Title

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Emerging Energy-efficiency and Greenhouse Gas Mitigation Technologies for the Pulp and Paper Industry

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Abstract

The pulp and paper industry ranks fourth in terms of energy consumption among industries worldwide. Globally, the pulp and paper industry accounted for approximately 5 percent of total world industrial final energy consumption in 2007, and contributed 2 percent of direct carbon dioxide (CO_2) emissions from industry. Worldwide pulp and paper demand and production are projected to increase significantly by 2050, leading to an increase in this industry's absolute energy use and greenhouse gas (GHG) emissions. Development of new energy-efficiency and GHG mitigation technologies and their deployment in the market will be crucial for the pulp and paper industry's mid- and long-term climate change mitigation strategies. This report describes the industry's processes and compiles available information on the energy savings, environmental and other benefits, costs, commercialization status, and references for 36 emerging technologies to reduce the industry's energy use and GHG emissions. Although studies from around the world identify a variety of sector-specific and cross-cutting energy-efficiency technologies that have already been commercialized for the pulp and paper industry, information is scarce and/or scattered regarding emerging or advanced energy-efficiency and low-carbon technologies that are not yet commercialized. The purpose of this report is to provide engineers, researchers, investors, paper companies, policy makers, and other interested parties with easy access to a well-structured resource of information on these technologies.

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Acronyms

Adt	air dry tonne
ANL	Argonne National Laboratory
BCP	Beck cluster press
BLG	black liquor gasification
BLGCC	black liquor integrated gasification with combined cycles
BOD	biological oxygen demands
$CaCO_3$	calcium carbonate/limestone
CaO	lime
$Ca(OH)_2$	calcium hydroxide
CCS	carbon capture and storage
CH_4	methane
CHP	combined heat and power production
CO	carbon monoxide
CO_2	carbon dioxide
COD	chemical oxygen demand
DIP	deinked pulp
DME	dimethyl ether
D-GLU	directed green liquor utilization
DS	dry solids
EC	European Commission
EJ	exajoules
g	gram
GHG	greenhouse gas
GJ	gigajoules
GRI	G. R. International
GTI	Gas Technology Institute
GWh	gigawatt-hour
H_2	hydrogen
H_2O	water
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
IPCC	Intergovernmental Panel on Climate Change
IPST	Institute of Paper Science and Technology at Georgia Tech
IR	infrared
kg	kilogram
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
LEF	low-energy flotation

m	meter
MEA	mono-ethanolamine
mm	millimeter
Mt	million tonnes
Mtoe	million tonnes of oil equivalent
MWh	megawatt hour
Na_2S	sodium sulfide
Na_2CO_3	sodium carbonate
NaOH	sodium hydroxide
NOx	nitrogen oxide
O_2	oxygen
O_3	ozone
OA	oxalic acid
O&M	operations and maintenance
ORNL	Oak Ridge National Laboratory
PCC	precipitated calcium carbonate
R&D	research and development
RMF PCC	recycled mineral filler precipitated calcium carbonate
RMP	refiner mechanical pulping
SO_2	sulfur dioxide
syngas	synthetic gas
t	tonne
TJ	terajoules
TMC	transport membrane condenser
TMP	thermomechanical pulp
TiO_2	titanium dioxide
tpd	tonnes per day

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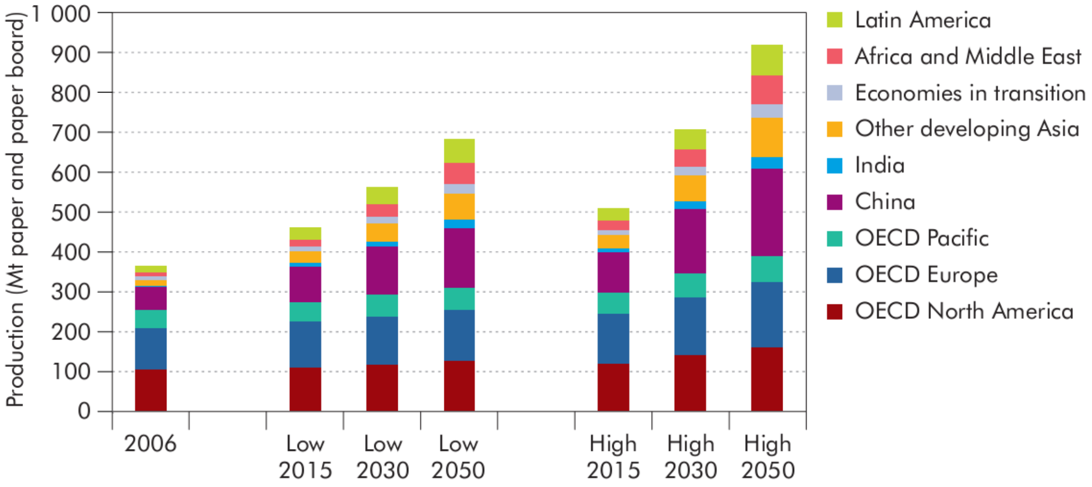
1. Introduction

The pulp and paper industry accounted for approximately 5 percent of total industrial final energy consumption and 2 percent of direct carbon dioxide (CO_2) emissions[1] from the industrial sector worldwide in 2007 (IEA 2011). World paper and paperboard demand and production are increasing; annual production is expected to grow from approximately 365 million tonnes (Mt) in 2006 to between 700 Mt (low estimate) and 900 Mt (high estimate) in 2050. In 2010, the paper and paperboard reached 394 Mt (FAOSTAT 2012). The largest share of this growth will take place in China, India, and other developing countries (Figure 1) (IEA 2009). This significant increase in paper production will cause a corresponding significant increase in the pulp and paper industry's absolute energy consumption and greenhouse gas (GHG) emissions.



Note: OECD is an acronym for the Organization for Economic Co-operation and Development

Figure 1. Annual world paper and paperboard production (IEA 2009)

Studies have documented the potential to reduce energy use and GHG emissions by implementing commercially available energy-efficiency technologies and measures in the pulp and paper industry worldwide (Worrell *et al.* 2001; Kinstrey and White 2006; IEA 2007; UNIDO

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[1] Direct CO_2 emissions are emissions from fossil fuel use and chemical reactions produced onsite and do not include emissions associated with purchased steam and electricity.

2010b; Zafeiris 2010; IEA 2011). However, given the projected continuing increase in absolute paper production, future reductions (e.g., by 2030 or 2050) in absolute energy use and CO_2 emissions will require additional innovations. Innovations will likely include development of different processes and materials for pulp and paper production or technologies that can economically capture and store the industry's CO_2 emissions. The development of these emerging technologies and their deployment in the market will be a key element in the pulp and paper industry's mid- and long-term climate change mitigation strategies.

Many studies from around the world have identified energy-efficiency technologies for the pulp and paper industry that have already been commercialized and are sector-specific or cross-cutting (Jaccard/Willis 1996; Alsema 2001; EC 2001; FOE 2005; ITP 2006c; NEDO 2008; Kramer *et al.* 2009; Bajpai 2010; EPA 2010; Zafeiris 2010; CEPI 2011b; ITP 2011c). However, information is scarce and scattered regarding emerging or advanced energy-efficiency and low-carbon technologies for the pulp and paper industry that have not yet been commercialized. This report consolidates available information on emerging technologies for the pulp and paper industry with the goal of giving engineers, researchers, investors, pulp/paper companies, policy makers, and other interested parties easy access to a well-structured resource of information on this topic.

The information presented in this report is collected from publicly available sources. Although the report covers the main emerging energy-efficiency and low-carbon technologies for the pulp and paper industry, the list of emerging technologies addressed is not exhaustive.

We present information about the 36 technologies covered in this report using a standard structure for each technology. First, we briefly describe the technology, including background, theory, pros and cons, barriers and challenges, and case studies if available. Next, we present the energy, environmental, and other benefits of the technology as well as cost information if available. For most technologies, we include a block diagram or picture. Finally, we identify the commercialization status of each technology along with resources for further information. The commercialization status for each technology is as of the writing of this report and uses the following categorization:

- Research stage: the technology has been studied, but no prototype has been developed.
- Development stage: the technology is being studied in the laboratory, and a prototype has been developed.
- Pilot stage: the technology is being tested at an industrial-scale pilot plant.
- Demonstration stage: the technology is being demonstrated and tested at the industrial scale in more than one plant but has not yet been commercially proven.
- Semi-commercial stage: the technology is proven and is being commercialized but has a very small market share.

Table 1 lists the 36 technologies covered in the report. It is important to note that the nature of emerging technologies is that many are proprietary and/or the primary source of information about them is the manufacturers who are developing them. In some cases, we mention the names of companies that are developing or providing a technology so that readers can obtain more information about the company and product. The purpose of this report is solely informational. Depending of their current commercialization status, most of these technologies need different levels of research, development, and demonstration before being ready to be fully commercial.

Table 1. Emerging energy-efficiency and GHG mitigation technologies for the pulp and paper industry

No.	Section	Category/Technology Name	Commercialization Status
	3.1.	**Emerging Pre-treatment Technologies**	
1	3.1.1.	Microwave Pre-treatment for Chemical Pulping	Development stage
2	3.1.2.	Biological Pre-treatment for Mechanical Pulping	Enzymatic pre-treatment: Pilot stage; Fungal pre-treatment: Semi-commercial
3	3.1.3.	Chemical Pre-treatment with Oxalic Acid for Mechanical Pulping	Pilot stage
	3.2.	**Emerging Pulping Technologies**	
4	3.2.1.	Directed Green Liquor Utilization Pulping	Demonstration stage
5	3.2.2.	Membrane Concentration of Black Liquor	Development stage
6	3.2.3.	Dual-pressure Reheat Recovery Boiler	Pilot stage
7	3.2.4.	Borate Auto-causticizing	Full Auto-causticizing: Development stage; Partial Auto-causticizing: Semi-commercial stage
8	3.2.5.	Steam Cycle Washing	Demonstration stage
9	3.2.6.	Recycled Paper Fractionation	Demonstration stage
10	3.2.7.	New Flotation Deinking	OptiCell Flotation^{TM}, Deaeration Foam Pump 4000^{TM}, and Low Energy Flotation^{TM}: Semi-commercial; Mac Flotation Cell: Demonstration stage.
11	3.2.8.	Surfactant Spray Deinking	Demonstration stage
12	3.2.9.	Pulsed Power Technology for Decontamination of Recycled Paper	Demonstration stage
	3.3.	**Emerging Papermaking Technologies**	
13	3.3.1.	Aq-vane Technology	Development stage
14	3.3.2.	High Consistency Papermaking	Pilot stage
15	3.3.3.	Dry Sheet Forming	Semi-commercial stage for specialty paper products; Development stage for producing standard paper grades
16	3.3.4.	Displacement Pressing	Development stage
17	3.3.5.	New Fibrous Fillers	Pilot stage
18	3.3.6.	Laser Ultrasonic Stiffness Sensor	Demonstration stage
	3.4.	**Emerging Paper Drying Technologies**	
19	3.4.1.	Gas-fired Dryer	Pilot stage
20	3.4.2.	Boost Dryer	Pilot stage
21	3.4.3.	Condebelt Drying	Semi-commercial stage
22	3.4.4.	Microwave Drying	Development stage
	3.5.	**Emerging Byproducts/Biomass/Waste Heat Utilization Technologies**	
23	3.5.1.	Black Liquor Gasification	Atmospheric low-temperature BLG: Demonstration stage; Pressurized high-

No.	Section	Category/Technology Name	Commercialization Status
			temperature BLG: Pilot stage
24	3.5.2.	Biomass Gasification	Different commercial status for different biomass gasification concepts, most of which are under pilot and demonstration stage currently
25	3.5.3.	Hemicellulose Extraction before Chemical Pulping	Pilot stage
26	3.5.4.	LignoBoost	Pilot stage
27	3.5.5.	Other Integrated Biorefinery	Commercial status for biomass combustion, biogas production; semi-commercial and demonstration for thermal gasification; research and pilot for pyrolysis
28	3.5.6.	Use of Residuals in Concrete Production	Pilot stage
29	3.5.7.	Transport Membrane Condenser	Semi-commercial stage for industrial boilers; Research stage for paper machine dryer section
	3.6.	**Emerging Carbon Capture and Storage Technologies for the Pulp and Paper Industry**	
30	3.6.1.	BLGCC with Pre-combustion Carbon Capture	Development stage
31	3.6.2.	Biomass Conversion with Pre-combustion Carbon Capture	Research stage
32	3.6.3.	Oxy-fuel Combustion Technology	Pilot stage
33	3.6.4.	Post-combustion Carbon Capture Using Chemical Absorption	Pilot stage
34	3.6.5.	Bio-Technological Carbon Capture	Development stage
35	3.6.6.	CO_2 Sequestration in Recycled Mineral Fillers	Pilot stage
36	**3.7.**	**Nanotechnology in Pulp and Paper Production**	Research stage

Because the nature of emerging technologies is constant and rapid change, the information presented in this report is also subject to change. If readers are aware of a new technology that is not presented in this report or have updated information about a technology that is described in this report, please contact the authors[2].

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2. Description of Pulp and Paper Production

The pulp and paper industry produces various types of pulp from virgin materials (wood and non-wood) and/or recycled materials (waste paper) 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 (EC 2001).

Before pulping, the raw materials have to be prepared to break down fibrous materials into small pieces and remove impurities. Pulp can be manufactured by chemical, mechanical, or semi-chemical methods. Bleaching may be required depending on the paper produced; bleaching entails a chemical reaction that removes additional lignin from brown pulp. In an integrated mill, prepared pulp is pumped to beating and stock preparation processes where different kinds of paper are manufactured; in a non-integrated pulp mill, the next step is pulp drying, which is also done with excess pulp produced in integrated mills. The subsections below describe the process by which pulp and paper are produced in more detail, with a focus on the energy and GHG impacts.

2.1. Pulp and Paper Production Processes and Energy Use

The major steps involved in manufacturing pulp and paper are: raw materials preparation, pulping, chemical recovery, bleaching, pulp drying, and papermaking. Pulping and paper drying are the most significant energy-consuming processes (Worrell *et al*. 2008). Figure 2 shows a flow diagram of the entire pulping and papermaking process. The actual manufacturing process in a pulp or paper mill varies depends on the raw materials employed and the paper products produced. However, the basic principle of pulping and papermaking remains the same for all facilities.

Raw Materials Preparation

The raw materials for pulp making can be wood, non-wood, or recycled paper. Wood is the primary source of cellulose fiber for paper products. Both softwood and hardwood are used. Non-wood (e.g., straw, bagasse, and bamboo) is also used in some areas with limited access to forest resources, especially in developing countries. Worldwide, non-wood materials make up about 6 percent of the total fiber supply for papermaking (IFC 2007). Waste paper has become another important raw material for papermaking as technology from removing ink (deinking) has developed. Using waste paper reduces the energy consumption of the process because recycled paper only has to be treated to remove impurities whereas virgin fibrous materials require more pre-treatment, digesting, and refining[3]. Current levels of paper recovering rate vary from 30 percent in the Russian Federation to more than 60 percent in Japan and Germany (IEA 2012). In 2011, 66.8 percent of all paper consumed in the U.S. was recovered for recycling (AF&PA 2012). Note that not all the paper recycled in the U.S. is used domestically. Much of the recycled paper is exported to China and is used as input to the Chinese pulp and paper mills. Nearly 63 percent

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[3] It should be noted that virgin paper production is critical to a functioning recycled paper sector. Without a constant feed of virgin material, the supply of recycled paper would be exhausted in a short period of time.

of the fiber raw material for papermaking in China came from recycled paper in the year of 2010[4] (CTAPI 2011).

The purpose of raw materials preparation is to remove impurities and cut the raw fibrous material into small chips or pieces suitable for the pulping unit. Wood preparation consists of de-barking, cutting, chipping, screening, and conveying. De-barking consumes about 8.5 kilowatt hours per tonne (kWh/t) wood, and chipping and conveying together use 30.3 kWh/t wood material (Martin *et al.* 2000a). A uniform chip size is necessary to maximize the quality and efficiency of the pulping process. Non-wood materials are handled in ways specific to their composition in order to minimize degradation of the fiber. Recycled paper is treated only to remove the impurities, using a small amount of electricity compared to what is required for pre-treatment of other types of raw materials. Among the different raw materials, wood preparation uses more energy. However, byproducts of wood preparation (e.g., bark and fines) are usually used as fuel for generating additional energy (steam or electricity), which offsets some requirements for fuel imported from off-site.

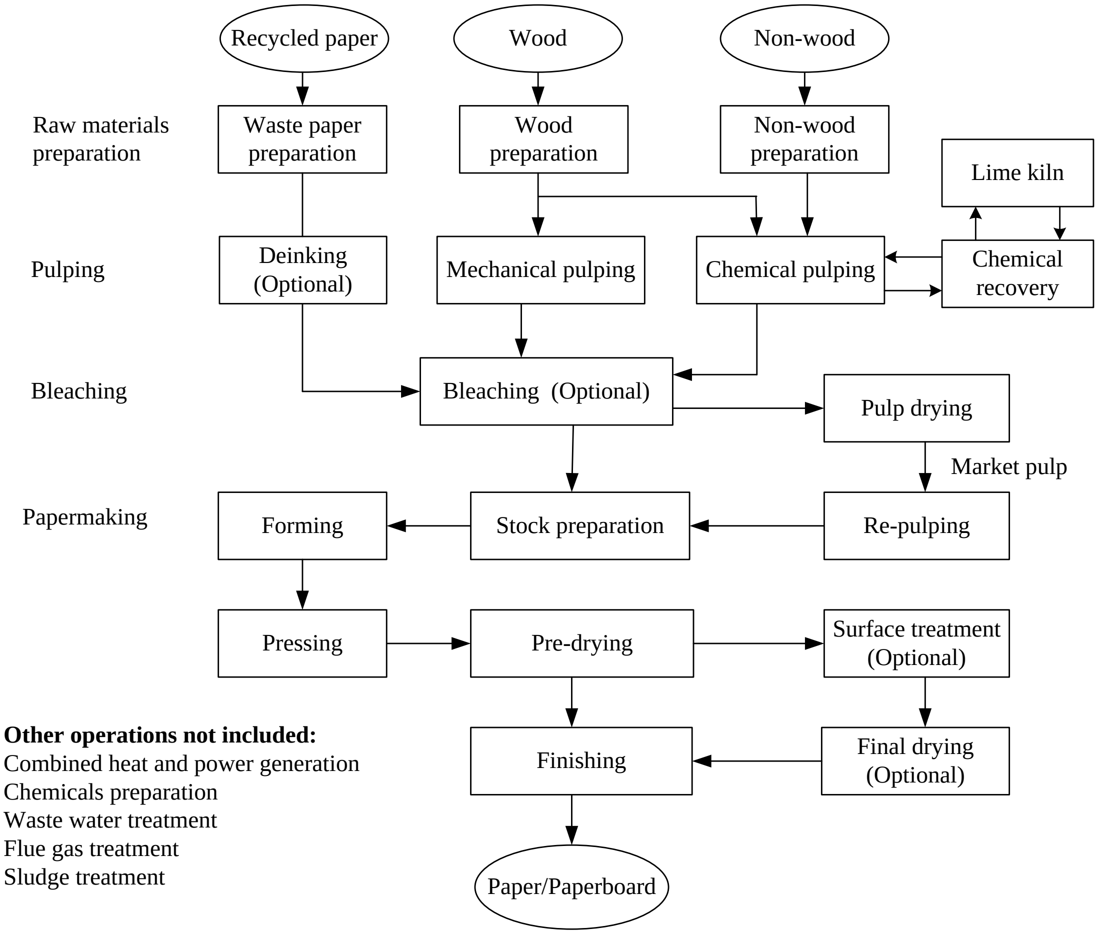

Figure 2. Flow diagram of the pulping and papermaking process

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[4] Although the utilization rate of recycled paper in China is high, large amount of the recycled paper (about 40% of the recycled paper used in China in 2010) is imported from developed economies across the world.

Pulping

Cellulose is the fibrous substance found in plant cells that are used to make pulp and paper; lignin acts as an adhesive holding the fibers together. The primary purpose of pulping is to separate fibers from lignin through chemical or mechanical measures to make the fibers suitable for papermaking. There are three types of pulping technologies: chemical (soda, sulfate/kraft, or sulfite), mechanical (e.g., SGW, RMP, TMP, or CTMP [5]), and semi-chemical pulping technologies. The pulping method employed in a given mill depends on the raw materials, the desired pulp properties, and the type of paper produced. Of the three types, chemical pulping is the most common pulping process. Globally, about 75 percent of wood pulp was produced with chemical pulping technology in 2010 (FAOSTAT 2012).

Chemical pulping relies on chemical reaction in an aqueous chemical solution and high temperature (thermal energy) to separate fibers by softening and dissolving the lignin that holds them together. Approximately 80 percent of the world pulp production worldwide uses the kraft process due to its advantages over the other methods (EC 2012). Mechanical pulping separates the fibers by physical treating method such as refining or grinding; the lignin remains in the pulp. Semi-chemical pulping is a combination of chemical and mechanical pulping in which wood chips are subjected to a mild chemical digestion process before being mechanically pulped. Generally, chemical pulping has a lower yield (45-55 percent) but higher pulp quality than mechanical pulping; the pulp quality and yield from semi-chemical pulping fall in between the quality and yield from the other two processes. Chemical pulping consumes 7.5-16.5 gigajoules (GJ) of thermal energy per tonne of air dried pulp (steam for producing electricity not included) and 550-900 kWh of electricity per tonne of pulp (EC 2012). Mechanical pulping processes are electricity intensive. The specific energy consumption in mechanical pulping is 1000-4300 kWh/Adt pulp for different mechanical pulping methods (SGW, RMP, TMP, or CTMP) (EC 2012). Pulping process is the second most energy-intensive process in the pulp and paper industry after the paper drying process.

When recycled paper is used as raw material, bales of waste paper are conveyed to pulpers and mixed with water via rotors or agitators that turn it into wet slurry. If deinking is required, the most commonly used process is flotation, in which chemicals are added during pulping that remove the hydrophobic ink from the fiber (as well as “stickies” – adhesives and other sticky products found in waste paper) and keep the ink particles suspended in the slurry. During the deinking process, the adsorption of dispersant and frother on fiber surfaces may reduce fiber-fiber bonding and create foaming problems in paper machines. The production of recycled paper pulp consumes 10 to 13 GJ less energy per tonne than the production of virgin pulp, depending on whether it is de-inked and whether it replaces mechanical or chemical pulping of other raw materials (IEA 2012). Schumacher and Sathaye (1999) report that producing paper from waste paper requires 40 to 60 percent less energy than producing paper from wood (Schumacher and Sathaye 1999).

Chemical Recovery

Chemical recovery is an important element for kraft/sulfite pulping process because it regenerates the pulping chemicals and energy from what is known as black/red liquor. Black/Red liquor is the

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[5] SGW = stone groundwood pulp, RMP = refiner mechanical pulp, TMP = thermomechanical pulp, and CTMP = chemi-thermomechanical pulp.

solution of residues from cooking or digesting raw materials to free the cellulose fibers in kraft/sulfite pulping process, which mainly include cooking chemicals and combustible component dissolved from raw materials, such as lignin and hemicellulose. The chemicals recovered from black liquor are reused in subsequent pulping. In addition, a large amount of energy can be generated by combusting the black liquor in recovery boilers. Chemical recovery is essential to the cost-effective operation of kraft pulp mills and is used in more than 80 percent of the U.S. wood pulp production (DOE 2005a).

Chemical recovery typically starts with brown stock washing of the pulp, followed by black liquor evaporation. This step uses the largest amount of steam in a kraft mill, about 2.2 to 5.4 GJ/t pulp (DOE 2005a). After being concentrated through evaporation and/or additional concentration operation, black liquor is sent to the recovery boiler for recovering the chemicals and energy by combustion. The recovery boiler uses an estimated 1.2 to 4.2 GJ/t pulp of fuel and electricity for furnace auxiliaries. However, the boiler also produces 9 to 15 times as much energy in the form of heat (Martin *et al.* 2000a). Roughly 22 GJ of black liquor can be combusted per tonne of pulp (IEA 2007). A large modern chemical pulp mill could be self-sufficient in energy terms, using only biomass and delivering surplus electricity to the grid (IEA 2011). After the black liquor is evaporated and combusted, the green liquor (the molten inorganic smelt formed in the recovery boiler with wash water) is causticized to regenerate pulping chemicals (white liquor) for the next digesting process. Lime kiln is an integral part of the chemical recovery system at kraft pulp mills. The lime mud ($CaCO_3$) exhausted from the causticizers will be calcined or reburned in lime kilns where $CaCO_3$ is converted back into lime (CaO) for reuse in the recausticing process (Miner and Upton 2002). Large amount of energy is used in lime kilns with high levels of process-related CO_2 emissions[6].

Bleaching and Pulp Drying

Bleaching is required for producing paper products with higher brightness such as printing and writing papers. The chemical reactions involved in bleaching remove the remaining lignin from the pulp. The most common bleaching chemicals are, chlorine dioxide, sodium hydroxide (NaOH), hydrogen peroxide, oxygen (O_2), ozone (O_3), and hypochlorite. Environmental concerns about chlorinated organic byproducts from elemental chlorine and its derivatives have driven the industry toward the development and use of elemental chlorine-free and totally chlorine-free bleaching technologies (DOE 2005a). Chemical pulp can be bleached to a greater extent because of its lower lignin content than mechanical pulp. The bleaching process is heat intensive but consumes only a small amount of electricity. The heat requirements range from 0.4 to 3.2 GJ/t pulp, and electricity requirements range from 60 to 185 kWh/t pulp (DOE 2005a).

In standalone pulp mills, the beached/unbleached pulp is pumped to pulp drying process. While the bleached/unbleached pulp is pumped to beating and stock preparation process directly for papermaking in integrated mills. Also, the pulp must be dried before transport to the paper mill in standalone mills. Pulp drying is an energy-intensive process that typically uses 4.5 GJ/t pulp of thermal energy and 155 kWh/t pulp of electricity (Martin *et al.* 2000a). The large amount of

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[6] Note the emissions from kraft pulp mill lime kilns contain both biomass and fossil carbon. The process-related CO_2 emissions that released from calcium carbonate originate in the wood chips and, generally, biomass based carbon are not included in GHG inventories (Miner and Upton 2002).

energy expended for pulp drying can be saved by integrating pulp and paper production into a single mill.

Papermaking

Papermaking is a process for laying pulp fibers uniformly in a planar web followed by a massive dehydration process. No matter what type of pulp is used or what type of paper is produced, the basic papermaking procedure follows the steps shown in Figure 2: beating and stock preparation, forming, pressing, drying, and finishing.

Beating and stock preparation process is an important intermediate step between the pulp and paper production lines and determines the final properties of the paper product. In this process, the pulp is refined or beat, blended, and screened to separate and clean the fibers. The stock consistency pumped to the headbox is about 0.2 to 1.0 percent (2-10 g fiber per kg water). Next, the stock is pumped to the paper machine through stock approach system. The headbox is employed to dispense the stock evenly onto fabric mesh spanning the entire width of the paper machine to form a paper web. A large amount of water within the stock is removed from the web by drainage and vacuum thickening in the forming section, after that a wet-sheet is formed. At the end of the forming process, the wet-sheet contains about 75 to 85 percent water. The wet-sheet then moves to the press section for dewatering by mechanical compression. The wet-sheet leaves the press section into the dryer section with water content of 45 to 67 percent, depending on the paper grade and press section design (Karlsson 2000). In the subsequent drying process, the remaining water is removed from the wet-sheet by evaporation. The final paper moisture content after the dryer section is 2 to 9 percent. Many types of paper also undergo surface treatments to improve printability and to add functional properties. Paper finishing is the last operation, which includes calendering, reeling, winding, trimming, roll wrapping and handling, and sheet finishing.

Papermaking is the most capital- and energy-intensive process in the pulp and paper industry. In addition to the electricity used for driving paper machine, various pumps, fans, motors, and conveyors, the process also uses thermal energy to dry paper. The paper drying process accounts for about 67 percent of the total energy required in papermaking, equivalent to 25 to 30 percent of the total energy used in the pulp and paper industry (IEA 2009). The electricity used for beating and stock preparation depends on the paper type and varies from 60 to 1,200 kWh/t paper (IEA 2007). The typical heat consumption for paper drying is 3 to 6 GJ/t paper, and electricity usage is 450 to 1,100 kWh/t paper (EC 2001). It should be noted that the energy consumption of the papermaking process varies greatly according to the pulp quality, paper grade produced, and technologies employed, etc.

