study* provides a detailed energy breakdown for the pulp and paper processes for both the large energy consuming processes as well as the less energy intensive ones. The authors reviewed the electricity, steam and direct fuel values for benchmark data as well as reported average values. This information was used to assign electricity, steam, and direct fuel values across the pulp and paper making processes for the various pulp and paper types.
EIA 2013	Manufacturing Energy Consumption Survey Data for 2010. This data comes from a survey that is taken by U.S. manufacturers. The data is scaled up to cover the entirety of U.S. manufacturing and for individual manufacturing subsectors. For the pulp and paper industry, it provides energy consumption data for the entire sector.

Compared to other industries, energy intensity in pulp and paper manufacturing is very sensitive to product mix. No two paper mills are identical and as a result an attempt to compare energy use even across similar mills requires strict adherence to system boundaries. When such an analysis is extended across countries, discrepancies in system boundaries may distort outcomes (IEA 2007).

Paper is produced from raw pulp or from recycled paper. Pulp production, especially virgin wood pulp, is energy-intensive. The pulp used in a given country may be produced in the country itself or be imported from other countries. If it is imported, this means that the energy consumption for pulp production has taken place in the exporting countries. Therefore, the energy performance of the paper industry of a given country is linked to the share of the wood pulp produced in the country in relation to the paper production (ADEME 2012).

Table 4-2 illustrates the relationship between energy consumption per ton of paper and the pulp to paper production ratio for different countries. As indicated in Table 4-2, France and Germany produce much more paper than pulp and therefore have a lower energy intensity ratio relative to the other countries listed. The United States, Canada, Brazil, Norway, Sweden, and Finland are the top wood pulp producers in the world (FOASTAT 2012). The United States and Canada are among the countries with the most energy intensive pulp and paper industries. The average technical age of their pulp and paper mills is perhaps the oldest. Both are rich in wood resources and are major virgin wood pulp producers with the United States the largest chemical pulp producer and Canada the largest mechanical pulp producer (IEA 2009). Both of these factors contribute to their higher specific energy consumptions relative to the other countries listed in Table 4-2. The energy consumption values as a function of the pulp to paper production ratio is also shown in Figure 4-1.

Table 4-2. Global Average Specific Energy Consumption Data for Pulp and Paper

Country	Wood Pulp (1,000 tons)	Paper & Paperboard (1,000 tons)	Final Total Energy (MMBtu)	Ratio of Pulp to Paper	Energy Intensity (MMBtu/ton paper)
Brazil	15,484	10,781	399×10^6	1.44	37.0
Canada	10,141	13,964	518×10^6	0.73	37.1
Finland	12,963	15,491	307×10^6	0.84	19.8
France	2,579	10,384	144×10^6	0.25	13.8
Germany	3,200	25,186	240×10^6	0.13	9.5
Norway	2,314	2,094	36×10^6	1.10	17.2
Sweden	13,306	12,871	265×10^6	1.03	20.6
U.S.	54,344	82,959	$2,110 \times 10^6$	0.66	25.4

Data Sources:

***Finland, France, Germany, Norway, Sweden**: ADEME 2012; CEPI 2010; CEPI 2011*

***Brazil**: Facaro et al. 2012; BRACELPA 2011*

***Canada**: CIEEDAC 2012*

***U.S.**: This study; AFPA 2011; EIA 2013*

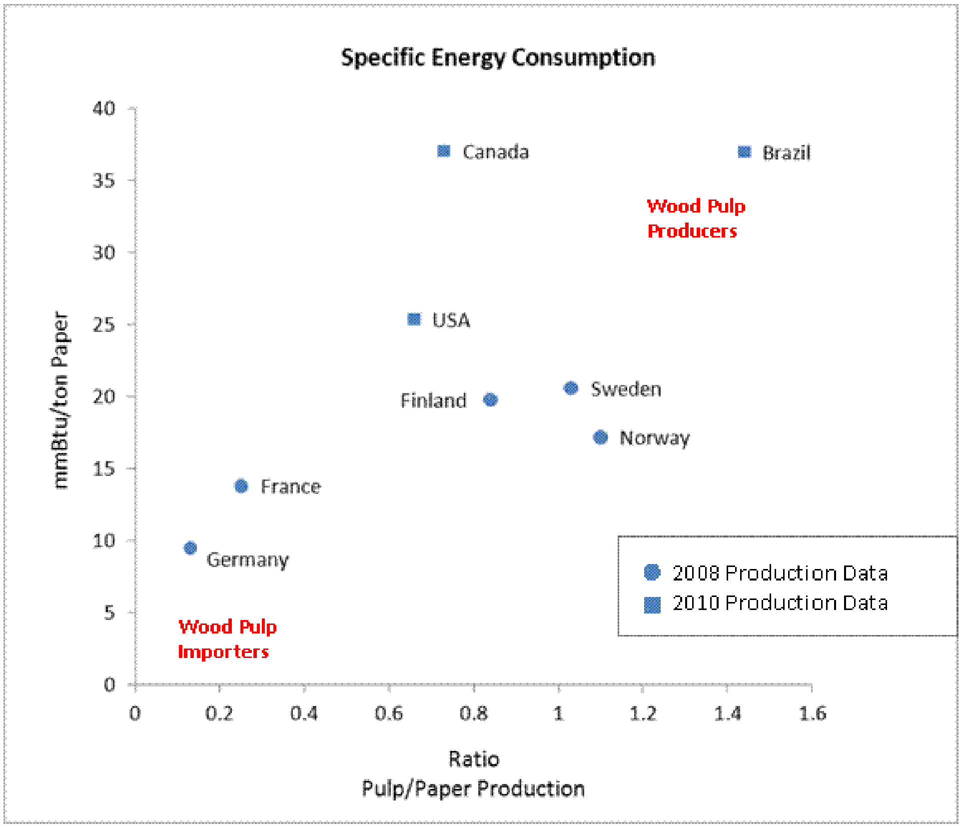


Figure 4-1. Selected Global-Specific Energy Consumption Values as a Function of the Pulp to Paper Production Ratio

Finland, Sweden, and Norway are large producers of pulp and paper, with about equal share between pulp and paper. The greater energy efficiency of the Nordic countries is, to some degree, attributable to a lower average technical age compared with Canada and the United States and perhaps a higher degree of integrated plants (IEA 2009).

Brazil has one of the highest production ratios but an intensity value that is similar to Canada. Approximately 80% of the pulp mills in Brazil are less than 14 years of age (IEA 2009). The higher percentage of more modern mills is a large contributor to the greater energy efficiency in this country.

4.3. CALCULATED CURRENT TYPICAL ENERGY CONSUMPTION FOR INDIVIDUAL PROCESSES

Table 4-3 presents the calculated average onsite CT energy consumption for the six processes studied. As previously mentioned, energy intensity in the pulp and paper industry is very product specific; Appendix A3 shows CT energy intensity by pulp or paper product type for the six processes. To calculate onsite CT energy consumption, energy intensity for each process (presented initially in Appendix A1) is multiplied by the 2010 production data (presented initially in Table 3-2 and also in Appendix A1). Feedstock energy is excluded from the consumption values. The CT energy consumption for these six processes is estimated to account for 1,103 TBtu of onsite energy, or 52% of the 2,110 TBtu of sector-wide onsite energy use in 2010. Appendix A1 and A3 also present the onsite CT energy consumption for the six processes individually.

Calculated primary CT energy consumption by process is also reported in Table 4-3. Primary energy includes offsite energy generation and transmission losses associated with electricity and steam from offsite sources. To determine primary energy, the net electricity and net steam portions of sector-wide onsite energy are scaled to account for offsite losses and added to onsite energy (see the footnote in Table 4-3 for details on the scaling method).

Table 4-3. Calculated U.S. Onsite Current Typical Energy Consumption for Processes Studied in 2010 with Calculated Primary Energy Consumption and Offsite Losses

Process	**Average CT Energy Intensity*** (MMBtu/ton)	**Production** (1,000 ton/year)	**Onsite CT Energy Consumption, Calculated** (TBtu/year)	**Offsite Losses, Calculated**** (TBtu/year)	**Primary CT Energy Consumption, Calculated** (TBtu/year)
Pulp Mills					
Liquor Evaporation	3.55	50,255	178	13	191
Pulping Chemical Prep	2.07	50,255	104	11	115
Wood Cooking	2.56	50,255	129	26	155
Bleaching	1.32	54,344	72	18	90
Paper Mills					
Paper Drying	4.68	91,728	430	59	488
Paper Machine Wet End	2.07	91,728	190	112	302
Total for Processes Studied			**1,103**	**239**	**1,341**

Current typical (CT)

** Shows the weighted average CT energy intensity. CT energy intensity by product type can be found in Appendix A3.*

*** Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and offsite steam transmission losses are estimated to be 10% (DOE 2007, Technical Guidelines Voluntary Reporting of Greenhouse Gases and EPA 2011, ENERGY STAR Performance Ratings Methodology).*

References for production data and energy intensity data are provided by process in Appendix A2. The other values are calculated as explained in the text.

4.4. CURRENT TYPICAL ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

In this Section, the CT energy consumption estimates for nine processes studied are provided.

Table 4-4 presents the onsite CT energy consumption by process and sector-wide for U.S. pulp and paper manufacturing. The six processes studied account for 52% of all onsite energy consumption by the U.S. pulp and paper sector in 2010. As shown in the last column of Table 4-4, the percentage of coverage of the processes studied is calculated. This indicates how well the processes studied represent total sector-wide MECS-reported energy.

Table 4-4 also presents CT primary energy consumption by process. Primary energy is calculated from onsite CT energy consumption databased on an analysis of MECS data (DOE 2014), with scaling to include offsite electricity and steam generation and transmission losses (DOE 2014).

Table 4-4. Onsite and Primary Current Typical Energy Consumption for the Six Processes Studied and Sector-Wide in 2010, with Percent of Sector Coverage

Process	Onsite CT Energy Consumption, calculated (TBtu/year)	Primary CT Energy Consumption, calculated* (TBtu/year)	Percent Coverage (Onsite CT as a % of Sector-wide Total)**
Pulp Mills			
Liquor Evaporation	178	191	8%
Pulping Chemical Prep	104	115	5%
Wood Cooking	129	155	6%
Bleaching	72	90	3%
Paper Mills			
Paper Drying	430	488	20%
Paper Machine Wet End	190	302	9%
Total for Processes Studied	**1,103**	**1,341**	**52%**
All Other Processes Including Env. & Utilities	304	515	14%
Powerhouse Losses	703	703	33%
Total for Pulp and Paper Sector-wide	**2,110*******	**2,559*******	**100%**

Current Typical (CT)

** Accounts for offsite electricity and steam generation and transmission losses. Offsite electrical losses are based on published grid efficiency. EIA Monthly Energy Review, Table 2.4, lists electrical system losses relative to electrical retail sales. The energy value of electricity from offsite sources including generation and transmission losses is determined to be 10,553 Btu/kWh. Offsite steam generation losses are estimated to be 20% (Swagelok Energy Advisors, Inc. 2011. Steam Systems Best Practices) and offsite steam transmission losses are estimated to be 10% (DOE 2007, Technical Guidelines Voluntary Reporting of Greenhouse Gases and EPA 2011, ENERGY STAR Performance Ratings Methodology).*

*** Calculated by dividing the onsite CT energy consumption for the processes studied by sector-wide onsite CT energy consumption (2,110 TBtu).*

*** Source for sector-wide values is DOE 2014.

As in the original study (DOE 2006a), the energy available for pulp and paper manufacturing processes is the energy remaining after an estimate of powerhouse energy use. The powerhouse is the area of the pulp or paper mill where electricity and steam is generated onsite. As noted in DOE 2006a, when referring to powerhouse energy consumption, this is actually "the energy that is lost within the powerhouse due to boiler efficiency, soot blowing, steam venting, turbine and transformer efficiency, etc. and is not the energy that exits the powerhouse and is used in the manufacturing process" (p. 5).

The powerhouse calculations estimate the generation of electric power and steam that is available for pulp and paper processes. It also estimates the amount of energy from fuels that are used directly in processes, such as natural gas used in yankee dryer machines or fuel used directly in the lime kiln. This fuel is categorized as "direct fuel" throughout this study. Note that the powerhouse is a simplified approach to allocate generation losses associated with different fuels in order to approximate process demand sector-wide. The powerhouse at an individual mill may be very different than the one presented in this study.

This study has also adjusted the powerhouse calculations from DOE 2006a by including a correction for a penalty that occurs when a reduction in process steam demand, from the CT energy consumption case through the PM and TM energy consumption cases, results in more condensing turbine generated electricity. This is represented by the electricity to net process steam ratio (E/NPS), or the ratio of steam energy that goes to electricity versus net process steam, and the different losses associated with cogenerated electricity generation (5%) versus condensing generation losses (60%). Again, not all mills have cogeneration facilities, therefore, this adjustment should be considered a useful simplification of the industry overall that will affect total energy consumption (refer to Anderson et al. 1991 for a detailed discussion).

Fuel consumption in the powerhouse is calculated first based on boiler efficiencies and energy estimates for auxiliary systems (fans, pumps, turbine losses, transformer losses, environmental systems, etc.) and other losses such as leaks and venting (see Table A2-2 in Appendix A2). Estimates for boiler efficiencies are based on boiler efficiency estimates recently cited for the pulp and paper industry (Wamsley 2012a; Schindler 2012; Gustafson 2009; Murray 2006) and on boiler capacities typically used in the pulp and paper industry (RDC 2002; ORNL 2005). Detailed tables on powerhouse energy consumption can be found in Appendix A2.

To determine the distribution of energy consumed in pulp and papermaking the energy intensity values from DOE 2006a were used as a starting point. A wide range of published data was reviewed in determining these intensity values. These numbers were adjusted for this study so that total energy consumption matched the energy available for manufacturing processes after the powerhouse. Appendix A2 also provides the estimate of pulp distribution across the different paper and paperboard grades that were used for this study and a summary of the energy intensity, production, and calculated onsite energy by product type.

5. State of the Art Energy Consumption for U.S. Pulp and Paper Manufacturing

As plants age, manufacturing processes and equipment are updated and replaced by newer, more energy-efficient technologies. This results in a range of energy intensities among U.S. pulp and paper manufacturing facilities. These facilities will vary widely in size, age, efficiency, energy consumption, and types and amounts of products. Modern pulp and paper mills can benefit from more energy-efficient technologies and practices.

