



UNIVERSAL INDUSTRIAL SECTORS  
INTEGRATED SOLUTIONS MODEL FOR PULP  
AND PAPER MANUFACTURING INDUSTRY –  
UNIVERSAL ISIS-PNP

# Universal Industrial Sectors Integrated Solutions Model for the Pulp and Paper Manufacturing Industry – Universal ISIS-PNP

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## Abstract

The United States Environmental Protection Agency (USEPA) has developed a model for the pulp and paper sector that provides an integrated approach for investigating, developing, and evaluating strategies for reducing the emissions of interest. This model is referred to as the Universal Industrial Sectors Integrated Solutions model for the Pulp and Paper sector and was recognized as an integrated modeling tool by the Clean Air Act Advisory Committee in its recent recommendations to USEPA. The model also was recognized by Resources for the Future which is a nonprofit and nonpartisan organization headquartered in Washington, DC, that conducts independent research on energy, environment and natural resources. With inputs from users, the model can identify technology options to meet various emission reduction strategies, provide estimates of the costs of these options, and indicate the potential economic responses that may be provided by the industry to accomplish these strategies. This document includes an introduction from the pulp and paper sector, data collection, mathematical modeling framework of the model, the objectives of the model, etc. Analysis examples are included to demonstrate how design of the model and its implementation strategies can handle the complex interactions between economic concerns and the environment successfully, thereby overcoming the techno-economic and emission-reduction challenges of multi-product, multi-market, and multi-pollutant sector-based analyses.

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## List of Acronyms and Chemical Symbols

ADMT	Air-dried Metric Ton
AFBC	Atmospheric Fluidized Bed Combustion
BACT	Best Available Control Technology
BAU	Business as Usual
BDST	Bone Dry Short Tons
BLS	Black Liquor Solids
Btu	British Thermal Unit
BXT	Boxboard and Other Board
CaCO <sub>3</sub>	Calcium Carbonate (limestone)
CaO	Calcium Oxide (Quicklime)
CH <sub>4</sub>	Methane
CNT	Containerboard
CO	Carbon Monoxide
CO <sub>2</sub>	Carbon Dioxide
CO <sub>2</sub> e	CO <sub>2</sub> Equivalents
COR	Corrugating Medium
CPW	Coated Printing and Writing Paper
CTMP	Chemi-thermo-mechanical Pulping
CYC	Cyclone
DBESP	Dry-Bottom Electrostatic Precipitator
ESP	Electrostatic Precipitator
FGD	Flue Gas Desulfurization
FGR	Flue Gas Recirculation
FST	Finished Short Ton
GAMS	General Algebraic Modeling System
GHG	Greenhouse Gas
HAP	Hazardous Air Pollutant
HHV	Higher Heating Value
ICR	Information Collection Request
ISIS	Industrial Sectors Integrated Solutions
kWh	Kilowatt Hour
LNB	Low NO <sub>x</sub> Burner
LoTOx	Low-Temperature Oxidation
LWS	Lime/Limestone Wet Scrubbing
MACT	Maximum Achievable Control Technology
MMBtu	Million British Thermal Units

N <sub>2</sub>	Nitrogen
N <sub>2</sub> O	Nitrous Oxide
Na	Sodium
Na <sub>2</sub> CO <sub>3</sub>	Sodium Carbonate
Na <sub>2</sub> S	Sodium Sulfide
Na <sub>2</sub> SO <sub>4</sub>	Sodium Sulfate
NaCl	Sodium Chloride
NAICS	North American Industry Classification System
NaOH	Sodium Hydroxide
NCASI	National Council for Air and Stream Improvement
NCG	Non-Condensable Gas
NESHAP	National Emission Standards for Hazardous Air Pollutants
NO	Nitric Oxide
NO <sub>x</sub>	Nitrogen Oxides
NSPS	New Source Performance Standard
O&M	Operation and Maintenance
OFA	Overfire Air
PC	Pulverized Coal
PFD	Process Flow Diagram
PIP	Packaging and Industrial Paper
PM	Particulate Matter
PM <sub>2.5</sub>	Particles Less Than or Equal to 2.5 Microns
PM <sub>10</sub>	Particles Less Than or Equal to 10 Microns
PNP	Pulp and Paper
ppm	Part(s) Per Million
PSC	Pulp Supply Center
RISI	Resource Information Systems, Inc.
ROW	Rest of the World
RMP	Refiner Mechanical Pulp
RSCR	Regenerative Selective Catalytic Reduction
SC	Supply Center
SCBR	Scrubber
SCR	Selective Catalytic Reduction
SDA	Spray Dryer Absorber
SNCR	Selective Non-Catalytic Reduction
SO <sub>2</sub>	Sulfur Dioxide
SO <sub>3</sub>	Sulfur Trioxide
TDF	Tire-Derived Fuel