2.2. GHG Impact of the Pulp and Paper Industry

GHG emissions from the pulp and paper industry are predominantly CO_2 with smaller amounts of methane (CH_4) and nitrous oxide (N_2O) (EPA 2009). The pulp and paper industry ranks fourth in terms of energy consumption among industries worldwide; however, it is one of the least CO_2-intensive industrial sectors because many plants utilize a significant percentage of biomass, although large variations exist among countries depending on biomass availability and industrial structure. Globally, the pulp and paper industry meets approximately 33 percent of its total energy use needs with biomass (IEA 2010a). In Organization for Economic Cooperation and Development (OECD) countries, biomass supplies 53.6 percent of energy use in the pulp and paper industry (WBCSD 2011). The U.S. pulp and paper industry gets more than 65% of energy from biomass (EIA 2011; AF&PA 2012). Note that CO_2 emissions from biomass fuels are considered carbon neutral by the Intergovernmental Panel on Climate Change (IPCC) (IPCC 2006). The widely use of biomass is the primary reason for the difference in CO_2 intensity between the paper industry and other industrial sectors. For some types of paper, pulp and paper can be produced without CO_2 emissions theoretically if residues were used efficiently (IEA 2007).

The GHG emissions involved in the pulp and paper industry consist of direct and indirect emissions. Direct emissions are from combustion of fossil fuels onsite and also include non-energy-related emissions such as CO_2 emissions from chemical reactions in lime kilns and CH_4 emissions from mill landfills and wastewater treatment operations. Indirect emissions are associated with off-site generation of steam and electricity that are purchased by or transferred to the mill. Of these GHG emissions sources, energy-related emissions, such as those arising from onsite fossil fuel combustion and energy purchases/transfers, are by far the most significant (NCASI 2008). Table 2 details the industry's direct GHG emissions sources (EPA 2009, 2010).

Non-integrated paper mills emit more GHG emissions than integrated mills per unit of production because the availability of biomass is limited in these non-integrated (or fully recycled) paper mills; thus, the majority of CO_2 emissions from these mills are likely to be generated from fossil fuel consumption.

Table 2. Direct GHG emissions sources in the pulp and paper industry (EPA 2009, 2010)

GHG emissions source	Types of pulp/paper mill where emissions source located	Types of GHG emissions
Fossil fuel/Biomass-fired boilers	All types of pulp/paper mills	CO_2, biogenic CO_2, CH_4, N_2O
Thermal oxidizers (TOs) / Regenerative TOs	Kraft/Semi-chemical pulp mills	CO_2, CH_4, N_2O
Direct-fired turbines/dryers	Gas-fired turbines/dryers in some mills	CO_2, CH_4, N_2O
Chemical recovery boilers	Kraft/Sulfite/Soda pulp mills	CO_2, biogenic CO_2, CH_4, N_2O
Lime kilns	Kraft/Soda pulp mills	CO_2, process/biogenic CO_2, CH_4, N_2O
Make-up chemicals	Kraft/Soda pulp mills	process CO_2
Flue-gas desulfurization systems	Mills that operate coal-fired boilers are required to limit sulfur dioxide emissions	process CO_2
Anaerobic wastewater treatment	All types of pulp/paper mills	biogenic CO_2, CH_4
Onsite landfills	All types of pulp/paper mills	biogenic CO_2, CH_4

3. Emerging Energy-Efficiency and GHG Mitigation Technologies for the Pulp and Paper Industry

The subsections below describe emerging technologies that are claimed to be able to reduce energy consumption and GHG emissions associated with pre-treatment, pulping, and papermaking, technologies related to utilize byproducts and biomass, carbon capture as well as nanotechnologies applicable to the pulp and paper industry.

3.1. Emerging Pre-treatment Technologies

The subsection describes three emerging wood chip pre-treatment technologies: microwave, biological, and chemical (oxalic acid), which are applied prior to the pulping process and improve the energy efficiency of that process.

3.1.1. Microwave Pre-treatment for Chemical Pulping

Description

In traditional chemical pulping, most of the energy and chemicals are used for driving the chemical reactions in wood chips to cleave covalent bonds between fibers during pulping process. Microwave pre-treatment technology alters the cellular microstructures that control permeability in wood so that the pulping chemicals can pass more easily to the center of the chips, which reduces both the amount of energy and chemicals needed for the pulping process (DOE 2005b).

Microwave pre-treatment reduces the amount of energy required for chemical pulping because it lowers the H-Factor required to meet target performance characteristics, which is a measure of the relative speed of delignification in pulping process. Microwave pre-treatment can also result in decreased lime kiln fuel consumption because fewer chemicals are needed for the pulping process. It is claimed that microwave pre-treatment could decrease chemical usage and H-Factor by around 40 percent while still producing pulp with acceptable quality through breaking the cellular microstructures which control permeability in wood (Compere 2006). The technology also allows pulping chemicals to pass easily into larger and more diverse-sized wood chips, such as four-inch-long by four-inch-diameter hardwoods (ITP 2011c). Hemicellulose removal from black liquor could decrease viscosity and increase solids, correspondingly reduces the energy required for black liquor concentration (Compere 2006). However, microwave pre-treatment will increase the electricity use at the mill significantly. Also, it may results in potential damage to pulp fibers and loss of paper strength.

Microwave pre-treatment technology can be retrofitted into existing kraft, soda, sulfite, and other chemical pulp mills to increase both pulp yield and energy efficiency, and minimize chemical usage (ITP 2007a). In the U.S., it is estimated that the market for this technology will be up to 75 percent of chemical pulp mills (ITP 2007a). Assuming 55 million tonnes per year of chemical pulp in the U.S. pulp and paper industry, annual energy savings could be as much as 116,050 terajoules (TJ) (Compere 2006).

Energy/Environment/Cost/Other Benefits

Some of the claimed benefits of microwave pre-treatment technology compared to conventional pre-treatment technology are (OIT 2001a; DOE 2005b; Compere 2006; ITP 2007a):

- Reduces energy use for chemical pulping
- Decreases lime kiln energy use
- Reduces energy required for black liquor concentration
- Improves pulp yield and throughput by 40 percent in existing kraft pulp mills
- Reduces pulping chemicals and H-factor by 40 percent
- Decreases temperature required to produce a given quality of pulp
- Increases recovery boiler throughput
- Has a capital cost of about $25 million for a 1,000 air-dry-tonne (Adt) mill with payback shorter than 2 years

Block Diagram or Photo
Not Available

Commercial Status
Development stage

References for Further Information
OIT 2001a; DOE 2005b; Compere 2006; ITP 2007a, 2010, 2011c.

3.1.2. Biological Pre-treatment for Mechanical Pulping

Description

In the mechanical pulping process, cellulose fibers are usually separated in a grinder or refiner by means of mechanical force applied to the wood matrix. Mechanical pulping is one of the most electricity-intensive processes in the pulp and paper industry, consuming 2 to 3.5 megawatt hours (MWh) of energy per tonne pulp, depending on raw material and process conditions (ETEPS 2007). A rough estimate of the international best practice average electricity consumption for mechanical pulping is 2.75 MWh/tonne pulp (CAI/BECE 2009). Only a portion of the electricity used in grinders or refiners is converted into the mechanical work to liberate the fibers; the rest is converted to heat through friction. Although some of the heat produced in mechanical pulping is recovered and reused, biological pre-treatment of wood chips before refining could significantly reduce the energy requirement for mechanical pulping.

Biological pre-treatment uses fungus or enzymes to modify the cellular structure of wood chips. The purpose is to decrease energy consumption by modifying the cell wall of fibers and changing its external environment to enhance refining without jeopardizing pulp quality (Viforr 2008). Although biotechnology has successfully been used in other phases of the pulp and paper production process, it has been challenging in the wood chips pre-treatment because of size incompatibility between the molecules of enzymes and the dimensions of pores (Bajpai 2012).

The two common biological pre-treatment technologies used on wood chips in mechanical pulping are fungal and enzymatic. Fungal pre-treatment was implemented on a conventional mechanical pulping line in Wisconsin (U.S.) that produced 220 tonnes per day (tpd), reducing energy costs by 33 percent from 121$/tonne to 81$/tonne (Swaney *et al.* 2003a). Biological pre-treatment also improves fiber strength and reduces pitch content. However, it will increases bleaching chemical consumption. Because biological pre-treatment is an additional operation, operations and maintenance (O&M) costs also increase compared to costs of mechanical pulping without biological pre-treatment. But the overall costs of mechanical pulping with biological pre-treatment technology are lower than the costs without biological pre-treatment because of the large amount of energy saved with biological pre-treatment. A case study conducted by Swaney *et al*. (2003a) shows the net cost savings are about 18 $/t of furnish pulp at the mill studied in Wisconsin. Economic analyses indicate that fungal pre-treatment is both technologically feasible and economically beneficial (Kramer *et al*. 2009). The fungal pre-treatment of wood chips prior to mechanical pulping has also been scaled up and demonstrated at a TMP mill in Brazil (Swaney 2002).

Enzymatic pre-treatment of wood chips uses one or more enzymes such as cellulase, hemi-cellulase, xylanase, pectinase, or laccase (Wang *et al*. 2007). The cellulase, xylanase, and pectinase pre-treatments have been tested jointly by several partners (including KCL, STFI-Packforsk, CTP, VTT, Holmen Paper, Stora Enso, UPM-Kymmene and Metso) that use different types of equipment. Use of xylanase resulted in the greatest energy savings: a 25-percent decrease. Cellulase pre-treatment resulted in a 20-percent energy reduction, and pectinase pre-treatment reduced energy usage by 10 percent compared to refining without enzymatic pre-treatment (Viforr 2008). The main drawback of all enzymatic treatments is that they decrease fiber length. More work is needed to optimize the process and demonstrate its maximum potential before commercialization.

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for mechanical pulping with biological (fungal and enzymatic) pre-treatment:

a) Fungal pre-treatment

- Saves 25 to 40 percent of refining energy compared to conventional refining without biological pre-treatment (Scott *et al*. 1998)
- Improves paper quality, e.g., enhanced paper strength and reduced pitch content
- Extends refiner lifetime

b) Enzymatic pre-treatment

- Pectinase pre-treatment of wood chips – saves up to 20 percent of refining process energy (Peng *et al*. 2005)
- Xylanase pre-treatment of hardwood chips – saves up to 26 percent of refining process energy (Girard *et al*. 2006)
- Using cellulase and cellulase mixture pre-treatment of softwood chips – possibly reduces refining energy use by up to 20 percent (Pere *et al*. 2007)
- Enzymatic pre-treatment generally – possibly reduces refining energy by 10 to 25 percent reduction in refining energy consumption is possible when using enzymatic pre-treatment (ECOTARGET 2009)

Block Diagram or Photo

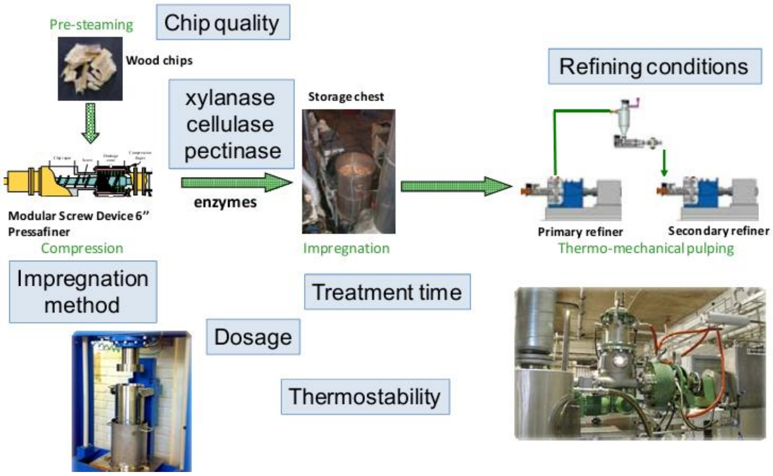

Figure 3. Enzymatic pre-treatment of wood chips for mechanical pulping (ECOTARGET 2009)

Commercial Status

a) Fungal pre-treatment
Semi-commercial stage

b) Enzymatic pre-treatment
Pilot state

References for Further Information

Scott *et al.* 1998; Swaney 2002; Swaney *et al.* 2003a; Peng *et al.* 2005; Girard *et al.* 2006; ETEPS 2007; Pere *et al.* 2007; Wang *et al.* 2007; Viforr 2008; CAI/BECE 2009; ECOTARGET 2009; Kramer *et al.* 2009; Bajpai 2012.

3.1.3. Chemical Pre-treatment with Oxalic Acid for Mechanical Pulping

Description

Similar to the biological pre-treatment technology explained above, chemical pre-treatment, which includes oxalic acid (OA) treatment, acid leaching, and electrochemically treated salt solutions, can be used on wood chips to enhance the process of separating fibers (known as defibration) and refining efficiency in mechanical pulping (ECOTARGET 2009). Chemical pre-treatment of wood chips can significantly reduce the energy consumed in the refining process and does not adversely affect the final paper product; under optimized conditions, chemical pre-treatment can improve web strength and paper brightness (Li *et al*. 2011).

OA pre-treatment is incorporated in a mechanical pulping in a manner similar to traditional chemical pre-treatments (Swaney *et al.* 2003b). BioPulping International Inc. of Wisconsin (U.S.) developed OA pre-treatment technology jointly with several industrial and university partners (ITP 2010). Brief pre-treatment of different types of wood chips using 0.05 to 6 percent of a dilute OA solution can reduce the electricity used in mechanical pulping by 20 to 30 percent compared to the amount used in conventional pulping without pre-treatment (Akhtar *et al*. 2007). In addition, OA pre-treatment improves paper strength and reduces resin content by approximately 30 percent prior to pulping (ITP 2011c).

A pilot-scale trial of OA pre-treatment at the Andritz pilot plant in Springfield OH (U.S.) reduced refiner energy use by approximately 25 percent. The expected payback period is 2 years or shorter, which makes this technology financially attractive (ITP 2010). The pilot trials conducted at the Forest Products Laboratory in Madison, WI (USA) shows that a combined oxalic acid/bisulfite treatment resulted in 21% refiner energy savings and 13% increase in brightness for aspen (Houtman and Horn 2011). The OA pre-treatment technology also removes hemicellulose, which can be directly in polymeric form for novel industrial applications such as biopoloymers, hydrogels, thermoplystic xylan derivative, or source of sugars for fementation to fuels (Bajpai 2012). However, OA pre-treatment increases consumption of bleaching chemicals. In addition, it will result in pulp yield and brightness loss. The O&M costs of mechanical pulping also increase because of the added OA pre-treatment unit.

ECOTARGET[7] research results show that chemical pre-treatment with oxalate has the largest energy saving potential among chemical pre-treatment methods; the other methods resulted in only minor energy savings (although they might show additional potential after further studies) (ECOTARGET 2009). Overall, chemical pre-treatment reduced energy use by 0 to 25 percent compared to the energy used in conventional mechanical refining.

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for mechanical pulping with OA chemical pre-treatment (Swaney *et al.* 2003b; ITP 2010; Houtman and Horn 2011; ITP 2011c):

- Reduces refiner energy use by 20 to 30 percent
- Reduces resin content by 30 percent prior to pulping
- Greatly improves paper strength
- Has payback period of 2 years or shorter
- Improves dewatering efficiency

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[7] The largest research project ever in the European pulp and paper industry, funded by the European Commission

Block Diagram or Photo

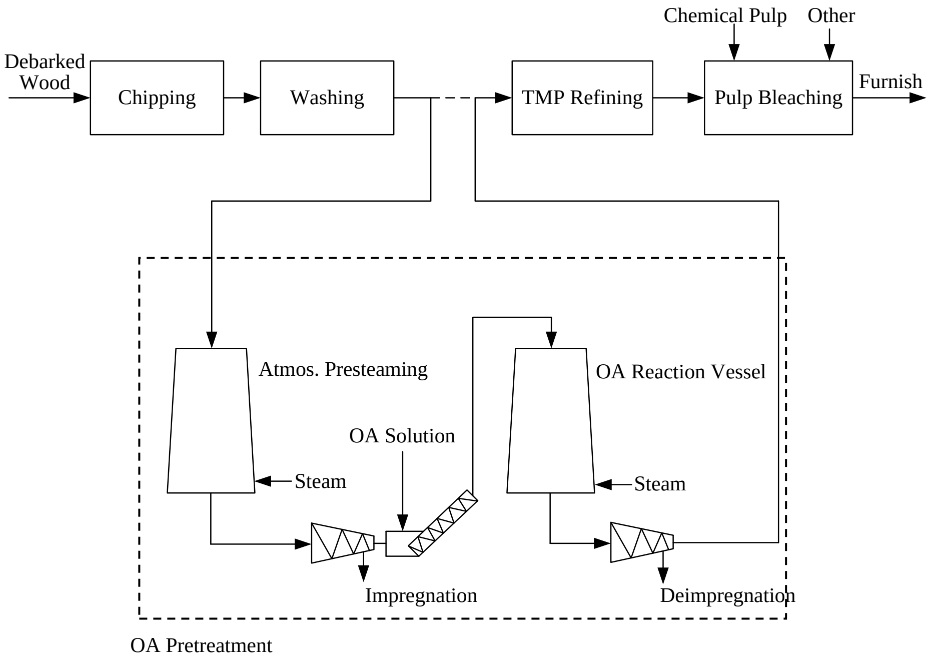


Figure 4. Chemical pre-treatment using OA in TMP mill (Swaney *et al.* 2003b)

Commercial Status

Pilot stage

References for Further Information

Swaney *et al.* 2003b; Akhtar *et al.* 2007; ECOTARGET 2009; ITP 2010; Houtman and Horn 2011; ITP 2011c; Li *et al.* 2011.

3.2. Emerging Pulping Technologies

The subsections below describe the following nine emerging technologies that can save energy and reduce CO_2 emissions in the pulping process: directed green liquor utilization, membrane concentration of black liquor, dual-pressure reheat recovery boiler, borate auto-causticizing, direct causticizing, steam cycle washing, recycled paper fractionation, new flotation deinking, surfactant spray deinking, and pulsed power technology for decontaminating recycled paper.

3.2.1. Directed Green Liquor Utilization Pulping

Description

Green liquor is the partially recovered form of kraft pulping liquor. It is a dissolved smelt of sodium carbonate (Na_2CO_3) and sodium sulfide (Na_2S) from the recovery boiler in kraft mill. Normally, green liquor is used to react with lime (CaO) in a process called causticizing to produce calcium carbonate ($CaCO_3$) and regenerate white liquor (a mixture of NaOH and Na_2S), which is reused in chemical pulping process (Naqvi *et al*. 2010). Green liquor is naturally rich in hydrosulfide ions, which can accelerate pulping and provide a high-value product (ITP 2011c). Using green liquor as a pre-treatment in conventional kraft pulping can reportedly result in pulps with substantially higher viscosities and strengths (Andrews *et al*. 1985).

Directed green liquor utilization (D-GLU) pulping is based on the reuse of green liquor for pre-treatment of wood chips prior to kraft pulping. Different from the conventional kraft pulping process in which all the green liquor is used to regenerate white liquor, this new pulping technology redirects 20 to 30 percent of the green liquor from the causticizing process 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.

North Carolina State University and the Georgia Institute of Technology performed laboratory-scale pulping and fiber analyses for some kraft mills (e.g., Evergreen Pulp mill, Temple-Inland mill, and Evadale pulp mill) as support for mill trials of the D-GLU pulping process (ITP 2006c). Green liquor use of this type has also been demonstrated in pulp mills in Finland and can reportedly increase pulp yields, produce higher fiber strength, reduce digester alkali demand, reduce lime kiln load by up to 30 percent, increase the bleachability of pulp, and reduce energy use by up to 25 percent (ITP 2011b). Compared to conventional kraft pulping, D-GLU pulping saves almost 50 percent alkali, and more than doubles pulp viscosity at the similar Kappa number with higher pulp yield (Lucia 2005).

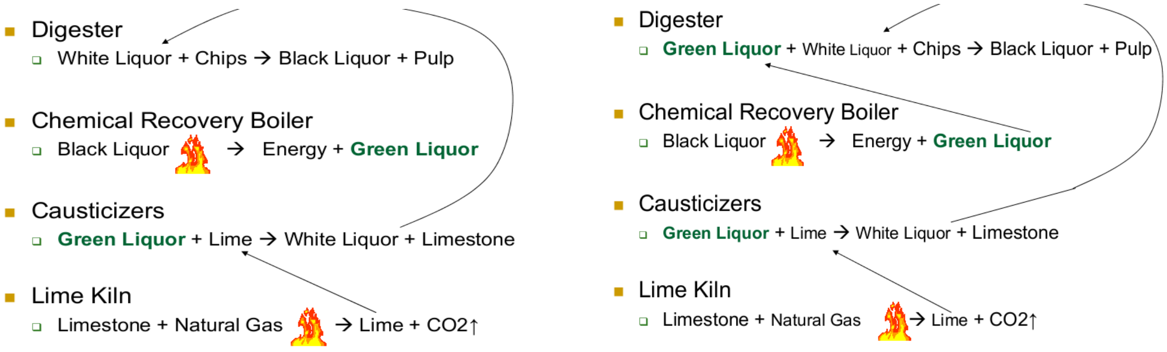
Implementation of D-GLU pulping is straightforward and requires minimal capital investment. Energy savings are the main driver for implementation of this technology. Among the potential negative impacts are that green liquor pulping might reduce the heat value of black liquor and increase black liquor dead load (Lucia 2006). A full-scale trial performed at Evadale pulp mill in Texas increased levels of rejects from the digester and decreased screened yield (Malmberg Aug. 2012). Environmental and scaling issues related to nitrogen emissions during recovery (because of the inclusion of organic additive), higher sulfide off-gassing during pulping, and build-up of scale in the digester and/or evaporators are other issues associated with this technology that need further investigation.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for D-GLU pulping compared to conventional kraft pulping (Lucia 2005; ITP 2011b):

- Reduces energy consumption by up to 25 percent
- Reduces effective alkali consumption in digesters by as much as 50 percent
- Reduces lime kiln load by up to 30 percent, which in turn reduces lime kiln fuel consumption
- Reduces H-factor by 30 percent at similar Kappa number
- Increases pulp yield 1 to 3 percent
- Increases pulp strength (10-percent gain in tear strength) as well as bleachability
- Reduces refining energy use by 20 percent

Block Diagram or Photo



a) Conventional kraft pulping b) D-GLU pulping

Figure 5. The difference between conventional kraft pulping and D-GLU pulping (Lucia 2006)

Commercial Status

Demonstration stage

Reference for Further Information

Andrews *et al.* 1985; Lucia 2005; ITP 2006c; Lucia 2006; ITP 2010; Naqvi *et al.* 2010; ITP 2011c, 2011b.

3.2.2. Membrane Concentration of Black Liquor

Description

In most modern pulp mills, the large amount of black liquor is concentrated in multiple effect evaporators, followed by incineration, smelting and causticization to recover 85% of the cooking chemicals (Bhattacharjee *et al.* 2006). Black liquor evaporation accounts for approximately 12 percent of the energy used in pulping and papermaking process (Kinstrey and White 2006). To improve energy efficiency of evaporation, the weak black liquor (the black liquor with lower solids content) usually have to be concentrated using steam to raise the solids content. However, the steam use efficiency of evaporation could be improved further if membrane technology were used to pre-evaporate the weak black liquor instead of the currently used steam-heated concentrator.

Membrane technology concentrates high molecular weight solids from low molecular weight fraction of weak black liquor. The most utilized membrane technologies in the pulp and paper industry are microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Dillard 1998). These technologies use pressure gradient to separate the liquid stream through a porous or semi-permeable membrane as two liquid stream (Dillard 1998). After membrane process, the concentrated black liquor could achieve higher solids content. Membrane technology has a broad range of separation capability at molecular level. The membranes used in black liquor concentration are classified according to pore size. The pore size of MF membrane ranged from a few microns to 0.1 microns (μm), UF membrane pore size is between 0.1μm and 0.01μm, NF membrane is ranging from 0.01μm to 0.001μm, and RO membrane is less than 0.001μm (Adnan *et al.* 2010). RO membranes only allowed water molecular passed through under extremely high pressure drops (10-100 MPa) compared to other membrane technologies mentioned above (Dillard 1998).

UF membranes have been operating since 1980s to separate color, BOD, COD, and AOX from caustic effluents (Dillard 1998). The background, research, development and applications of membrane technologies including MF, NF, UF, and RO in different areas of the pulp and paper industry are surveyed by Adnan and coworkers (Adnan *et al.* 2010). UF has so far been employed mainly for the following three purposes: separation of lignin compounds from low molecular weight inorganic fraction; fractionation of high molecular weight lignin compounds; and recovery of water (Bhattacharjee and Bhattacharya 2006). Many studies have been conducted to investigate UF membrane technology for treating black liquor to recovery the valuable organics (Dafinov *et al.* 2005; Holmqvist *et al.* 2005; Wallberg *et al.* 2005; Bhattacharjee *et al.* 2006; Jönsson and Wallberg 2009). Most of these applications are still in the laboratory stage. The solids content of weak black liquor could be concentrated to over 30 percent using UF membrane technology (Wallberg *et al.* 2005).

One of the drawbacks in the utilizing of membrane technology for black liquor pre-evaporation is the marked decline of permeate flux and associated fouling problems (Bhattacharjee and Bhattacharya 2006). The membranes must be operated at very high pH conditions (Sholl 2011). In addition, capital and operating costs are high, but improvements are being made in membranes and process equipments. Fouling and successful cleaning are of great importance if membrane technology for black liquor concentration is to be implemented on an industrial scale (Wallberg *et al.* 2003).

The U.S. DOE's Innovative Manufacturing Initiative announced in June 2012 for development of highly durable membrane coating for black liquor concentration process with US$2.6 million award, led by Teledyne Scientific & Imaging, LLC (TS&I) in partnership with the Agenda 2020 Technology Alliance (Teledyne 2012). By replacing the first two stages in conventional multiple-effect evaporators, this new technology has the ability to save the U.S. pulp and paper industry energy about 116 PJ per year (Teledyne 2012).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for membrane concentration of black liquor (Holmqvist *et al.* 2005; Stowell 2007; Adnan *et al.* 2010; Sholl 2011):

- Reduces energy cost for black liquor evaporation
- Reduces evaporation volume
- Decreases inorganic content to evaporators resulting in less fouling
- Active alkali concentrated in permeate for improved make up liquor
- Lower boiling point rise with ultra-filtration concentration
- Eliminate evaporator or recovery boiler bottlenecks

Block Diagram or Photo

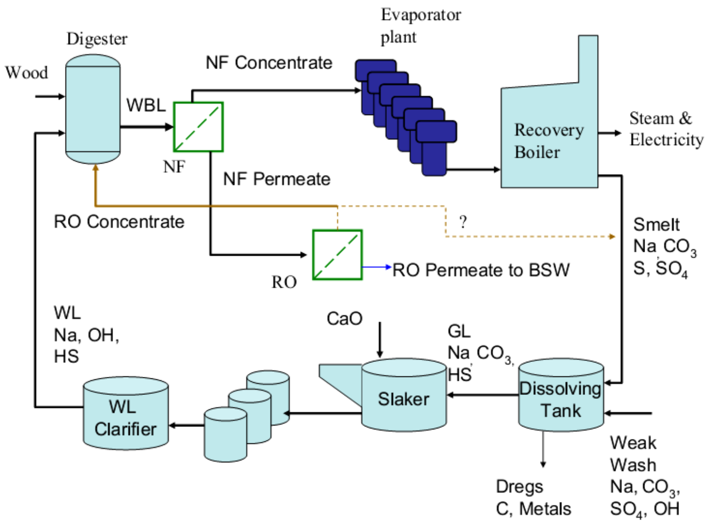


Figure 6. Membrane technology for black liquor pre-evaporation (Sholl 2011)

Commercial Status

Development stage

References for further information

(De and Bhattacharya 1996; Dillard 1998; Wallberg *et al.* 2003; Dafinov *et al.* 2005; Holmqvist *et al.* 2005; Wallberg *et al.* 2005; Bhattacharjee and Bhattacharya 2006; Bhattacharjee *et al.* 2006; Stowell 2007; Jönsson and Wallberg 2009; Adnan *et al.* 2010; Sholl 2011; Agenda2020 2012; Teledyne 2012)

3.2.3. Dual-pressure Reheat Recovery Boiler

Description

Recovery boiler is widely used in the pulp and paper industry to provide means for recovery of certain chemicals from black liquor, generation of electricity through a steam turbine, and production of process steam used in other pulping and papermaking process in the mill.