This Chapter estimates the energy savings possible if U.S. pulp and paper mills adopt the best technologies and practices available worldwide. State of the art (SOA) energy consumption is the minimum amount of energy that could be used in a specific process using existing technologies and practices. However, it is important to consider that it is unrealistic to assume that long-existing facilities can be easily upgraded to new, state-of-the-art facilities (NAS 2010) or that there are no other barriers to adapting new technologies (Fleiter et al. 2012).

5.1. CALCULATED STATE OF THE ART ENERGY CONSUMPTION FOR INDIVIDUAL PROCESSES

Appendix A1 presents the onsite SOA average energy intensity and consumption for the six processes considered in this bandwidth study. The SOA energy consumption for each pulp and paper manufacturing process is calculated by multiplying the SOA energy intensity for each process by the relevant production (all relevant data are presented in Appendix A1).

The onsite SOA energy consumption values are the net energy consumed in the process using the single most efficient process and production pathway. No weighting is given to processes that minimize waste, feedstock streams, and byproducts, or maximize yield, even though these types of process improvements can help minimize the energy used to produce a pound of product. The onsite SOA energy consumption estimates exclude feedstock energy.

The SOA energy intensity values were estimated using published data for either modern and/or model mills. For this study, information published since 2006 was reviewed. Most of these studies listed the SOA energy intensity values as best available technology (or BAT) for select processes in pulp and paper production in terms of heat and electricity consumption. Table 5-1 presents the published sources referenced to identify the SOA energy intensities. Appendix A3 also shows the SOA energy intensities for the six processes based on product type.

Table 5-1. Published Sources Referenced to Identify State of the Art Energy Intensities for Six Select Processes

Source Abbreviation	Description
AF-Eng 2011	**Energy Consumption in the pulp and paper industry – Model mills 2010: Integrated fine paper mill** Updates were made to hypothetical reference mills developed in 2005 to reflect technical changes affecting energy consumption and production.
IEA 2009	**Energy Technology Transitions for Industry: Strategies for the Next Industrial Revolution** • Best available technology (BAT) values (heat and electricity) are listed for six types of pulp and seven paper grades. A comparison is also made between total energy consumption based on BAT versus total energy consumption reported for selected OECD countries and Brazil. *Data Sources used in this report: IPPC (2001); Finnish Forestry Industries Federation (2002); Jochem et al. (2004)*
IPPC 2010	**2010 European Commission Draft Reference Document on Best Available Techniques in the Pulp and Paper Industry** Best available techniques of a wide range of manufacturing processes are listed with specific emphasis on reducing environmental impact and energy consumption.
LBNL 2008	**World Best Practices Energy Intensity Values for Selected Industrial Sectors** • World best practice energy intensity values, representing the most energy-efficient processes that are in commercial use in at least one location worldwide, are provided for selected pulp and paper processes in both integrated and non-integrated mills. *Data Sources used in this report: IPPC (2001); Karlsson (2005); Francis et al. (2002)*
NRC 2008	**Benchmarking Energy Use in Canadian Pulp and Paper Mills** • This benchmarking study conducted by the Pulp and Paper Research Institute of Canada compares the energy performance of 49 Canadian pulp and paper mills. *Data Source: Data from 49 mills collected for four consecutive quarters*
TAPPI 2011a	**Paper Machine Energy Conservation** Good performance values are given for tissue machine drying steam and gas usage.
TAPPI 2011b	**Paper Machine Performance Guidelines** Performance ranges are given for effective paper machine performance.
Wamsley, 2012b	**Optimize Your Tissue Machine Steam System** Good performance values are given for relative energy consumption values for gas, steam, and electricity for several tissue products.

Several types of sources were used to determine SOA values. Some BAT values were available for a select number of pulp types and paper grades and are based on the best technologies currently available somewhere in the world. Benchmarking studies were also a useful source of information. In this instance, a range of values was typically given, and the values representing minimum energy consumptions were assumed to represent the state of the art. In cases where no new state of the art information was found for a particular pulp or paper process, values from the previous bandwidth study (DOE 2006a) were used for this study.

Steam systems are by far the most significant end use of energy in the U.S. pulp and paper industry. Over 80% of the energy consumed by the industry is in the form of boiler fuel. Energy efficiency improvements to steam systems therefore represent the most significant opportunities for energy savings in pulp and paper mills (LBNL 2009; EPA 2010). Table 5-2 contains some projected energy savings from state of the art, energy efficient technologies. Technologies identified that are in a pre-commercial stage of development or that are extremely expensive were not considered in the SOA analysis (instead they were considered in Chapter 6 on the practical minimum (PM) energy consumption).

Table 5-2. Energy Savings Estimates for Select State of the Art and Energy Efficient Technologies

Process Area and/or Product Type	Fuel Savings (MMBtu/ton)	Electricity Savings (MMBtu/ton)
Pulping: mechanical pulp		
Refiner improvements		0.70
Pulping: TMP		
Heat recovery in TMP	5.2	-0.46
Pulping: chemical pulp		
Continuous digester	5.42	-0.23
Continuous digester modifications	0.84	-
Batch digester modification	2.75	-
Chemical Recovery		
Falling film black liquor evaporation	0.69	-
Lime kiln modification	0.40	-
Papermaking		
Extended nip press (shoe press)	1.38	-
Reduced air requirements	0.65	0.02
Waste heat recovery	0.43	-
General Measures		
Efficient motor systems	-	0.53
Pinch analysis	1.54	-
Efficient steam production and distribution		
Boiler maintenance	1.08	-
Improved process control	0.46	-
Flue gas heat recovery	0.22	-
Blowdown steam recovery	0.20	-
Steam trap maintenance	1.54	-
Automatic steam trap monitoring	0.77	-

Source: Adapted from IEA 2009

Sources providing estimates of general savings for SOA in the pulp and paper industry were also reviewed. There were 135 plant assessments conducted in the pulp and paper industry between 2006 and 2011 as part of the DOE Save Energy Now program (DOE 2011d). The average recommended source energy savings per plant was 5% with the most frequently identified opportunities in steam systems. Targeted steam system improvements included changing process steam requirements by reducing the steam demand; changing boiler efficiencies; and improving insulation. While some of these changes may not require large capital investments, the energy savings are comparatively small compared to potential savings opportunities. Note that boiler efficiency improvements are captured in the powerhouse calculations.

Paper machine energy scorecards were developed in 2008 to help benchmark paper machine energy performance and identify opportunities for reducing energy consumption in papermaking processes (Reese 2008; Reese 2008b). Scorecards were developed because "average" paper machines consume 20% more energy than top performing paper machines (Reese 2012). The scorecards contain separate worksheets for grade specific information, energy monitoring, dryer section, press section and a number of auxiliary systems to help improve paper machine performance. According to Reese (2012), 10% to 25% of the typical energy savings opportunities can be implemented with no capital expenditures and most likely have contributed to savings over CT energy consumption.

5.2. STATE OF THE ART ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

Table 5-3 presents the onsite SOA energy consumption for the six U.S. pulp and paper processes studied. Table 5-3 also presents the onsite SOA energy savings, or the *current opportunity*. The SOA energy savings is also expressed as a percent in Table 5-3. This is also shown in Figure 5-1. It is useful to consider both TBtu energy savings and energy savings percent when comparing the energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same. In Figure 5-1, the percent savings is the percent of the overall energy consumption bandwidth, with CT energy consumption as the upper benchmark and TM as the lower baseline. In Figure 5-2, the *current* energy savings opportunity is shown in terms of TBtu/year savings for each process. The pie chart in Figure 5-2 captures the blue portions of the bar chart shown in Figure 5-1. Among the processes studied, the greatest *current opportunity* in terms of percent energy savings is wood cooking at 75% energy savings; the greatest *current opportunity* in terms of TBtu savings is paper drying at 111 TBtu per year savings.

The remainder of the pulp and paper sector (i.e., all processes that are not included in the six processes studied) is referred to as All Other Processes Including Environmental and Utilities in Table 5-3).

Table 5-3 also presents the SOA energy savings percent. To calculate the onsite SOA energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with SOA technologies and practices compared to CT energy consumption, considering that the TM may not be zero. When comparing energy savings percent from one process to another, the absolute savings is the best measure of comparison. The equation for calculating onsite SOA energy savings percent is:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

Table 5-3. Onsite State of the Art Energy Consumption, Energy Savings, and Energy Savings Percent for the Processes Studied and Sector-Wide

Process	Onsite CT Energy Consumption (TBtu/year)	Onsite SOA Energy Consumption (TBtu/year)	SOA Energy Savings† (CT-SOA) (TBtu/year)	SOA Energy Savings Percent (CT-SOA)/(CT-TM)*
Pulp Mills				
Liquor Evaporation	178	153	25	35%
Pulping Chemical Prep	104	81	23	38%
Wood Cooking	129	103	25	75%
Bleaching	72	49	22	54%
Paper Mills				
Paper Drying	430	319	111	37%
Paper Machine Wet End	190	123	67	65%
Total for Processes Studied	**1,103**	**829**	**273**	**45%**
All Other Processes Including Env. & Utilities**	304	264	40	75%
Powerhouse Losses***	703	552	151	N/A
Total for Pulp and Paper Sector-wide	**2,110**	**1,645**	**465**	**61%**

Current typical (CT), State of the art (SOA)

† SOA energy savings is also called Current Opportunity.

** SOA energy savings percent is the SOA energy savings opportunity from transforming pulp and paper manufacturing processes. Energy savings percent is calculated using TM energy consumption shown in Table 7-2 as the minimum energy consumption. The energy savings percent, with TM as the minimum, is calculated as follows: (CT- SOA)/(CT- TM)*

*** Includes utilities outside of the powerhouse and additional processes such as wastewater treatment.*

**** See Appendix A2 for detailed summary table on powerhouse.*

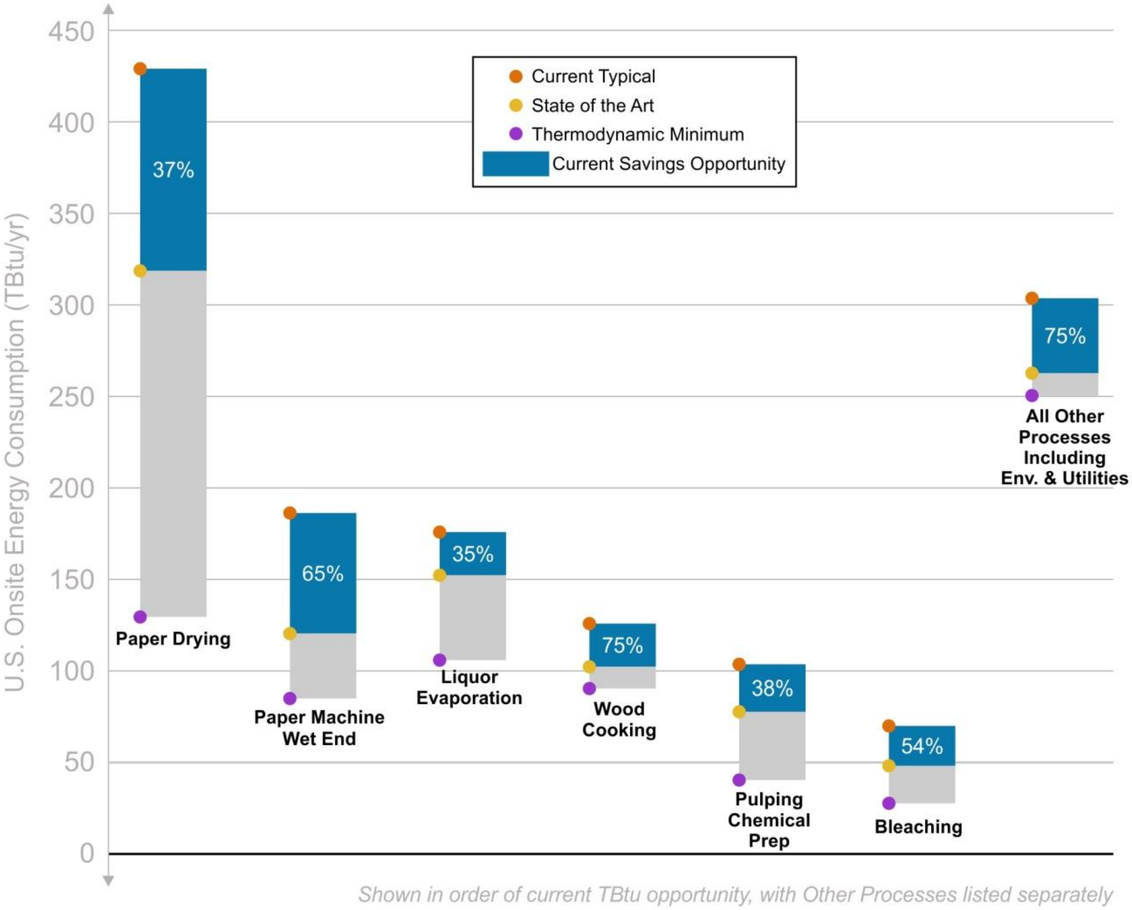


Figure 5-1. Current Opportunity Energy Savings Bandwidths for Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

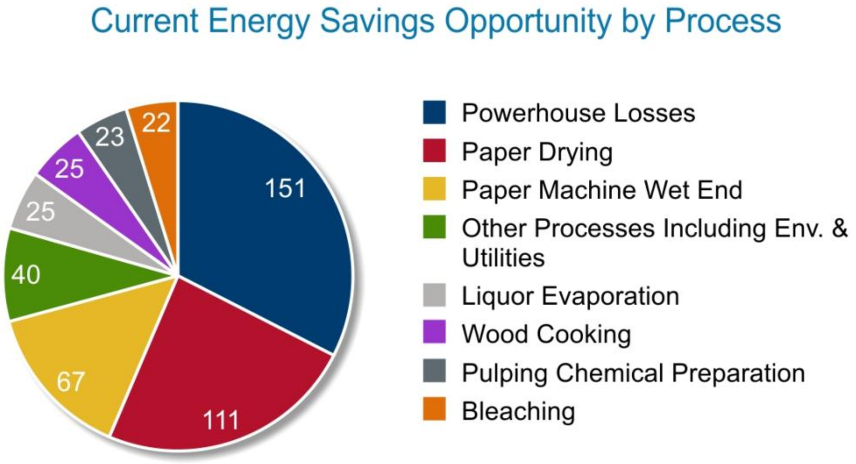


Figure 5-2. Current Energy Savings Opportunity by Process

The state of the art energy consumption is calculated by multiplying the pulp and paper electrical, steam, and direct fuel energy intensity data by the production data to estimate total fuel used as well as energy distribution by fuel type. This information is then used to back calculate through the powerhouse (see Table A2-3 in Appendix A2). The boiler efficiencies used in the powerhouse are the best rather than the average and the E/NPS ratio was increased to 20% for SOA energy consumption (Fleischman 2013). Since the quantity of pulp produced is constant (2010 values), the amount of energy available from waste pulping liquor and wood/bark is maintained, causing the energy available from other sources to change in order to produce the amount of process energy required.