TMCP	Thermo -mechanical -chemi Pulping
TMP	Thermo-mechanical Pulp
TRS	Total Reduced Sulfur
ISIS	Industrial Sectors and Integrated Solutions (model)
ULNB	Ultra Low-NO <sub>x</sub> Burner
UPW	Uncoated Printing and Writing Paper
USEPA	US Environmental Protection Agency
VOC	Volatile Organic Compound

## Conversion Table – English Units to SI Units

To Obtain	From	Multiply by
m	ft	0.3048
m <sup>2</sup>	ft <sup>2</sup>	$9.29 \times 10^{-2}$
m <sup>3</sup>	ft <sup>3</sup>	$2.83 \times 10^{-2}$
°C	°F	$5/9 \times (°F - 32)$
kg	lb	0.454
J/kg	Btu/lb	$1.33 \times 10^{-4}$
m <sup>3</sup> /s	Cfm	$4.72 \times 10^{-4}$
m <sup>3</sup> /s	Gpm	$6.31 \times 10^{-5}$
J/kWh	Btu/kWh	1054.8
mills	¢	0.001
kg/m <sup>2</sup>	inches of Hg	345.31
metric ton	short ton*	0.907

\*Note: in this document, “ton” refers to short ton and equals 2000 lb or 907 kg, unless otherwise specified.  
 “Metric ton” equals 1000 kg.

# 1. Introduction

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In the National Academy of Science's 2004 report, "Air Quality Management in the United States," the National Research Council recommended to the US Environmental Protection Agency (USEPA) that standard setting, planning, and control strategy development should be based on integrated assessments that consider multiple pollutants, and that these integrated assessments should be conducted in a comprehensive and coordinated manner (NAS, 2004). With these recommendations, USEPA began to transition to establishing multi-pollutant and sector-based approaches to manage air quality and environmental protection. The benefits of multi-pollutant and sector-based analyses include the ability to identify optimal strategies that consider feasibility, costs, and benefits across all pollutant types such as criteria air pollutants, hazardous air pollutants (HAPs), and greenhouse gases (GHGs), while streamlining administrative and compliance complexities and reducing conflicting and redundant requirements.

The development of policy options for managing emissions and air quality can be made more effective and efficient through sophisticated analyses of relevant technical and economic factors. Such analyses are greatly enhanced by the use of an appropriate modeling framework and, as a result, the Universal Industrial Sectors Integrated Solutions (Universal ISIS) model has been developed at USEPA (ARCADIS, 2010). The Universal ISIS was first populated with US cement manufacturing data (Universal ISIS-Cement), with subsequent efforts aimed at building a representation of the US pulp and paper sector (Universal ISIS Pulp and Paper [Universal ISIS-PNP] model). This document describes the framework of USEPA's Universal ISIS-PNP developed in the General Algebraic Modeling System (GAMS) and its application to the US pulp and paper industry.