Babcock & Wilcox company (B&W) developed the world's first kraft recovery boiler in 1929 (B&W, 2008). The first recovery boilers had horizontal evaporator surfaces, followed by super-heaters and more evaporation surfaces. B&W has the largest installation of recovery boilers in the world (B&W 2009). The traditional recovery boilers offer high availability with safe operation and low maintenance. In the recovery boiler heat is used to produce high pressure steam, which is used to generate electricity in a turbine. The turbine exhaust low pressure steam is used for process heating. As the development of new technology, the recovery boiler design also evolved with many new features. The latest innovation is a patented dual pressure furnace to allow pulp mills to take advantage of the power generation potential of the high pressure reheat cycle on a recovery boiler (Monacelli *et al.* 2008).

Dual pressure recovery boiler has been designed as a combination of a classic recovery boiler and a classic subcritical utility boiler (Hicks *et al.* 2009). An enhanced steam cycle utilizing a dual pressure recovery boiler with reheat allows a large increase in power generation with various turbine cycles while overcoming traditional lower furnace material limitations (Monacelli *et al.* 2008). The dual pressure recovery boiler consists of a lower furnace and an upper furnace. The lower furnace is operated at a lower temperature to prevent or reduce corrosion of the lower furnace tubes caused by the reducing environment. The lower furnace can be either a low pressure natural circulation steam generating system or economizer. While the upper furnace is not exposed to a reducing environment, so it is not as susceptible to severe corrosion rates. The upper furnace is operate at higher temperatures and pressures which permit implementation of higher efficiency reheat steam cycles (Graves *et al.* 2007). This design eliminates the need for the exotic metals that are required to withstand a corrosive operating environment in the lower furnace (B&W 2009).

The dual pressure recovery boiler can be coupled to a variety of condensing, non-condensing or a combination of condensing and non-condensing turbine cycles to provide a large increase in power generation efficiency (Monacelli *et al.* 2008). The new reheat recovery technology will generate more electrical power from the pulp mill steam cycle. Efficiency improvements that result from incorporating a gas-over-tube tubular air heater into the recovery boiler design will increase boiler efficiency and allow for greater application of feedwater heating which will improve the steam cycle efficiency (Hicks *et al.* 2009).

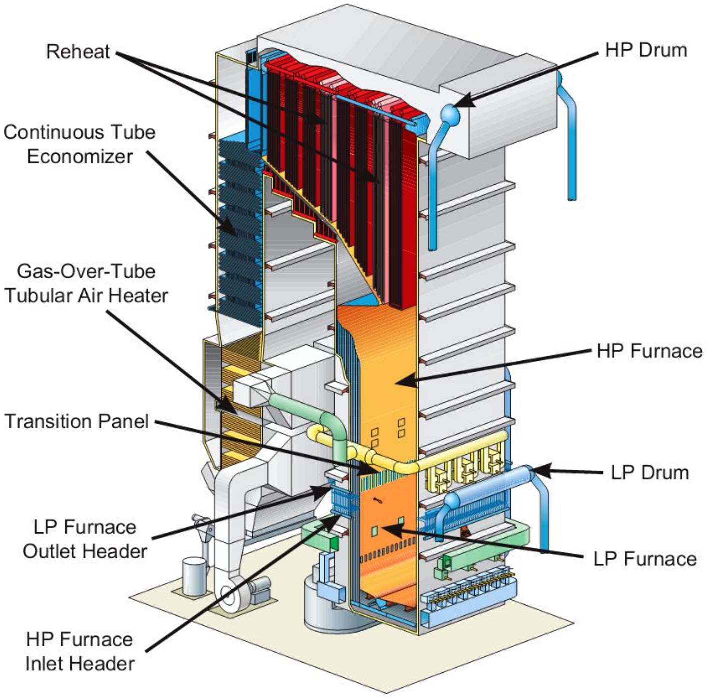
Although this is a new configuration of equipment in recovery boiler, the technologies are mature, proven and very familiar to the boiler industry. It could increase the power generated from recovery boiler by 30 to 130 percent for pulp mills that have low solids and direct contact evaporators (B&W 2009). This additional generated power can transform some mills into net power generators with little or no increase in heat input and reduce the mill's CO_2 emissions at the same time (B&W 2009; Hicks 2011). Currently, this newly designed dual pressure recovery boiler has not had a commercial installation (Brown Sept. 2012).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for high consistency papermaking (Monacelli *et al.* 2008; B&W 2009; Hicks *et al.* 2009; Hicks 2011):

- Improves steam cycle efficiency
- Increases electricity generation for the same fuel input
- Takes advantage of existing plant infrastructure
- Lower GHG emissions due to higher efficiency and reduced fossil fuel use
- Short return on investment

Block Diagram or Photo



LP: low pressure; HP: high pressure

Figure 7. Diagram of dual pressure reheat recovery boiler (Hicks *et al.* 2009)

Commercial Status

Pilot stage

References for Further Information

Graves *et al.* 2007; B&W 2008; Monacelli *et al.* 2008; B&W 2009; Hicks *et al.* 2009; Hicks and Gries 2010; Hicks 2011.

3.2.4. Borate Auto-causticizing

Description

The main function of the re-causticizing plant in a pulp mill is to regenerate the caustic. Caustic is typically recovered from the spent pulping chemical in two stages: first, Na_2CO_3 is formed by the combustion of black liquor in the recovery boiler, and then caustic is formed by the addition of CaO to Na_2CO_3 in the re-causticizing plant. Lime is then recovered in the lime cycle through the calcination of lime mud. Auto-causticizing could be an attractive alternative for kraft mills because it allows higher caustic production without increasing lime demand and can even eliminate lime demand (Kochesfahani and Bair 2002).

Borate auto-causticizing technology uses Neobor, a form of sodium borate ($Na_2B_4O_7 \cdot 5H_2O$) to replace lime. Each tonne of Neobor added to the pulping process replaces 10 to 30 times its weight in lime (RTM 2010). The principal auto-causticizing reaction that occurs in the recovery boiler is between sodium metaborate ($NaBO_2$) and Na_2CO_3 in the molten smelt, which forms tri-sodium borate (Na_3BO_3) (Reaction 1). The Na_3BO_3 reacts with the water in the smelt dissolving tank to form sodium hydroxide (NaOH) and regenerate $NaBO_2$ (Reaction 2) (Bjork *et al*. 2005).

- Auto-causticizing in the recovery boiler:

  $Na_2CO_3 + NaBO_2 \rightarrow Na_3BO_3 + CO_2$ (Reaction 1)

- Hydrolysis in smelt dissolving tank:

  $Na_3BO_3 + H_2O \rightarrow NaBO_2 + 2NaOH$ (Reaction 2)

$NaBO_2$ stays in solution and circulates through the chemical recovery cycle to continue forming caustic in the recovery boiler. The borate compounds remain in the liquor cycle, self-regenerating to be used again in producing caustic. $NaBO_2$ drives auto-causticizing reactions in the recovery boiler and forms NaOH in the smelt dissolving tank without the use of lime or additional recovery processes, so this technology reduces energy consumption and increases causticizing and calcining capacities. For kraft and soda pulp mills, reducing the lime kiln load not only translates to lower operating costs, energy consumption, and emissions, but also significantly reduces the amount of lime mud that requires special handling and disposal (ITP 2011c).

The concept of borate auto-causticizing was first investigated during the early 1980s in Europe; however, after technical difficulties in only one mill trial, it was not pursued. Rio Tinto Minerals, with support from the U.S. DOE, developed partial borate auto-causticizing, which is being implemented in pulp mills worldwide to supplement conventional lime causticizing with almost no capital investment (ITP 2011c).

A trial of partial auto-causticizing with sodium borate was first conducted at Georgia-Pacific Camas mill WA (U.S.) from 1999 to 2000 for a period of more than16 months (Hunter *et al*. 2001). In Europe, a full-scale partial borate auto-causticizing trial has been under way since November 2002 at the Stora Enso Norrsundet mill in Sweden (Bjork *et al*. 2005). In this trial, the total lime requirement has been reduced by about 7 percent, and the auto-causticizing level has typically been 9 to 11 percent during the 15-month period. There is some indication that borates may enhance pulp yield as well (Bjork *et al*. 2005). Partial auto-causticizing in the P.H. Gladfelter Co. mill in Spring Grove PA (U.S.) increased production by roughly 5 percent in 2007 (ITP 2011c). However, the full borate auto-causticizing, which uses borates to drive all the causticizing reactions instead of just lime causticizing and may cause corrosion in the recovery boiler, is still undergoing further research and testing (ITP 2006c).

Energy/Environment/Cost/Other Benefits

The following benefits have been identified for borate auto-causticizing (RTM 2010):

- Increases energy efficiency in chemical recovery process
- Reduces lime demand, which reduces fossil fuel use in traditional lime kiln
- Decreases fresh lime usage and limestone purchase
- Reduces lime mud disposal costs
- Reduces CO_2 emissions from fuel burning and from calcining process in lime kiln
- Increases causticizing capacity and pulp production without major investments
- Decreases lime kiln operation and maintenance costs

Block Diagram or Photo

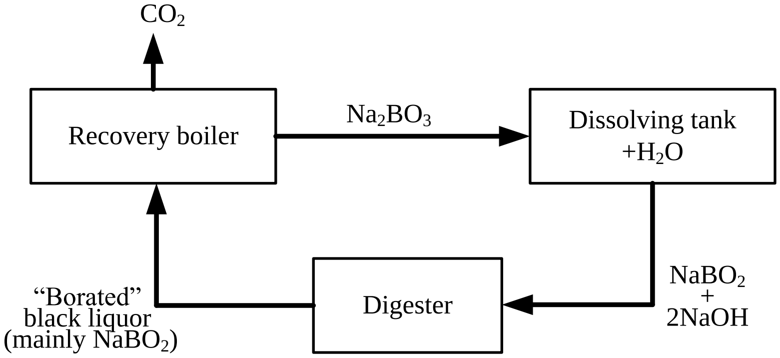


Figure 8. Borate auto-causticizing process (ITP 2011c)

Commercial Status

Partial auto-causticizing: Semi-commercial stage
Full auto-causticizing: Development stage

References for further information

Hunter *et al.* 2001; Kochesfahani and Bair 2002; Bjork *et al.* 2005; ITP 2006c; RTM 2010; ITP 2011c.

3.2.5. Steam Cycle Washing

Description

Pulp washing is the most common unit operation in the pulping and bleaching process. The general purpose of pulp washing is to maximize recovery from the pulp of inorganic pulping chemicals and dissolved organic substances that can be used for fuel while minimizing the use of fresh water and producing a clean pulp without spills into environment (Gullichsen 2000). Efficient washing is critical to maximize return of pulping liquor to chemical recovery and to minimize the cost of steam evaporation as well as to minimize washing loss into the bleach plant because excess pulping liquor will increase consumption of bleaching chemicals (Bajpai 2010). In addition, if not recovered by washing, the dissolved organic compounds (lignin and hemicellulose) contained in the liquor will react with bleaching chemicals and thus increase bleach chemical consumption.

Various washing technologies have been developed during the past 50 years, including drum washing, diffusion washing, press washing, displacement washing, belt washing, and dilution/extraction washing (Bajpai 2010). Rotary drum washing is the most common washing technology used in pulp mills today with a dilution factor[8] of 3 to 4 tonnes water per tonne of oven-dry pulp. The amount of wash water required is about 12 to 13 tonnes/tonne oven-dry pulp (Muehlethaler *et al*. 2008). However, there still exists a large potential for improving the washing efficiency. The steam cycle washing technology was developed for this purpose.

The steam cycle washer is designed to dewater and wash wood pulp using counter current washing, steam, and high-differential pressure. The entire process takes place within a pressure vessel at 8 bar operating pressure. Within the pressure vessel is a Fourdrinier type dewatering mechanism (Muehlethaler *et al*. 2008). The washing consistency[9] of the developed steam-cycle washer is 28 to 32 percent (fiber concentration about 280 to 320 kg/m^3), and the dilution factor is only 0 to 0.5 tonnes of water per tonne of oven-dry pulp. The amount of wash water required is between 2.5 and 3 tonnes/tonne oven-dry pulp, compared to 12 to 13 tonnes/tonne oven-dry pulp with the most common rotary drum washing technology, i.e., a reduction of 70 to 75 percent (Muehlethaler *et al.* 2008). This technology uses less water compared to conventional washers because it allows the pulp mat to be washed at a high consistency (ITP 2006f). As a result, less energy is required for pumping and heating in the thickening, screening, and evaporation operations. A pilot demonstration conducted at the Port Townsend Paper Mill (WA, U.S.) achieved a 40-percent overall reduction in fuel or steam consumption for unbleached pulp production (Muehlethaler *et al*. 2008).

The Idaho National Laboratory is collaborating with Steam Filter LLC in the design, fabrication, and installation of a 450 to 500 Adt per day steam cycle washing machine for unbleached pulp. The feasibility of this process has been tested and demonstrated through bench-scale and pilot tests as of 2008 (DOE 2008). Given that current U.S. pulp washing equipment has an average age of 45 years (ITP 2006f), significant energy saving opportunities exist with the commercialization

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[8] The dilution factor is the actual quantity of water used in pulp washing compared with the theoretical amount required to displace the liquor from the thickened pulp.

[9] The washing consistency means the fiber concentration in the pulp slurry during washing process, to some extent, it reflects how much water be used indirectly. A lower washing consistency represents higher water consumption.

of more efficient steam cycle pulp washing technology. However, this undergoing project was discontinued by DOE due to unavailability of funding (Sastri Sept. 2012).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for steam cycle washing technology compared to conventional washers (DOE 2008; Muehlethaler *et al*. 2008):

- Reduces fuel/steam consumption 40 percent overall
- Reduces evaporative load 50 percent
- Reduces plant effluent and freshwater usage 45 percent
- Increases fiber yield 1 to 2 percent
- Improves pulp quality
- Reduces bleaching chemical consumption
- Can reduce operational costs by $40 to $60/Adt pulp

Block Diagram or Photo

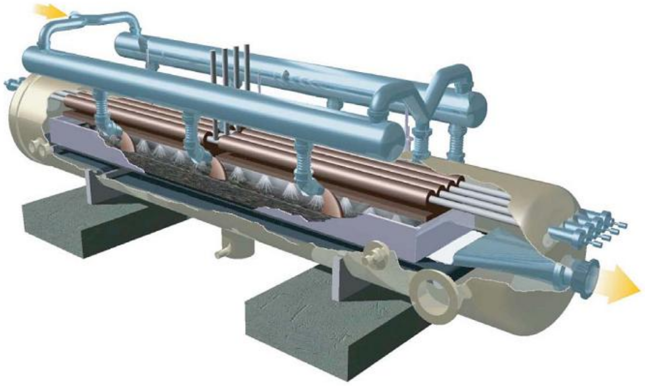

Figure 9. A steam cycle washer (Muehlethaler *et al*. 2008)

Commercial Status

Demonstration stage

References for Further Information

Gullichsen 2000; ITP 2006f; DOE 2008; Muehlethaler *et al.* 2008; Bajpai 2010.

3.2.6. Recycled Paper Fractionation

Description

Although recycled paper fractionation is not a new concept, only a small number of recycled paper mills use this technology in deinking process. The purpose of fractionation is to improve the quality of deinked pulp (DIP) by separating long fibers from short fibers and fines, according to defined criteria such as size or deformability.

Fractionation can be done both in pressure-screens and in centrifugal cleaners. Fractionation during recycled paper pulping can removes the detached ink particles from the vicinity of fibers and thus prevents their excessive redeposition into the fibers. The ink particles need to be removed once they are released to minimize the concentration of ink that remains after pulping. This may require that the detached ink particles be removed from the pulp before defibration is completed. Removing detached ink particles with multiple repeated pulping and fractionation stages reduces the amount of attached ink to significantly lower levels than are possible with a conventional pulping arrangement (Kemppainen *et al*. 2010).

The energy requirement for recycled paper fractionation is lower than conventional multi-stage flotation deinking system. However, when fractionation is used, additional bleaching chemicals might be required to compensate for the reduced flotation capacity. Andritz in Austria has tested the potential of using recycled paper fractionation in a deinking line. The fractionation deinking line has a 13- to 22-percent lower capital cost compared to traditional DIP lines. Using fractionation can reduce electricity use by 11 to 13 percent and thermal energy use by 40 percent (Hertl 2008). The technology is also being implemented and tested at Pearl Paper Mill in Switzerland (Kramer *et al*. 2009).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for deinking with recycled paper fractionation, compared to that without fractionation (ECOTARGET 2009; Kemppainen *et al*. 2011; Korkko *et al*. 2011):

- Decreases energy consumption
- Improves efficiency of ink detachment
- Reduces redeposition of ink on fibers
- Reduces virgin fiber consumption
- Increases DIP production
- Improves pulp quality

Block Diagram or Photo

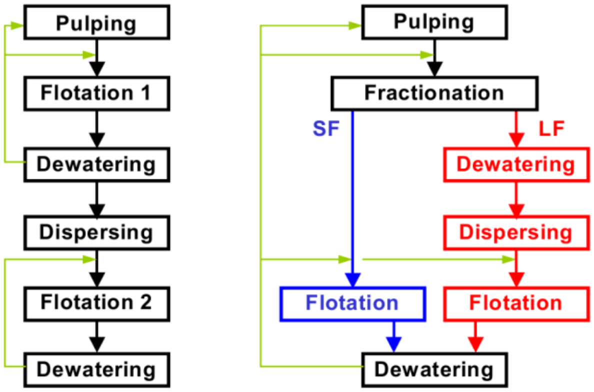

Figure 10. Single-loop fractional deinking
(Standard 2-loops [left]; new single-loop deinking with recycled paper fractionation [right])
(ECOTARGET 2009)

Commercial Status
Demonstration stage

References for Further Information
Hertl 2008; ECOTARGET 2009; Kramer *et al.* 2009; Kemppainen *et al.* 2010; Kemppainen *et al.* 2011; Korkko *et al.* 2011.

3.2.7. New Flotation Deinking

Waste paper is an important raw material for the pulp and paper industry. The recovery and utilization rate of waste paper has been increasing during the past decade due to the developments of deinking technology. Deinking (e.g., flotation, washing, or centrifugal cleaning) is the industrial process of removing printing ink from fibers of recycled paper (Vashisth *et al.* 2011). Flotation deinking is the predominant technology worldwide because of its advantages with regard to selectivity, yield, water management and reject handling (Kemper 1999). The term flotation is the generalization of processes in which the main stage is the bubble-particle adhesion (or attachment), which is controlled by surface chemistry and by the hydrodynamic and operational parameters of the flotation cell (Costa and Rubio 2005).

Flotation deinking processes were originally developed based on the experience obtained from mineral flotation process and have not been fully optimized for paper deinking. In contrast to the mineral flotation, the accept in flotation deinking is not the foam but the remaining suspension. The detached ink particles are accumulated in the foam by means of the introduced air (Kemper 1999). In addition, flotation deinking is a relatively young process compared to mineral flotation and it is still not effective to remove the tiny ink particles and only limited process control mechanisms are available (Deng and Zhu 2004; ITP 2007d). The following subsections describe four new flotation deinking processes or equipments.

3.2.7.1. OptiCell Flotation^{TM}

Description

OptiCell Flotation^{TM} by Metso is based on computational fluid dynamics and uses new image analysis methods. It is designed to provide smooth flow velocities that allow unobstructed transfer of bubbles to the surface of the pulp mixture or froth, which enhances the efficiency of ink removal. The heart of OptiCell Flotation^{TM} is the aeration injector, which ensures optimal bubble size distribution. The injector is designed based on the experiences gained with earlier flotation technologies combined with modern computational fluid dynamics calculations and new image analysis methods.

The linear structure of the flotation cells has a large surface area, which has reject separation and fiber loss. This flotation cell design also contributes to high sludge consistency (less water in the sludge) by ensuring smooth drainage of froth (Aksela 2008). The elliptical shape of the flotation cells in this technology is optimal for internal pulp circulation for improved ink removal. Moreover, the flatness of the cells intensifies the rise of air bubbles within the available volume. The first OptiCell flotation system started operation in September, 2008 at Stora Enso's Maxau mill in Germany which has approximately 1,000 tpd deinking facility (Metso 2012b).

Energy/Environment/Cost/Other Benefits

Metso claims the following benefits for OptiCell Flotation^{TM} compared to conventional systems (Aksela 2008; Metso 2012b):

- Low energy consumption
- Improves flotation capacity
- Removes ink effectively
- Reduces fiber loss
- Improves pulp brightness
- Reduces operation costs
- Reduces space requirements

Block Diagram or Photo

Figure 11. OptiCell flotation^{TM} cell (Metso 2012b)

Commercial Status

Semi-commercial

References for Further Information

Aksela 2008; Metso 2012b.

3. 2.7.2. Deaeration Foam Pump 4000^{TM}

Description

The Deaeration Foam Pump (DFP) 4000^{TM}, developed by Voith, is a compact unit that integrates several elements of the flotation deinking system. Combining the pump and deaeration machine into one unit, the deaeration foam pump replaces the foam destroyer, foam tank, stirring unit, and pump and costs less than the current suite of equipment.

The DFP 4000 has two parts: in the upper part, foam is pre-deaerated by a mechanical foam destroyer; in the lower part, centrifugal force generated by a quick rotational movement further deaerates the foam. The resulting low-air-content suspension is brought to the required pressure so that it can be conveyed out of the machine to the next process stage. The air released during deaeration is conveyed out of the machine through a special air chamber on the side so that the airflow does not obstruct the foam entering from above (Dreyer 2010).

The new pump can be linked directly to the deinking machine, forming a clean and closed disposal system. Because the deaeration pump can be placed at the same level as the flotation cells, the entire system requires less space than previous systems, so a cellar (or additional floor height) is no longer needed to accommodate the system. When the foam mass passes through the DFP 4000, the foam's air content is reduced from 80 percent to an average of 8 percent (Voith 2011a). Conventional deaeration systems reduce the air content to approximately 12 percent. The first DFP 4000 operating in a paper mill has been in service since September 2009 (Dreyer 2010).

Energy/Environment/Cost/Other Benefits

Voith claims the following benefits for the DFP 4000^{TM} compared to conventional systems (Dreyer 2010; Voith 2011a):

- Eliminates foam tanks used in conventional deinking flotation
- Reduces total investment
- Reduces air requirement in flotation
- Improves foam deaeration
- Has stable operation even with fluctuations in foam action and quantity
- Reduces operating costs
- Reduces space requirement

Block Diagram or Photo

Figure 12. Deaeration Foam Pump 4000^{TM} (Voith 2011a)

Commercial Status
Semi-commercial

References for Further Information
Dreyer 2010; Voith 2011a.

3. 2.7.3. Low Energy Flotation^{TM}

Description
Flotation deinking system integrated with Low Energy Flotation^{TM} (LEF) is another new technology developed by Voith for removing inks and other contaminants from recovered paper. LEF is designed with a two-stage (primary and secondary) system to ensure maximum elimination of hydrophobic components with maximum DIP yield. The specific energy consumption for this new flotation technology is 10 to 15 kWh/t (Voith 2011b).

The LEF unit consists of several flotation cells. The diffusers, which are self-operating aeration elements that draw air in, are the core of each flotation. The diffusers draw in the air they need to remove the particles of printing ink. The aeration elements are structured in such a way that they cause a whirl that reduces the size of the air bubbles while creating a uniform mixture. The small water-repellent particles of printing ink attach themselves to the air bubbles. When the turbulence calms, the smaller air bubbles combine to create larger ones. Small particles of ink continue to adhere to the bubbles while larger particles become attached to them. In this way, the size of the air bubbles adapts optimally to the size of the ink particles (PearlPaper 2010).

LEF is applied in all graphic and tissue grades of recovered paper. It has self-regulating control with reject flow control, high operational reliability, and a wide production range due to interconnecting cells. The first LEF system with a production of 800 tpd is already running successfully. To date, more than 15 systems have been installed worldwide (Voith 2011b).

Energy/Environment/Cost/Other Benefits

Voith claims the following benefits for the LEF system compared to conventional systems (PearlPaper 2010; Voith 2011b):

- Reduces flotation energy use by approximately 33 percent
- Increases air (60 percent) available for flotation
- Increases DIP capacity
- Minimizes fiber loss
- Separates inks over a broader particle range (approximately 5 to 500 micrometers)
- Reduces space requirement

Block Diagram or Photo

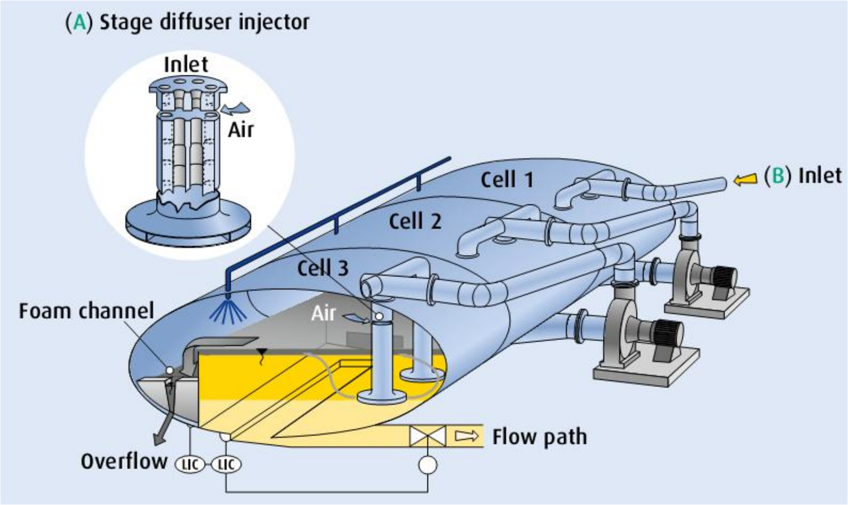

Figure 13. Low Energy Flotation Cell structure (Voith 2011b)

Commercial Status
Semi-commercial

References for Further Information
PearlPaper 2010; Voith 2011b.

3. 2.7.4. Mac Flotation Cell

Description
The Mac flotation cell developed by Kadant-Lamort Inc. is another innovation that could save energy compared to conventional flotation systems. It integrates small new auto-clean low-pressure injectors with a flotation cell. The injectors aerate the stock before it is pumped and sent tangentially to the top of the cell. In the cell, air bubbles collect ink particles and rise up to the top to create a thick foam mat that is evacuated because of the slight pressurization of the cell. The partially de-inked stock then goes to a de-aeration chamber and is pumped to the next stage. In the second stage, the operation is exactly the same as for the first stage, with the same number of

injectors and same flow (Kadant 2011). This operation is repeated up to five times for a high ink removal rate. Re-mixing of the air coming from downstream stages of the process aids the upstream stages, improving overall cell efficiency. Adjustable and selective losses of fiber depend on the application and technical requirements (inks, or inks and fillers). The use of low-pressure injectors in the Mac flotation cell could save 25 to 30 percent of the energy used in conventional flotation systems (ECOTARGET 2009).

Energy/Environment/Cost/Other Benefits

Kadant-Lamort Inc. claims the following benefits for the Mac flotation cell compared to conventional cells (ECOTARGET 2009; Kadant 2011):

- Reduces energy consumption by 25 to 30 percent
- Has low specific power consumption
- Has high rate of ink and hydrophobic particle removal
- Improves flotation efficiency
- Reduces fiber loss
- Eliminates second-stage cell
- Reduces space requirement

Block Diagram or Photo

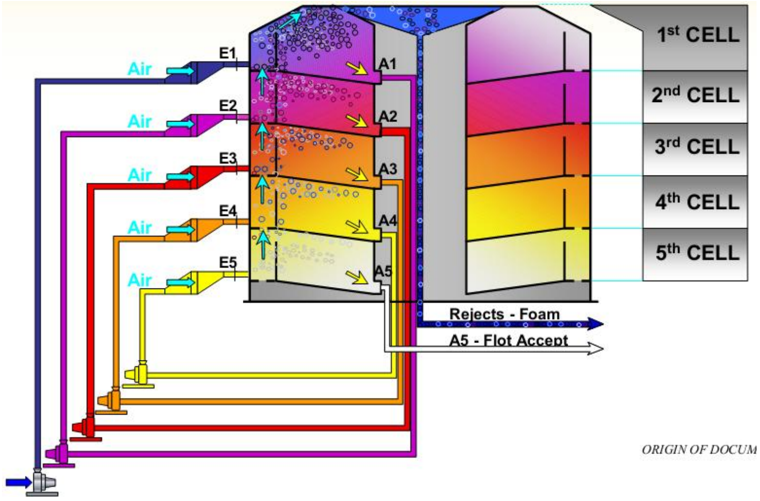

Figure 14. Mac flotation cell with low-pressure injectors (ECOTARGET 2009)

Commercial Status

Demonstration stage

References for Further Information

ECOTARGET 2009; Kadant 2011.