6. Practical Minimum Energy Consumption for U.S. Pulp and Paper Manufacturing

Technology innovation is the driving force for economic growth. Across the globe, R&D is underway that can be used to make pulp and paper products in new ways and improve energy and feedstock efficiency. Commercialization of these improvements will drive the competitiveness of U.S. pulp and paper manufacturing. In this Chapter, the R&D energy savings made possible through R&D advancements in pulp and paper manufacturing are estimated. Practical minimum (PM) is the minimum amount of energy required assuming the deployment of applied R&D technologies under development worldwide.

6.1. R&D IN THE PULP AND PAPER INDUSTRY

Investing in R&D in the short term ensures long term future prosperity. Increasing the energy efficiency of an existing process often requires capital investment and taking manufacturing equipment offline to perform the necessary updates. The risks and rewards of this type of business decision needs to be clearly assessed.

Most pulp and paper manufacturing plants in the U.S. are approaching the end of their operating life. They will need to be replaced or significantly overhauled in the next 5-15 years (IEA 2007; IEA 2009). During this time period, the industry will be presented with a window of opportunity to apply emerging technologies and practices that can have a significant impact on energy savings for the future.

The U.S. Forest Products Industry, of which the pulp and paper industry makes up more than 80% based on total energy consumption, developed a technology roadmap in 2006, and subsequently updated in 2010, to identify critical R&D needs and research pathways to develop new technology solutions (Brown 2010; Brown 2012). Reducing carbon emissions and energy consumption is identified as one of the six top-priority areas for collaborative research among industry, federal agencies, and universities. This roadmap has aided in identifying key energy-intensive processes to focus R&D efforts.

6.2. CALCULATED PRACTICAL MINIMUM ENERGY CONSUMPTION FOR INDIVIDUAL PROCESSES

In this study, PM energy intensity is the estimated minimum amount of energy consumed in a specific pulp or paper process assuming that the most advanced technologies under research or development around the globe are deployed.

For this study, two methodologies are used to estimate the R&D energy savings possible through research and development. The first approach uses the methodology developed in the prior bandwidth study (DOE 2006a) and updated with 2010 production and energy consumption data.

This method is consistent with the CT energy consumption, SOA energy consumption, and TM energy consumption calculations. The second approach examines the energy savings of individual research projects and is the same method used in the other bandwidth analyses produced in parallel with this one for chemicals, iron and steel, and petroleum refining. Energy savings are applied to appropriate pulp or papermaking processes and production data to provide a range of PM savings. Results from both methods will be shown for comparison, but the results from the latter method (hereafter referred to as the R&D analysis method) were used in the summary figures and tables. The other method will be referred to as the 2006 bandwidth method).

6.2.1. R&D Analysis Method

R&D progress is difficult to predict and potential gains in energy efficiency can depend on financial investments and market priorities. To estimate PM energy consumption for this bandwidth analysis, the R&D analysis method involved a broad search of R&D activities in the pulp and paper industry was conducted. A large number and range of potential technologies were identified.

The focus of this study’s search was applied research, which was defined as investigating new technology with the intent of accomplishing a particular objective. Basic research, the search for unknown facts and principles without regard to commercial objectives, was not considered. Some technologies identified were disqualified from consideration due a lack of data from which to draw energy savings conclusions.

Appendix A1 presents the onsite PM energy consumption for the six processes considered in this bandwidth study. The PM energy consumption for each process is calculated by multiplying the estimated PM energy intensity for each process by the process’s 2010 production volume (the energy intensity and production data are also presented in Appendix A1).These values exclude feedstock energy. The lower limit for onsite PM energy intensity and onsite PM energy consumption are presented in Appendix A1.The upper limit of the PM range is assumed to be the SOA energy consumption. The PM energy consumption for each process is expressed as a range because the energy savings impacts are speculative and based on unproven technologies.

Table 6-1 presents the key sources consulted to identify PM energy intensities in pulp and paper manufacturing. Additionally, numerous fact sheets, case studies, reports, and award notifications were referenced; a more detailed listing of references is provided in Appendix A4 (Table A4 and References for Table A4).

Table 6-1. Key Published Sources Reviewed to Identify Practical Minimum Energy Intensities for Processes Studied

Reference Abbreviation	Source
DOE 2006a	"Pulp and Paper Industry Energy Bandwidth Study," Jacobs Engineering, 2006
DOE 2011a	"Grand Challenge Portfolio: Driving Innovations in Industrial Energy Efficiency'" DOE ITP 2011
DOE 2011c	IMPACTS: Industrial Technologies program: Summary of Program Results for CY 2009, DOE ITP 2010
LBNL 2012	"Emerging Energy-Efficiency and Greenhouse Gas Mitigation Technologies for the Pulp and Paper Industry", LBNL Publication LBNL-5956E, L. Kong et al., 2012
Martin et al. 2000	"Emerging Energy-Efficient industrial Technologies," LBNL Publication 46990, N. Martin et al., 2000

Numerous fact sheets, case studies, reports, and award notifications were referenced. Details of all of the practical minimum sources consulted can be found in Appendix A4.

Appendix A4 presents details on the R&D technologies that were selected and used to estimate the PM energy intensities. Energy savings from R&D advancements were directly estimated for the six processes. In Appendix A4, technologies are aligned with the most representative process. Some of the technologies have applicability to more than one process (e.g., are crosscutting).

Analysis of the range of energy savings offered by groups of technologies is complicated in that the savings offered by multiple technologies may or may not be additive. Each technology contributes discrete or compounding savings that increase the ultimate savings of the group and some energy savings may be duplicative. As a result, all values are presented as sourced from the literature and energy savings were not aggregated for multiple technologies. A separate study of the individual technologies would be necessary to verify and validate the savings estimates and interrelationships between the technologies. If more than one technology was considered for a particular process, the technology that resulted in the lowest energy intensity was conservatively selected for the PM energy intensity.

R&D in some process areas is more broadly applicable, such as utility/power generation improvements and crosscutting technologies. Cross-cutting technologies applied during the PM analysis included new high-temperature, low-cost ceramic media for natural gas combustion burners, advanced energy and water recovery technology from low-grade waste heat, and control systems for recycling steel residues. The estimated energy savings from crosscutting improvements were assumed to be applicable to all six processes studied. To calculate PM energy consumption, the CT energy intensity and TM energy intensity were multiplied by the combined estimated savings for crosscutting improvements (1%-16%) and subtracted from the CT energy consumption.

In Appendix A4, the range of technologies considered offer a corresponding range of estimated energy savings. Brief descriptions of the technologies are followed by reported savings in terms of dollars, Btu, and percent savings. The technology developers' estimated savings were taken at face value and adjusted to represent the overall average energy savings potential.

Table 6-2 provides a summary of the technologies considered for the practical minimum energy intensities. For each technology, Appendix A4 presents a brief explanation of the energy savings and a summary of adjustments necessary to determine the overall average energy savings potential and PM energy intensity. Research savings are speculative in nature. The energy savings will vary depending on the source; they can be reported in terms of primary energy savings, plant-wide energy savings, process energy savings, or energy-type savings. In each case, the reported energy savings were adjusted to determine PM energy intensity.

Table 6-2. Summary Table of Evaluated Technologies (Calculations are provided in Appendix A4)

Technology Name	Energy Savings Factor (see Appendix A4 for more details)	Applicable Processes	Applicable Pulp/Paper Grades	Reference
Black Liquor Gasification	16%	Chem Prep & Sulfur Burner	Kraft Pulps	LBNL 2012
Directed Green Liquor Utilization	25%	Cooking Liquor Evaporation Bleaching	Kraft Pulps	LBNL 2012; DOE 2011b
Membrane Concentration of Black Liquor	36%	Liquor Evaporation	Sulfite-bleached Kraft Pulps NSSC	DOE 2013; LBNL 2012
Dry Kraft Pulping	30%	Cooking Liquor Evaporation Chem Prep & Sulfur Burner	Kraft Pulps	Deng 2012
Oxalic Acid Technology	25%	Bleaching	SGW TMP	DOE 2011c
Condebelt Drying	Reduced steam by 1.52MMBtu/ton and electricity by 0.068 MMBtu/ton	Dryers, drying	Paperboard	IPPC 2010; LBNL 2012; DOE 2006a
New Fibrous Fillers	40%	Dryers, drying	All Paper (except Market Pulp & Dissolving)	DOE 2006b; GRI 2009
High Consistency Forming	8% (electricity)	Wet End (Stock Prep-Forming)	Newsprint Tissue Yankee	DOE 2006a; Martin et al. 2000; LBNL 2012; Cichoracki et al. 2001
Pulse Drying of Paper Pulp	59%	Dryers, drying	Newsprint Tissue Yankee	DOE 2011c
Gas Fired Drum Dryer	10%	Dryers, drying	Paperboard	DOE 2011c; GTI 2004
Dry Sheet Forming	50%	Wet End (Stock Prep-Forming) Dryers, drying	Papers Newsprint Tissue Yankee	LBNL 2012
New Manufacturing Method for Paper Filler and Fiber Material	10%	Wet End (Stock Prep-Forming) Dryers, drying	Papers Newsprint	DOE 2011a
Microturbines (crosscutting)	8%	All (savings considered across sector)	All (savings considered across sector)	Martin et al. 2000
New Ceramic Media for Natural Gas (crosscutting)	11%	All (savings considered across sector)	All (savings considered across sector)	DOE 2011a

6.2.1.1. Weighting of Technologies

The technologies described in Appendix A4 can be weighted differently depending on the audience. Plant managers may primarily be interested in productivity and quality implications; business managers may primarily be interested in relative cost and payback; technology investors may primarily be interested in market impact, technology readiness, and development risk factors; and government regulators may primarily be interested in environmental impacts. Each factor plays heavily into R&D investment considerations.

Appendix A5 (Table A5) considers how to weigh these various perspectives. Six technology weighting factors were considered for each technology:

A	Technology Readiness
B	Market Impact
C	Relative Cost and Savings Payback
D	Technical Risk
E	Productivity/Product Quality Gain
F	Environmental Impacts

Appendix A5 (Table A5) presents the PM technology weighting factors that could be applied to the technologies for specific processes (as identified in Appendix A4). Best engineering judgment was employed to rate each of the technologies with these weighting factors. A score of High, Medium, or Low was assigned to each factor along with a brief explanation for the score. The parameters referenced in scoring are detailed in Appendix A5 (Table A5). An overall importance rating for the technology was determined based on the weighting factor scores. Each weighting factor is assigned a DOE importance level of "1."This importance level can be altered; for example, if Technology Readiness and Market Impact carry higher importance, the importance level for these factors can be changed to "2" or "3" and the resulting Overall Importance Rating would change accordingly.

The weighting factors presented in Appendix A5 can be used for further study of the R&D technologies identified in Appendix A4. The weighting factor study was part of the analysis of the R&D technologies, and serves as a guide for prioritizing the technologies. However, the weighting factors were not utilized to estimate onsite PM energy intensity or consumption.

6.2.2. 2006 Bandwidth Method

Three large energy consuming processes or systems are closely evaluated in the practical minimum energy consumption calculations for the 2006 bandwidth method (DOE 2006a):

- Lime kilns supply reburned lime to the recausticizing operation. Reducing the moisture content of lime mud is critical to reducing energy consumption of the lime kiln. PM calculations include the practical minimum energy (as direct fuel) requirements in a modern lime kiln to reduce the moisture content of the lime mud. Practical minimum estimate is the energy consumption at 35% of a state of the art lime kiln or about 1.0 MMBtu/adst.

- Evaporators raise the weak liquor solids generated during washing (about 14%) to that required for firing in a recovery boiler (about 65%). PM calculations are based on membrane technology to dewater to 22-30% black liquor solids followed by multiple effect evaporators to 80% solids (see Appendix A6).
- Paper drying PM calculation assumes press section dewatering to 65% solids followed by drying of the remaining water at steam usage of 1.3 lb steam/lb water evaporated. The result is an estimated steam usage of 1.3 MMBtu/short ton.

Practical minimum energy intensity calculations based on 2010 production data can be found in Appendix A6. Powerhouse energy consumption after applying PM is shown in Table A2-4 in Appendix A2. For the practical minimum energy consumption case, the E/NPS ratio is increased to 22% (Fleischman 2013) and boiler efficiencies are the maximum attainable efficiency levels (Walmsley et al. 2012a). Energy available for manufacturing processes after powerhouse losses is 840 TBtu, a difference of 40% relative to the current typical (1,407 TBtu).

6.3. PRACTICAL MINIMUM ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

Table 6-3 presents the onsite PM energy consumption for the six processes studied and pulp and paper sector-wide. The onsite PM energy savings is the difference between CT energy consumption and PM energy consumption. PM energy savings is equivalent to the sum of *current* and *R&D opportunity* energy savings.

In Table 6-3, PM subsector energy savings is also expressed as a percent. This is also shown in Figure 6-1. It is useful to consider both TBtu energy savings and energy savings percent when comparing energy savings opportunity. Both are good measures of opportunity; however, the conclusions are not always the same.