The US pulp and paper industry is a diverse sector that utilizes a variety of pulping processes and manufactures hundreds of different grades of paper (DOE, 2005). The industry is grouped under paper manufacturing (North American Industry Classification System [NAICS] code 322) and includes pulp, paper, and paperboard mills (NAICS code 3221) and converted paper product manufacturing (NAICS code 3222). Pulp, paper, and paperboard mills are facilities primarily engaged in producing pulp and/or paper and paperboard; paperboard is distinguished from paper as a thicker product (>0.3 mm) but is manufactured in a similar manner (USEPA, 2002). A facility primarily engaged in producing pulp is considered a pulp mill (NAICS code 32211), whereas a facility primarily engaged in converting pulp into paper or paperboard is a paper mill (NAICS code 32212) or paperboard mill (NAICS code 32213). A facility producing pulp and making paper with paper as the primary product is considered an integrated mill and is classified as a paper or paperboard mill. Converted paper product manufacturing includes facilities primarily using paper and/or paperboard products as a raw material to produce paper-derived products (e.g., cardboard) that are not typically engaged in pulping or papermaking.

The US Census estimated there were 561 pulp, paper, and paperboard mills (NAICS code 3221) in the 2002 Economic Census, 32 of which were classified as pulp mills. In the 2007 Economic Census, there were 514 mills, 39 of which were classified as pulp mills. In the early 1980s, 40 percent of paper mills and 33 percent of paperboard mills were integrated with pulp mills. By 1992, these numbers had fallen slightly to 38 percent and 29 percent, respectively (USDOC, 1996). However, more recently the industry has begun to move toward integrated mills (DOE, 2005). The database used for Universal ISIS-PNP contains 514 facilities currently in operation.

In 2009, the United States was the world's leading producer, consumer, and exporter of pulp and paper products (RTI, 2009). Domestic production of paper and paperboard was 78.3 million tons in 2009 with a projected 2010

production of 82.6 million tons (USDA, 2011). The 2007 US economic census estimates that the pulp, paper, and paperboard industry (code 3221) produced \$80 billion in revenue, and that US production of pulp, paper and paperboard experienced a sharp decline during 2008-2009 associated with the global financial crisis. Production has recovered from these lows but has failed to reach the previous production peak of 2007. Capacity utilization declined during the 2008-2009 crises but has recovered to nominally 84 percent in line with capacity utilization in 2007. Recovery of capacity utilization with lower overall production suggests shutdowns and capacity reductions in the industry (UNECE, 2011).

Exports of paper and paperboard were 43.9 million tons in 2009 while imports were 20.3 million tons (USDA, 2011). US paper and paperboard exports exceeded imports in 2009, and the US remained a net exporter through the first half of 2011 (UNECE, 2011). Canada leads in shipping newsprint to this country while the United States predominates in wood pulp exports to Canada (MFI, 1998), and Canada is the industry's largest trading partner; 21.9 million tons of pulp, paper, and paperboard flowed between the two countries in 2001. Exports of pulp and paper products to China, Japan, Europe, South America and Mexico have been increasing steadily. Exports of pulp to China, Japan and Korea were valued at more than \$700 million in 2004 (DOC, 2004).

Historical production, export, and import data were obtained from the Food and Agriculture Organization of the United Nations for "pulp for paper" and "paper and paperboard." In 2011, the five biggest world producers of pulp for paper were the US (50.2 million metric tons), China (21.1 million metric tons), Canada (18.3 million metric tons), Brazil (13.9 million metric tons), and Sweden (11.7 million metric tons). The largest importers of pulp were China (14.0 million metric tons), the US (5.3 million metric tons), Germany (4.6 million metric tons), Italy (3.5 million metric tons), and Korea (2.5 million metric tons). The largest exporters of pulp were Canada (9.2 million metric tons), Brazil (8.5 million metric tons), the US (8.3 million metric tons), Chile (4.0 million metric tons), and Indonesia (2.9 million metric tons). In 2011, the five highest world producers of paper and paperboard were China (103.1 million metric tons), the US (77.4 million metric tons), Japan (26.2 million metric tons), Germany (22.7 million metric tons), and Canada (12.1 million metric tons). The largest importers were Germany (10.5 million metric tons), the US (9.4 million metric tons), the United Kingdom (6.9 million metric tons), France (5.6 million metric tons), and China (5.2 million metric tons), and the largest exporters were the US (13.9 million metric tons), Germany (13.3 million metric tons), Finland (10.5 million metric tons), Sweden (10.5 million metric tons), and Canada (9.1 million metric tons). Historically, the US and China have been the leaders in pulp and paper production. China production of paper began to increase significantly in 2002 and surpassed US production in 2008, as shown in Figure 1-1a. Pulp production did not follow this trend, as the US maintains a significantly higher pulp production for all of the years analyzed (1980-2011), as shown in Figure 1-1b. As expected with China's large increase in paper production but minimal increase in pulp production, China's pulp imports increased significantly from 2002 to 2011 (Figure 1-1c). The US's exports of pulp also increased during this time (Figure 1-1d).