3.2.8. Surfactant Spray Deinking

Description

Surfactant spray is a new technology for recycling various grades of paper that improves ink removal, reduces the use of chemicals and the loss of fiber and water during deinking, and provides better process control than current deinking technologies (Zhao *et al.* 2004). The surfactant increases ink removal by adsorbing onto the surfaces of the ink particles and reducing their hydrophobic characteristics, so they can more readily be separated and removed from the pulp suspension. Use of surfactants also improves process control by preventing dilution of the foaming agent in the bulk volume of the pulp mixture. Because surfactant spray significantly improves the deinking process, reduces the use of chemicals and the loss of fiber and water, it reduces operating costs.

Surfactant spray deinking uses an atomizer to spray foam at the top of the flotation cell. The foaming agent generates stable foam for ink removal, a collector is applied to agglomerate small ink particles for removal, and a dispersant is used to prevent ink particles from re-depositing onto fiber surfaces (Zhao *et al.* 2004). The concentration and distribution of various surfactants is controlled during the surfactant spray deinking process (Deng and Zhu 2004).

Surfactant spray technology has been demonstrated in both laboratory- and pilot-scale flotation deinking trials at IPST in the U.S. and in Voith-Sulzer’s commercial flotation cells for deinking old newsprint, old magazines, and old corrugated container board (Deng and Zhu 2004; Delozier *et al.* 2005). The brightness of the DIP produced using surfactant spray deinking was slightly lower that DIP from conventional deinking but was considered acceptable in view of the significantly increased yields (Delozier *et al*. 2005). This technology was successfully implemented in a single flotation unit within the deinking line of a mill producing newsprint from 100-percent secondary fiber, with a more than 50-percent reduction in fiber loss from the unit without negatively affecting final pulp quality (Delozier *et al*. 2005). Single-cell commercial runs (450 tpd DIP) using surfactant spray in a flotation deinking line showed a 3.5-percent increase in yield, 380 liters per minute savings in water use, and 10-percent chemical savings (Deng and Zhu 2004).

Surfactant spray technology can be easily retrofitted into an existing system without significant modifications and capital cost. The estimated capital investment is approximately $10,000 for one flotation cell (Deng and Zhu 2004).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for the surfactant spray technology compared to conventional flotation deinking (Deng and Zhu 2004; Delozier *et al.* 2005; ITP 2007d):

- Reduces fiber loss up to 50 percent
- Increases DIP yield (IPST demonstrated a 3.5-percent yield increase)
- Improves deinking efficiency
- Reduces water and deinking chemical use (380 liters per minute of water savings and 10 percent of chemical savings were realized in IPST)
- Reduces formation of stickies

- Improves paper quality
- Requires low capital expenditure and minimal equipment modification

Block Diagram or Photo

Figure 15. Surfactant spray deinking in a mill trial (Deng and Zhu 2004)

Commercial Status
Demonstration stage

References for Further Information
Deng and Zhu 2004; Zhao *et al.* 2004; Delozier *et al.* 2005; ITP 2007d.

3.2.9. Pulsed Power Technology for Decontamination of Recycled Paper

Description
Contaminants in recycled paper can degrade the properties of the final products and can also lead to substantial downtime in the recycled paper mill. A category of contaminants known as "stickies," which includes pressure-sensitive adhesives and hot melts, is especially troublesome. Stickies are usually controlled during the recycling process by screening and cleaning equipment or chemical additives such as minerals and polymers (Banerjee 2005). However, these controls are not 100-percent effective, so many stickies remain on DIP and negatively affect the remainder of the pulping process. Pulsed power technology is a new decontamination method based on the principle of electro-hydraulic discharge. It can effectively remove stickies from recycled paper pulp and can replace the costly minerals and polymers used in conventional control of sticky contaminants (OIT 2002; ITP 2007c).

Pulsed power technology diffuses stickies with a shock wave from a spark discharging underwater and then oxidizes them using hydroxyl radicals created from the water. Oxidation causes the stickies to lose their tack and become benign, thus allowing recycling to continue unimpeded (ITP 2007c). Experiments carried out by IPST have shown that discharging a 3 kilovolt (kV) and 50 kiloampere (kA) underwater spark over a period of 50 to 100 milliseconds can diffuse and oxidize the stickies in recycled paper pulping process (OIT 2002).

Full-scale trials of pulsed- power technology have been conducted at several papers mills in the U.S.: Appleton paper mill in West Carrollton OH, Graphics Packaging mill in Kalamazoo MI, Stora Enso mills in Duluth MN and Wisconsin Rapids WI (owned by NewPage now), and the Jackson Paper mill in Sylva NC. In these trials, the sparker not only detackified stickies effectively but also increased the efficiency of their removal by centrifugal cleaners, improved the effectiveness of the flotation systems, and increased the efficiency of flotation deinking (Banerjee 2005). It is estimated that the sparker improves the efficiency of hydrocyclone cleaners, deinking cells, and dissolved and dispersed air flotation units by 10 to 15 percent (Banerjee 2005).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for the pulsed power technology compared to conventional methods for decontamination in recycled paper mill (OIT 2002; Banerjee 2005; ITP 2007c):

- Reduces energy use by 10 to 15 percent
- Increases brightness
- Reduces need for bleaching and agglomeration chemicals
- Reduces down time
- Improves product quality
- Has low installation cost
- Reduces operational costs

Block Diagram or Photo

Not Available

Commercial Status

Demonstration stage

References for Further Information

OIT 2002; Banerjee 2005; ITP 2007c.

3.3. Emerging Papermaking Technologies

The subsections below describe the following six emerging technologies that save energy and/or reduce GHG emissions in the papermaking process: Aq-vane technology, high consistency papermaking, dry sheet forming, displacement pressing, new fibrous fillers, and laser ultrasonic stiffness sensor.

3.3.1. Aq-vane Technology

Description

Stratified forming is used to produce multi-layer paper and paperboard. Instead of being made from a single paper web that forms a sheet containing mixed or uniform materials throughout, conventional linerboard consists of several distinct layers composed of different raw materials that are formed with different headboxes. Stratified forming technology was developed to produce multi-layer paper and paperboard using only a single headbox, which reduces complexity as well as energy and raw materials consumption (Soderberg 2006).

However, in a stratified forming set-up, the pulp streams are separated by vanes or lamellas which form a wake in which uncontrolled mixing can take place, which degrades the purity of the layers formed using this technology (Soderberg 2009). A new type of stratified technology, Aq-vane, was developed by STFI-Packforsk to overcome this problem (Soderberg 2006). This technology entails injecting a thin passive liquid layer (a liquid vane or Aq-vane) in the headbox through a narrow hollow channel between neighboring pulp streams, which prevents mixing between the layers (Soderberg 2008).

Trials of Aq-vane technology on three types of paper produced by the EuroFEX pilot paper machine showed that, with this technology, the filler content in papermaking can be increased to 45 percent from the previous 35, and energy consumption was reduced by 16 percent (ECOTARGET 2009). Another feature of the Aq-vane technology is that the layer purity and separation can be controlled externally by tuning a set of process parameters. This creates the possibility of widespread industrial application of stratified forming, improved product quality, and the possible development of new paper grades. The new stratified forming technology can be applied to paper grades of almost any grammage (Soderberg 2009).

Energy/Environment/Cost/Other Benefits

STFI-Packforsk claims the following benefits for the Aq-vane technology compared to conventional stratified forming technology (Soderberg 2008; ECOTARGET 2009):

- Reduces fibrous raw material use
- Reduces energy consumption due to less fiber raw materials usage
- Improves paper properties with higher layer purity
- Improves web surface roughness and bending stiffness
- Reduces operation costs

Block Diagram or Photo

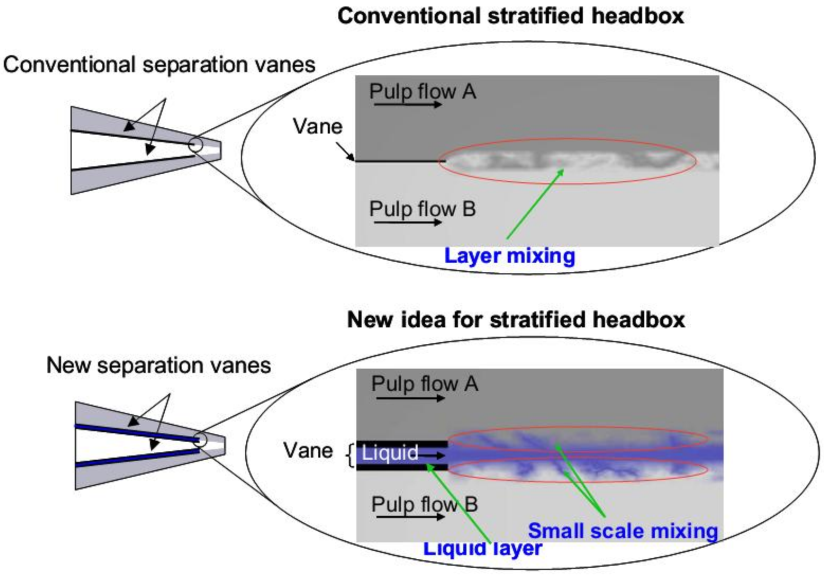

Figure 16. Comparison of conventional and new stratified forming technology (Soderberg 2006)

Commercial Status
Development stage

References for Further Information
Soderberg 2006, 2008; ECOTARGET 2009; Soderberg 2009.

3.3.2. High Consistency Papermaking

Description
In the current papermaking process, the Fourdrinier and twin-wire formers are widely applied for thin paper and multilayered paper or paperboard in papermaking. However, both Fourdrinier and twin-wire formers use low consistency forming technology, which means the paper is formed in a range of 0.5-1.0% low consistency of stock (5-10 g fibers per kg water). The high levels of dilution (due to low slurry consistency) make the short circulation of modem paper machines large and energy intensive (Cichoracki *et al.* 2001). In the low consistency forming process, chemicals have to be employed to increase the retention of furnishing components on paper web. In addition, the recovery of un-retained material and water requires several units of equipment and operation, which consumes high amount of energy (EC 2012).

The high consistency papermaking process would require that the approach and short circulation systems, fluidization and dewatering processes take place at high consistency (EC 2012). In high consistency forming, the processed pulp enters at the forming section, and has more than double the consistency (3 percent) compared to that of normal slurry. High consistency papermaking could increase forming speed and leads to energy savings in the pressing section, due to reduced dewatering and vacuum power requirements (Martin *et al.* 2000b). Increasing the forming consistency from 0.7% to 7% would reduce the flows around the wet end by 10 fold. Since 25% of a paper machine’s energy consumption is used for pumping water and stock alone, significant energy savings could be realized (Cichoracki *et al.* 2001).

Efforts aimed at increasing the forming consistency have been going on since 1980s, but with little success (EC 2012). This development has been limited to a consistency of around 3% due to the deterioration in sheet properties. Recently, it has been suggested that up to 6% may be possible while still achieving good formation (Cichoracki *et al.* 2001). A high consistency device was built by Cichoracki et al. (2001) for forming webs at high consistency (5-15%). To date, webs have been formed at 5-12% consistency, with grammages ranging from 275 to 1000 g/m^2. The web width is 300 mm and speeds up to 700 m/min are currently possible. However, a current drawback, which still needs to be overcome, is the defiberability of the sheet as compared to that of conventional market pulp sheets. Also, the modern paper machines have winder web width and higher machine speed than can be achieved with the current technology mentioned above.

It is expected that high consistency short circulation process will consume 50% less energy and 30% less vacuum energy (EC 2012). Due to improved fibers retention, the consumption of chemicals and the environmental load of the process will also be reduced. Results from early high consistency research indicate that in addition to economic and environmental benefits other advantages may be gained in terms of sheet properties and process variables. Stock storage and pump size could be reduced, and initial dewatering elements in the forming section could be eliminated, all resulting in simplified wet end section of papermaking and a shorter less expensive paper machine (Cichoracki *et al.* 2001; EC 2012). It was reported that 10-15 percent savings in capital costs can be realized for the paper machine wet-end since it allows for reductions of the size of both the forming and drainage area (Martin *et al.* 2000b).

The technology can be installed as an add-on technology to existing processes with some modifications (Martin *et al.* 2000b). Currently, the fundamental problem of high consistency forming is the lack of control of fiber orientation (Johansson 2001). A breakthrough in high consistency papermaking would require new technology where current unit operations, i.e. head-box, drainage and pressing are integrated together in a compact way (EC 2012). Progress is needed in the mixing of fibers and chemicals and in screening, air removal, fluidization, dewatering of furnish, and in process control (EC 2012).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for high consistency papermaking (Martin *et al.* 2000a; Martin *et al.* 2000b; Cichoracki *et al.* 2001; EC 2012):

- Reduces energy use in stock preparation, vacuum system, and dewatering
- Electricity savings are estimated at 8%
- Reduces water consumption in papermaking
- Saving fiber use by 5-8 percent
- Reduces chemical additives
- Simplifies wet end process of papermaking
- Improves product quality
- Reduction of 10-15 percent in capital costs for the wet end of the machine

- High consistency formers are expected to cost $70/t paper with an additional maintenance cost of $0.72/t paper

Block Diagram or Photo
Not available

Commercial Status
Pilot stage

References for Further Information
Martin *et al.* 2000a; Martin *et al.* 2000b; Cichoracki *et al.* 2001; Johansson 2001; EC 2012.

3.3.3. Dry Sheet Forming

Description
With current papermaking technology, a large amount of water has to be added during the stock preparation process to dilute the fibers to a specified concentration. The water in the pulp then has to be removed in the paper machine with different dewatering equipments in the following forming, pressing, and drying process. The majority of the energy consumed in papermaking is used for dewatering. The dryer section, in particular, uses about 67 percent of total energy use in papermaking (Chudnovsky *et al*. 2004). If the papermaking process could use less water or no water, a large amount of energy that is now used for paper drying could be saved.

The principle behind dry sheet forming is the production of paper without adding water (de Beer *et al.* 1998). It relies on high levels of turbulence in the air stream to produce paper products. Fibers can be dispersed either mechanically or using “air laying” techniques. In air laying, the fibers are suspended in the air, and the paper is formed in this suspension. Resins are sprayed on the sheet and are then polymerized to help form the web (de Beer *et al.* 1998). The air laying technology permits a higher production rate and better control of air streams compared to other dry sheet forming processes, so most dry sheet forming processes are using this technology. A typical dry sheet forming line consists of four units: fiber preparation, web formation, web consolidation, and finishing (Jiang 1997).

Air-laid dry sheet forming technology was first commercialized during the early 1980s by Moeller and Jochumsen, a Danish firm. The worldwide installed capacity of this technology is about 350,000 t/year and growing rapidly (Xu *et al.* 2010). New capacity additions of 120,000 t/year are expected during the next few years, mostly in North America (Xu *et al.* 2010). 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 (Martin *et al.* 2000b; Xu *et al.* 2010). Because no water is used in this technology, it avoids the wastewater effluent and treatment that are part of conventional paper mill operations.

The disadvantages of dry sheet technology include increase electricity use in paper forming, less uniform paper thickness, lower sheet strength, and reduced smoothness. However, the paper produced with dry sheet technology tends to be softer than that produced by conventional technology. As a result, dry sheet forming technology is often used to produce personal care products (diapers, feminine hygiene and adult incontinence products, etc.) and some specialty products (tableware, medical products, hot towels, etc.) (Martin *et al.* 2000b). Another barrier facing the dry sheet forming is its lower speed for producing the standard paper grades compared to the conventional technology.

If this technology were commercialized to manufacture standard paper grades, direct investment costs could be 30 to 50 percent of those for a conventional non-integrated paper mill. In addition, O&M costs are expected to be lower (Jiang 1997; de Beer *et al.* 1998). The current installed dry sheet technology capacity in North America is estimated to be only 0.1 percent of total paper production (Xu *et al.* 2010). The market potential in the U.S. for the production of specialty products is estimated to be 5 percent of total U.S. paper production (Xu *et al.* 2010). The technology has not yet been used for producing other types of paper products although it has been demonstrated that producing corrugated medium and molding board with dry sheet forming is possible. It appears that dry sheet forming technology will continue to be developed for specialty applications and is not likely to be adapted in the near future for production of standard paper grades (Martin *et al.* 2000b; Xu *et al.* 2010).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for dry sheet forming technology compared to conventional technology (Jiang 1997; de Beer *et al.* 1998; Martin *et al.* 2000b; Xu *et al.* 2010):

- Reduces drying energy consumption by 50 percent
- Eliminates wastewater effluent and treatment
- Has investment costs 30 to 50 percent of those for a conventional non-integrated paper mill
- Has lower O&M costs compared to conventional technology
- Produces softer paper products

Block Diagram or Photo

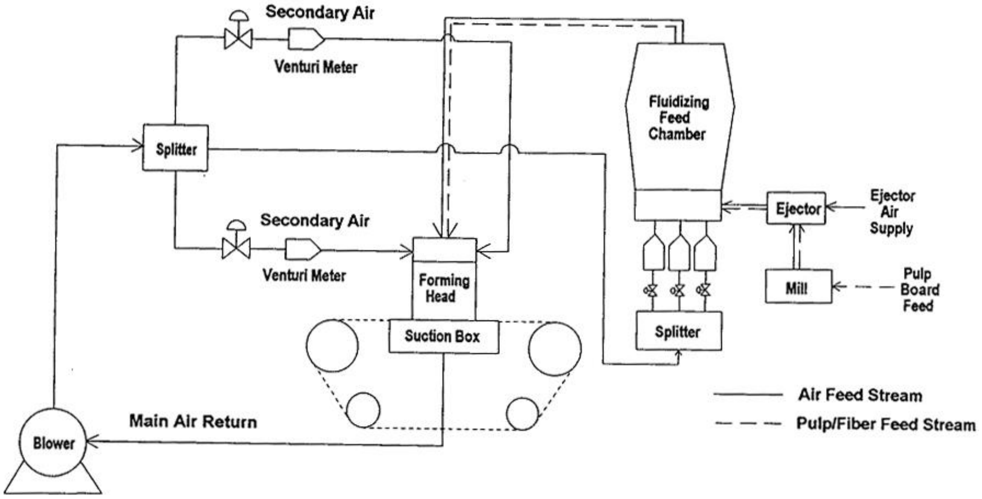

Figure 17. Diagram of a dry sheet forming process (Ng. and Grandmaison 1995)

Commercial Status

Semi-commercial for production of specialty products (diapers, feminine hygiene and adult incontinence products, etc.);
Development stage for producing standard paper grades

References for Further Information

Ng. and Grandmaison 1995; Jiang 1997; de Beer *et al.* 1998; Martin *et al.* 2000b; Chudnovsky *et al.* 2004; Xu *et al.* 2010.

3.3.4. Displacement Pressing

Description

The dryer section accounts for about 78 percent of dewatering costs; of the rest, 12 percent are attributable to the press section and 10 percent to the forming section (Ghosh 2009). Thus, improving the dewatering performance before the dryer section is the most cost effective way to reduce drying energy consumption.

The current pressing technology uses mechanical pressure to remove water from the wet web. Although this method is effective, it produces a maximum solids content of 50 to 55 percent. Solids content of 65 percent has been reported in laboratory studies, and the current theoretical limit of paper press is 80-percent solids (Agenda2020 2010).

Displacement pressing technology is a new method for pressing the paper web that has been developed at the laboratory scale to enhance the solids content of the web out of the press section. This technology combines mechanical and air pressure, pressing web lightly while forcing air through it and using special pressing fabrics with a special four-roll Beck cluster press (BCP). BCP provides a pressurized atmosphere that acts on the moving web and fabric. The special fabric designed for this process use this atmosphere to press the sheet and at the same time force air through the sheet to carry out displacement pressing. The effective dewatering as a result of its higher pressures and longer dwell times giving displacement pressing technology tremendous high speed potential (Beck 2006).

A displacement pressing simulator was built by Voith Fabrics to develop and test pressing fabric on a small scale. Voith Fabrics also designed and built a narrow laboratory-scale BCP that is 5 inches wide. This study also looked at the effect of displacement pressing on sheet properties and found that this technology can produce a paper web with maximum paper solids content exceeding 60 percent (Beck 2006). If this technology is successful, more than 30 percent of drying energy consumption could be reduced. Based on the significant results of the small-scale BCP trial, Voith Fabrics built a one-meter pilot BCP press stand to determine scalability of the process.

Energy/Environment/Cost/Other Benefits

Voith Fabrics Inc. claims the following benefits for displacement pressing technology compared to conventional pressing technology (OIT 2001b; Beck 2006):

- Reduces drying energy consumption
- Increases web solids content before dryer
- Improves paper strength properties
- Reduces paper breaks
- Reduces raw material costs

Block Diagram or Photo

Figure 18. Photo of displacement dewatering equipment (Beck 2006)

Commercial Status

Development stage

References for Further Information

OIT 2001b; Chudnovsky *et al.* 2004; Beck 2006; Ghosh 2009; Agenda2020 2010.

3.3.5. New Fibrous Fillers

Description

Mineral fillers are commonly used to replace wood fibers in the production of paper products and to reduce production cost and energy consumption. The filler loading is limited to roughly 15 to 20 percent of a product because of paper strength and quality requirements (ITP 2006b). If mineral filler exceeding those percentages was used in papermaking, it could degrade paper properties. However, G.R. International Inc. (GRI), in cooperation with several major industrial partners, has developed a new fibrous filler that may overcome these problems and achieve additional replacement of high cost wood fibers.

The fibrous fillers based on calcium and silica in some cases can displace more than 40% of the pulp in papermaking while maintaining paper properties and reducing energy consumption (ITP 2010). GRI and Lawrence Livermore National Laboratory (LLNL) demonstrated the chemical reaction that forms the new filler, and the filler manufacturing process and its paper-enhancing capabilities were optimized in a scaled-up pilot reactor (ITP 2006b). GRI has been working with the University of Washington and Washington State University to optimize and evaluate fibrous fillers and with various industrial partners, including Georgia-Pacific Camas and E3 Energy Partners, to evaluate the performance of the technology in papermaking (ITP 2010).

Energy savings from using new fibrous fillers are attributable to avoided wood pulp production and reduced drying energy due to an increase in the percentage of press solids in the sheet (Mathur 2006). Reportedly, the use of this fibrous fillers could reduce energy consumption by 25 percent and costs by $10 to $50/t paper produced (ITP 2006b).

The new advanced fibrous filler can also be used to replace other expensive fillers, such as TiO_2 and silica. Fibrous fillers will also lead to better retention of fibers, additives, and pulp fines, resulting in significantly reduced COD and biological oxygen demand (BOD) in the mill process water. Fibrous fillers could be used in all paper and paperboard products. Free sheet papers are the most likely targets in the near term, but wood-containing papers and newsprint could eventually use this product as well (ITP 2006b). GRI has a plan to expand the current prototype plant to a full commercial plant, and the technology is available for licensing (ITP 2010).

Energy/Environment/Cost/Other Benefits

GRI claims the following benefits for fibrous filler technology compared to conventional papermaking and/or filler technology (ITP 2006b):

- Reduces energy use by 25 percent
- Replaces expensive fillers, such as TiO_2 and silica
- Increases solid content of paper web
- Improves retention/ Increases water drainage rate
- Improves paper optical properties (brightness, opacity, printing quality)
- Reduces BOD, COD, and turbidity in mill process water
- Reduces costs by $10 to $50 per tonne paper manufactured
- Creates additional revenue in new products

Block Diagram or Photo

Not Available

Commercial Status

Pilot stage

References for Further Information

ITP 2006b; Mathur 2006; ITP 2010.

3.3.6. Laser Ultrasonic Stiffness Sensor

Description

Stiffness is one of the most important parameters for papermaking process and quality control. The current measurement method is using offline samples that cut from the reel after the paper has been already manufactured. The measurements are conducted manually, slowly, and cannot provide feedback to adjust paper quality during manufacturing (ITP 2006e). If the sample doesn't meet specifications, the entire roll is sold as an inferior grade or remanufactured. To avoid this costly outcome, manufacturers often over-engineer paper, using more pulp than necessary to ensure the final product meet stiffness and other quality standards. This results in excess raw materials and energy consumption (LBNL 2002). As much as 5 percent of the paper produced each year is considered substandard and must be re-pulped and remanufactured to improve its mechanical properties and strength (ITP 2007b). Large amounts of raw materials and energy used for remanufacturing could be avoided if the web stiffness could be measured and controlled in real time in papermaking process.

The velocity of ultrasound can be used to determine various mechanical properties of the paper. For example, the square of ultrasonic velocity is proportional to paper stiffness (ITP 2007b). Researchers at LBNL have developed a laser ultrasonic stiffness sensor that could measure paper's bending stiffness and shear strength in real time, allowing manufacturers to optimize the amount of raw materials used by running closer to specifications (LBNL 2005). Using this technology, manufacturers could focus the manufacturing process on stiffness targets (rather than the current practice of using basis weight targets) and adjust paper machines accordingly during production. Real-time control of paper machines would enable more efficient use of materials, including a higher percentage of recycled fibers (ITP 2006e).

The ultrasonic laser stiffness sensor has been tested successfully at three sites in the U.S.: Mead Paper Company's research center in Chillicothe OH, a paper mill in Boise ID, and a paper mill in Jackson AL (LBNL 2005; ITP 2006c). The sensor was installed on a pilot paper-coating machine and ran six paper grades, ranging from lightweight copy paper to heavy linerboard. The sensor's signals remained clear, even at paper speeds up to 1500 meters per minute (m/min), and the laser did not damage the paper.

Implementation of this technology at the mill scale could result in an estimated 3 percent energy savings: a 2-percent decrease in basis weight (because manufacturers would be able to run closer to specifications rather than over-engineering their products), and a 1-percent reduction in off-grade paper that must be recycled (which avoids the additional energy necessary to reprocess the recycled fiber in the mill) (Kramer *et al*. 2009).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for using laser ultrasonic stiffness sensor compared to conventional methods (LBNL 2002; ITP 2006e; Kramer *et al.* 2009):

- Reduces refining and re-pulping
- Reduces energy consumption by about 3 percent at the plant level
- Improves product quality and consistency
- Increases use of recycled paper

- Reduces raw material use in papermaking
- Reduces costs other than energy by reducing the production of below-specification paper
- Minimizes waste, including lost fiber quality during drying and re-wetting

Block Diagram or Photo

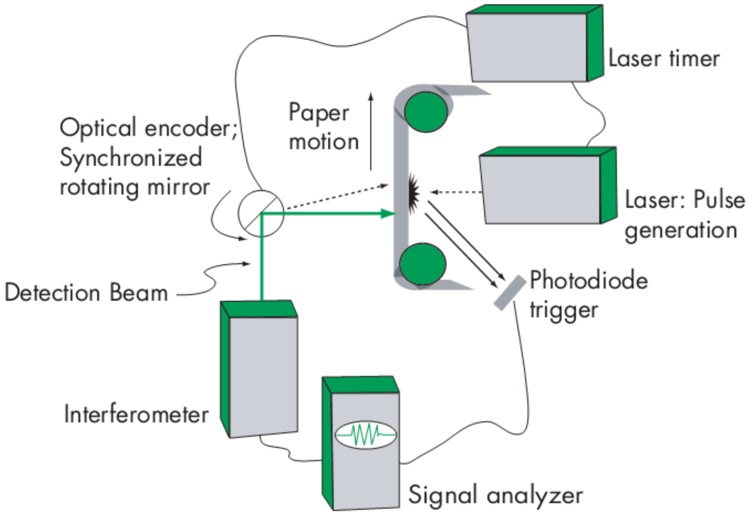

Figure 19. Laser ultrasonic stiffness sensor working principle (LBNL 2002)

Commercial Status

Demonstration stage

References for Further Information

LBNL 2002, 2005; ITP 2006c, 2006e, 2007b; Kramer *et al.* 2009.