Table 6-3. Onsite Practical Minimum Energy Consumption, Energy Savings, and Energy Savings Percent for the Processes Studied and Sector-Wide

Process	Onsite CT Energy Consumption (TBtu/year)	Onsite PM Energy Consumption (TBtu/year)	PM Energy Savings † (CT-PM) (TBtu/year)	PM Energy Savings Percent (CT-PM)/ (CT-TM)*
Pulp Mills				
Liquor Evaporation	178	114-153	25-64	35-89%
Pulping Chemical Prep	104	72-81	23-32	38-54%
Wood Cooking	129	95-103	25-34	78-100%
Bleaching	72	49	22	54%
Paper Mills				
Paper Drying	430	254-319	111-175	37-59%
Paper Machine Wet End	190	123	67	65%
Total for Processes Studied	**1,103**	708-829	273-394	45-65%
All Other Processes Including Env. & Utilities	304	251-264	40-53	75-100%
Powerhouse Losses**	703	539-552	N/A	N/A
Total for Pulp and Paper Sector-wide	**2,110**	**1,498-1,645**	**465-612**	**61-80%**

Current typical (CT), Practical minimum (PM), Thermodynamic minimum (TM)

† PM energy savings is the Current Opportunity plus the R&D Opportunity.

** Calculated using TM from Table 7-2 as the minimum energy of production. This accounts for the energy necessary to perform the process. Potential opportunity reflects the difference between CT and TM energy consumption. Calculation: (CT- PM)/(CT- TM).*

*** See Appendix A2 for detailed table on powerhouse.*

Figure 6-1 presents the *current opportunity* and the *R&D opportunity* for each process; the *current opportunity* is the difference between CT energy consumption and SOA energy consumption (shown in blue) and the *R&D opportunity* is the difference between the SOA energy consumption and the PM energy consumption (shown in green). In Figure 6-1, the percent savings is the percent of the overall energy consumption bandwidth where TM is the lower baseline. For the processes studied, the greatest *current opportunity* and *R&D opportunity* in terms of percent savings is wood cooking at 78% energy savings and 100% savings respectively. In Figure 6-2, the *current* and *R&D* savings opportunity is shown in terms of TBtu per year savings. The pie chart in Figure 6-2 captures the blue and green portions of the bar chart shown in Figure 6-1, each in a separate pie chart. For the processes studied, the greatest *current opportunity* and *R&D opportunity* in terms of TBtu savings is paper drying at 111 TBtu per year savings and 175 TBtu per year savings respectively.

Table 6-3 also presents the PM energy savings percent. To calculate the onsite PM energy savings percent, the thermodynamic minimum (TM) energy consumption serves as the baseline for estimating percent energy savings, not zero. The energy savings percent is the percent of energy saved with PM energy consumption (i.e., the deployment of R&D technologies under development worldwide) compared to CT energy consumption, considering that the TM energy consumption may not be zero (i.e., the TM energy consumption may be negative). When comparing energy savings percent from one process to another (or one subsector to another), the absolute savings is the best measure of comparison. The equation for calculating onsite PM energy savings percent is:

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

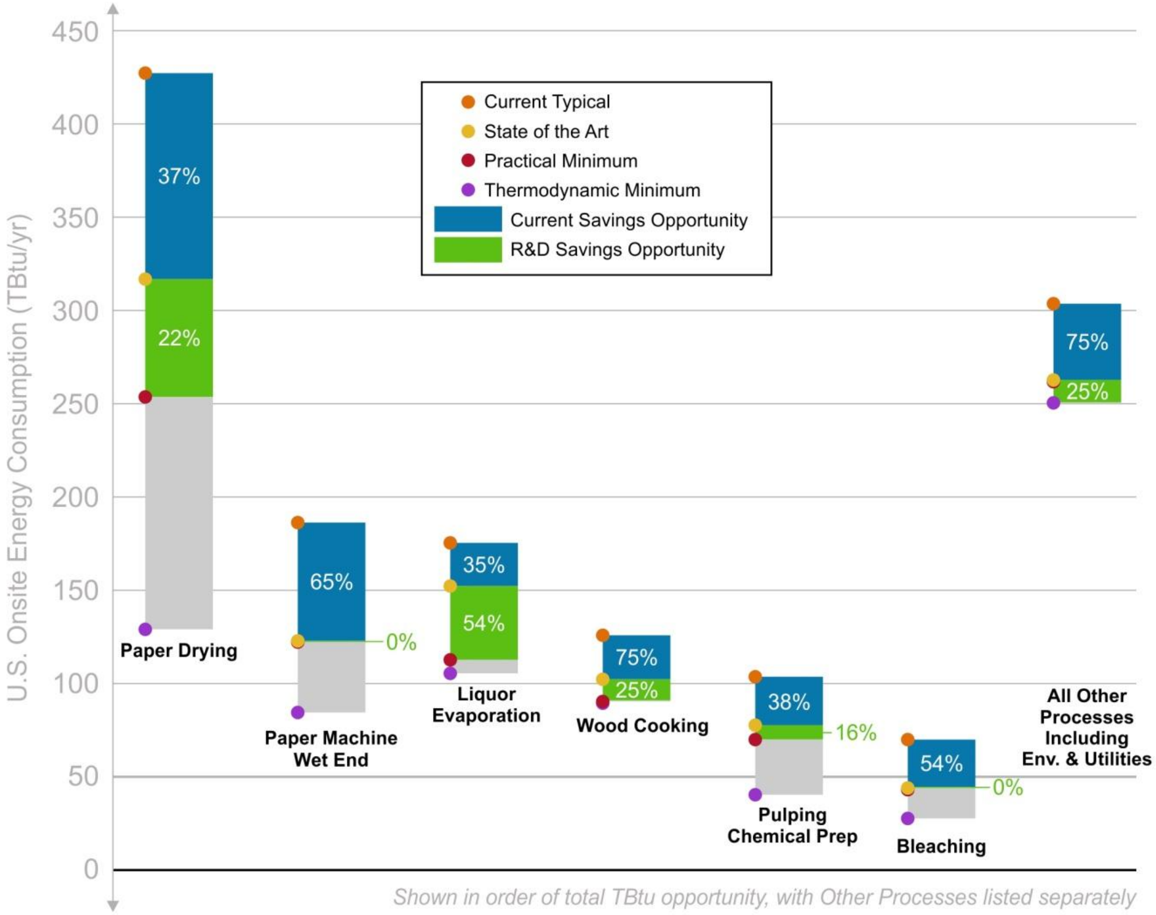


Figure 6-1. Current and R&D Opportunity Energy Savings Bandwidths for the Pulp and Paper Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

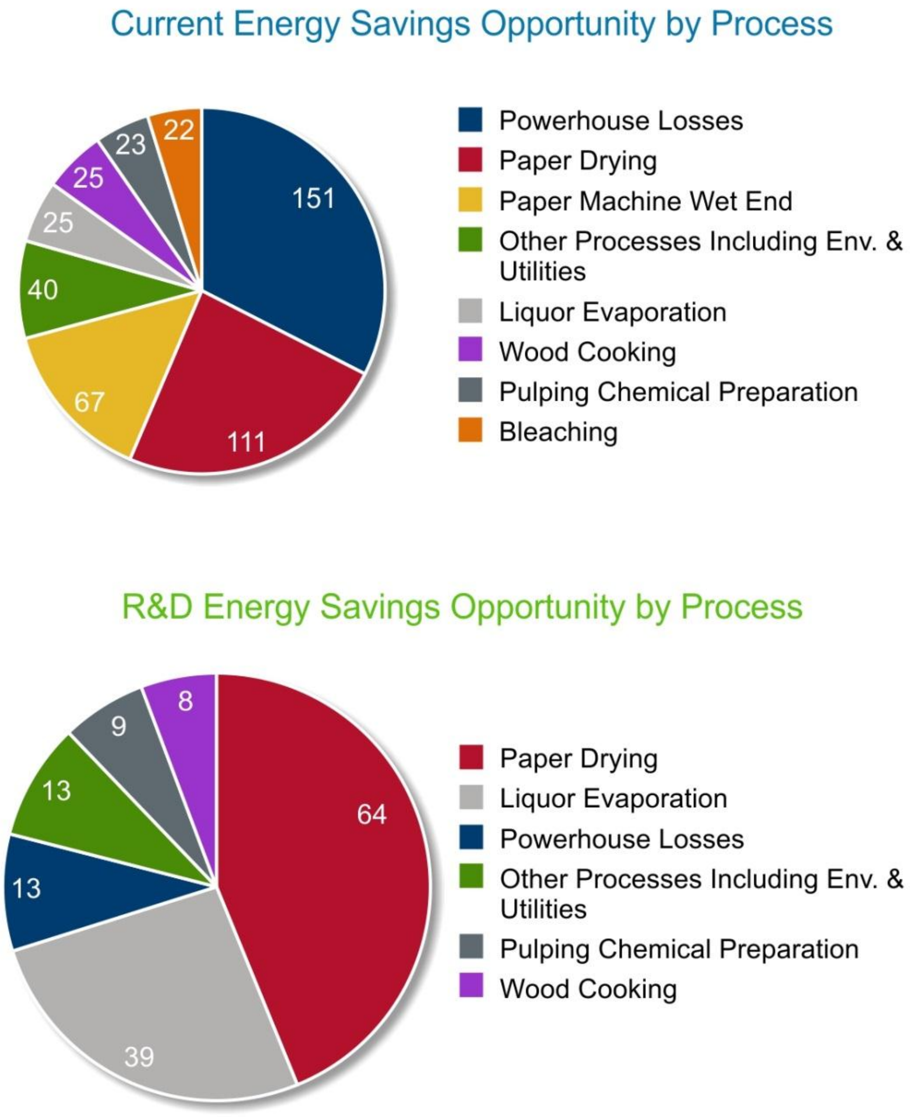


Figure 6-2. Current and R&D Energy Savings Opportunities by Pulp and Paper Process Studied *(Energy Savings Per Year in TBtu)*

The PM energy savings opportunity is different than SOA energy savings opportunity in that the scope of the R&D technologies contributing energy savings can essentially be boundless. Putting aside obvious financial, timing, and resource limitations, the process improvements and increased energy efficiency that can be gained through unproven technology is speculative. For this reason, a range is used to represent the potential onsite PM energy consumption, PM energy savings, and PM energy savings percent in Table 6-3. The upper limit of the PM energy consumption range is assumed to be equal to the SOA energy consumption. The lower limit of the PM energy consumption range was estimated using the method explained in Section 6.2. The lower limit is shown as a dashed line with color fading in the summary figures that present subsector and sector-wide data. This is done because the PM is speculative and depends on unproven R&D technologies; furthermore, the potential energy savings opportunity could be bigger if additional unproven technologies were considered.

7. Thermodynamic Minimum Energy Consumption for U.S. Pulp and Paper Manufacturing

Real world pulp and paper manufacturing does not occur under theoretically ideal conditions; however, understanding the theoretical minimal amount of energy required to manufacture pulp and paper can provide a more complete understanding of opportunities for energy savings. This baseline can be used to establish more realistic projections of what R&D energy savings can be achieved. This Chapter presents the thermodynamic minimum (TM) energy consumption required for the processes studied and for the entire sector.

7.1. THERMODYNAMIC MINIMUM ENERGY

TM energy consumption is the calculated minimum amount of energy theoretically needed to complete a pulp and paper manufacturing process, assuming ideal conditions that are typically unachievable in real-world applications; in some cases, it is less than zero. TM energy consumption assumes all the energy is used productively and there are no energy losses.

7.2. CALCULATED THERMODYNAMIC MINIMUM ENERGY CONSUMPTION FOR INDIVIDUAL PROCESSES

Appendix A1 presents the onsite TM energy consumption for the six processes considered in this bandwidth study. For a given process, the TM energy intensity is multiplied by the annual U.S. production or throughput to determine the total onsite TM energy consumption (the energy intensity and production/throughput data are also presented in Appendix A1).

For exothermic manufacturing processes, a zero baseline would result in negative percent savings, a physical impossibility. TM energy consumption was instead referenced as the baseline (or minimum amount of energy) when calculating the absolute energy savings potential. The equations used to determine the absolute energy savings for SOA and PM are as follows:

$$SOA\ Savings\ \% = \frac{CT - SOA}{CT - TM}$$

$$PM\ Savings\ \% = \frac{CT - PM}{CT - TM}$$

For processes requiring an energy intensive transformation (e.g., liquor evaporation or paper drying), this percent energy savings approach results more realistic and comparable energy savings estimates. Using zero as the baseline (or minimum amount of energy) would exaggerate the total bandwidth to which SOA energy savings and PM energy savings are compared to determine the energy savings percent. When TM energy consumption is referenced as the baseline, SOA energy savings and PM energy savings are relatively more comparable, resulting in more accurate energy savings percentages.

This study used the previous bandwidth methodology to determine thermodynamic minimums for select pulp and paper processes (DOE 2006a). Three processes or systems were closely evaluated: the theoretical limit of water removal by pressing in the paper drying process, the thermodynamic minimum energy required for liquor evaporation based on the use of membrane technology in the evaporators, and thermodynamic energy requirements of a modern lime kiln. Powerhouse energy consumption after applying TM assumptions outlined above is shown in Table A2-5 in Appendix A2. Boiler efficiencies and E/NPS ratio are the same as in the PM case (Fleischman 2013).

7.2.1. Paper Drying Thermodynamic Minimum

Building upon the case for practical minimum energy, the thermodynamic minimum in the paper drying process is based on the fact that water removal by pressing is ultimately limited to about 70% due to the amount of water contained within the fiber cell itself. Based on exiting solids of 70%, the theoretical dryer energy required was calculated to be 0.88 MMBtu/finished short ton (fst). This calculation is based on energy required to heat the water and fiber, to evaporate the water, and to desorb the water. If the solids were raised to 70%, then the potential energy reduction for drying is 79%. Calculations and conditions are listed in Appendix A7 and are those stated in the original pulp and paper bandwidth study (DOE 2006a).

7.2.2. Liquor Evaporation Thermodynamic Minimum

The thermodynamic minimum energy required for liquor evaporation is based on the use of membrane technology in the evaporators as for the practical minimum case. The conditions for the thermodynamic minimum case are the same as for the practical minimum case with the exception being that there are four evaporative stages instead of 3.2. Calculations and conditions are listed in Appendix A7 and are those stated in the original pulp and paper bandwidth study (DOE 2006a).