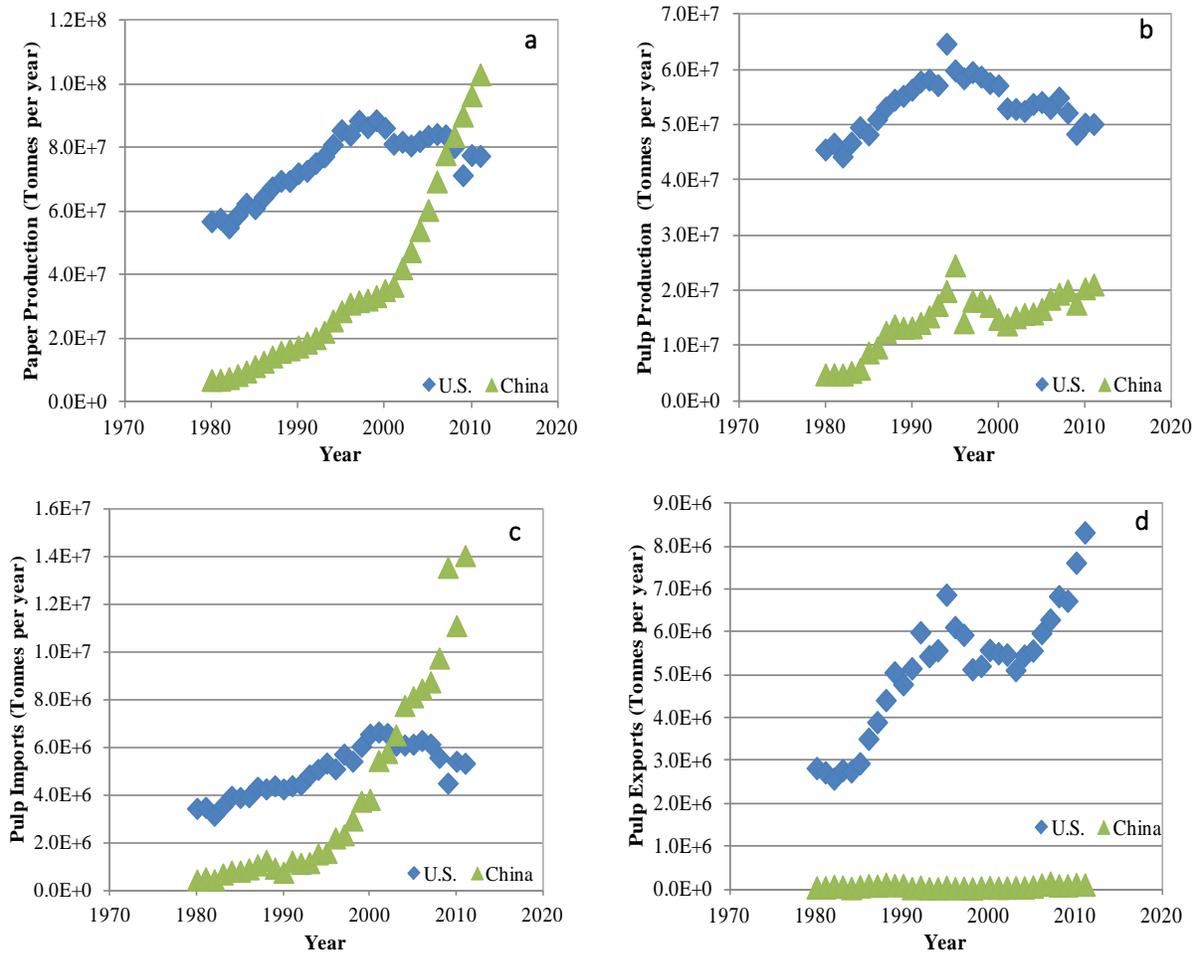


Figure 1-1. Historical Pulp and Paper Trends for the US and China

## 1.1. Pulp and Paper Facility Classifications

The properties and markets for pulp and the derived paper/paperboard products depend on the raw material inputs and the processing. Pulp is produced by separating cellulosic fibers from the cellulose-hemicellulose-lignin matrix of wood utilizing mechanical, chemical, or thermal methods. Pulping is broadly comprised of three types of processes: chemical, mechanical, and semi-chemical (DOE, 2005). The dominant chemical pulping process is the kraft (sulfate) process. However, a few sulfite and soda processes remain in operation. Common mechanical processes include stone ground wood, refiner mechanical pulp, thermo-mechanical pulp, and chemi-thermo-mechanical pulp processes. Common semi-chemical processes include neutral sulfite semi-chemical pulping and high-yield kraft and sulfite pulping. In the last two processes, cooking is minimal and defibrillation occurs mechanically (USEPA, 2010). Table 1-1 summarizes the pulping processes, applicable raw materials, and end products (DOE, 2005). A single mill may utilize multiple pulping processes and products may be produced using different types of pulp or a combination of pulp types (e.g., printing/writing paper made from a mixture of bleached kraft and recycled pulp).

A facility can be an integrated or a non-integrated facility. An integrated facility consists of a pulp mill and a paper mill on the same site, whereas a non-integrated mill buys pre-processed pulp slurry in a dried and baled