3.4. Emerging Paper Drying Technologies

The papermaking process is essentially a massive dewatering process with drying as the most significant element in terms of equipment investment or energy consumption. Currently, the most common paper drying method uses steam as the main source of heat energy in a series of rotating cylinders (about 1.5 to 2 meters [m] in diameter and each cylinder up to 10 m long) as the heat transfer area. This method is used in 85 to 90 percent of installations in the paper industry (Mujumdar 2006). Although the paper drying process removes only about 1 percent of the original water, it consumes about 67 percent of the total energy required in papermaking, equivalent to 25 to 30 percent of the total energy used in the pulp and paper industry (IEA 2009). As mentioned previously, the paper drying process is the most expensive part of the paper machine. Although retrofit measures such as spoiler bars and stationary siphons have been developed and widely applied to conventional dryers for improving their energy efficiency and drying rate, these dryers are still relatively inefficient and capital intensive. The emerging paper drying technologies described in the subsections below increase both the energy efficiency and productivity of conventional paper drying technology.

3.4.1. Gas-fired Dryer

Description

To improve the current paper drying efficiency, the Gas Technology Institute (GTI), with Boise Paper Solutions, Groupe Laperrière and Verreault (GL&V) USA Inc., and Flynn Burner Corporation in the U.S., developed a high efficiency gas-fired paper dryer based on the combination of ribbon flame and advanced heat transfer enhancement technique. This gas-fired cylinder dryer involves combusting natural gas and air in small dimples or cavities. The airflow creates a vortex within each dimple, resulting in highly stable mini flames and uniform drum surface temperatures (ITP 2006d). This is a high-efficiency alternative to traditional steam-heated dryers and is expected to exceed the performance of existing paper drying systems.

This new gas-fired dryer was initially evaluated in GTI's combustion laboratory and then successfully tested at Western Michigan University's pilot paper machine. The conventional steam heated dryer at Western Michigan University consumed about 21 kW of saturated steam heat to reach 120ºC on the drum surface compared to less than 14.7 kW of heat is necessary for the gas-fired dryer to reach the same surface temperature. Moreover, about 260 ºC dryer surface temperature was reached during linerboard production, which increased the drying rate by 4 to 5 times compared to the rate of existing steam-heated dryers (Chudnovsky *et al.* 2004). A full-scale demonstration is being conducted on a linerboard paper machine at Liberty Paper Inc., an LDI Company (ITP 2006c).

This gas-fired dryer can be installed in new or existing equipment. This new gas-fired dryer is 75- to 80-percent energy efficient compared to 65-percent efficiency of steam-heated dryer, so its implementation would save significant energy. In addition, it would help the paper industry increase production by 10 to 20 percent, resulting in significant capital costs savings for both retrofits and new capacity (Chudnovsky *et al.* 2004). Even if an existing paper machine is not drying-rate limited, the gas fired dryers will still reduce energy consumption. The payback period is estimated to be less than 1 year (Chudnovsky *et al.* 2004).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for gas-fired dryers compared to conventional steam-heated dryers (Chudnovsky *et al.* 2004; ITP 2006d):

- Reduces drying energy consumption by 10 to 20 percent
- Increases production by up to 20 percent
- Improves drying rate
- Achieves higher surface temperatures
- Has lower initial capital investment

Block Diagram or Photo

Figure 20. Photo of gas-fired dryer (Chudnovsky 2011)

Commercial Status

Pilot stage

References for Further Information

Chudnovsky *et al.* 2004; Chudnovsky and J.DiGiacomo 2006; ITP 2006c, 2006d; Chudnovsky 2011.

3.4.2. Boost Dryer

Description

The boost dryer technology combines condensate drying and press drying principles by using a dryer cylinder and a pressure hood. The web runs directly over the drying cylinder, which is heated with saturated steam at 6 to 12 bars above atmospheric pressure. On the outside of the web is a special engineered fabric and a steel belt. The belt, fabric and paper are pressed against the cylinder surface by water pressure. The water pressure is generated in a hood that encloses approximately three-quarters of the cylinder circumference and is set between 0.5 and 4 bars. The water temperature is between 60 and 90°C (Haase 2005). The moisture in the web evaporates and condenses in the meshes of the cooled fabric. A small amount of the web moisture remains as steam between the fabric meshes. The fabric temperatures range between 70°C and 90°C. The hot condensate evaporates after leaving the pressure hood. The evaporating condensate is exhausted as in a conventional dryer section, and its heat can be recovered using heat exchangers (Karner and Herzog 2008).

Boost dryer technology could increase production where space is limited and improve paper strength. It can achieve higher drying rates than conventional drying because of the hood pressure, which presses the web against the cylinder surface and creates a better contact than in a conventional dryer. The heat-transmission coefficient of the web can also be significantly increased. Boost drying is primarily suitable for board and packaging paper production. It is reported that one boost dryer can replace several conventional dryers (Karner and Herzog 2008).

The first prototype of the boost dryer was installed after the press section on the Voith pilot paper machine to evaluate boost drying during continuous process. The tests showed higher drying rates can be achieved with only 4.5 seconds of dwell time in the boost dryer compared 13 seconds in conventional drying. In addition, there was 40-percent improvement in the surface smoothness of the paper. Klingele paper mill in Weener (Germany) installed the first commercial-scale boost dryer technology in 2008 (Karner and Herzog 2008).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for boost dryer technology compared to a conventional drying technology (Haase 2005; Karner and Herzog 2008):

- Reduces specific energy consumption
- Increases drying efficiency, and increases drying capacity by approximately 12 percent
- Reduces drying time
- Reduces space needed for dryer section
- Improves paper quality (e.g., breaking strength, bending stiffness, smoothness)

Block Diagram or Photo

Figure 21. Photo of a boost dryer (Karner and Herzog 2008)

Commercial Status

Pilot stage

References for Further Information

Haase 2005; Karner and Herzog 2008.

3.4.3. Condebelt Drying

Description

The Condebelt drying process is a new paper drying technology that is based on the condensing belt principle. In the Condebelt drying process, the paper web is dried in a drying chamber between two steel belts instead of on traditional steam-heated cylinders (de Beer *et al.* 1998). One the up side of the web is the upper steel belt, and on the down side of the paper web are three layers: fine wire gauze, coarse wire gauze, and the lower steel belt (see Figure 22). The upper steel belt is heated by steam at temperatures of 110 to 160°C, and the lower one is cooled by circulating water to approximately 80°C (Lee *et al*. 2000). The top side of the web is in direct contact with the upper steel belt, and the lower side of the web contacts a fine wire with a coarse wire underneath. The evaporated water passes through the wire gauze and condenses on the steel belt. The condensate is removed by pressure and suction. The pressure on the web can range from atmospheric to 10 bars.

Laboratory tests of this technology showed very high drying rates, exceeding 145 kilograms per square meter per hour (kg/m^2h) at a metal temperature of 170℃. The drying rate went as high as 500 kg/m^2h for low-grade paper in pilot-scale tests (Mujumdar 2006). Condebelt drying can also significantly improvement the resulting product’s strength (by 20 to 60 percent), surface smoothness, dimensional stability, and resistance against humidity (EC 2001). Currently, the Condebelt drying is best fit for paperboard drying. For other paper grades, drying under such unsymmetrical conditions will result in two-sidedness.

Two mills have installed this technology (Retulainen 2001). The first installation is 2.5 m wide with a machine speed of 200 m/min and has been running since 1996 at Stora Enso’s Pankakoski board mill in Finland (Retulainen and Hamalainen 2000; Retulainen 2001). The second is 4.5 m wide with a machine speed of 650 m/min and began operation in 1999 at Dong II Paper Mfg. in South Korea, producing linerboard and fluting (Lee *et al.* 2000; Retulainen 2001). This technology can save an estimated 15 percent in steam consumption (1.6 GJ/tonne paper) and can slightly reduce electricity consumption (20 kWh/tonne paper), with investment costs of $28/t paper for a retrofit and $110/t for new construction (Martin *et al.* 2000a). O&M costs are not expected to be significantly different from current practice (Xu *et al.* 2010). As a promising drying technology, Condebelt drying could be widely applied in the paper industry.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for Condebelt drying technology compared to conventional steam-heated dryer (de Beer *et al.* 1998; Martin *et al.* 2000a; EC 2001):

- Reduces steam consumption by 10 to 20 percent
- Saves an estimated 1.6 GJ/t paper in steam, 20kWh/t paper in electricity
- Increases drying rates by 5 to 15 times
- Increases machine productivity
- Improves paper properties, and significantly improves paper strength (by 20 to 60 percent)
- Does not significantly change O&M costs
- Makes the sheet two-sided and much rougher than normal on the back side

Block Diagram or Photo

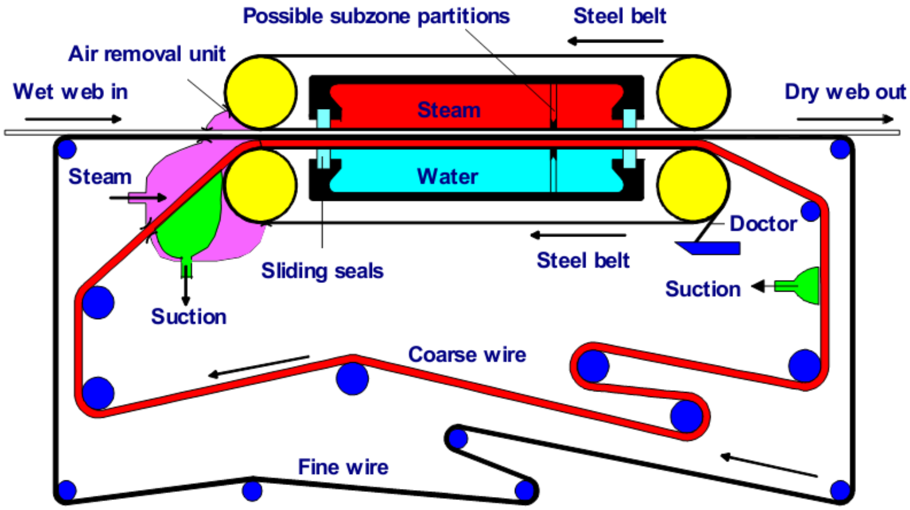

Figure 22. Schematic of Condebelt drying process (Lee *et al.* 2000)

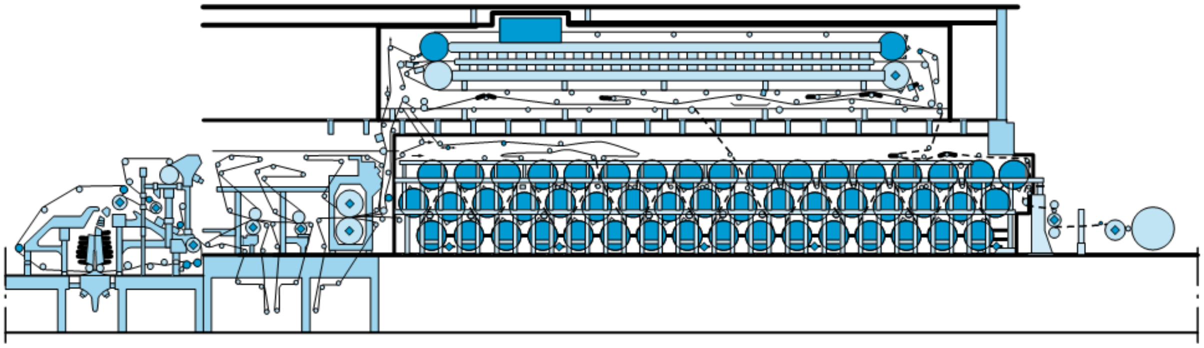

Figure 23. Paper machine with Condebelt drying (Retulainen and Hamalainen 2000)

Commercial Status

Semi-commercial stage

References for Further Information

de Beer *et al.* 1998; Lee *et al.* 2000; Martin *et al.* 2000a; Retulainen and Hamalainen 2000; EC 2001; Retulainen 2001; Mujumdar 2006; Xu *et al.* 2010.

3.4.4. Microwave Drying

Description

Microwaves can perform a useful function in leveling out the moisture profiles across the wet paper web (Sander *et al*. 2003). When paper is heated using microwaves, high drying rates can be realized. Microwave paper drying has been investigated periodically since the 1960s. One of the first studies reported a 30-kW microwave dryer tested on a pilot paper machine (Ahrens 2003). Previous studies indicated favorable economics and no damage to paper quality. Because the microwave energy absorption efficiency increases with greater water loads, microwave technology is especially suited for drying high basis weight paper grades. For lower basis weight paper, larger microwave applicators are needed to achieve high absorption efficiencies.

Microwave technology would be an add-on to the paper machine. It can be used in the press section to preheat the web and reduce the water load delivered to the dryer section. It can also be applied to the dryer section for pre-heating and to supplement existing cylinders that operate by conduction heating (ITP 2006a). Microwave heating can be classified as a volumetric heat source. Therefore, microwave drying rates are not limited by the usual conductive or convective heat input resistances (Ahrens 2003). If microwave drying technology is used in the press section, it will increase press dewatering, reduce dryer energy consumption, and enhance dryer efficiency and productivity. In addition, O&M costs will be lower due to the reduction in numbers of cylinders relative to conventional dryer sections. Although additional electricity or natural gas will be required in order to produce the microwaves, overall energy consumption will decrease because of the high energy efficiency when microwave drying is employed.

IPST conducted a three-year project funded by the U.S. DOE. The project initially aimed at evaluating the feasibility of microwave paper drying technology and commercializing it. The feasibility study showed that microwave paper drying technology can increase paper machine speeds by 30 percent and reduce paper drying energy consumption by 20 percent with a payback period shorter than 2.5 years (Ahrens 2003).

Energy/Environment/Cost/Other Benefits

The following benefits are reported from adding microwave drying compared to conventional drying technology (Ahrens 2003; ITP 2006a):

- Reduces overall energy consumption by 12 percent
- Increases dryer temperature and drying efficiency
- Increases paper machine speed by 30 percent
- Has lower overall investment costs for new machines
- Reduces maintenance costs
- Has payback period is shorter than 2.5 years (for high basis weight paper machine, payback is only 0.5 to 1 year)
- Eliminates over drying

Block Diagram or Photo

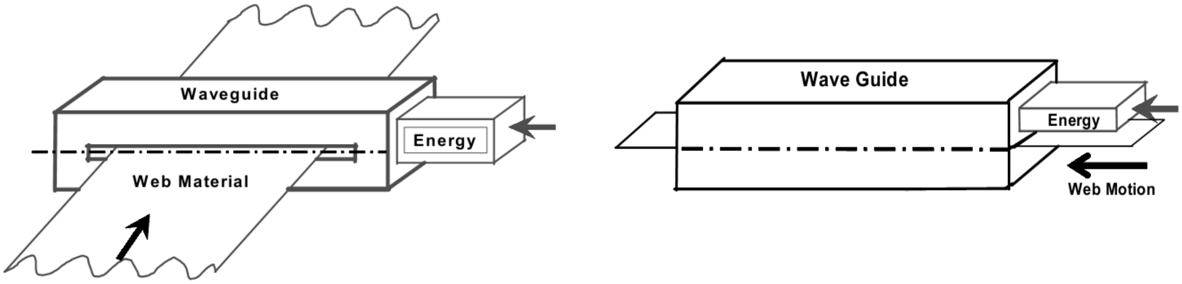

Figure 24. Cross- and machine-direction oriented microwave drying (Ahrens 2003)

Commercial Status

Development stage

References for Further Information

Ahrens 2003; Sander *et al.* 2003; ITP 2006a.

3.5. Emerging Byproduct/Biomass/Waste Heat Utilization Technologies

The subsections below describe emerging technologies for using byproducts, biomass, and waste heat generated by the pulp and paper industry to reduce waste and the need for waste disposal and to increase waste heat utilization level as well as to manufacture additional products that are of value to other industries or sectors and that could be sources of additional revenue for the pulp and paper industry.

3.5.1. Black Liquor Gasification

Description

As mentioned earlier, black liquor is a mixture of cooking chemicals, lignin residues, and other wood components that is a byproduct of the chemical pulping process. It has an approximate energy content of 14 MJ/kg dry solids (DS), which is about half of the energy content of 1 kg of coal equivalent (Gebart 2006; Program 2011). The current black liquor handling technology uses a Tomlinson recovery boiler to reclaim the energy and chemicals from black liquor. However, the efficiency of the current recovery technology is relatively low because of black liquor's relatively high water content, which limits combustion efficiency. According to IEA, combustion of black liquor produced about 2.6 exajoules (EJ) of energy worldwide in 2006 and is expected to produce between 4.0 EJ and 6.0 EJ by 2050 (IEA 2009).

Black liquor gasification (BLG) is an emerging technology with a long research and development (R&D) history. BLG entails pyrolyzing concentrated black liquor into an inorganic phase and a gas phase through reactions with oxygen or air at high temperatures (EC 2001). BLG technology can be an alternative to using a recovery boiler to produce electricity, chemicals, or fuels such as dimethyl ether (DME), synthetic gas (syngas), methanol, hydrogen, or synthetic diesel (Naqvi *et al.* 2010). BLG can also be integrated with combined-cycle (CC) technology (BLGCC), which has potential to produce significantly more electricity than current boiler/steam turbine systems and could even make the mill an electricity exporter (Martin *et al.* 2000b). Alternatively, the syngas can be used as a feedstock to produce chemicals, thereby using the pulp mill as a biorefinery (Worrell *et al*. 2004).

BLG can increase energy recovery efficiency by 10 percent compared with conventional recovery technology (Cheremisinoff and Rosenfeld 2010). In addition, it can increase the amount of generated at the pulp mills and sold to power grid by two to three times (Gebart 2006). However, the investment for a full-scale pressurized BLG process unit is larger than for a new conventional recovery boiler. It is estimated that the first large demonstration units will cost two to three times more than a conventional recovery boiler (Bajpai 2010). BLG is 2-3 times as expensive in capital costs relative to a conventional recovery boiler. The capital costs for BLG were estimated at $200-500 million (depends on different end-use configurations, among which BLGCC is the lowest one), compared to $100-150 million for conventional recovery system, and the annual non-fuel O&M costs were estimated at $10-20 million (Larson *et al.* 2003; Larson *et al.* 2009). The greater investment that is required will limit the commercialization of BLG in the pulp and paper industry. The causticizing and lime kiln load increases 20% which can adversely impact the mill's capacity for pulp production. However, the increased causticizing load can be eliminated by including a titanate-based cyclic process called direct causticization technology (Chen and van Heiningen 2006;

Sinquefield *et al.* 2010; Naqvi *et al.* 2012b). Up to now, direct causticization technology is under development state (Chen and van Heiningen 2006; Heiningen 2008; ITP 2011c). Another major disadvantage for BLG is that a new method for recovering sulfur and sodium must be installed since kraft pulping economics require nearly complete recovery of inorganic chemicals (Brown Sept. 2012).

To date, only small, commercial, atmospheric low-temperature BLG units have been built, e.g. Weyerhaeuser's 300 tonnes/day low pressure, entrained flow booster gasifier in New Bern, North Carolina; Georgia-Pacific's 200 tonnes/day fluidized bed steam reformer system in Big Island, Virginia; Norampac 100 tonnes/day steam reformer in Trenton, Ontario; while similar-size pressurized demonstration BLG units do not yet exist (Bajpai 2010; Naqvi *et al.* 2010).

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for BLG (Worrell *et al.* 2004; Gebart 2006; IEA 2009; Cheremisinoff and Rosenfeld 2010; Program 2011; Chemrec 2012):

- Increases pulping process energy recovery by 10 percent
- Increases power production by two to three times at the pulp mills that exported electricity sold to power grid
- BLGCC system has investment 60 to 90 percent higher than for standard boiler system, ranging from $200-400 million
- Increases pulp yield by about 5 to 7 percent if done in conjunction with significant changes in pulping conditions

Block Diagram or Photo

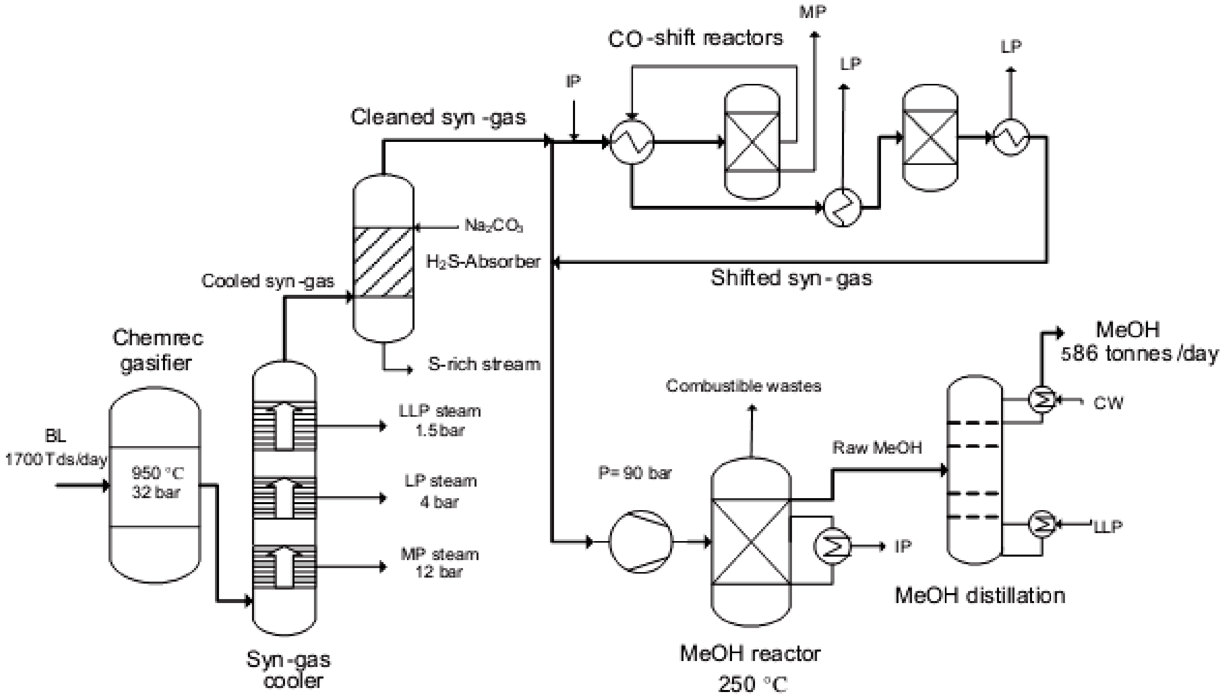

Figure 25. Schematic of methanol production with BLG (Naqvi *et al.* 2012a)

Commercial Status

a) Atmospheric low-temperature BLG
Demonstration stage – Small-scale application, 100 to 350 tonnes DS/day

b) Pressurized high-temperature BLG
Pilot stage - 20 tonnes DS/day, and ready for scale up to 300 tonnes DS/day

References for Further Information

Larson and Raymond 1997; Martin *et al.* 2000b; EC 2001; Larson *et al.* 2003; Worrell *et al.* 2004; Chen and van Heiningen 2006; Gebart 2006; Larson *et al.* 2006; Lindblom and Landälv 2007; Heiningen 2008; Larson *et al.* 2008; IEA 2009; Larson *et al.* 2009; Bajpai 2010; Cheremisinoff and Rosenfeld 2010; Naqvi *et al.* 2010; Sinquefield *et al.* 2010; ITP 2011c; Program 2011; Chemrec 2012; Naqvi *et al.* 2012b, 2012a; Pettersson and Harvey 2012.

3.5.2. Biomass Gasification

Description

Biomass gasification[10] is a thermochemical process to decompose the complex hydrocarbons of biomass into syngas that mainly consists of H_2, carbon monoxide (CO) and CH_4. In most cases, some char and tars are also formed during biomass gasification, along with CO_2, water, and other constituents (Ciferno and Marano 2002). Gasification differs from combustion because it uses just 20 to 30 percent of the air or oxygen needed for complete fuel combustion. During gasification, the amount of air supplied to the gasifier is carefully controlled so that only a small portion of the fuel burns completely (Nexterra 2012).

The generated syngas from biomass gasification can be used as auxiliary fuel in boilers for electricity and steam generation via gas turbines or fuel cells, or as the feedstock in the production of biofuel and industrial chemicals. There exists different biomass gasification paths, including gasification of biomass or waste for co-firing with coal, biomass integrated gasification gas engine (BIGGE), biomass integrated gasification combined cycle (BIGCC) and biomass gasification with dimethyl ether production (BIGDME) (Wetterlund 2012). Figure 26 presents a general overview of biomass integrated gasification combined cycle (BIGCC) integrated with the pulp and paper mill. One of the advantages of biomass gasification over biomass combustion is that the power generation efficiency of BIGCC can be as much as twice the efficiency of conventional biomass-based CHP system, which uses a steam cycle alone (Ahl 2012).

The principle of gasification has been used for decades with coal and wood. The co-production of transport fuels by biomass gasification offers an opportunity for integrated pulp and paper mills to produce additional products onsite and increase profitability. Both the gasification and synthesis processes produce large amounts of byproduct steam or fuel gas, which can be integrated into the energy system of a pulp and paper mill (IEA 2009). However, biomass has a

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[10] BLG is a special case of biomass gasification, applicable only for kraft pulp mills. Given BLG has already been discussed earlier as an independent emerging technology, the biomass discussed here does not include black liquor, but only means the lignocellulosic feedstock generated in pulp and paper mills.

considerably lower energy density than coal and is more scattered, which makes collection and distribution more cumbersome and costly (Wetterlund 2012).

An entire biomass gasification system commonly comprises biomass feeding, gasification, and gas cleanup systems. Capital and operating costs vary widely. Generally, biomass gasification is more expensive than BLG. For gasification, the biomass input to the mill would need at least to double, which might require additional investments in infrastructure (IEA 2009). Assuming a base feedstock cost of $1.9/GJ, the cost of production from gasification has been estimated at 6.7¢/kWh for electricity for a 75-MW plant. Steam costs were estimated by the U.S. National Renewable Energy Laboratory at $14.77/t steam. Assuming a base feedstock cost of zero, the cost of production from gasification would be about 5¢/kWh for electricity for a 75 MW plant and steam costs would be $11.02/t steam (Bain *et al*. 2003).

Most of the biomass gasification technology suppliers are located in North America and Europe (Ahl 2012). Many technology developments are in the prototype or first commercial demonstration stage now. Nexterra Systems Corp. supplied its first biomass gasification system for Kruger Products Paper Mill in New Westminster, British Columbia in 2009. This biomass gasification equipment has the potential to displace approximately 445,000 GJ of natural gas (54 percent of current natural gas consumption of the plant) annually for Kruger Products Paper Mill with a payback period of 3 to 3.5 years (Nexterra 2012). Commercial-scale demonstration projects are underway at NewPage's pulp and paper mill in Wisconsin Rapits, WI, and at Flambeau River Paper in Park Falls, WI. Both of these biomass gasifier systems were supplied by ThermoChem Recovery International (TRI) (Brown Sept. 2012).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for biomass gasification technology (Nexterra 2012; Wetterlund 2012):

- Reduces fossil fuel consumption and CO_2 emissions of pulp and paper mills
- Lowers nitrogen oxide (NOx) emissions 30 to 40 percent compared to conventional combustion of wood
- Reduces waste solids disposal costs
- Provides significant added value to the traditional pulp and paper industry
- Can provide feedstock for chemical industry
- Can provide biofuel for transport sector

Block Diagram or Photo

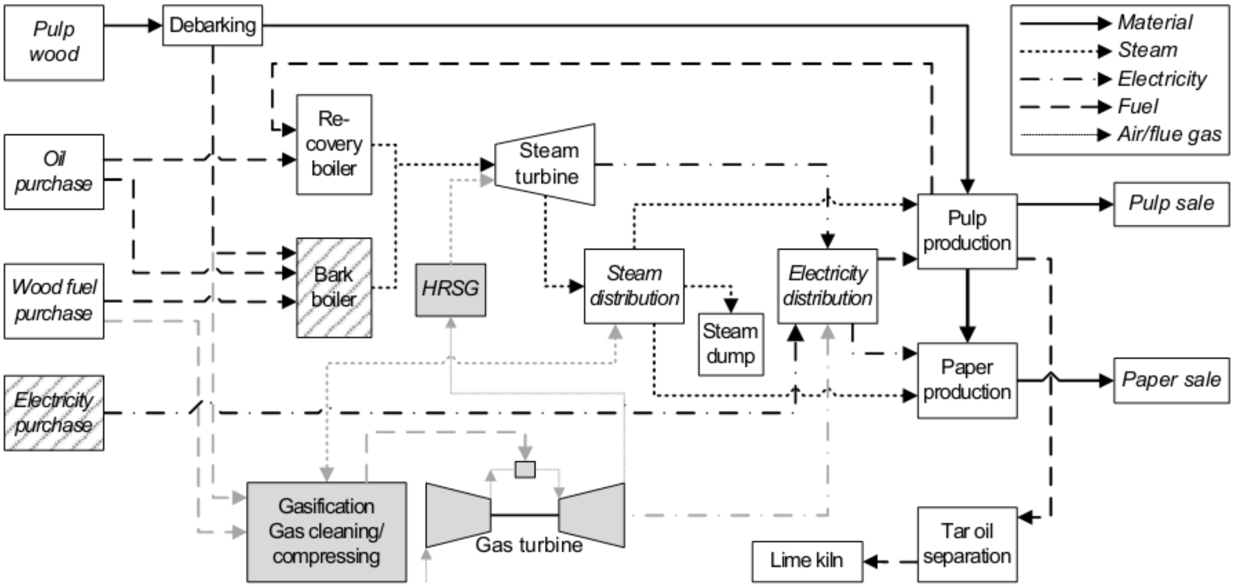

Figure 26. Overview of BIGCC integrated with the pulp and paper mill (Wetterlund 2012)

Commercial Status

Different commercial status for different biomass gasification concepts, most of which are under pilot and demonstration stage currently.