7.2.3. Lime Kiln Thermodynamic Minimum

Based on assumptions made in the 2006 study and theoretical energy requirements stated in the study, the thermodynamic minimum for direct fuel in a kiln is approximately 35% of the SOA case or 0.65 MMBtu/adst pulp. Electrical requirements for forced draft and induced draft fans, electrostatic precipitators, vacuum pumps, the kiln drive, and other pumps and conveyors add an estimated 0.04 MMBtu/adst pulp. The thermodynamic limit then for the lime kiln is 0.69 MMBtu/adst pulp (DOE 2006a).

7.3. THERMODYNAMIC MINIMUM ENERGY CONSUMPTION BY PROCESS AND SECTOR-WIDE

The minimum baseline of energy consumption for a pulp and paper manufacturing process is its TM energy consumption. If all the 2010 level of pulp and paper production occurred at TM energy intensity, there would be 100% savings. The percentage of energy savings is determined by calculating the absolute decrease in energy consumption and dividing it by the total possible savings (CT energy consumption-TM energy consumption).

Table 7-1 provides the TM energy consumption for the six processes studied (excluding feedstock energy)It is an imperative to keep in mind that ideal conditions are largely unrealistic goals in practice and these values serve only as a guide to estimating energy savings opportunities.

The TM energy consumption was used to calculate the *current* and *R&D* energy savings percentages (not zero).

Table 7-1. Thermodynamic Minimum Energy Consumption by Process and Sector-Wide for the Six Processes Studied and Sector Total

Process	**Onsite TM Energy Consumption** (TBtu/year)
Pulp Mills	
Liquor Evaporation	106
Pulping Chemical Prep	45
Wood Cooking	95
Bleaching	31
Paper Mills	
Paper Drying	132
Paper Machine Wet End	88
Total for Processes Studied	**498**
All Other Processes including Environmental & Utilities [a]	251
Powerhouse Losses**	596
Total for Pulp and Paper Sector-wide	**1,344**

Thermodynamic minimum (TM)

[a] *Includes utilities outside of the powerhouse and additional processes such as wastewater treatment.*

*** See Appendix A2 for detailed powerhouse table.*

8. U.S. Pulp and Paper Manufacturing Energy Bandwidth Summary

This Chapter presents the energy savings bandwidths for the pulp and paper manufacturing processes studied and sector-wide based on the analysis and data presented in the previous Chapters and the Appendices. Data for the six processes studied and the energy savings potential for all of U.S. pulp and paper is presented.

8.1. PULP AND PAPER BANDWIDTH PROFILE

Table 8-1 presents the *current opportunity* and *R&D opportunity* energy savings for the six processes studied and sector total. The process totals are summed to provide a sector-wide estimate. Each row in Table 8-1 shows the opportunity bandwidth for a specific pulp and paper manufacturing process and sector-wide.

As shown in Figure 8-1, four hypothetical opportunity bandwidths for energy savings are estimated (as defined in Chapter 1). To complete the six processes studied, the analysis shows the following:

- *Current Opportunity* – 273 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 121 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

To complete all of the U.S. pulp and paper sector processes, the analysis shows the following:

- *Current Opportunity* – 465 TBtu per year of energy savings could be obtained if state of the art technologies and practices are deployed.
- *R&D Opportunity* – 147 TBtu per year of additional energy savings could be attained in the future if applied R&D technologies under development worldwide are deployed (i.e., reaching the practical minimum).

Figure 8-1 also shows the estimated *current* and *R&D* energy savings opportunities for individual pulp and paper processes. The area between *R&D opportunity* and *impractical* is shown as a dashed line with color fading because the PM energy savings impacts are speculative and based on unproven technologies.

Table 8-1. Current Opportunity and R&D Opportunity Energy Savings for the Six Processes Studied and Sector-Wide Total

Process	**Current Opportunity** (CT-SOA) (TBtu/year)	**R&D Opportunity** (SOA-PM) (TBtu/year)
Pulp Mills		
Liquor Evaporation	25	39
Pulping Chemical Prep	23	9
Wood Cooking	25	8
Bleaching	22	0
Paper Mills		
Paper Drying	111	64
Paper Machine Wet End	67	0
Total for Processes Studied	**273**	**121**
All Other Processes including Environmental & Utilities [a]	40	13
Powerhouse Losses	151	13
Total for Pulp and Paper Sector-wide	**465**	**147**

Current typical (CT), state of the art (SOA), practical minimum (PM)

From the processes studied the greatest *current* and *R&D* energy savings opportunity for pulp and paper manufacturing comes from upgrading production methods in paper drying.

The *impractical* bandwidth represents the energy savings potential that would require fundamental changes in pulp and paper manufacturing. It is the difference between PM energy consumption and TM energy consumption. The term *impractical* is used because the significant research investment required based on today’s knowledge would no longer be practical because of the thermodynamic limitations. The TM energy consumption is based on ideal conditions that are typically unattainable in commercial applications. It was used as the baseline for calculating the energy savings potentials (not zero) to provide more accurate targets of energy savings opportunities.

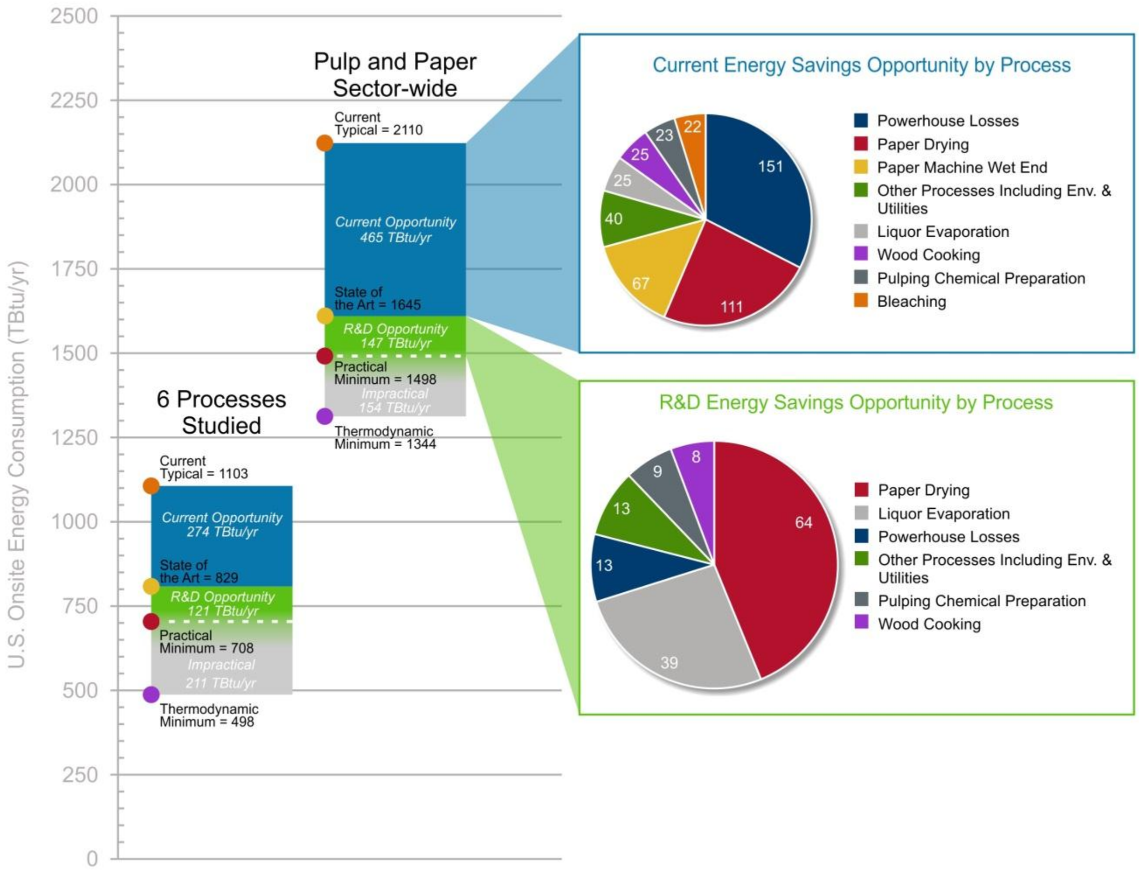


Figure 8-1. Current and R&D Energy Savings Opportunities in U.S. Pulp and Paper for the Processes Studied and for Sector-Wide

Figure 8-2 shows the bandwidth summaries for the pulp and paper processes presented in order of highest current plus R&D energy savings opportunity. Paper drying is the largest energy consuming process in pulp and paper manufacturing. If the lower limit of PM energy consumption could be reached, this would save about 175 TBtu/year compared to CT, amounting to 8% of CT energy consumption for the entire pulp and paper sector. Other processes, such as wood cooking, pulping chemical prep, and bleaching, have a much smaller difference between CT energy consumption and the PM energy consumption.

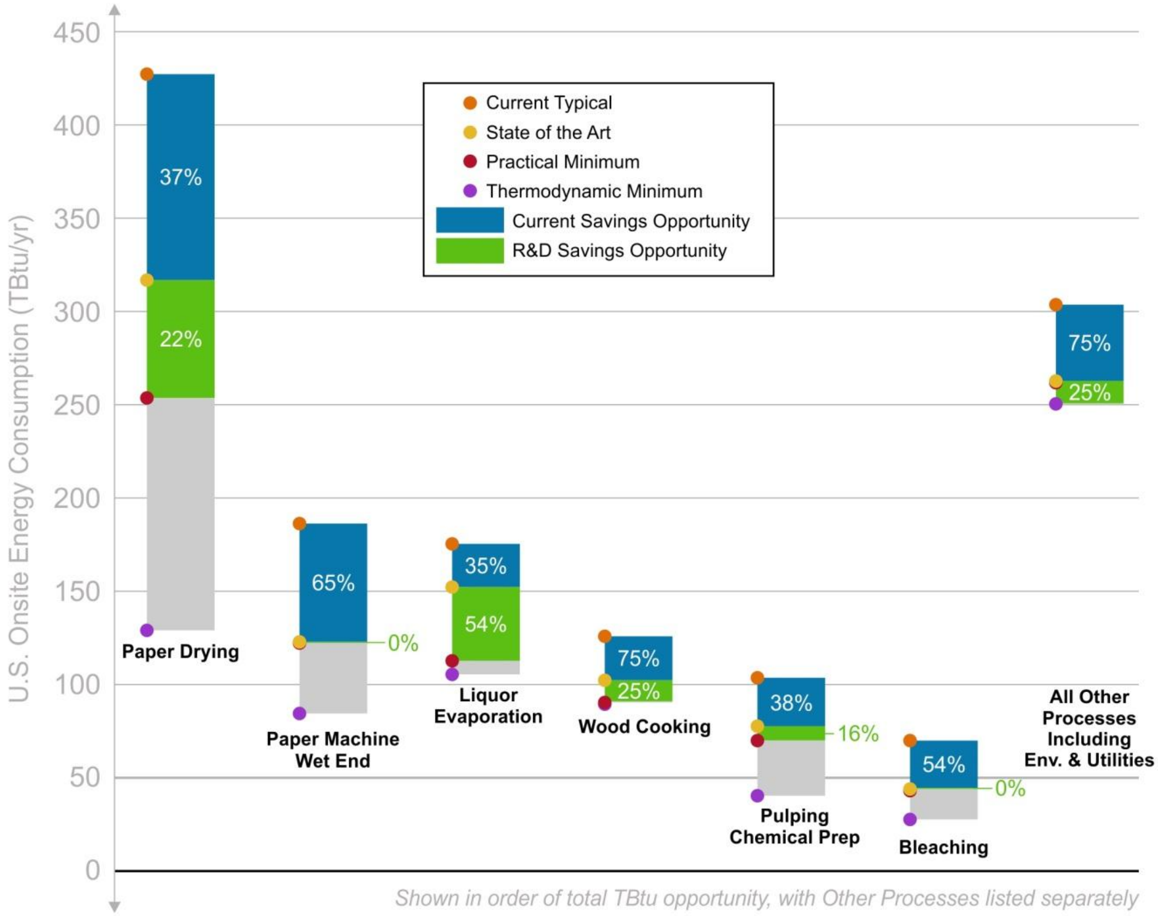


Figure 8-2. Current and R&D Opportunity Energy Savings Bandwidths for the Pulp and Paper Processes Studied *(with Percent of Overall Energy Consumption Bandwidth)*

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Appendix A1: Summary Pulp and Paper Table

Table A1. U.S. Production Volume of Six Pulp and Paper Processes in 2010 with Energy Intensity Estimates and Calculated Onsite Energy Consumption for the Four Bandwidth Measures (Excludes Feedstock Energy)

Process	**2010 Production** (1,000 tons)	**Average Onsite Energy Intensity** (MMBtu/ton)				**Calculated Onsite Energy Consumption** (TBtu/year)			
		CT	**SOA**	**PM Lower Limit**	**TM**	**CT**	**SOA**	**PM Lower Limit**	**TM**
Liquor Evaporation	50,255	3.55	3.04	2.27	2.11	178.2	152.7	114.0	106.2
Pulping Chemical Prep	50,255	2.07	1.62	1.43	0.90	104.0	81.4	72.0	45.1
Wood Cooking	50,255	2.56	2.06	1.89	1.89	128.8	103.4	95.0	95.0
Bleaching	54,344	1.32	0.91	0.91	0.57	71.7	49.5	49.5	30.9
Paper Drying	91,728	4.68	3.47	2.77	1.44	429.7	318.7	254.3	132.3
Paper Machine Wet End	91,728	2.07	1.35	1.35	0.93	190.3	123.5	123.5	87.9

The four bandwidth measures are current typical (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