form called market pulp from an integrated mill or from a pulp mill or purchases recycled paper. A non-integrated pulp mill produces pulp and sells it to other facilities for conversion into paper. Integrated mills share common systems for generating steam and energy and for treating wastewater and eliminate transportation costs for acquiring pulp. Non-integrated mills must obtain pulp from another source but are typically smaller and can be located in urban locations (MGH 1999; AF&PA 1998; Paperloop, 2003; Saltman, 1998). Figure 1-2 shows a general process scheme for the pulp and paper production industry.

**Table 1-1. General Classification of Pulping Processes**

Category	Chemical	Semi-Chemical	Mechanical
Description	Pulping with chemicals and heat (little or no mechanical energy)	Pulping with combinations of chemical and mechanical treatments	Pulping by mechanical energy (small amount of chemicals and heat)
Yield <sup>a</sup>	Lower yield (45-50 % for bleachable or bleached pulp, 65-70 % for brown papers)	Intermediate yield (55-85 %)	High yield (85-96 %) (lignin not removed)
Wood Used	All woods (kraft); some hardwoods and non-resinous softwoods (sulfite)	Mostly hardwoods	Non-resinous softwoods, some hardwood like poplar
Pulp Properties	High strength High water absorption Low brightness	“Intermediate” pulp properties Good stiffness and moldability	Low strength High brightness High opacity, softness, and bulk Good print quality
Major Processes	Kraft (sulfate) Sulfite	Neutral sulfite semi-chemical High-yield kraft High-yield sulfite	Stone ground-wood Refiner mechanical pulp Thermo-mechanical pulp Chemi-thermo-mechanical pulp
Products	Kraft: bag, wrapping, linerboard, bleached pulps for white writing and printing papers Sulfite: fine paper, tissue, glassine, newsprint, dissolving pulp	Corrugating medium Food packaging board Newsprint, magazine	Newsprint, magazines, catalogs Books Container board

a. Yield = weight of pulp produced (oven dry) divided by weight of original wood (oven dry).