References for Further Information

Ciferno and Marano 2002; Bain *et al.* 2003; IEA 2009; Ahl 2012; EBTP 2012a; Nexterra 2012; Wetterlund 2012.

3.5.3. Hemicellulose Extraction before Chemical Pulping

Description

As mentioned earlier, the chemical pulp can be either manufactured by kraft or sulphite pulping method. The kraft pulping, which representing about 80 percent of the world pulp production, is the most applied chemical pulping worldwide (EC 2012). Hence, here we only discuss hemicellulose extraction before pulping for kraft pulping, while it can also be applied to sulphite pulping.

In kraft pulping, 50 percent of hemicellulose is removed by dissolving in the black liquor along with lignin (Hamzeh *et al.* 2013). Black liquor is then concentrated and burnt in chemical recovery process to recovery the energy and pulping chemicals. However, the degraded hemicelluloses in the black liquor have a negative impact on the overall energy efficiency of pulp mill because the heating value of hemicellulose is only about half of that of lignin (Amidon and Liu 2009; Huang *et al.* 2010). As a result, extracting hemicellulose before pulping offers an attractive economic opportunity for the pulp and paper industry (Agenda2020 2010).

Hemicellulose extraction could decrease residence times in kraft pulping thus resulting in potentially increased pulping capacity or the option of using lower cooking temperatures (Jun *et al.* 2012). In addition, the recovery boiler and lime kiln may be off-loaded by about 20% when integrated with hemicellulose extraction technology (Mao *et al.* 2008). This will increase the pulp production capacity for the pulp mills that are limited by chemical recovery unit (Walton *et al.* 2010). A study that using kraft white liquor pre-treatment of extracting the hemicellulose from aspen chips found that the pulp yield could be maintained or even increased by 10-20 g/kg dry wood (Jun *et al.* 2012). It is expected as well that this technology could substantially improve pulp mill operations (Bajpai 2012). Hemicelluloses are hetero-polysaccharides, which contain hexosan and pentosan monomer units (Hamzeh *et al.* 2013). They can be used directly in polymeric form for novel industrial applications such as fiber additives, biopolymers, hydrogels, or thermoplastic xylan derivatives; or, once hydrolyzed, they can serve as a source of sugars for fermentation to fuels, such as ethanol or chemicals (Al-Dajani and Tschiner 2008). These process benefits and biofuel possibilities are strong drivers for the development of wood hemicellulose extraction technologies for kraft mills.

In recent years, the interest in the extraction of hemicellulose prior pulping has greatly increased. Several research groups are exploring various pre-treatments of lignocellulosic materials including autohydrolysis, hydrothermolysis, and aqueous liquefaction (Al-Dajani and Tschiner 2008; Jun *et al.* 2012). Pre-extraction before pulping using water/steam as the only solvent has been investigated because it is cheap and environmentally friendly and results in simpler downstream processes compared to dilute acid and alkaline pre-hydrolysis (Walton *et al.* 2010). Other methods for hemicellulose extraction include mild alkaline solutions with or without addition of cations such as Na, K, Li and borate low temperature, organosolv fractionation, supercritical carbon dioxide, ionic liquids, and microwave heat-fractionation (Bajpai 2012). Of these methods, pretreatment of lignocellulosic materials with water has been demonstrated as an excellent option for the extraction of hemicellulose since no chemicals other than water are involved (Al-Dajani *et al.* 2009). The study of near-neutral hemicellulose extraction shows that less steam is produced in the recovery boiler because some of the energy content in the wood is contained in the by-products and steam is required in the processing. In addition, considerable sulfuric acid is required for the hydrolysis step in the process and lime is required for neutralization of the extract (Mao *et al.* 2008; Mora *et al.* 2011; Yoon *et al.* 2011b; Lundberg *et al.* 2012).

Removal of hemicelluloses from wood chips as a pre-treatment step is presently being practiced commercially in the production of dissolving pulps (Bajpai 2012; Jun *et al.* 2012). While for the production of chemical pulps, hemicellulose extraction is currently under pilot stage (Brown Sept. 2012). Hemicellulose extraction before pulping is being built for demonstration at Old Town in Maine, U.S. (Agenda2020 2010). It was reported that hemicellulose extraction before pulping could result in pulps that refine difficultly and forms a weaker paper than obtained pulps from un-extracted raw materials for soda-AQ (anthraquinone) pulping of rice straw (Jahan *et al.* 2012). Hot-water extraction was found to negatively impact some pulp properties including decreases in burst and tensile indices while addition of chitosan and cationic starch could improve the strength properties. However, no significant differences in tear index were observed, indicating that the fiber strength remains unaffected, but the inter-fiber bonding decreases with extraction (Hamzeh *et al.* 2013). There is a trade-off in how much hemicellulose is to be extracted without adversely affecting the amount and quality of the pulp to be made, which should be studied further before commercialized.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for hemicellulose pre-extraction technology (Mao *et al.* 2008; Amidon and Liu 2009; Walton 2009; Huang *et al.* 2010; Walton *et al.* 2010; Yoon *et al.* 2011a; Bajpai 2012; Jun *et al.* 2012):

- Reduces kraft cooking time
- Enhances cooking liquor impregnation
- Decreases alkali consumption
- Improves the energy efficiency of kraft pulp mill
- Improves the profitability of kraft mill
- Increases production capacity for pulp mills that are limited by the recovery boiler
- No significant change in paper strength except for a minor reduction in tear
- Reduces organic and inorganic load for recovery boiler and lime kiln

Block Diagram or Photo

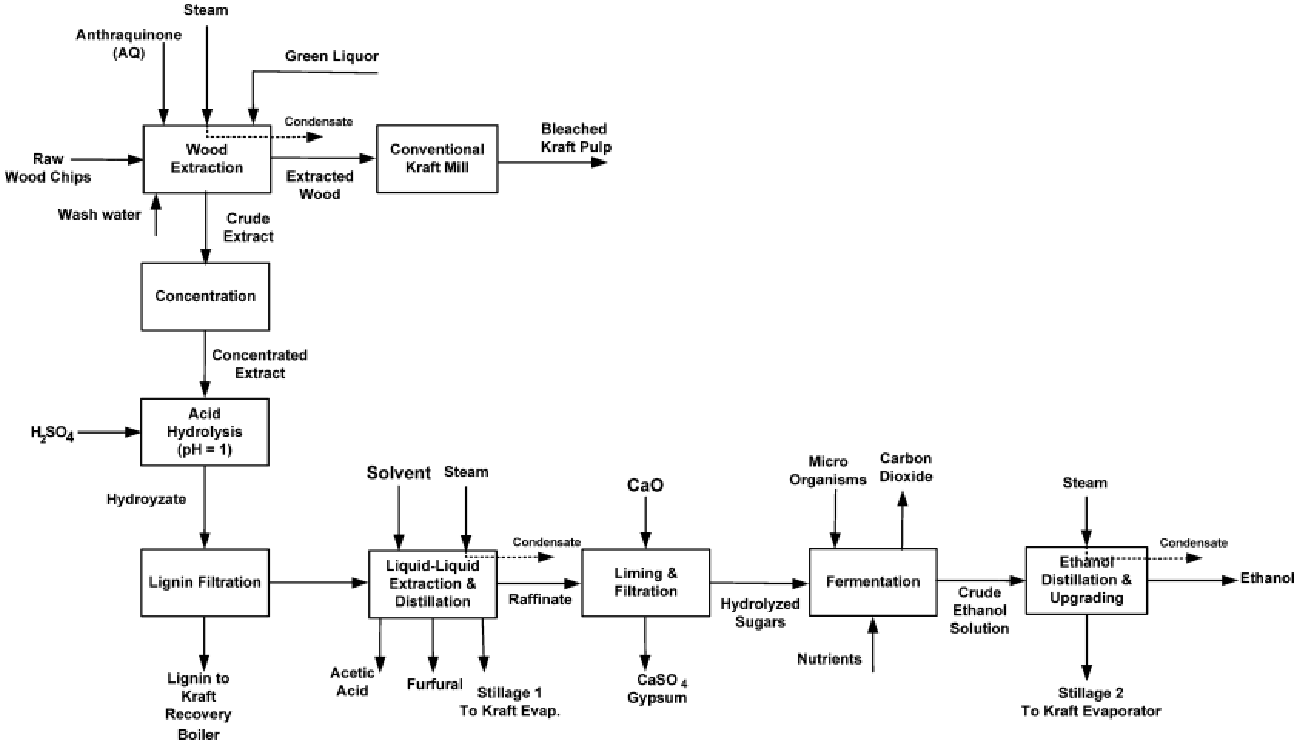

Figure 27. Diagram of a hemicellulose extraction process (Walton *et al.* 2010)

Commercial Status

Pilot stage

References for Further Information

Al-Dajani and Tschiner 2008; Mao *et al.* 2008; Al-Dajani *et al.* 2009; Amidon and Liu 2009; Walton 2009; Agenda2020 2010; Axegård 2010; Huang *et al.* 2010; Walton *et al.* 2010; Houtman and Horn 2011; Mora *et al.* 2011; Yoon *et al.* 2011a; Yoon *et al.* 2011b; Bajpai 2012; Jahan *et al.* 2012; Jun *et al.* 2012; Lundberg *et al.* 2012; Hamzeh *et al.* 2013; Brown Sept. 2012.

3.5.4. LignoBoost

Description

Lignin is one of the most abundant organic polymers on earth, second to cellulose in mass. An estimated more than 50 Mt of lignin is available from the current pulp and paper industry worldwide without counting other possible biomass utilization (Gosselink *et al*. 2004). However, much of this is not extracted but is burned onsite to provide steam for heat and power production.

LignoBoost is a new technology that extracts lignin from black liquor with the potential to create new revenues for pulp mills. The technology uses CO_2 to lower the pH of the black liquor which causes precipitation of lignin. The precipitate is then dewatered using a filter press. LignoBoost then overcomes conventional filtering and sodium separation problems by re-dissolving the lignin in spent wash water and acid. The resulting slurry is once again dewatered and washed with acidified wash water to produce virtually pure lignin cakes (Metso 2012a). An estimated 25 to 50 percent of the lignin can be removed from black liquor using this process (IEA 2009).

Lignin is an outstanding biofuel with high heat value. It can be used in a power plant boiler, recovery boiler, or lime kiln to replace fossil fuel (SETIS 2011b). Potential savings from using lignin in a lime kiln are as much as 50 liters of fuel oil per tonne of pulp. Lignin can also be used as the raw material for making chemicals instead of petroleum-based products, which makes it a very interesting substance for the chemical industry where many companies are looking for renewable raw materials for manufacturing food, dyes, plastics, pharmaceuticals, and other products. Activated carbon is another product with potential to be made from lignin (Innventia 2012). There are successful trials using lignin to make carbon fibers. Pulp mills can derive additional income from using lignin as fuel and selling it for further refining.

LignoBoost technology was first developed by researchers at Innventia and Chalmers University of Technology. A demonstration plant with a capacity of 6,000 to 10,000 t lignin/year is integrated into the pulping process of Nordic Paper in Sweden in 2007 (Innventia 2012). In 2008, Metso purchased the LignoBoost technology in an agreement with Innventia that includes further development, design tool improvement, and industrial scaling-up. In 2011, Metso announced the sale of the first commercial LignoBoost technology to Domtar pulp mill in North Carolina. This LignoBoost plant will be integrated with the Plymouth North Carolina pulp mill and will be in commercial operation in 2013 (Metso 2012a). The IEA estimates that if the surplus lignin (i.e., the lignin that is not used by the mill itself but is sold to the market) sells for more than US$ 140/t lignin[11], this process would generate additional profits for the mill (IEA 2009).

Energy/Environment/Cost/Other Benefits

The following benefits are reported for the LignoBoost technology (Innventia 2012; Metso 2012a):

- Replaces fossil fuel in lime kilns and power boilers
- Gives pulp mill new potential to increase production and reduce costs
- Generates additional income for pulp and paper mills
- Supplies renewable raw materials for other industrial sectors

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[11] Assuming the typical heat value of lignin is 25-27 MJ/kg, according to Metso (2012a).

Block Diagram or Photo

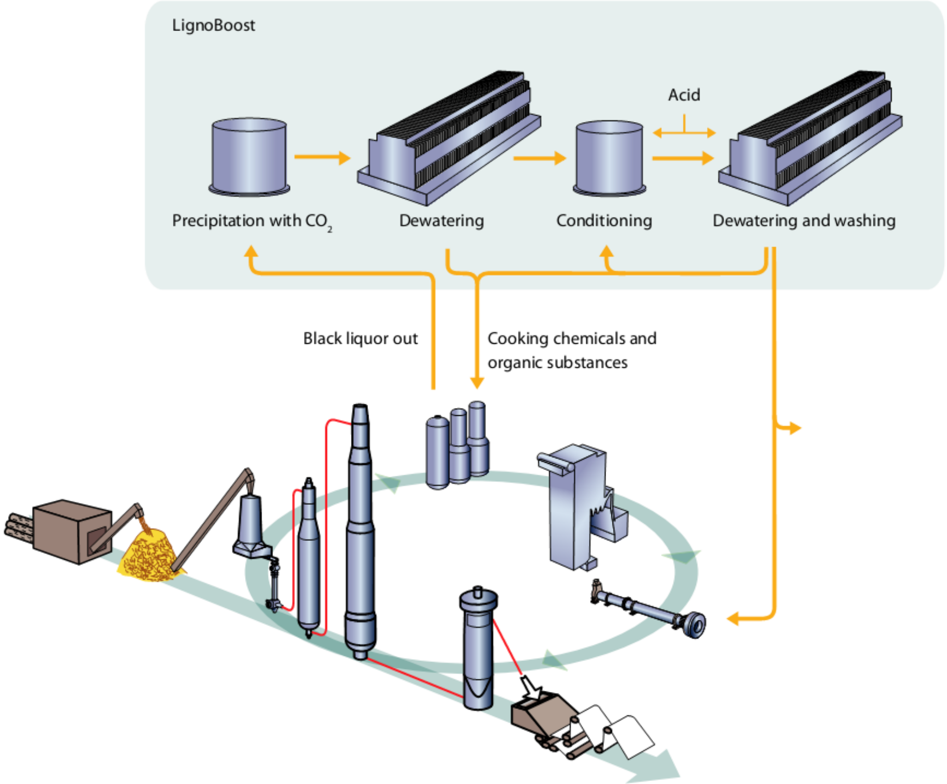

Figure 28. LignoBoost in chemical pulping plant (Metso 2012a)

Commercial Status
Pilot stage

References for Further Information
Gosselink *et al.* 2004; IEA 2009; SETIS 2011b; Innventia 2012; Metso 2012a.

3.5.5. Other Biorefinery Concepts

Description
The pulp and paper industry is currently in transition. Many mills are no longer producing only pulp and paper but are also producing other products that can increase both their profitability and overall energy efficiency. These mills are functioning as biorefineries in addition to their traditional manufacturing (Jönsson *et al*. 2011). A biorefinery can use all types of biomass available at a pulp and paper mill, including de-barking waste, waste wood chips, forest residues, paper mill residues, and sludge generated from the pulping and papermaking process (Mäkinen *et al*. 2011). Even for the waste paper, it was reported that it can be used for bioethanol production (Wang *et al.* 2012). By integrating biorefinery operations with the pulp and papermaking process, the industry can produce a wide variety of materials, from chemicals to fuels, in addition to paper products (CEPI 2009).

According to the IEA Bioenergy Task 42, biorefining is the sustainable processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat). The biorefinery can be a concept, a facility, a process, a plant, or even a cluster of facilities (IEA 2010b). The biorefinery concept also embraces a wide range of conversion technologies that can separate biomass resources into their building blocks (carbohydrates, proteins, triglycerides, etc.), which can then be converted to value-added products, biofuels, and chemicals (Cherubini 2010). Biorefinery technology pathways are typically categorized as chemical (extraction, fractionation, synthesis, etc.), biochemical (digestion, carbohydrate, fermentation, etc.) and thermochemical (pyrolysis, gasification, torrefaction, etc.) (Stawicki and Read 2010).

Biorefining is similar in concept to the petroleum refining except that local, renewable biomass materials are the feedstock rather than crude oil. The two types of products that result from biorefining are energy products (e.g., bioethanol, biodiesel, and synthetic biofuels) and material products (e.g., chemicals, materials, food and feed) (IEA 2010b). Biorefining involves multi-step processes. The first step, following feedstock selection, is typically pre-treatment of the biomass. Next, the biomass components are subject to a combination of biological and/or chemical treatments. The outputs from this step (which are specialty chemicals or sugars) can be further converted to chemical building blocks, specialty polymers ready for market use, fuel/energy sources, or use in composite materials (FitzPatrick *et al*. 2010).

The pulp and paper industry with its existing capital infrastructure provides an opportunity to expand the range of products that is manufactured to an integrated forest biorefinery thus more fully utilizing the woody biomass and possibly additional forest residues (Huang *et al.* 2010). Biorefinery concepts for chemical pulp mills have been extensively investigated, but recycled fiber biorefineries have not yet been fully investigated (Wang *et al.* 2012). Most of the large paper recycling and deinking mills already produce some bioenergy and other bio-products from their reject materials but do not yet produce liquid biofuels or biochemicals (Stawicki and Read 2010).

The pulp and paper industry is working with the chemical and energy sectors to develop biorefineries in Europe, Canada and the U.S., and biorefinery roadmaps have been developed in these regions (IEA 2009). A number of large programs under the European Union's Seventh Framework Programme (FP7) for research and innovation focus on developing biorefinery and related technologies in Europe. Work is currently being done to further develop of second-generation lignocellulosic biofuels (SETIS 2011b). Some pre-commercial, industrial-scale demonstration plants are producing cellulosic ethanol. In 2011, the Mossi & Ghisolfi Group (M&G) (Chemtex) started building a commercial-scale 50 million liters/year cellulosic ethanol production facility in Crescentino, Italy. The plant will use Novozymes enzyme technology to convert a range of cellulosic feedstocks to ethanol (EBTP 2012b). A first large-scale bio-dimethyl ether (DME) plant in connection to a pulp mill is currently being constructed in Sweden (SETIS 2011b). However, the technological and economic challenges must be overcome before commercialization of these biorefinery technologies.

Table 3 shows seven promising biorefinery paths from European Industrial Bioenergy Initiative (EIBI), which also shows the final products from each biorefinery path. Because of the scale of investment needed and the risks involved (technology, feedstock & end product prices, regulatory framework evolution), financing the latest stages of development of innovative bioenergy technologies is a major obstacle for large scale industrial deployment of these technologies. However, all the seven promising biorefinery paths are expected to be first commercialized by 2020 (EBTP 2011, 2012a). It presents the general information about these seven biorefinery paths, including preliminary estimates of capital cost, the status of development, and main technology challenges. Further information such as brief description of each path, examples of ongoing pilot/demonstration projects, and technical challenges for all value chains can be found at (EBTP 2011, 2012a).

Table 3. General information on seven promising biorefinery chains under development now (EBTP 2011)

	Biorefinery chain name	**Technology challenges**	**Development status**	**Preliminary costs estimates (demonstration plant/ first commercial plant) (Million Euros)***
Thermochemical paths				
1	Synthetic liquid fuels and/or hydrocarbons (e.g. gasoline, naphtha, kerosene or diesel fuel) and blending components through gasification	Feeders, gas cleaning, catalysts	Demonstration stage	40-100/ 400-1000
2	Bio-methane and other bio-synthetic gaseous fuels through gasification	Feeders, gas cleaning, catalysts	Pilot stage	20-40/ 200-300
3	High efficiency heat & power generation through thermochemical conversion	Bio-feedstock compatible materials, high share of power generation	Demonstration stage	20-40/ 150-250
4	Intermediate bioenergy carriers through techniques such as pyrolysis and torrefaction	Handling/stability of bio-oil, materials, specifications of intermediates	Demonstration stage	20-40/ 50-100
Biochemical paths				
5	Ethanol and higher alcohols from lignocellulosic feedstock through chemical and biological processes	Preparation of feedstock, enzymes	Demonstration stage	20-40/ 100-200
6	Hydrocarbons (e.g. diesel and jet fuel) through biological and/or chemical synthesis from biomass containing carbohydrates	Microorganisms, catalyst performance, bioprocessing	Demonstration stage	5-20/ 50-100
7	Bioenergy carriers produced by micro-organisms (algae, bacteria) from CO_2 and sunlight	Selection of strains, process design, water treatment, scale up	Pilot stage	20-40/ 100-300

* It should be noted that because demonstration and first commercial plants are by definition "first ever built", the costs cannot be accurately estimated, until a basic design engineering study (+ or – 30% estimate) or a detailed engineering study (+ or – 10 % estimate) have been performed.

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for integrated forest biorefinery:

- Improves energy efficiency for the pulp and paper industry
- Potentially lower the greenhouse gas emissions
- Provides significant added value to the traditional pulp and paper industry
- Reduces raw materials use in other industrial sectors

Block Diagram or Photo

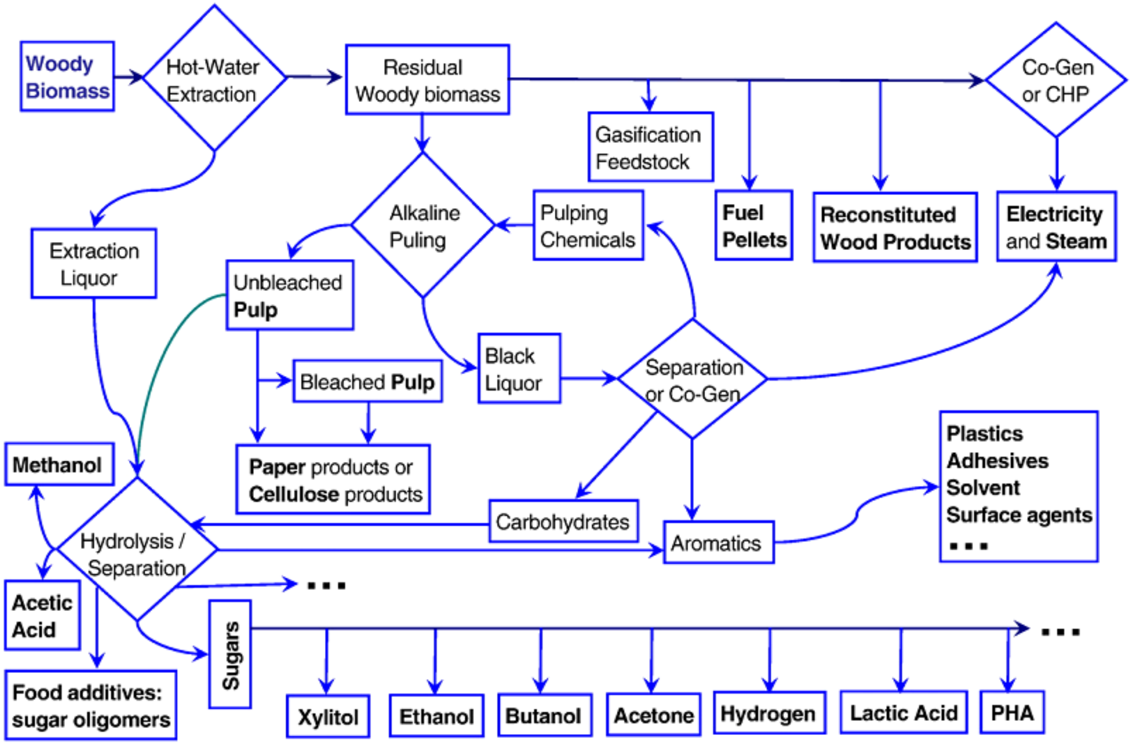

Figure 29. Flow diagram of integrated forest biorefinery (Amidon and Liu 2009)

Commercial Status

Different stages of development for different parts of the biorefining process: commercial status for biomass combustion, biogas production; semi-commercial and demonstration for thermal gasification; research and pilot for pyrolysis (SETIS 2010).

References for Further Information

Amidon and Liu 2009; CEPI 2009; IEA 2009; Cherubini 2010; FitzPatrick *et al.* 2010; Huang *et al.* 2010; IEA 2010b; SETIS 2010; Stawicki and Read 2010; EBTP 2011; Hellsmark 2011; Jönsson *et al.* 2011; Mäkinen *et al.* 2011; Mora *et al.* 2011; SETIS 2011b; EBTP 2012b, 2012a; Fornell and Berntsson 2012; Heyne and Harvey 2012; Moshkelani *et al.* 2012; Naqvi *et al.* 2012a; Wang *et al.* 2012.

3.5.6. Use of Residuals in Concrete Production

The highest volume residuals generated by the pulp and paper industry are wastewater treatment sludge and ash (from burning coal, wood/bark, and wastewater treatment residuals). Other solid residuals include wood yard waste, pulping or papermaking rejects, causticizing waste, and general mill refuse. Pulp and paper mill residuals (also called sludge) are composed mainly of cellulose fibers, papermaking fillers (kaolinitic clay, calcium carbonate, and/or titanium carbonate), and water (Naik *et al*. 2003). Managing these residuals is an ongoing concern for the pulp and paper industry. Traditionally, they are sent to landfills which is costly, or incinerated after being dewatered. For example, more than 3.7 Mt of residuals from the U.S. pulp and paper industry require disposal each year; two-thirds of them are sent to landfills and incinerators (ITP 2006g).

Recent research projects have shown that fibrous residuals from the pulp and paper industry have the potential to improve concrete quality (Chun and Naik 2004; Naik *et al.* 2004). Concrete has weak tension (3 to 9 megapascals [Mpa]) whereas wood cellulose fiber has strong tension (300 to 900MPa) (Naik *et al.* 2004). Adding cellulose fiber residuals from pulp and paper mills to concrete increases the life span of concrete. In a laboratory study, mechanical agitation in room temperature water to separate the individual cellulose fibers as required before adding the cellulose to a concrete mixer because the residual from the pulp and paper mills are usually dewatered to reduce their weight and volume. Then the cellulose fiber slurry can be mixed with the concrete in a mixing tank at a rate of 0- to 1.2-percent residuals by weight of the concrete (Chun and Naik 2004). Residuals from pulp and paper mills have also been shown to somewhat reduce the chloride-ion penetrability of concrete and increase the resistance of non-air-entrained concrete to freezing and thawing and to salt scaling (Naik *et al.* 2003).

This technology will also lead to reduced amount landfill of pulp mill residual solids (Kraus and Naik 2007; Kraus *et al.* 2010). In addition, it also provides the concrete industry with a low-cost source of fibers to produce a better product. Replacing mineral raw materials normally used in concrete production with pulp mill residuals will significantly reduce the concrete industry's annual energy use and CO_2 emissions. This practice will benefit both of paper industry and concrete industry if commercialized.