Appendix A2: Pulp Distribution and Powerhouse Energy Consumption Tables

Table A2-1. Pulp Distribution by Pulp and Paper Type

Paper/ Pulp Product	**2010 Shipments** (1,000 tons)	**% of Total**	**Filler %**	**Pulp Required** (1,000 tons)	**NSSC** (1,000 tons)	**Bl. Sulfite** (1,000 tons)	**Bl. SW Kraft** (1,000 tons)	**Bl. HW Kraft** (1,000 tons)	**Unbl. Kraft** (1,000 tons)	**SGW** (1,000 tons)	**TMP** (1,000 tons)	**OCC** (1,000 tons)	**Non De-inked MOW** (1,000 tons)	**De-inked ONP** (1,000 tons)
Corrugating Material	9,786	10.7	0.0	9,786	3,121							6665		
Linerboard	24,119	26.3	0.0	24,119					16,671			4,944	1,053	
Recycled Board	3,601	3.9	0.0	3,601								3,601		
Gypsum Board	865	0.9	5.0	822								374	448	
Folding Boxboard	2,421	2.6	20.2	1,932					1,166			442	324	
Bleached Folding Boxboard/ Milk & Food	5,378	5.9	12.0	4,733			3,646	645						
Other Board	1,288	1.4	0.0	1,288					888					
Unbleached Kraft Papers	1,427	1.6	0.0	1,427			389		563				475	
Specialty Packaging & Industrial	2,683	2.9	0.0	2,683			738		1,050			30	314	
Newsprint	3,429	3.7	0.0	3,429						242	1,353			1,834
Uncoated Mechanical	2,130	2.3	12.0	1,874			198			80	292			1,275
Coated Mechanical	3,765	4.1	30.0	2,636			477			863	1,259			

Table A2-1. Pulp Distribution by Pulp and Paper Type

Paper/ Pulp Product	2010 Shipments (1,000 tons)	% of Total	Filler %	Pulp Required (1,000 tons)	NSSC (1,000 tons)	Bl. Sulfite (1,000 tons)	Bl. SW Kraft (1,000 tons)	Bl. HW Kraft (1,000 tons)	Unbl. Kraft (1,000 tons)	SGW (1,000 tons)	TMP (1,000 tons)	OCC (1,000 tons)	Non De-inked MOW (1,000 tons)	De-inked ONP (1,000 tons)
Bleached Packaging	185	0.2	0.0	185			185							
Bleached Bristol	848	0.9	15.0	721			156	565						
Uncoated Freesheet	9,556	10.4	15.0	8,123		29	815	4,025						
Coated Freesheet	4,146	4.5	25.0	3,110		36	497	1,589						
Other Specialties	23	0.0	0.0	23			23							
Tissue	7,309	8.0	2.5	7,126			1,801	2,213				372	664	
Paper Subtotal	**82,959**	**90.4**		**77,616**	**3,121**	**65**	**8,925**	**9,037**	**20,338**	**1,185**	**2,904**	**16,428**	**3,278**	**3,109**
Kraft Pulp, Bleached & Semi-bleached	8,508	9.3		8,508			4,228	4,280						
Kraft Pulp, unbleached	na	na												
Sulfite Pulp	na	na												
Recycled Pulp	na	na												
Other Pulp/ Dissolving Pulp	261	0.3		261		261								
Pulp Subtotal	**8,769**	**9.6**												
Total (Pulp & Paper)	**91,728**	**100.0**		**86,385**	**3,121**	**326**	**13,153**	**13,317**	**20,338**	**1185**	**2,904**	**16,428**	**3,278**	**3,109**

Table A2-2. Powerhouse Energy Consumption for Current Typical Case

	MECS 2010 Table 3.2 NAICS 322	Fuel Utilized In Boilers	Boiler Efficiency	Gross Steam Energy	Used for Soot Blowing Steam	Used for Boiler Aux.	Net Steam Energy	Steam Energy for Process and Cogen	Electric Gen Loss	System & Mechanical Loss	Total Process Demand	Electricity Demand	Electricity Demand	Direct Fuel Demand	Steam Demand	System and Elec Gen Losses
	TBtu	TBtu	%	TBtu	%	%	TBtu	TBtu	%	%	TBtu	TBtu	BkWh	TBtu	TBtu	TBtu
Net Electricity	206.0									2.0%		201.9	59.2			4.1
Coal	207.0	207.00	85.0%	176	2.5%	6.0%	161									-
Residual Fuel Oil	35.0	35.00	87.0%	30		4.0%	29									-
Distillate Fuel Oil	6.0	4.50	87.0%	4		3.0%	4							1.5		-
Natural Gas	399.0	304.60	83.0%	253		3.0%	245							94.4		-
LPG	4.0	-	83.0%	-			-							4.0		-
Waste Pulping Liquors	824.0	824.00	65.0%	536	7.5%	4.0%	474									-
Wood / Bark	343.0	343.00	69.0%	237	1.5%	5.0%	221									-
Other By Products	39.0	33.70	69.0%	23		4.0%	22							5.3		-
Other	47.0	47.00	69.0%	32		4.0%	31									-
Subtotal - Fuels	1,904.0	1,799		1,291			1,188	1,012.05		6.4%					947.1	64.9
On Site Elec Gen					Cogen	18%	E/NPS	169.08	5.0%	6.4%		150.3	44.1			18.8
On Site Elec Gen					Condensing			6.87	60.0%	6.4%		2.6	0.8			4.3
Totals	2,110.0						1,188	1,188			1,407.12	354.8	104.0	105.2	947.1	92.1
						Steam Gen Losses	611	87%								
						System and Cogen losses	92	13%								
						Total losses	703	100%								

Notes:

- Boiler Efficiency: conversion efficiency of the boiler. Efficiency estimates based on efficiency ranges (Wamsley 2012a; Schindler 2012; Gustafson 2009; and Murray 2006) for boiler sizes commonly found in the pulp and paper industry (RDC 2002; ORNL 2005).
- Soot Blowing Steam: steam used in the boiler for tube cleaning, based on Jacobs' design rule of thumb (DOE 2006).
- Boiler Auxiliaries: includes energy consumed for fans, pumps, coal crushers, bark hogs, environmental controls, steam leaks and venting, etc.
- Electrical Generator Conversion Loss: energy/heat loss in the generator and condenser.
- System and Mechanical Loss: energy/heat loss in transformers, radiation losses from pipes, venting and leaks.
- Total fuel consumed by the industry is 1,904 TBtu of which 1,188 TBtu is available for use in the pulp and paper manufacturing processes after the powerhouse, including 105 TBtu of fuel used directly as fuel in manufacturing processes. The 1,799 TBtu difference between 1,904 TBtu and 105 TBtu is the fuel consumed in the powerhouse to co-generate the 1,100 TBtu (947 TBtu + 153 TBtu) of process steam and electricity. There is also 206 TBtu of Net Electricity available for manufacturing processes.

Table A2-3. Powerhouse Energy Consumption for State of the Art Case

	Estimate Based on SOA	Fuel Utilized In Boilers	Boiler Efficiency	Gross Steam Energy	Used for Soot Blowing Steam	Used for Boiler Aux.	Net Steam Energy	Steam Energy for Process and Cogen	Electric Gen Loss	System & Mechanical Loss	Total Process Demand	Electricity Demand	Electricity Demand	Direct Fuel Demand	Steam Demand	System and Elec Gen Losses
	TBtu	TBtu	%	TBtu	%	%	TBtu	TBtu	%	%	TBtu	TBtu	BkWh	TBtu	TBtu	TBtu
Net Electricity	156.8									2.0%		153.7	45.0			3.1
Coal	27.6	27.55	86.0%	24	2.0%	6.0%	22									-
Residual Fuel Oil	29.9	29.93	88.0%	26		4.0%	25									-
Distillate Fuel Oil	8.6	5.93	88.0%	5		3.0%	5							2.7		-
Natural Gas	180.0	96.10	84.0%	81		3.0%	78							83.9		-
LPG	4.4	0.39	84.0%	0			0							4.0		-
Waste Pulping Liquors	824.4	824.44	68.0%	561	5.5%	4.0%	507									-
Wood / Bark	342.8	342.75	70.0%	240	1.0%	5.0%	226									-
Other By Products	14.7	12.51	70.0%	9		4.0%	8							2.2		-
Other	57.2	57.16	70.0%	40		4.0%	38									-
Subtotal - Fuels	1,489.6	1,397		986			910	763.92		6.0%					718.1	45.8
On Site Elec Gen					Cogen	20%	E/NPS	143.62	5.0%	6.0%		128.2	37.6			15.4
On Site Elec Gen					Condensing			2.94	60.0%	5.0%		1.1	0.3			1.8
Totals	1,646.4						910	910			1,093.92	283.0	83.0	92.8	718.1	66.2
						Steam Gen Losses	486	88%				283.0		92.8	718.1	Reference
						System and Cogen losses	66	12%								
						Total losses	552	100%								

Table A2-4. Powerhouse Energy Consumption after Applying Practical Minimum

	Estimate Based on PM	Fuel Utilized In Boilers	Boiler Efficiency	Gross Steam Energy	Used for Soot Blowing Steam	Used for Boiler Aux.	Net Steam Energy	Steam Energy for Process and Cogen	Electric Gen Loss	System & Mechanical Loss	Total Process Demand	Electricity Demand	Electricity Demand	Direct Fuel Demand	Steam Demand	System and Elec Gen Losses
	TBtu	TBtu	%	TBtu	%	%	TBtu	TBtu	%	%	TBtu	TBtu	BkWh	TBtu	TBtu	TBtu
Net Electricity	142.9									2.0%		140.0	41.0			2.9
Coal	0.1	0.14	88.0%	0	2.0%	6.0%	0									-
Residual Fuel Oil	0.0	-	89.7%	-		4.0%	-									-
Distillate Fuel Oil	1.7	-	89.7%	-		3.0%	-							1.7		-
Natural Gas	62.4	-	86.5%	-		3.0%	-							62.4		-
LPG	3.3	-	87.0%	-			-							3.3		-
Waste Pulping Liquors	824.0	824.00	68.0%	560	5.5%	4.0%	507									-
Wood / Bark	343.0	343.00	70.0%	240	1.0%	5.0%	226									-
Other By Products	1.7	-	70.0%	-		4.0%	-							1.7		-
Other	0.0	-	70.0%	-		4.0%	-									-
Subtotal - Fuels	1,236.2	1,167		801			733	528.55		6.0%					496.8	31.7
On Site Elec Gen					Cogen	22%	E/NPS	109.30	5.0%	6.0%		97.6	28.6			11.7
On Site Elec Gen					Condensing			95.04	60.0%	5.0%		36.1	10.6			58.9
Totals	1,379.1						733	733			839.71	273.8	80.2	69.1	496.8	105.2
						Steam Gen Losses	434	80%								
						System and Cogen losses	105	20%								
						Total losses	539	100%								

Table A2-5. Powerhouse Energy Consumption After Applying Thermodynamic Minimum Energy Consumption

	Estimate Based on TM	Fuel Utilized In Boilers	Boiler Efficiency	Gross Steam Energy	Used for Soot Blowing Steam	Used for Boiler Aux.	Net Steam Energy	Steam Energy for Process and Cogen	Electric Gen Loss	System & Mechanical Loss	Total Process Demand	Electricity Demand	Electricity Demand	Direct Fuel Demand	Steam Demand	System and Elec Gen Losses
	TBtu	TBtu	%	TBtu	%	%	TBtu	TBtu	%	%	TBtu	TBtu	BkWh	TBtu	TBtu	TBtu
Net Electricity	118.8									2.0%		116.4	34.1			2.4
Coal	0.0	0.02	88.0%	0	2.0%	6.0%	0									-
Residual Fuel Oil	0.0	-	89.7%	-		4.0%	-									-
Distillate Fuel Oil	1.6	-	89.7%	-		3.0%	-							1.6		-
Natural Gas	52.9	-	86.5%	-		3.0%	-							52.9		-
LPG	2.8	-	87.0%	-			-							2.8		-
Waste Pulping Liquors	824.0	824.00	68.0%	560	5.5%	4.0%	507									-
Wood / Bark	343.0	343.00	70.0%	240	1.0%	5.0%	226									-
Other By Products	1.4	-	70.0%	-		4.0%	-							1.4		-
Other	0.0	-	70.0%	-		4.0%	-									-
Subtotal - Fuels	1,225.7	1,167		800			733	442.10		6.0%					415.6	26.5
On Site Elec Gen					Cogen	22%	E/NPS	91.43	5.0%	6.0%		81.6	23.9			9.8
On Site Elec Gen					Condensing			199.27	60.0%	5.0%		75.7	22.2			123.5
Totals	1,344.5						733	733			748.07	273.8	80.2	58.7	415.6	162.2
						Steam Gen Losses	434	73%								
						System and Cogen losses	162	27%								
						Total losses	596	100%								

Appendix A3: CT, SOA, and TM Energy Intensities by Pulp or Paper Type

Table A3-1. Current Typical Energy Intensities for Pulp Processes

Type of Pulp		Production (1,000 tons/year)	Energy Intensity by Process (MMBtu/ton)			
			Wood Cooking	Liquor Evaporation	Lime Kiln / Pulping Chemical Prep	Bleaching
Chemical Pulp	Sulfite	326	2.99	2.64	2.20	2.39
	Kraft, Unbleached	20,338	2.58	3.69	2.12	-
	Kraft, Bleached, SW	13,153	2.51	3.66	2.07	2.32
	Kraft, Bleached, HW	13,317	2.41	3.29	2.05	2.33
	NSSC, SemiChem	3,121	3.24	3.35	1.84	-
	Subtotal Chemical Pulp	**50,255**				
	Weighted Average Energy Intensity (MMBtu/ton)		**2.56**	**3.55**	**2.07**	**2.33**
Mechanical Pulp	SGW	1,185				1.97
	TMP	2,904				2.41
	Subtotal Mechanical Pulp	**4,089**				
	Weighted Average Energy Intensity (MMBtu/ton)					**2.28**

Table A3-2. Current Typical Energy Intensities for Paper Processes

Type of Paper	**Production** (1,000 tons/year)	**Energy Intensity by Process** (MMBtu/ton)	
		Paper Drying	**Paper Machine Wet End**
Corrugating Medium	9,786	4.84	2.62
Linerboard	24,119	4.88	2.61
Recycled Board	3,601	4.75	2.54
Folding Boxboard	2,421	4.75	2.26
Gypsum Board	865	4.74	2.58
Bleached Folding Boxboard / Milk	5,378	4.71	2.40
Other Board, unbleached	1,288	4.39	2.42
Kraft Paper	1,427	4.62	2.36
Special Industrial	2,683	4.62	2.35
Uncoated Free, Bristol & Bleached Packaging	10,589	4.80	2.39
Coated Freesheet	4,146	4.42	2.35
Newsprint	3,429	4.02	1.80
Groundwood Specialties	2,130	4.02	1.80
Coated Groundwood	3,765	4.03	1.61
Tissue / Towel	7,309	6.34	0.94
Other Specialties	23	5.00	2.30
Market Pulp	8,769	3.31	0.14
Subtotal Paper	**91,728**		
Weighted Average Energy Intensity (MMBtu/ton)		**4.68**	**2.07**