In 2002, a pilot trial was conducted using the residuals from a U.S. paper mill in northern Wisconsin. The results showed that the concrete made with residuals had effectively the same strength as similar concrete without residuals, but the concrete without residuals was not as durable and was severely damaged by freezing and thawing and salt exposure (Naik *et al*. 2005). The most effective residuals were those that were easy to disperse into individual cellulose fibers (Chun and Naik 2004). The best concrete performance seems to be achieved if the residual solids are collected prior to chemical conditioning and solidification.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for the use of fibrous residuals in concrete production (Naik *et al.* 2003; Chun and Naik 2004; Naik *et al.* 2004; ITP 2006g):

- Significantly reduces concrete industry's energy use and CO_2 emissions
- Reduces landfilling of high-carbon fly ash and sludge from pulp and paper mills
- Improves concrete strength and durability
- Increases concrete life span by 50 percent
- Reduces disposal costs for the pulp and paper industry
- Reduces concrete production costs

Block Diagram or Photo

Not available

Commercial Status
Pilot stage

References for Further Information
Naik *et al.* 2003; Chun and Naik 2004; Naik *et al.* 2004; Naik *et al.* 2005; ITP 2006g; Kraus and Naik 2007; Kraus *et al.* 2010.

3.5.7. Transport Membrane Condenser

Description
The hood exhaust from the paper machine is an important source of low-temperature heat that can be used in the mill. The dryer section consumes most of the heat energy in a paper mill. In addition, almost all of the energy leaving the dryer section can be found in the hood exhausts. The use of conventional heat exchangers with low-temperature streams requires impractically large surface areas, which reduces the energy efficiency of the heat recovery system. Recovering energy from relatively low-temperature waste streams at a large scale is challenging.

Oak Ridge National Laboratory (ORNL) in cooperation with the University of Tennessee – Knoxville, GTI, and Media and Process Technology Inc. is developing an innovative energy recovery system based on advanced membrane separation technology, named Transport Membrane Condenser (TMC). TMC technology utilizes a nanoporous ceramic membrane tube designed to condense water vapor by capillarity and recovery waste heat. A partial vacuum inside of each tube aids the transport of water through the tube wall. This new heat recovery technology enables the capture, recovery, and reuse of all sensible and latent waste heat, as well as water vapor from exhaust/flue gas (HPAC 2010). It has been tested on laboratory clean systems (ITP 2011a).

When used with industrial and commercial boilers, TMC can increase fuel-to-steam efficiency by as much as 15 percent (for up to 95-percent fuel-to-steam efficiency), and can capture 20 percent of boiler water for reuse without the need for further water treatment (HPAC 2010). In 2011, Cannon Boiler Works Inc. and GTI commercialized TMC (branded as “Ultramizer”) for use in a standard range of boiler sizes. However, it is not yet applied to recovery the waste heat generated from the pulp and paper industry.

This technology can also be used to recover waste heat from exhaust gases (including flue and stack gases, flared gases, vent gases, combustion gases, and exhaust from metal heat treating furnaces and dryer vents) in a number of other industrial sectors, including chemical, forest products, and petroleum industries, etc. (ITP 2011a).

Energy/Environment/Cost/Other Benefits
The following benefits are reported for TMC technology (HPAC 2010; ITP 2011a):

- Enables energy recovery from relatively low-temperature waste streams
- Improves thermal efficiency of current heat recovery system
- Reduces freshwater consumption in boiler
- Reduces water treatment costs for steam generation

Block Diagram or Photo

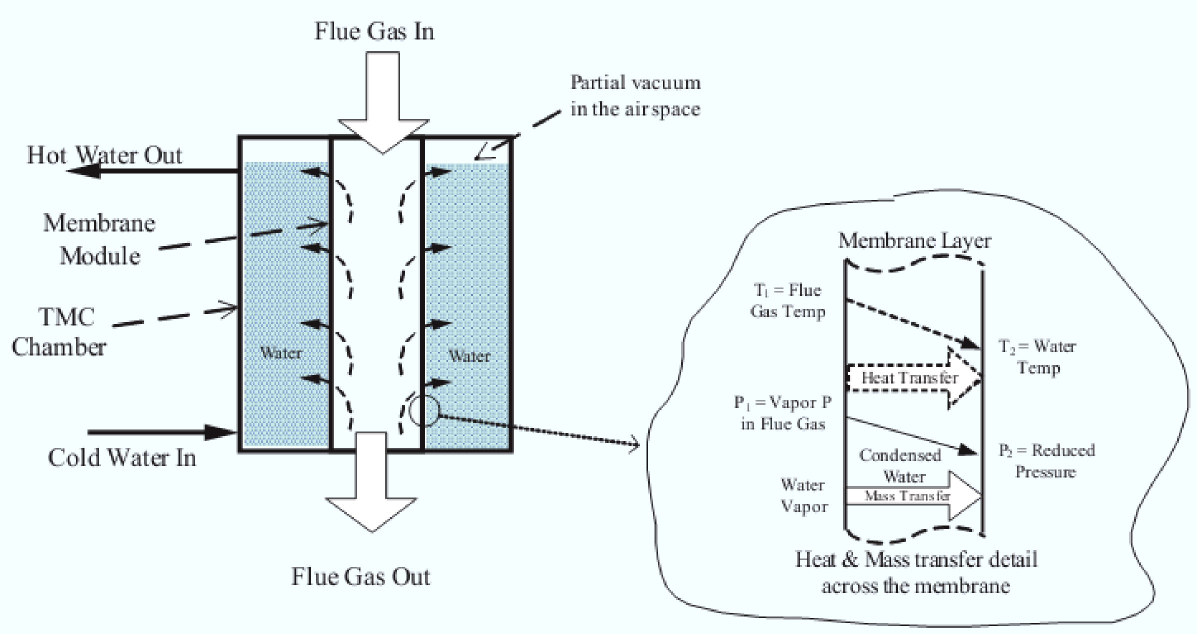

Figure 30. Schematic of TMC mechanism (ITP 2011a)

Commercial Status

Semi-commercial stage for industrial boilers
Research stage for paper machine dryer section heat recovery

References for further information

HPAC 2010; ITP 2011a.

3.6. Emerging Carbon Capture Technologies for the Pulp and Paper Industry

Introduction

If carbon capture and storage (CCS) develops into an economical technology, it could be an useful component of a portfolio of technologies and measures to reduce GHG emissions and help avoid the most serious impacts of climate change. Pulp and paper industry is one of the industrial sectors with the largest GHG mitigation potential (Bernstein *et al*. 2007). Energy-related emissions, such as those arising from onsite fossil fuel combustion and energy purchases/transfers, are by far the most significant CO_2 sources from the pulp and paper industry (NCASI 2008).

There are in principle three different CO_2 capture technology options overall: pre-combustion capture, oxy-fuel combustion capture, and post-combustion capture, as illustrated in Figure 31 (IPCC 2005). In pre-combustion capture, carbon is removed from the fuel before combustion. IN oxy-combustion, the fuel is burned in an oxygen stream that contains little or no nitrogen (Figueroa *et al.* 2008; SETIS 2011a). In post-combustion capture, carbon is separated from other flue gas constituents either originally present in the air or produced by combustion. Table 4 summarizes the advantages and disadvantages of each of these CO_2 capture technologies. Pre-combustion capture technology applies to those pulp and paper mills that are integrated with black liquor and/or biomass gasification technologies. Post-combustion capture applies primarily to fossil fuel, black liquor or bark fired boilers that are air fired. Oxy-fuel combustion capture technology can be applied to new plants or retrofitted in existing plants (Figueroa *et al*. 2008).

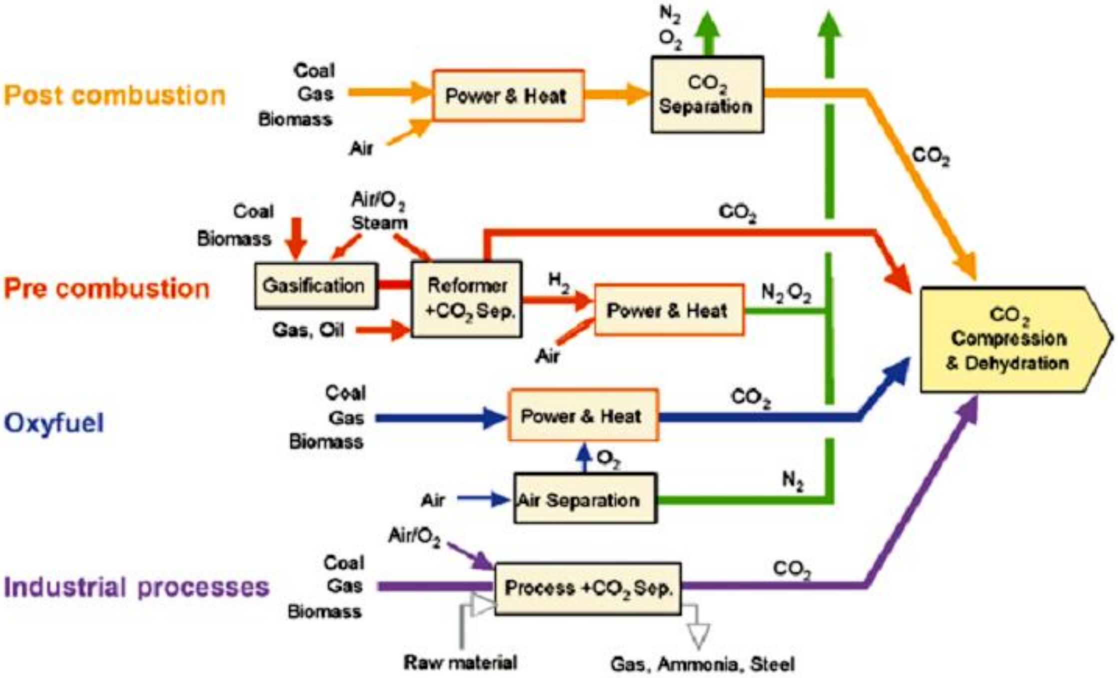

Figure 31. CO_2 capture technologies (IPCC 2005)

Table 4. Comparison of different CO_2 capture (CC) technologies (Figueroa *et al*. 2008)

CC technology	Advantages	Barriers to implementation
Post-combustion	● Applicable to the majority of existing coal-fired power plants ● Retrofit option	Flue gas is • dilute in CO_2 • at ambient pressure This results in ● Low CO_2 partial pressure • Significantly higher performance or circulation volume required for high capture levels • CO_2 produced at low pressure compared to sequestration requirements
Pre-combustion	Syngas is • concentrated in CO_2 • higher pressure This results in ● High CO_2 partial pressure • Increased driving force for separation • More technologies available for separation ● Potential for reduction in compression costs/loads	● Applicable mainly to new plants because few gasification plants are currently in operation ● Barriers to commercial application of gasification are common to pre-combustion capture • Availability • Cost of equipment • Extensive supporting system requirements
Oxy-fuel combustion	● Very high CO_2 concentration in flue gas ● Retrofit and repowering technology option	● Large cryogenic O_2 production requirement may be cost prohibitive ● Cooled CO_2 recycle required to maintain temperatures within limits of combustor materials • Decreased process efficiency • Added auxiliary load

CCS is an emerging technology to capture and compress CO_2 into liquid form and transport it via pipeline to a sequestration site where it can be permanently stored deep underground or in the ocean. Approximately 60 percent of CO_2 emissions in the pulp and paper industry are from biomass fuel combustion (IEA/UNIDO 2011). It is more appropriate to consider CCS technologies in the context of pulp and paper production process. Currently, most of the CCS technologies development are applied to power plants. Considering almost all the modern pulp and paper mills are equipped with self-generated power plants, the technologies discussed below are focused on capturing CO_2 emissions from power generation. For information about how to capture process-related CO_2 emission from lime kilns, which is somewhat similar to the cement industry, we refer you to (Hasanbeigi *et al.* 2012). GHG emissions from other auxiliary processes (e.g. landfill operation and wastewater treatment) are insignificant compared to those from energy use in pulping and papermaking process, we do not discuss the technologies applicable to these auxiliary processes in this report.

Biomass conversion and BLG can be applied to produce biofuels (syngas, ethanol, DME, etc.) or can be incorporated into integrated gasification combined-cycle (IGCC) technology, allowing for easier carbon capture with pre-combustion CCS technologies. Flue gases of pulp and paper mills contain 13 to 14 percent CO_2, and post-combustion capture of CO_2 from these diluted streams is costly (IEA/UNIDO 2011). Post-combustion capture using chemical absorption is a proven way to separate CO_2 from flue gases, and does not need to be fundamentally altered to be used for the boilers (Hektor and Berntsson 2007). Oxy-fuel combustion uses oxygen instead of air for combustion in boilers and lime kilns, producing a flue gas with pure CO_2 (IPCC 2005).

Oxy-fuel combustion capture technology is currently being demonstrated in small-scale plants. Further research is required to make this technology a viable option for pulp and paper mills. The oxygen is usually produced by low-temperature (cryogenic) air separation, and novel techniques to supply oxygen to the fuel, such as membranes and chemical looping cycles, are being developed. For the latter alternatives, the special task of the recovery boiler, to recover the chemicals used in the pulping process, demands further investigation before implementation (Hektor and Berntsson 2007). However, oxy-fuel technology cannot be applied directly to existing kilns or boilers (Jönsson 2011).

The main obstacles of implementing CCS technologies are the high capital and operating costs and reduced energy efficiencies, and the absence of a carbon abatement policy or regulatory mandate, as a result, the pulp and paper industry does not currently use this technology as a CO_2 mitigation option. The transportation costs associated with transferring CO_2 to storage cites is costly. However, assuming that the R&D currently under way on lowering CCS cost is successful, application of this technology to industrial CO_2 sources should begin before 2030 and be widespread after that date if incentivized by carbon abatement policies (carbon tax or cap-and-trade) or mandated by law as a requirement for operations (Bernstein *et al*. 2007). Although some CCS technologies are commercially available today, the reliability and safety of long-term storage needs to be demonstrated, and the costs need to be lowered to make this an economically viable option (Figueroa *et al*. 2008; Lipponen *et al*. 2011).

3.6.1. BLGCC with Pre-combustion Carbon Capture

Description

BLG technology is described in Section 3.5.1. In existing kraft pulp mills with modern combined heat and power (CHP) systems based on recovery boilers and biomass boilers, electricity conversion efficiencies are low (less than 15 percent) (Larson *et al*. 2000). Improved overall energy efficiency, increased electricity conversion efficiency, and reduced CO_2 emissions can be accomplished by the introduction of black liquor-integrated gasification combined-cycle (BLGCC) technology (Larson *et al.* 2000; Maunsbach *et al.* 2001; Möllersten *et al.* 2004).

The technical CO_2 reduction potential of BLGCC in kraft pulp mills can be further enhanced by incorporating pre-combustion carbon capture (Möllersten *et al.* 2003b). BLGCC is similar to coal-fired IGCC technology and similarly capable of being equipped with CO_2 capture (IEA 2009). BLGCC with pre-combustion carbon capture involves reacting black liquor with oxygen or air to give mainly a syngas composed of carbon monoxide (CO) and hydrogen (H_2). This is followed by the "shift" reaction to convert CO to CO_2. When CO-shift is added prior to CO_2 absorption, CO in the gasifier reacts with water to form CO_2 and more H_2, enhancing the CO_2 capture ratio ($CO + H_2O \rightarrow CO_2 + H_2$) (Möllersten *et al*. 2006). The generated CO_2 is then separated, usually by a physical or chemical absorption process, resulting in a hydrogen-rich fuel that is then integrated into the gasification combined cycle to generate electricity. Separation can also be achieved with selective membranes. However, membranes cannot currently achieve a high degree of separation, and improvement is needed for their use to be cost effective on a large scale (IEA/UNIDO 2011).

Möllersten *et al*. estimated reduction potentials and specific CO_2 reduction costs of several carbon-capture alternatives in Swedish pulp and paper mills (Möllersten *et al.* 2003a; Möllersten *et al.* 2003b; Möllersten *et al.* 2006). They found that introduction of BLGCC could reduce net CO_2 emissions by approximately 9 percent if marginal electricity from coal-fired power plants were displaced (based on Swedish net emissions in 1998). Combining BLGCC with pre-combustion carbon capture increases this potential to approximately 15 percent of the Swedish net CO_2 emissions (Möllersten *et al.* 2003b). BLGCC with pre-combustion carbon capture can be achieved at approximately US\$23/t CO_2 (Möllersten *et al.* 2003a). Based on a preliminary cost assessment and a literature review, Möllersten *et al*. also concluded that the cost of CO_2 capture in pulp and paper mills seems to be competitive with the cost of CO_2 capture in some fossil fuel based power plants evaluated in the literature (Möllersten *et al.* 2006).

According to IEA, the electricity conversion efficiency of a BLGCC is 28 percent, which reduces to 25 percent with CO_2 capture. Steam efficiency would remain at 44 percent in both cases. Capital costs would increase by US\$ 320/kW of electricity if carbon capture was installed (IEA 2009). Total black liquor production worldwide is around 72 Mt of oil equivalent (Mtoe), which gives a BLGCC with pre-combustion carbon capture potential of around 300 Mt of CO_2 per year, according to IEA's estimation (IEA 2009).

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for BLGCC with pre-combustion carbon capture (Möllersten *et al.* 2003a; Möllersten *et al.* 2003b; IEA 2009):

- Reduces the net CO_2 emissions by approximately 15 percent
- Can be achieved at approximately US$23/t CO_2
- Decreases electricity conversion efficiency to 25 percent from 28 percent
- Adding CCS increases capital costs of BLGCC by US$ 320/kW of electricity

Block Diagram or Photo

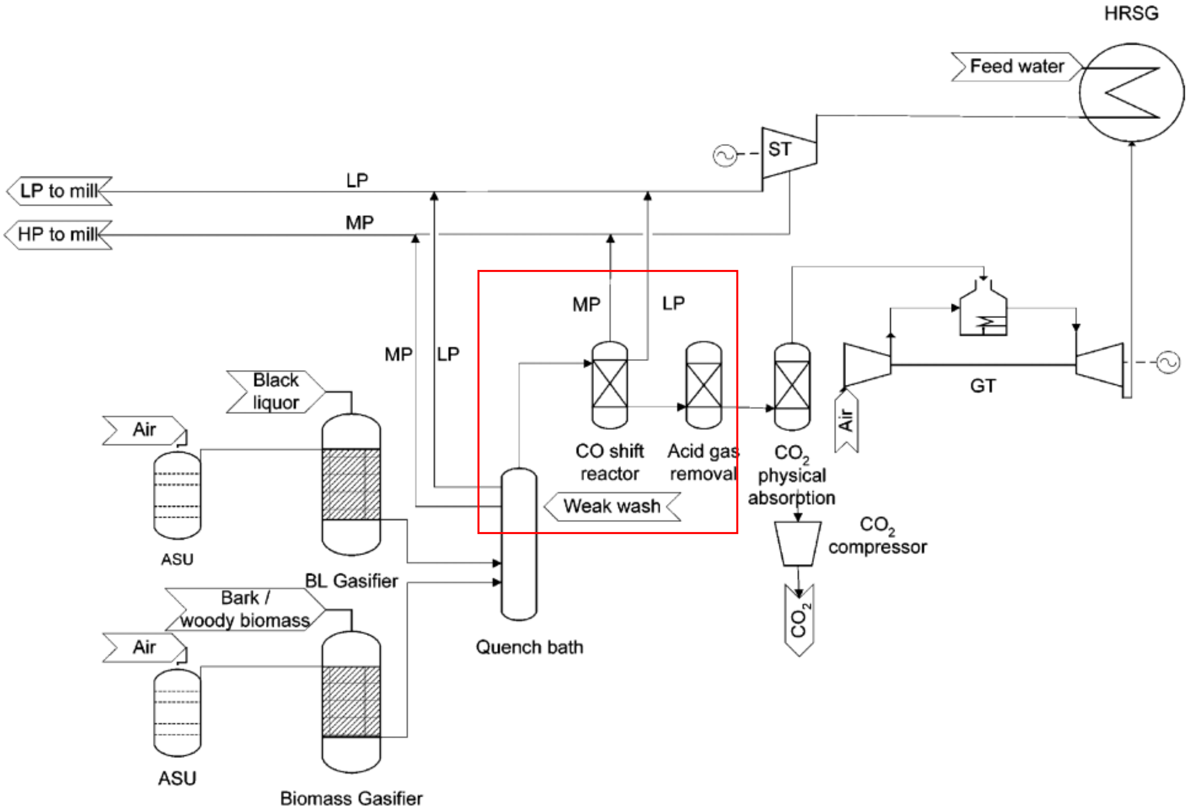

Figure 32. BLGCC with pre-combustion carbon capture (Möllersten *et al.* 2004)

Commercial Status
Development stage

References for Further Information
Larson *et al.* 2000; Maunsbach *et al.* 2001; Möllersten *et al.* 2003a; Möllersten *et al.* 2003b; Möllersten *et al.* 2004; Möllersten *et al.* 2006; IEA 2009; IEA/UNIDO 2011.

3.6.2. Biomass Conversion with Pre-combustion Carbon Capture

Description

The pulp and paper industry is more reliant on biomass fuels than any other industry (Bernstein *et al*. 2007; Carbo 2011). In developed countries, biomass-based waste and byproducts (e.g., wood, spent pulping liquors, chips, sawdust, bark) provide 53.6 percent of energy used in the pulp and paper industry (WBCSD 2011). The U.S. pulp and paper industry gets more than 65% of energy from biomass (EIA 2011; AF&PA 2012).

Biomass conversion routes with CCS include biological processing with capture of CO_2 byproducts to produce liquid fuels, biomass gasification with shift (conversion of CO to CO_2) and CO_2 separation to produce hydrogen, and biomass combustion to produce electricity with CCS (either oxy-fuel or post-combustion capture technologies). These basic routes can be combined or integrated, for example, by gasification with CCS of residual biomass from biological processes, or by syngas conversion to liquid fuels with CCS, or by burning hydrogen-rich syngas to produce electricity with CCS (see Figure 33) (Rhodes and Keith 2005). In most biomass conversion processes, high CO_2 concentrations enable straightforward capture of CO_2 (IEA/UNIDO 2011).

Biological conversion processes, for example fermentation, use living microorganisms to break down the feedstock and produce liquid and gaseous fuels (Carbo 2011). Biomass can also be processed thermo-chemically, enabling pre-combustion CO_2 capture (UNIDO 2010a). Thermo-chemical biomass conversion, or gasification, is a thermal treatment that results in the production of gaseous products and a small amount of char and/or ash (Demirbas 2002). Biomass gasification results in a syngas made up of CO, CO_2, hydrogen, CH_4, and nitrogen. The synthesis gas then undergoes a water-gas shift reaction to produce a stream rich in CO_2, CO, and hydrogen. The CO_2 is removed from the stream using pre-combustion capture technologies such as absorption by organic solvents, membrane separation or the use of adsorption materials. The hydrogen can then be used to produce synthetic natural gas through the process of methanation (IEA/UNIDO 2011). The syngas can also be used for generating electricity with IGCC, and the CO_2 separation technologies employed are the same as those that are foreseen for BLGCC with pre-combustion CO_2 capture, explained in Section 3.6.1.

Biomass conversion combined with CCS has the potential to generate useful energy products, such as electricity, bioethanol, diesel, synthetic natural gas, bio-DME, and hydrogen, while removing CO_2 from the natural carbon cycle (Carbo 2011).

Cost data for biomass-to-biofuel conversion processes are scarce, in particular for conversion processes combined with CCS (Carbo 2011). Typically, biomass conversion plants require higher levels of capital investment than fossil fuel conversion plants because the energy density of biomass is usually lower than that of fossil fuels, its moisture content is higher, and its composition is less homogenous and often more fibrous (UNIDO 2010a). Although a number of biomass gasifiers have recently entered the market, there are at present no CCS demonstration projects involving biomass gasification (UNIDO 2010a).

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for biomass conversion with pre-combustion carbon capture (Rhodes and Keith 2005; UNIDO 2010a; Carbo 2011):

- Reduces CO_2 significantly, even generating negative atmospheric carbon emissions
- Has potential to generate useful energy products such as electricity, bioethanol, diesel, substitute natural gas (bio-methane), and hydrogen
- Cost of retrofitting of standalone kraft pulp mills estimated between 30 to 35 Euros per tonne of CO_2 abated, including storage and transportation costs
- For integrated kraft pulp and paper mills, the additional energy needs for CO_2 capture will be higher than standalone mill; costs of avoided emissions for optimal configuration (heat pump for upgrading low-temperature excess heat) range from 35 to 40 Euros/t CO_2

Block Diagram or Photo

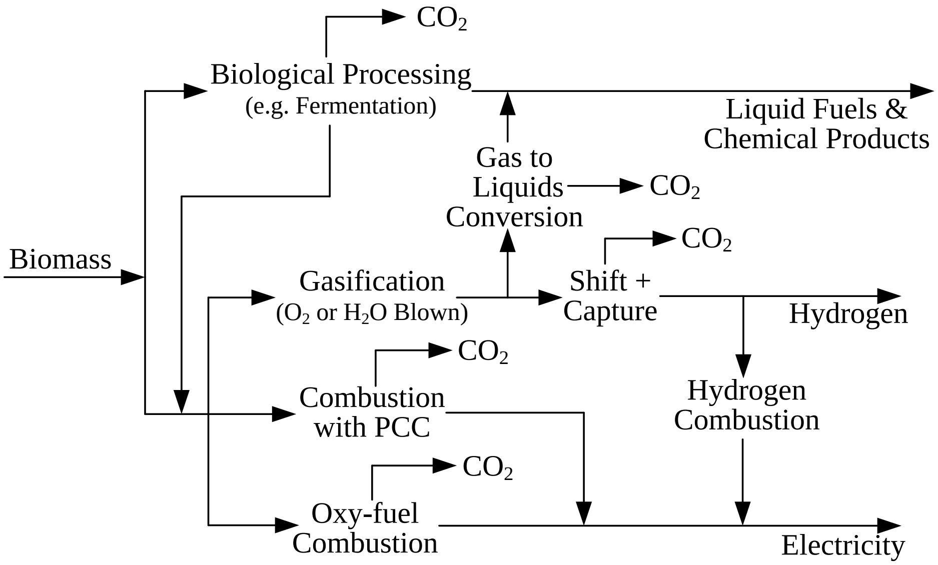

Figure 33. Biomass conversion with CO_2 capture (Rhodes and Keith 2005)

Commercial Status

Research stage

References for Further Information

Demirbas 2002; Rhodes and Keith 2005; Bernstein *et al.* 2007; UNIDO 2010a; Carbo 2011; IEA/UNIDO 2011; WBCSD 2011.

3.6.3. Oxy-fuel Combustion Technology

Description

Oxy-fuel combustion can be used to produce a CO_2-rich flue gas, suitable for carbon capture, from the combustion process (Bernstein *et al*. 2007). Oxy-fuel technology differs from oxygen enrichment in that oxygen enrichment does not replace air but injects oxygen into the combustion zone along with combustion air. In contrast, oxy-fuel technology replaces the air with a pure oxygen stream for fuel burning (IPCC 2005). Because this eliminates the nitrogen that would normally be in the air that is used in traditional fuel burning, fuel requirements and flue gas volumes are reduced.

A fuel that combusted in pure oxygen has a combustion temperature of about 3,500°C, which is far too high for typical boiler materials. The combustion temperature is limited to about 1,300-1,400°C in a typical gas turbine cycle and to about 1,900°C in an oxy-fuel coal-fired boiler using current technology. The combustion temperature is usually controlled by the proportion of flue gas and gaseous or liquid water recycled back to the combustion chamber (IPCC 2005). The oxy-fuel technology has been demonstrated in power plants using coal and waste oils as fuel. Because much less nitrogen is present in the combustion chamber, NO_x emissions are very low, even without external control, and the system was compatible with integrated pollution removal technology for the control of mercury, sulphur, and particulate emissions (Bernstein *et al*. 2007). If the flue gas can be recycled before sulfur dioxide (SO_2) scrubbing, the SO_2 scrubber can be reduced in size, and significant cost savings are possible (Figueroa *et al*. 2008).

Another option for oxy-fuel combustion carbon capture in the pulp and paper industry, aside from oxy-fuel combustion in the various boilers, would be to capture CO_2 from the lime kiln at kraft mills. The essential features of lime kiln in kraft mill are almost the same as for a cement kiln. Grönkvist *et al*. (2006) found oxy-fuel combustion carbon capture is far more energy efficient if it is used together with lime kilns than together with power production processes. In addition, kraft pulp mills often use pure oxygen for bleaching purposes; it would be technically and economically suitable to produce pure oxygen for several purposes at the same site (Grönkvist *et al*. 2006).