Table A3-3. State of the Art Energy Intensities for Pulp Processes

Type of Pulp		Production (1,000 tons/year)	Energy Intensity by Process (MMBtu/ton)			
			Wood Cooking	Liquor Evaporation	Lime Kiln / Pulping Chemical Prep	Bleaching
Chemical Pulp	Sulfite	326	2.98	2.34	2.20	2.59
	Kraft, UnBleached	20,338	2.09	3.27	1.67	-
	Kraft, Bleached, SW	13,153	1.91	3.05	1.68	1.56
	Kraft, Bleached, HW	13,317	1.89	2.70	1.50	1.52
	NSSC, SemiChem	3,121	3.10	3.05	1.44	-
	Subtotal Chemical Pulp	**50,255**				
	Weighted Average Energy Intensity (MMBtu/ton)		**2.06**	**3.04**	**1.62**	**1.55**
Mechanical Pulp	SGW	1,185				0.71
	TMP	2,904				2.41
	Subtotal Mechanical Pulp	**4,089**				
	Weighted Average Energy Intensity (MMBtu/ton)					**1.92**

Table A3-4. State of the Art Energy Intensities for Paper Processes

Type of Paper	**Production** (1,000 tons/year)	**Energy Intensity by Process** (MMBtu/ton)	
		Paper Drying	**Paper Machine Wet End**
Corrugating Medium	9,786	3.00	1.95
Linerboard	24,119	3.04	1.59
Recycled Board	3,601	3.86	1.34
Folding Boxboard	2,421	3.86	1.14
Gypsum Board	865	3.86	1.34
Bl. Folding Boxboard / Milk	5,378	3.04	1.39
Other Board, unbleached	1,288	3.54	1.39
Kraft Paper	1,427	3.04	1.29
Special Industrial	2,683	3.04	1.39
Uncoated Free, Bristol & Bleached Packaging	10,589	4.05	1.47
Coated Freesheet	4,146	3.39	1.43
Newsprint	3,429	3.12	1.07
Groundwood Specialties	2,130	3.76	1.07
Coated Groundwood	3,765	3.79	1.35
Tissue / Towel	7,309	6.16	0.74
Other Specialties	23	3.94	1.39
Market Pulp	8,769	2.40	0.54
Subtotal Paper	**91,728**		
Weighted Average Energy Intensity (MMBtu/ton)		**3.47**	**1.35**

Table A3-5. Thermodynamic Minimum Energy Intensities for Pulp Processes

Type of Pulp		Production (1,000 tons/year)	Energy Intensity by Process (MMBtu/ton)			
			Wood Cooking	Liquor Evaporation	Lime Kiln / Pulping Chemical Prep	Bleaching
Chemical Pulp	Sulfite	326	2.98	1.55	2.20	2.59
	Kraft, UnBleached	20,338	1.71	2.15	0.93	-
	Kraft, Bleached, SW	13,153	2.04	2.06	0.90	0.72
	Kraft, Bleached, HW	13,317	1.71	2.15	0.82	0.96
	NSSC, SemiChem	3,121	3.10	1.99	0.88	-
	Subtotal Chemical Pulp	**50,255**				
	Weighted Average Energy Intensity (MMBtu/ton)		**1.89**	**2.11**	**0.90**	**0.86**
Mechanical Pulp	SGW	1,185				0.71
	TMP	2,904				2.41
	Subtotal Mechanical Pulp	**4,089**				
	Weighted Average Energy Intensity (MMBtu/ton)					**1.92**

Table A3-6. Thermodynamic Minimum Energy Intensities for Paper Processes

Type of Paper	Production (1,000 tons/year)	Energy Intensity by Process (MMBtu/ton)	
		Paper Drying	Paper Machine Wet End
Corrugating Medium	9,786	1.11	1.35
Linerboard	24,119	1.14	0.99
Recycled Board	3,601	1.31	0.74
Folding Boxboard	2,421	1.31	0.74
Gypsum Board	865	1.31	0.74
Bleached Folding Boxboard / Milk	5,378	1.14	0.99
Other Board, unbleached	1,288	1.24	0.99
Kraft Paper	1,427	1.14	0.99
Special Industrial	2,683	1.14	0.99
Uncoated Free, Bristol & Bleached Packaging	10,589	1.39	1.07
Coated Freesheet	4,146	1.20	1.03
Newsprint	3,429	1.06	0.87
Groundwood Specialties	2,130	1.25	0.87
Coated Groundwood	3,765	1.27	1.25
Tissue / Towel	7,309	4.61	0.74
Other Specialties	23	1.40	0.99
Market Pulp	8,769	0.90	0.54
Subtotal Paper	**91,728**		
Weighted Average Energy Intensity (MMBtu/ton)		**1.44**	**0.96**

Appendix A4: Technologies Analyzed to Estimate Practical Minimum Energy Intensities with References

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities							
Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Pulping Processes							
Black Liquor Gasification (BLG)	BLG entails pyrolyzing concentrated black liquor into an inorganic phase and a gas phase through reactions with oxygen or air at high temperatures. BLG can be integrated with combined-cycle technology which has the potential to produce significantly more electricity than current boiler/steam turbine systems and may even make the mill an electricity exporter.	Kraft process/ chemical pulp	LBNL 2012	Increase energy recovery efficiency by 10%; Increase amount of electricity generated at the pulp mill by 2 to 3 times (LBNL 2012); 16% electricity savings in chemical pulp process step	Savings reported as 10% of Kraft pulping process; 16% specific electricity saving potential for chemical pulp step	Current typical range for the chemical pulp step is 922-1,100 Btu/lb. Estimated saving is 16% of chemical pulp step energy. Practical minimum energy intensity for pulping chem prep employing this technology = 824-877 Btu/lb (pulping chem prep)	824-877 Btu/lb
Directed Green Liquor Utilization	This technology is based on the reuse of green liquor for pre-treatment of wood chips prior to kraft pulping. Twenty to 30% of the green liquor from the causticizing process is redirected to pulp pre-treatment before cooking in the digester. As a result, not only the lime kiln load but also the energy consumption of the digester can be reduced.	Kraft pulp	LBNL 2012; DOE 2011a	Reduce energy use by up to 25%	Savings reported as 25% of Kraft pulping process	Estimated savings are 25% of Kraft pulping process energy, so for each of these steps. Practical minimum energy intensity for each key process employing this technology = 905-969 Btu/lb (wood cooking), 1,232-1,383 Btu/lb (liquor evaporation), 736-783 Btu/lb (pulping chem prep), 869-875 Btu/lb (bleaching)	905-969 Btu/lb (wood cooking), 1,232-1,383 Btu/lb (liquor evap.), 736-783 Btu/lb (pulping chem prep), 869-875 Btu/lb (bleaching)

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Pulping Processes (continued)							
Membrane concentration of Black Liquor - Regenerative/sacrificial membrane coatings	A chemically resistant, anti-fouling coating for low-cost polymeric membranes that can be regenerated in situ will be developed that will enable membrane-based concentration of weak black liquor from 15% to 30% solids.	Chemical pulp	DOE 2013; LBNL 2012	Energy reduced from 3.5 MMBtu/adt to <2.2 MMBtu/adt	Overall energy needed to concentrate weak black liquor will be reduces from 3.5 MMBtu/adt to < 2.2 MMBtu/adt resulting in 110 TBtu/yr savings for process sector wide	Current typical range for liquor evaporation for chemical pulp is 1,322-1,844 Btu/lb. Estimated reduction in energy to concentrate the black liquor is at least 37%. Practical minimum energy intensity for liquor evaporation employing this technology = 846-1,180 Btu/lb	846-1,180 Btu/lb
Dry Kraft Pulping	This method demonstrates that free liquor in the pulping digester is not necessary if woodchips are pre-soaked with pulping solution. The pulp quality is similar to traditional Kraft pulp. Because no free liquor is required in the digester, up to 55% of heating energy can be saved.	Kraft pulp (un-bleached)	Deng 2012	30% heat energy savings over traditional Kraft pulping process	30% heat energy savings over traditional Kraft pulping process	Current typicalranges for the four energy intensive pulping processes is listed to the right. Estimated savings are 30% of Kraft pulping process energy, so for each of these steps. Practical minimum energy intensity for each key process employing this technology = 845-905 Btu/lb (wood cooking), 1,150-1,291 Btu/lb (liquor evaporation), 687-730 Btu/lb (pulping chem prep)	845-905 Btu/lb (wood cooking), 1,150-1,291 Btu/lb (liquor evap.), 687-730 Btu/lb (pulping chem prep)
Oxalic Acid Technology	Pretreatment of wood chips with dilute oxalic acid solution for about 10 minutes reduces electrical energy requirements for mechanical pulping by 25%, improves paper strength properties, reduces pitch content, and improves dewatering.	Mechanical pulping process	DOE 2011b	Reduce energy requirements of pulping by up to 25%	25% of electrical/energy requirements for pulping	Current typical energy intensity for the bleaching process of mechanical pulp is 984 Btu/lb for SGW and 1,204 Btu/lb for TMP. Estimated savings are 25% of mechanical pulping energy requirements. Practical minimum energy intensity for bleaching of mechanical pulp employing this technology = 738 Btu/lb for SGW and 903 Btu/lb for TMP	738 Btu/lb (SGW) and 903 Btu/lb (TMP)

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	Technology Description	Applicability (Product, process)	Source (See Reference list at end)	Reported Energy Savings (Literature-reported savings, Btu, %, etc.)	Explanation of Savings Baseline, or Reference (Adjustment, conversion, scale up of reported savings)	Calculated Product/ Process Savings (Savings compared to SOA or CT energy use. PM savings estimate.)	PM Energy Intensity (MMBtu/ ton) or % savings
Papermaking							
Condebelt Drying	The paper web coming from the press section is dried between two steel belts instead of traditional steam cylinders. The web travels between a steam-heated upper, and a water-cooled lower steel belt. The hot upper belt evaporates the moisture in the web which condenses on the cooler lower belt. No significant direct energy savings but better strength products give the potential for savings through reduced basic weight. It is also possible for recycled fibers to achieve the same strength values as virgin fibers using condebelt drying.	Paperboard	IPPC 2010; LBNL 2012; DOE 2006	1.588 MMBtu/ton paper (LBNL 2012)	Reduction of 1.52 MMBtu/t paper is from steam savings, .068 MMBtu from electricity savings	This technology is best for paperboard. Current typical energy intensity for drying for paperboard ranges from 2,195 to 2,438 Btu/lb. Steam is projected to be reduced by 1.52 MMBtu/t and electric is projected to be reduced by .068 MMBtu/t. Practical minimum energy intensity employing this technology = 1,400-1,644 Btu/lb	1,400-1,644 Btu/lb
New Fibrous Fillers	Current studies are investigating the viability of manufacturing paper containing up to 50% ash, at equal or better quality and performance and at a lower cost. Filler loading has been limited to 15% to 20% because higher levels cause a loss of sheet strength and bulk as well "dusting" during printing.	Sector-wide	DOE 2006, GR International 2009	Could reduce energy use by up to 25%, 43% energy savings (drying)	Improved pressing - 25% energy savings; reduced basis weight - 18% energy savings; increased nano material level - 9% energy savings	This technology was developed for fine paper but has wide applicability across the sector. Current typical energy intensity for drying for paper ranges from 1,654-3,171 Btu/lb. Increasing press solids by 10% is estimated to reduce the required energy by 40% (final report). Practical minimum energy intensity employing this technology = 1,205-1,902 Btu/lb	1,205-1,902 Btu/lb

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	Technology Description	Applicability (Product, process)	Source (See Reference list at end)	Reported Energy Savings (Literature-reported savings, Btu, %, etc.)	Explanation of Savings Baseline, or Reference (Adjustment, conversion, scale up of reported savings)	Calculated Product/ Process Savings (Savings compared to SOA or CT energy use. PM savings estimate.)	PM Energy Intensity (MMBtu/ ton) or % savings
Papermaking (continued)							
High Consistency Forming	Applicable only to certain paper grades – especially to low-basis weight grades such as tissue, toweling, and newsprint. – in this process, the furnish pulp which enters the forming stage has more than double the consistency (3%) than the normal furnish pulp. This increases the forming speed and reduces the dewatering and vacuum pumping requirements (Martin et al.). The main components of the former include: the fluidization chamber, suction roll and press roll (Cichoracki et al.)	Certain papers	DOE 2006; Martin et al. 2000; LBNL 2012; Cichoracki et al.	41 kWh/t paper	Electricity savings are estimated at 8% that is about 41 kWh/t of paper (Martin et al.)	This technology is recommended for low-basis weight grades such as tissue and newsprint. Current typical energy intensity for the wet end process for newsprint is 902 Btu/lb and for tissue is 471 Btu/lb. It is estimated that this technology will allow an 8% reduction in electricity. Practical minimum energy intensity employing this technology = 936 Btu/lb (newsprint) and 567 Btu/lb (tissue)	567-936 Btu/lb
Pulse Drying of Paper Pulp	Pulse impingement drying improves efficiency of the evaporative drying stage by 59% and speeds overall paper production by 21%. Pulse drying of paper webs applies directly to "Yankee" and "MG" style paper drying equipment, and indirectly to newsprint, box board, and finer grades of paper (DOE 2011b).	Newsprint, tissue yankee	DOE 2011b	Improves efficiency of paper drying stage by 59%	Estimated to increase the efficiency by 59% for the paper drying process	It is estimated that paper drying efficiency will increase by 59%. Current typical energy intensity of paper drying for applicable products ranges from 2,008-3,171 Btu/lb. Practical minimum energy intensity employing this technology ranges from 823-1,300 Btu/lb	823-1,300 Btu/lb