Technical issues associated with oxy-fuel combustion technology include: heat transfer characteristics that are influenced by changing the atmosphere within the combustion chamber; deterioration of lime kiln walls at higher oxygen levels; clinkering process chemistry in different atmospheres needs further investigation; costly removal of contamination from the CO_2-rich exhaust gas resulting from excessive air infiltration; power consumption increases of 200 to 240 kWh/t O_2 for oxygen delivery using an air-separation unit (Barker *et al*. 2009).

Although elements of oxy-fuel combustion technologies are in use in the aluminum, iron and steel, and glass melting industries today, oxy-fuel technologies for CO_2 capture have yet to be deployed on a commercial scale (IPCC 2005). Moreover, this technology cannot be applied directly to existing kilns or boilers (Jönsson 2011). Further research is required to make this technology a viable option for the pulp and paper industry. ANL is studying all engineering aspects of retrofitting oxy-combustion to existing boilers, including the effect of impurities and options for CO_2 transportation, use, and sequestration. (Figueroa *et al*. 2008).

Energy/Environment/Cost/Other Benefits

The following benefits and costs have been identified for oxy-fuel combustion technology (Grönkvist *et al.* 2006):

- Significant CO_2 reductions
- In large units, energy penalty of 0.9-1.0 MJ/kg O_2, used in the form of mechanical work
- In lime kilns, could avoid almost 100 percent of CO_2 emissions although greater technical uncertainties are associated with this application

Block Diagram or Photo

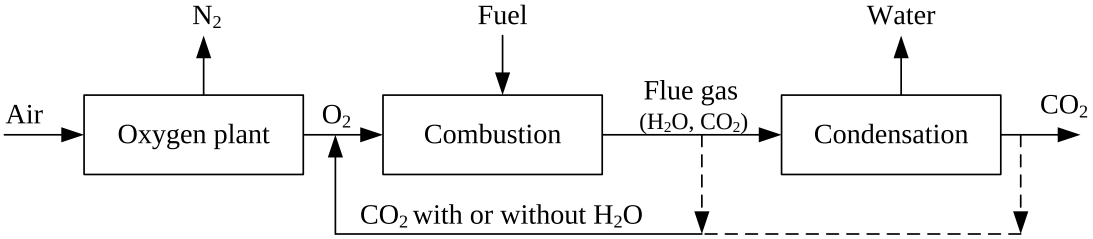

Figure 34. Diagram of oxy-fuel combustion CO_2 capture technology (Grönkvist *et al.* 2006)

Commercial Status

Pilot stage

References for Further Information

IPCC 2005; Grönkvist *et al.* 2006; Bernstein *et al.* 2007; Figueroa *et al.* 2008; Barker *et al.* 2009; Jönsson 2011.

3.6.4. Post-combustion Carbon Capture Using Chemical Absorption

Description

Another carbon capture technology for pulp and paper mills would be capture from the flue gases (post-combustion capture) of fossil fuel- or biomass-fired boilers using chemical absorption. Solvent scrubbing has been used to separate CO_2 in chemical industry exhaust streams (UNIDO 2010a). Post-combustion carbon capture takes advantage of this commercially mature technology and applies a common solvent, such as mono-ethanolamine (MEA) and chilled ammonia, for CO_2 scrubbing. Because of the high cost of this solvent, it has to be regenerated and reused, an energy-consuming process that results in additional CO_2 emissions. SO_2, NO_2, and oxygen play an important role in solvent degradation. Therefore, the SO_2, NOx, and particulate matter concentrations in flue gases need to be reduced to a minimum before the flue gases go through the solvent scrubbing CO_2 capture system (CSI/ECRA 2009).

Möllersten *et al.* (2003) evaluated the CO_2 mitigation potential of CCS in CHP systems based on recovery boilers and pressurized BLGCC, respectively, in existing-standard kraft pulp mills, and found that recovery boilers with post-combustion CO_2 capture offered a larger reduction potential than BLGCC with pre-combustion CO_2 capture (Möllersten *et al.* 2003a).

Post-combustion capture using chemical absorption does not require any reconstruction of the recovery boilers. However, the CO_2 capture cost is depends heavily on the energy demand (Hektor and Berntsson 2008). For post-combustion with chemical absorption, the energy cost for CO_2 capture is 50 to 70 percent of the total cost in the pulp and paper industry (Jönsson 2011). Hence, for CO_2 capture to be economically and technically realistic, the source of CO_2 must be large enough and the energy demand of the capture process should preferably be integrated (fully or partly) with other processes at the capture site. The potential for heat integration of post-combustion CO_2 capture to kraft pulp and paper mills has been studied by Hektor and Berntsson who show that thermal integration is possible to a substantial extent (Hektor and Berntsson 2007, 2008, 2009).

Hektor and Berntsson report that using MEA absorption to capture the CO_2 from the flue gases in pulp and paper mills can be a cost-effective way of reducing CO_2 emissions. Performance is enhanced when chilled ammonia is used for the absorption (Hektor 2008). A study of the use of chemical absorption technology in recovery boilers concluded that post-combustion CO_2 capture technology would be economical at a price of US\$ 30 to US\$ 50/t CO_2 in modern pulp mills that generate sufficient surplus heat for the capture process. For integrated pulp and paper mills, the most economic configuration would be to power the mill using a natural gas combined-cycle plant with CCS, allowing the maximum use of byproduct biofuels elsewhere (Hektor 2008).
Today, CO_2 is captured from the flue gases at two Swedish pulp and paper mills, the M-real Husum mill and the Stora Enso Nymölla mill. However, this CO_2 is not transported and stored as pure CO_2 but is chemically bound in the production of precipitated calcium carbonate (Jönsson 2011).

Availability of a transport (pipeline) grid and storage sites are also important factors necessary to support this CO_2 capture technology.

Energy/Environment/Cost/Other Benefits

The following benefits have been identified for chemical absorption post-combustion carbon capture (Möllersten *et al.* 2006; Hektor and Berntsson 2007, 2008):

- Economic at a price of US\$ 30 to US\$ 50/t CO_2 in modern pulp mills that generate sufficient surplus heat for the capture process
- Requires 2.7-3.3 MJ of energy per t CO_2, based on the chemical solvent MEA, for CO_2 capture from flue gases in pulp and paper mills and is cost effective for reducing CO_2 emissions
- CO_2 capture using chilled ammonia absorption is more energy efficient and cost effective compared to MEA absorption for the same application in pulp and paper mills

Block Diagram or Photo

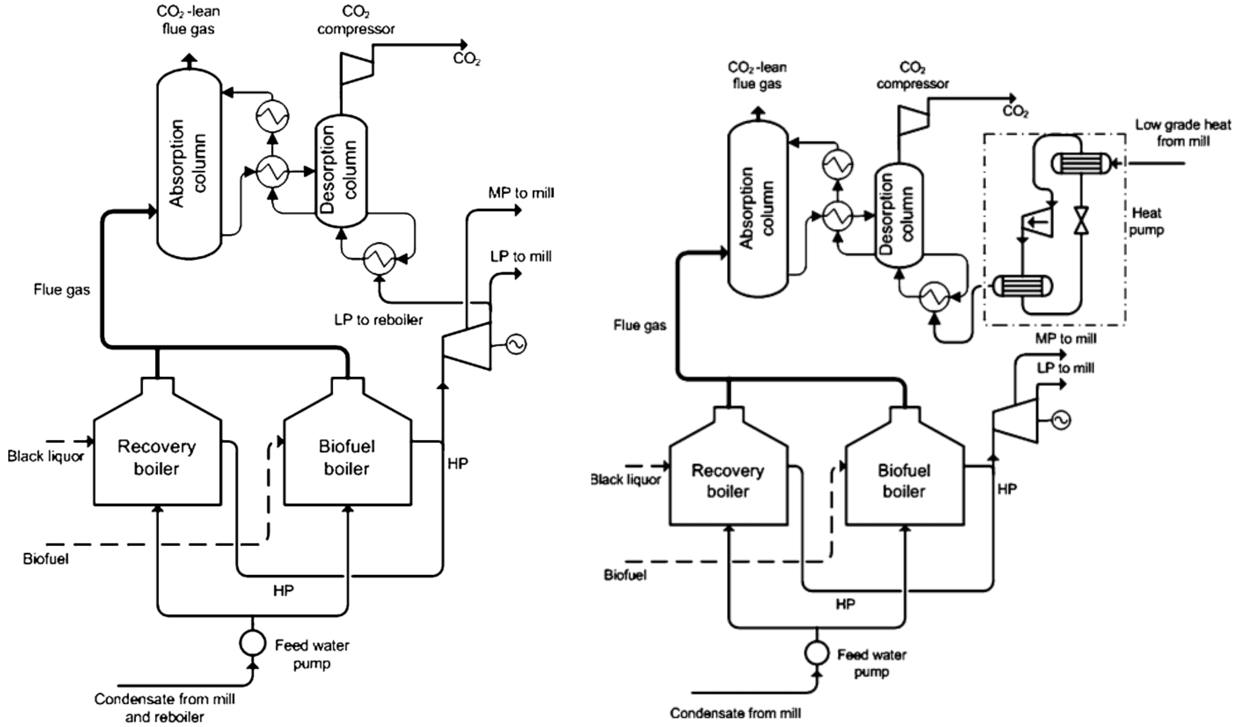

Figure 35. Two post-combustion carbon capture schemes for kraft pulp and paper mills (Hektor and Berntsson 2009)

Commercial Status
Pilot stage

References for Further Information
Möllersten *et al.* 2003a; Möllersten *et al.* 2006; Hektor and Berntsson 2007; Hektor 2008; Hektor and Berntsson 2008; CSI/ECRA 2009; Hektor and Berntsson 2009; UNIDO 2010a; Jönsson 2011.

3.6.5. Bio-Technological Carbon Capture

Description
CO_2 Solution, Inc. has taken a biomimetic approach to efficiently capture CO_2 using the natural power of a biocatalyst (enzyme) and carbonic anhydrase, which are substances that manage CO_2 during respiration in mammals. In this technology, the biocatalyst and carbonic anhydrase are used within a reactor to create an “industrial lung” that captures CO_2 from industrial flue gases. After the waste CO_2 is captured, pure CO_2 is produced with the help of the enzyme and then stored underground and/or used in enhanced oil recovery. This technology can be applied to coal-fired power generation, oil sands, and other CO_2-intensive industries such as cement, iron and steel, and pulp and paper. Prototypes tested at Alcoa Inc.'s aluminum smelting facility in Quebec, Canada demonstrated the full functionality and stability of the enzyme under real-world conditions (CO_2 Solution 2012).

This patented process has three phases. First, flue gas containing CO_2 enters the reactor where it is dissolved or captured in an aqueous solution. CO_2 is then converted into a bicarbonate ion (HCO_3^-) in the presence of the enzyme. This bicarbonate-ion-enriched solution from the reactor is regenerated either by production of pure CO_2 for underground storage, enhanced oil recovery, or other industrial uses; or by production of solid carbonate for various industrial uses. The capture solution is reused in another cycle.

Traditional post-combustion CO_2 capture methods are based mainly on amine solvents, which are energy intensive and require high temperatures to strip CO_2 for underground capture and storage. CO_2 Solution, Inc. claims that the enzyme can materially lower the cost of carbon capture by allowing a reduction in the size of the absorber equipment and reducing process energy requirements (CO_2 Solution 2012).

Energy/Environment/Cost/Other Benefits

According to CO_2 Solution, Inc. their carbon capture technology showed the following benefits at prototype scale (CO_2 Solution 2012):

- Increases CO_2 removal by 30 percent for a given quantity of solvent solution compared to conventional solvent scrubbing technology
- Lowers capital and operating costs by allowing a reduction in the size of the absorber column and reducing total energy requirements
- When stripping CO_2-rich solvent (desorption), reduces energy consumption by increasing the CO_2 transfer rate. This is significant because, in conventional technology, the desorption stage is a major contributor to the cost of the total CO_2 capture process.

Block Diagram or Photo

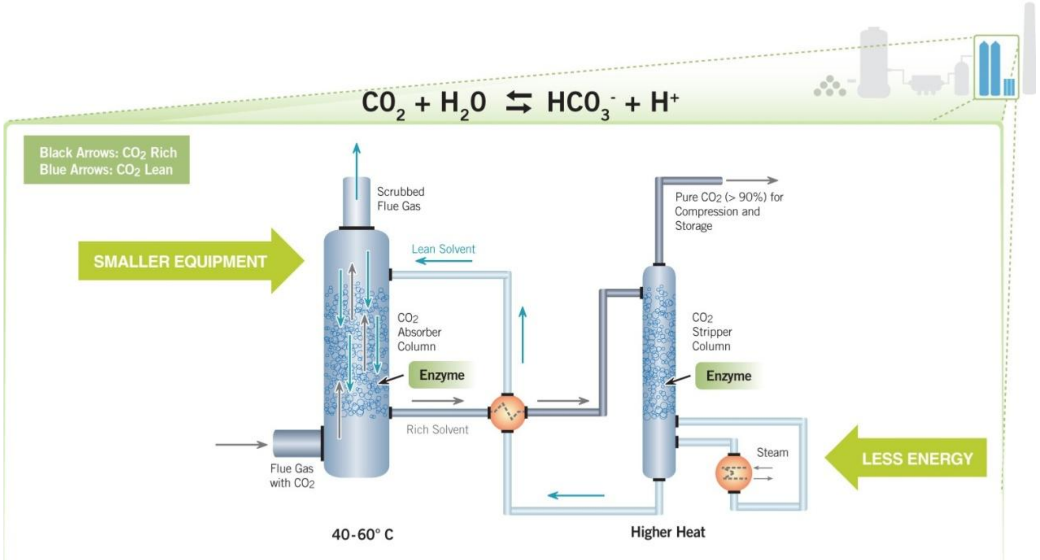

Figure 36. CO_2 Solution Inc. bio-technological CCS system (CO2 Solution 2012)

Commercial Status

Development stage

Reference for Further Information

CO_2 Solution (2012)

3.6.6. CO_2 Sequestration in Recycled Mineral Fillers

Description

Precipitated calcium carbonate (PCC) is one of the mineral fillers used for paper production. PCC is chemically identical to natural calcium carbonate (ground limestone or chalk) but is generally more pure. The main advantage to the papermaker, however, is that the chemical process of PCC production allows individual PCC particles to take a variety of shapes and sizes (morphologies). Careful selection of size and shape can maximize PCC functionality over a wide range of papermaking applications. These advantages are also imparted to the paper when recycled mineral filler precipitated calcium carbonate (RMF PCC) is used instead of pure PCC (Sohara and Young 1998).

The production of RMF PCC utilizes both fly ash, which results from the combustion of deinking residue, and CO_2 generated during combustion. The process can be described by the following equation (EC 2001):

Materials	Boiler Ash +	$Ca(OH)_2$ +	CO_2 =>	$Ash/CaCO_3$ +	H_2O
Quantities	5-50g	37-70g	22-43g	100g	9-18g

The ash resulting from the combustion of paper mill residuals or deinking sludge contains mainly compounds rich in calcium, silicon, and aluminum. These result from the minerals contained in the waste, mainly $CaCO_3$ and kaolin clay ($H_2Al_2Si_2O_8$-H_2O) (EC 2001).
The deinking residue is heated in an oxygen-containing atmosphere to a temperature sufficient to completely oxidize all the organic hydrocarbons present. Heat, water, and CO_2 also are generated and may be captured and reused in the process. Combustion causes a chemical reaction that converts the original pigments contained in the deinking residue to new, stable mineral forms. The ash containing the mixed mineral phases is added to a reactor in which CO_2 gas is bubbled through an aqueous slurry of calcium hydroxide so that PCC is produced. Because the mineral phases in the ash contain calcium as part of their crystal structure, the PCC will precipitate and grow on the ash particles (Sohara and Young 1998).

Utilization of boiler ash as a raw material in the production of PCC reduces consumption of fossil fuels for production of CaO from limestone quarry ($CaCO_3$) by up to 50 percent, and thus reduces emissions of CO_2 by a corresponding amount. If paper mills that generate large quantities of deinking residuals and reduce the amount of solid waste from the deinking process by incineration, CO_2 is emitted, and ash must still be disposed of. A process to produce RMF PCC can partly or completely consume ash and CO_2 generated at these mills (Bajpai 2010). The process significantly reduces the amount of solid waste deposited from deinking plants. A German paper mill (Haindl Schongau) has conducted pilot test to adapt the existing plant for production of pure PCC to the production of RMF PCC.

Energy/Environment/Cost/Other Benefits

The following benefits are reported for the use of RMF PCC compared to pure PCC (EC 2001; Bajpai 2010):

- Reduces fossil fuel consumption for lime kiln by up to 50 percent
- Reduces pulp and paper mill CO_2 emissions
- Significantly reduces solid waste to deposited from deinking plant

- Has better opacity properties than pure PCC

Block Diagram or Photo

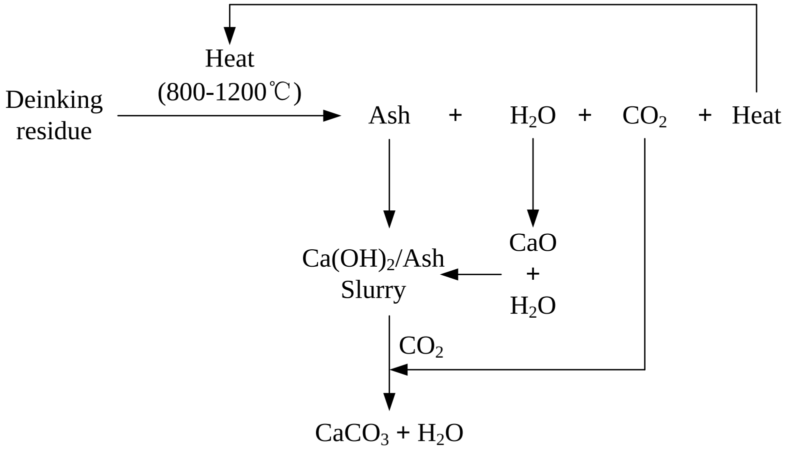

Figure 37. The main principles of the RMF PCC process (Sohara and Young 1998)

Commercial Status

Pilot stage

References for Further Information

Sohara and Young 1998; EC 2001; Bajpai 2010.

3.7. Nanotechnology in Pulp and Paper Production

Description

Nanoscience and nanotechnology are the study and application of extremely tiny particles (1 to 100 nanometers) that can be used in other fields of science, such as chemistry, biology, physics, materials science, and engineering (NNI 2012). Nanotechnology is a recently emerged science-based technology that could benefit numerous industries. Nanostructures can be integrated into larger systems. Nanotechnology in pulp and papermaking dates back to the 1970s; since then, there has been substantial new research and innovation in the field (CEPI 2011a).

The possible applications of nanotechnology in the pulp and paper industry, especially in emissions reduction and dematerialization, have attracted only limited consideration to date (Puurunen and Vasara 2007). The paper industry currently uses nanotechnology to enhance current products and create new ones, and to develop ways that cellulose fibers can be used for products outside the paper industry (Walker 2012). Some areas where nanotechnology might be applied in pulp and papermaking processes are: new materials, wet-end chemistry, nanofiltration in closure of water circulation, coating, calender rolls, sensors, microscopy, and nanoscale assemblers (Mohieldin *et al*. 2011). Among the many possibilities suggested for new wood fiber-based products incorporating nanomaterials are moisture-resistant cell-phone components; advanced membranes and filters; improved loudspeaker cones; and additives for paints, coatings, and adhesives (TAPPI 2005).

Nanocellulose (NCC) is one of the products manufactured from biomass under moderate conditions of acid or enzyme hydrolysis (Lam *et al.* 2012). It can be used for high-strength composite structures (Development stage), lightweight paper and packaging (Development stage), barrier coatings (Research stage), and optical applications (Research stage) (Brown Sept. 2012). The world's first NCC pilot plant was inaugurated at the Domtar pulp and paper mill in Windsor, Quebec in 2012. At peak production, the plant can produce about 1 t of NCC/day (CelluForce 2012). Nova Scotia-based BioVision Technology Inc. makes NanoCell, a chemically modified version of NCC at a pilot plant in Montreal, Canada, while Alberta Innovates Inc. also in Canada is planning to build a pilot plant capable of producing up to 100 kg/week of NCC from both wood and straw pulp (Jost 2012).

Increased efficiency from use of nanotechnology in modern paper industry will reduce costs and use of resources such as wood, water and energy, thereby reducing GHG emissions and the environmental impacts (EC 2011). Environmental benefits result from reduced process water consumption, e.g. via improved wet-end chemistry, nanofiltration and waterless coating (Puurunen and Vasara 2007). Correspondingly, energy efficiency will be improved as less heated water is used in the pulp and paper making processes. New levels of pulp and paper quality could also be achieved, which could decrease the materials input to the papermaking process and reduce energy consumption (CEPI 2011a).

All the stages of pulp and paper manufacturing can benefit from nanotechnology (Norris 2011). Pulping, bleaching, process chemistry, paper coating, and recycling are the key areas that can benefit in the near term from nanotechnology (NPP 2012). Within the past few years, a number countries, including the U.S., Sweden and Finland, have systematically evaluated the potential of nanotechnology in the forest industry and worked out roadmaps and national strategies (Reitzer

2007). To date, research focuses primarily on the following seven applications of nanotechnology in the forest industry (TAPPI 2005):

- Liberating nanodimensional cellulose fibrils
- Using nanomaterials, nanosensors, and other nanotechnology to improve the raw material and energy efficiency of conversion processes
- Achieving directed design of biopolymer nanocomposites
- Developing biomimetic processes for synthesizing lignocellulosic-based nanomaterials
- Utilizing self-assembly of nanodimensional building blocks for functional structures and coatings
- Exploiting the nanoscale architecture of lignocellulosics
- Biofarming lignocellulosic materials with unique multifunctional properties

Energy/Environment/Cost/Other Benefits

The following benefits can be achieved by the use of nanotechnology in the pulp and paper industry (Puurunen and Vasara 2007; Patel 2009; Agenda2020 2010; CEPI 2011a; NPP 2012):

- Reduces process water consumption via improving retention and drainage at the wet end, nanofiltration, and waterless coating
- Increases energy efficiency resulting from decreased water usage by minimized production losses through the application of new materials and better sensor technology
- Decreases cost and use of raw materials
- Reduces pollutant concentration in effluents (nanotechnology opens possibilities of more sustainable production processes, moving toward zero emissions)
- Greater strength, water resistance, and fire retardant qualities of products, and new forms of packaging
- Reduces materials costs (cellulosic nanocrystallite may provide bio-based nanomaterials for a fraction of the cost of synthetic materials such as carbon nanotubes)
- Use of pulp for smart nanomaterials in new applications, such as drug and protein nanoencapsulation, stabilizing of colloids, and organic dye protective encapsulation

Block Diagram or Photo

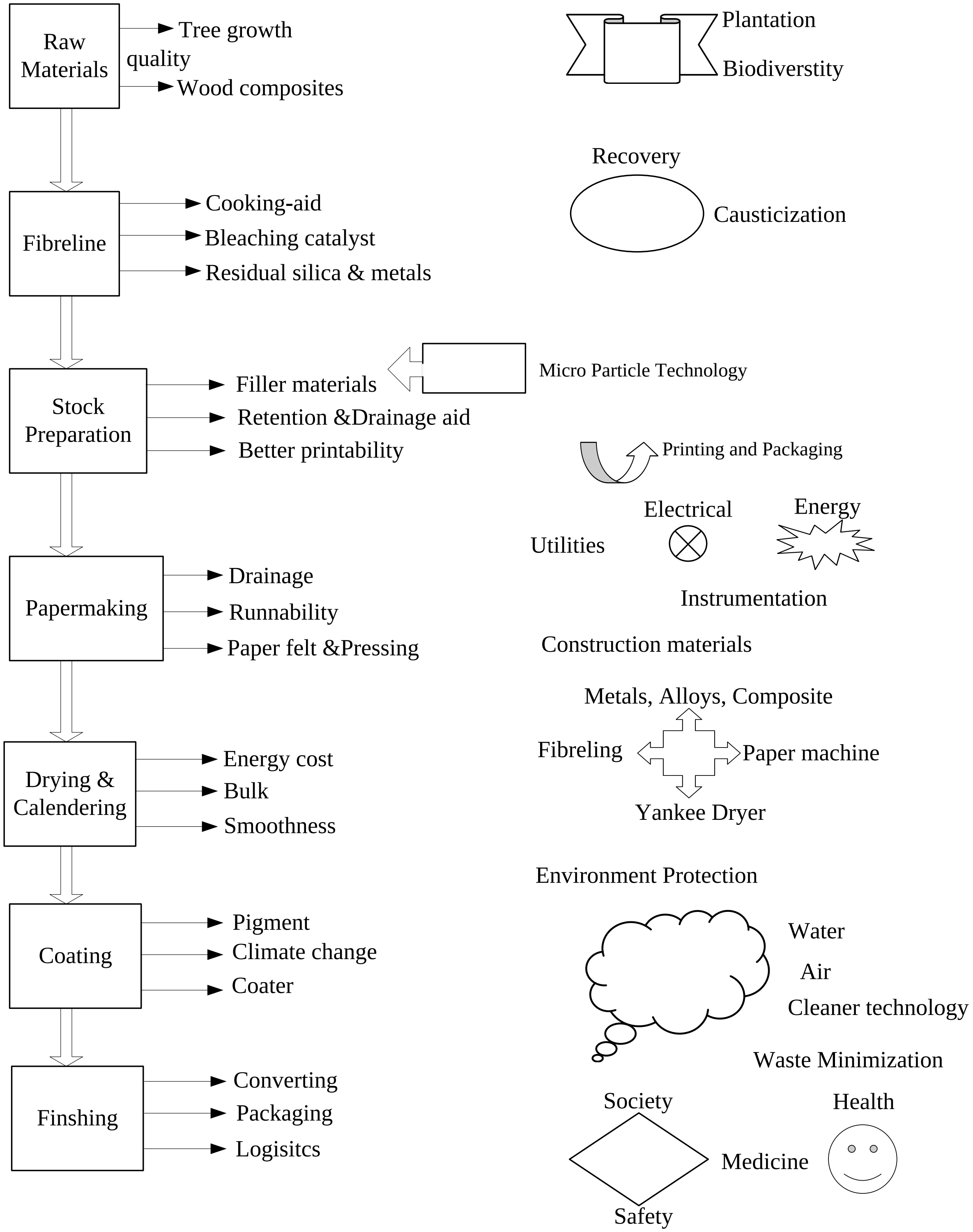

Figure 38. Application of nanotechnology in the pulp and paper industry (Patel 2009)

Commercial Status

Research stage

References for Further Information

TAPPI 2005; Puurunen and Vasara 2007; Reitzer 2007; Patel 2009; Agenda2020 2010; CEPI 2011a; EC 2011; Mohieldin *et al.* 2011; Norris 2011; NNI 2012; NPP 2012; Walker 2012.

Summary and Conclusions

This report describes 36 emerging energy-efficiency and GHG mitigation technologies for the pulp and paper industry. The information presented for each technology was collected from various publically available sources and equipment vendors throughout the world. All the emerging energy-efficiency and low-carbon technologies presented in this report are alternatives to conventional production of pulp and paper or production of conventional or new raw materials used in other manufacturing sectors, e.g., chemicals, food, dyes, plastics, and pharmaceuticals. It is likely that no single technology described here will be the best or only solution; instead, a portfolio of technologies should be developed and deployed to address the increasing energy consumption and CO_2 emissions of the pulp and paper industry.

Most of the technologies described in this report have an energy (CO_2) penalty associated with their operation. Further research is needed to minimize these energy penalties. For some technologies described, little information was available other than that provided by the developers of the technology developers. Independent studies and validation of the fundamentals and operation of these emerging technologies would be helpful to the private and public sectors as well as academia.

Shifting away from conventional processes and products will require a number of changes including: education of producers and consumers; new standards; aggressive research and development to address issues and barriers confronting emerging technologies; government support and funding for development and deployment of emerging technologies; rules to address intellectual property issues related to dissemination of new technologies; and financial incentives (e.g., through carbon trading mechanisms) to make emerging low-carbon technologies, which might have a higher initial costs, competitive with conventional processes and products.

Finally, it should be noted that the purpose of this report is solely informational.

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