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Papermaking (continued)							
Gas Fired Drum Dryer	The Gas-Fired Paper Dryer (GFPD) is a natural-gas-fired system that uses a combination of a flame sheet and dimpled pattern on the drum's inner surface to improve combustion stability, reduce pollutant emissions, and cost-effectively enhance heat transfer from combustion products to the paper web. This patented approach could be implemented into new or existing equipment. The GFPD will ultimately help the paper industry (especially drying limited mills) reduce energy use and increase the production rate of paper machines by 10% to 20%.	Drying (Paperboard)	DOE 2011b; Chudnovsky 2004	Improves boiler efficiency by 10-15%	Successful development of the GFPD will provide large energy savings to the industry according to energy efficiency increase from 65% (steam operated) to 75-80% (gas operated); could significantly reduce steam consumption	Assume that the current dryer efficiency is 65% and it is projected that this technology will increase efficiency to 75%. The current typical energy intensity of paper drying ranges from 2,195-2,438 Btu/lb for applicable products. Practical minimum energy intensity employing this technology = 1,976-2,195 Btu/lb	1,976-2,195 Btu/lb
Dry Sheet Forming	The principle behind dry sheet forming is the production of paper without adding water. It relies on high levels of turbulence in the air stream to produce paper products. A typical dry sheet forming line consists of four units: fiber preparation, web formation, web consolidation, and finishing.	Tissue yankee	LBNL 2012	Reduces drying energy consumption by 50%, increases electricity of 150-250 kWh/t paper for forming	It estimated that 50 percent of drying energy consumption could be eliminated with 150 to 250 kWh/t paper of additional electricity consumption to maintain the air stream and motor drive for the equipment using air-laid dry sheet forming technology	It is estimated that drying energy consumption will be reduced by 50% and wet end electricity will increase by up to 250 kWh/t paper. Current typical energy intensity range for applicable paper is 471 Btu/lb for wet end and 3,171 Btu/lb for drying. Practical minimum energy intensity employing this technology = 1,031 Btu/lb for wet end (INCREASE) and 1,535 Btu/lb for drying	1,031 Btu/lb (wet end), 1,535 Btu/lb (drying)

Table A4. Technologies Analyzed to Estimate Practical Minimum Energy Intensities

Technology Name	**Technology Description**	**Applicability** (Product, process)	**Source** (See Reference list at end)	**Reported Energy Savings** (Literature-reported savings, Btu, %, etc.)	**Explanation of Savings Baseline, or Reference** (Adjustment, conversion, scale up of reported savings)	**Calculated Product/ Process Savings** (Savings compared to SOA or CT energy use. PM savings estimate.)	**PM Energy Intensity** (MMBtu/ ton) or % savings
Papermaking (continued)							
New Manufacturing Method for Paper Filler and Fiber Material	This study seeks to produce paper grades suitable for printing and writing while increasing the filler content of the paper with a composite produced from kraft and process pulp. Increasing the filler content would reduce the pulp requirement and generate corresponding energy savings for pulp production; however, increased filler content can adversely affect paper quality.	Papers	DOE 2011c	Estimated 10% energy savings	Energy savings are estimated with 10% in stock preparation, forming, pressing & finishing, and drying - papermaking average	A 10% energy savings is estimated for both wet end and paper drying. CT energy intensity for paper ranges from 805-1,194 Btu/lb for the wet end process and 2,008-2,399 Btu/lb for drying. Practical minimum energy intensity employing this technology = 724-1,075 Btu/lb for wet end and 1,808-2,159 for drying	724-1,075 Btu/lb (wet end), 1,808-2,159 (drying)
Crosscutting Technologies							
Microturbines	Microturbines are a new class of small combustion turbine engines, where simple-cycle microturbines are projected to be 26-30% efficient; 40% efficiency can be attained through heat recover. Fuel efficiency can reach 80% when combined with CHP or cogeneration.	w/CHP	Martin et al. 2000	14% increase in efficiency over typical CHP efficiency by adding microturbines	14% increase in efficiency of CHP Systems	Referencing MECS 2006 data for paper, 1,419 TBtu of direct end use is from CHP systems, which equates to 60% (1419/2354) of plant wide energy use. 14% savings of 60% energy use results in 8% average savings in a typical plant. Practical minimum specific energy savings of 8% over CT applied to all processes**.**	8% savings over CT for all processes
New High-Temperature, Low-Cost Ceramic Media for Natural Gas Combustion Burners	Combining four different technologies into a single radiant burner package that functions as both a burner and a catalyst support.	Could potentially apply when electric or natural gas radiant heaters used in process heating.	DOE 2011c	25% reduction in energy for process heat	Potential to reduce energy consumption by 25% for process heat.	Referencing MECS 2010 data, 141 TBtu of direct end use for process heating. This equates to 43% of direct end use. 25% savings of 43% energy use results in 11% average savings. Practical minimum specific energy savings of 11% over CT applied to all processes.	11% savings over Ct for all processes

The four bandwidth measures are current typical; (CT), state of the art (SOA), practical minimum (PM), and thermodynamic minimum (TM).

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Appendix A5: Practical Minimum Technology Weighting Factors

METHODOLOGY TO DETERMINE WEIGHTING FACTORS

In this section the practical minimum technology weighting factors methodology is explained. The application of this methodology is presented in Table A4.

Six Weighting Factors, A through F, are considered for each technology and scored as shown (High (H) = 3, Medium (M) = 2, Low (L) = 1, Not Available (NA) = 0). The factors are also scaled according to DOE Importance Level, e.g., an importance level of 2 carries twice the weight of an importance level of 1. For the pulp and paper bandwidth, factors A-F each carried a DOE Importance Level of 1.

The DOE Importance Level is multiplied by the score for each factor and divided by the total possible score to determine overall weighting of technology. The NA score of 0 is excluded from overall weighting.

Factor A - Technology Readiness

- High = Technology Readiness Level (TRL) 7-9
- Medium = TRL 4-6
- Low = TRL 1-3

Factor B - Market Impact

- High = widely applicable to all establishments
- Medium = applicable to many establishments
- Low = applicable to select few establishments or unique process

Factor C - Relative Cost and Savings Payback

- High = implementation cost >90% of reference technology, or payback > 10 years
- Medium = cost <90% and >40% of reference technology, payback <10 years
- Low = cost <40% of reference, payback < 2 years

Note: the score is reversed such that H = 1 and L = 3

Factor D – Technical Risk

- High = high likelihood of technology success and deployment, minimal risk factors
- Medium = insufficient evidence of technology success, some risk factors
- Low = low likelihood of success, multiple and significant risk factors

Note: the score is reversed such that H = 1 and L = 3

Factor E – Productivity/Product Quality Gain

- High = significant gain in productivity, either quantity or quality of product produced
- Medium = moderate gain in productivity
- Low = no gain in productivity

Factor F – Environmental Benefits

- High = multiple and significant environmental benefits,
- Medium = some environmental benefits,
- Low = little or no environmental benefit

Table A5. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Pulping Processes													
Black Liquor Gasification (BLG)	M	Engineering judgment	M	Even though applies only to kraft process, majority of pulp produced in U.S. is kraft pulp	H	Investment is 60 to 90% higher than standard boiler system; 15 year payback	M	Moderate process change	M	May increase pulp yield 5 to 7 percent	na	na	60%
Directed Green Liquor Utilization	M	Engineering judgment	M	Even though applies only to kraft process, majority of pulp produced in U.S. is kraft pulp	L	Reported as minimal capital investment	H	Engineering judgment	H	Increases pulp yield .	M	Reduces alkali consumption by as much as 50% and reduces energy consumption by up to 25%	72%
Membrane concentration of Black Liquor	M	TRL5	M	Even though applies only to kraft process, majority of pulp produced in U.S. is kraft pulp	L	Goal is to reduce the payback period to <2 years	H	Engineering judgment	H	Engineering judgment	na	na	73%

Table A5. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Pulping Processes (continued)													
Dry Kraft Pulping	L	Engineering judgment	M	Even though applies only to kraft process, majority of pulp produced in U.S. is kraft pulp	L	Lower capital costs	H	Engineering judgment	na	na	M	Save about 50 wt% NaOH and about 3 wt% Na_2S.	60%
Oxalic Acid Technology	H	TRL 7 - demonstrated at pilot scale	L	Majority of U.S. pulp kraft, not mechanical	L	Payback of 2 years or less	L	Engineering judgment	M	Improves paper strength	na	na	80%
Papermaking													
Condebelt Drying	H	TRL 9	M	Not suitable for high basis weight papers	H	High capital costs	M	Engineering Judgment	M	Strength improvements, 5-15 times higher drying rates	na	na	67%
New Fibrous Fillers	H	TRL 8 - Engineering Judgment	H	Could be used in all paper and board products	H	High capital costs	M	Engineering Judgment	M	Creates additional revenue	M	Reduces use of wood fillers	72%
High Consistency Forming	M	TRL 4 - Engineering Judgment	L	Applicable to only certain grades	H	Engineering Judgment	M	Engineering Judgment	na	na	na	na	50%

Table A5. Practical Minimum Technologies Analysis with Weighting Factors

Importance Level	1		1		1		1		1		1		
Technology Name	Technology Weighting Factors												Overall Importance Rating
	A – Technology Readiness		B- Market Impact		C- Relative Cost and Savings Payback		D- Technical Risk		E – Productivity/ Product Quality Gain		F- Environmental Benefits		
	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	H, M, or L	Explanation	
Papermaking (continued)													
Pulse Drying of Paper Pulp	L	TRL 2 - Engineering Judgment	M	Applies either directly or indirectly	M	High cost, 3-6 year payback	M	Engineering Judgment	H	Speeds up paper production by 21%	na	na	67%
Gas Fired Drum Dryer	H	TRL 7 – demon-strated at pilot scale	H	Wide applicability for paper and paperboard	M	Lower capital investment	M	Engineering Judgment	H	Increase production rate by 10-20%/paper drying rate by 2-3 times	M	Reduce NO_x emissions	83%
Dry Sheet Forming	M	TRL 1-3 for standard paper; TRL 9 for tissue	M	Currently applicable to ~5% of total paper production, but in development for standard paper	M	Lower investment costs	M	Engineering Judgment	L	Some product quality issues	M	Reduces wastewater	61%
New Manufacturing Method for Paper Filler and Fiber Material	M	TRL 5 - Engineering Judgment	M	Applicable to printing and writing paper grades	H	Estimated to be >100% of cost	M	Engineering Judgment	L	Quality may be affected	na	na	50%

Table A5. Practical Minimum Technologies Analysis with Weighting Factors													
Importance Level	**1**		**1**		**1**		**1**		**1**		**1**		
Technology Name	**Technology Weighting Factors**												**Overall Importance Rating**
	A – Technology Readiness		**B- Market Impact**		**C- Relative Cost and Savings Payback**		**D- Technical Risk**		**E – Productivity/ Product Quality Gain**		**F- Environmental Benefits**		
	H, M, or L	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	**H, M, or L**	**Explanation**	
Crosscutting Technologies													
Microturbines	H	Engineering Judgment - TRL 9	L	Small targeted application	H	Major capital investment	M	Moderate process change	NA	Engineering judgment	H	Large energy savings	56%
New High-Temperature, Low-Cost Ceramic Media for Natural Gas Combustion Burners	H	Engineering Judgment - TRL 7	H	Wide ranging applications	M	Moderate capital investment	M	Moderate process change	M	Better heating	H	Large energy savings	83%

Appendix A4 provides the methodology used to identify the weighting factors and the definitions for the abbreviations.

Appendix A6: Practical Minimum Energy Intensity Summary (2006 Method)

See DOE AMO Web site for full Excel Workbook

Appendix A7: Thermodynamic Minimum Energy Intensity Conditions

Table A7-1. Minimum Thermodynamic Drying Energy Intensity

(70% Exiting Press Solids) (Calculations as in Table C, Tab G – Drying Calculations, DOE 2006a)

Condition	Value	Notes
Sheet temperature	50 ºC	Assume no energy needed for: • Heating supply air • Heating leakage air • Heat leakage through hood walls and roof
Evaporation temperature	100 ºC	
Heat of evaporation at 70ºC	2333 kJ/kg	
Steam temperature in dryer can	120 ºC	
Heat of condensation at 120ºC	2,203 kJ/kg	
Specific heat of water	4.18 kJ/kg/ºC	
Specific heat of fiber	1.25 kJ/kg/ºC	
Moisture ratio of entering sheet	0.4286 kg water/kg fiber	
Moisture ratio of exiting sheet	0.05 kg water/kg fiber	
Heat of sorption	175 kJ/kg	
Moisture ratio @start of desorption	0.3 kg water/kg fiber	
Moisture ratio @end of desorption	0.05 kg water/kg fiber	
Energy to heat water	89.6 kJ/kg fiber	Mass of all water x specific heat x temperature change
Energy to heat fiber	62.5 kJ/kg fiber	Mass of fiber x specific heat x temperature change
Energy to evaporate water	883 kJ/kg fiber	Mass of evaporated water heat of vaporization
Energy to desorb water	44 kJ/kg fiber	Mass of desorbed water x heat of sorption
Total energy required	1,079 kJ/kg fiber	
Total energy required	**0.88 MMBtu/fst paper**	
kJ energy req'd/kJ steam condensed	1.29 kJ/kJ	Total energy/(heat of condensation x mass evaporated water)

Table A7-2. Thermodynamic Minimum Evaporation Energy Intensity (with Membrane) (Calculations as in Table 8.6, DOE 2006a)

Condition	Value	Explanation
Weak black liquor solids (WBLS) concentration before evaporation	30%	13-15% is "average'" 17% is SOA with drum washers considering soda loss/energy balance
Solids concentration after evaporation	80%	Normal range is 62-80% with 70% considered "good"; SOA is 80%
Number of effects	4	Also, assume that evaporation in each effect is the same. Note that there is no steam economy into account directly (steam economy = (0.8)N where N=7. This would give steam economy = 5.6, which is close to design; actual can be only 70% of that.)
Amount BLS/unit amount of pulp	3,200	
Specific Heat of WBL, Cpl	0.8 Btu/lb ºF	
Product liquor from first effect, Tb	275 ºF	
Liquor feed temp, Ti	200 ºF	
Average latent heat of steam for entire evaporator set, λb	980 Btu/lb	
Sensible heat to bring WBLS to boiling temperature	640,000 Btu/BDmt	Mass of BL entering evaporator x BL specific heat x (liquor boiling T entering vapor head – liquor inlet T)
Latent heat of vapor produced (water evaporated)/(no. of effects)	1,633,333 Btu/BDmt	Vapor produced (water evaporated) x latent heat of steam at boiling conditions
Total energy required	**2,273,333 Btu/BDmt (1.9 MMBtu/adst)**	

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