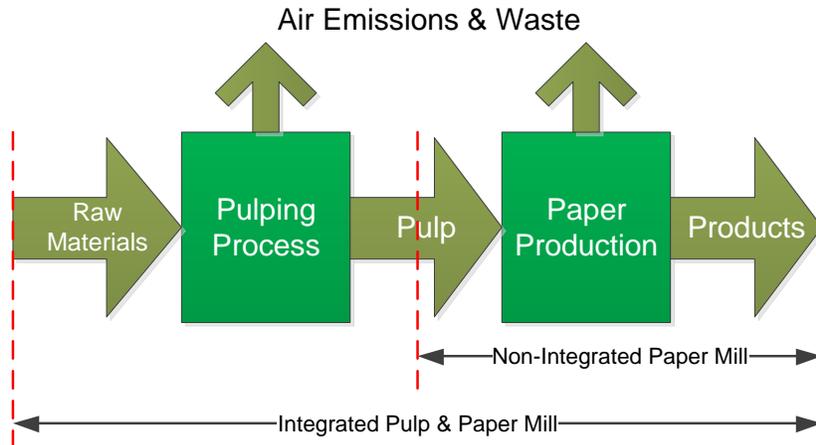


Figure 1-2. General Process Scheme for the Pulp and Paper Production Industry

### 1.1.1. Overview of Manufacturing Processes

Integrated pulp mills produce paper using six general processing stages: wood preparation, cooking or pulping, pulp washing, pulp screening, bleaching (optional, depending on product), and paper making.

*Wood preparation:* The wood preparation process involves wood cutting, transporting, debarking, chipping, and screening of the wood material. Hardwoods and softwoods can be harvested from tree plantations or from forests and species vary based on harvesting location. Wood is delivered to the pulp mill in one of two ways: logs or sawmill chips (residuals from sawmills). The logs are trimmed to appropriate processing lengths and the bark is removed (i.e., debarking) and burned in hog fuel boilers or sold for landscaping purposes. After debarking, the logs are reduced to chips that are the appropriate size for pulping. The chips are screened to remove oversized chips and sawdust. Oversized chips are re-chipped until they are the appropriate size, and sawdust is typically burned in a hog fuel boiler with the bark. From wood preparation, the chips proceed to pulping.

*Cooking or pulping:* The cooking (pulping) process is where the wood is broken down into fibers that can be used for papermaking. In the case of chemical pulping, cellulosic fibers are separated from the cellulose-hemicellulose-lignin matrix in wood using high temperatures, pressure, and chemicals. In the case of mechanical pulping, logs are chipped and mechanically broken into smaller pieces. These pulping methods are discussed in more detail in the following section. From the pulping process, pulp and spent cooking liquor proceed to pulp washing.

*Pulp washing:* The pulp washing process is used to remove cooking chemicals and the dissolved wood components in the cooking liquor for recovery and for energy generation. The recovery of these materials may also minimize the addition of chemicals and solids to the effluent treatment plant. The chemicals (inorganic and organic) are separated (washed) from the cooked pulp and screened. Pulping and pulp washing steps are very similar in kraft and sulfite processes. The pulp proceeds to pulp screening and the liquor proceeds to the chemical recovery process.

*Pulp screening:* The pulp screening process separates cooked pulp fibers from uncooked fiber bundles and knots. In the screening process, unwanted particles are removed by passing the pulp over pulp screens equipped with fine holes or slots. These screens may operate using gravity, vibrations, centrifugal force, or pressure. The pulp

proceeds from screening to bleaching if the final product requires bleached pulp or to the papermaking process if the final product utilizes unbleached pulp.

*Bleaching:* The bleaching process involves removing the lignin that still remains after cooking (chemically whitening) or breaking double bonds in the lignin without removing it (brightening), as the lignin contains the chromophoric groups that make the pulp dark. Bleaching and cooking are both delignification processes, and modern developments have tended to blur the difference between the two processes. However, traditionally the term 'bleaching' is reserved for delignification that is taking place downstream of the cooking process. Not all products require bleaching or the same amount of bleaching. Bleached pulp proceeds to the papermaking process.

*Paper making:* The paper-making process involves stock preparation, dewatering, pressing, drying and finishing. Pulp fibers are treated mechanically by refining to produce flexible fibers suitable for papermaking. These fibers are blended with product specific additives (e.g., fillers for printing paper, or wet strength agents for tissue) and are diluted significantly with water (<1 % fibers). This slurry is processed on a paper machine, which creates a fiber mat and removes water by gravity, suction, pressure, and heat. The paper can be converted to final products onsite, or may be shipped to another location for conversion.

These six processes could occur at an integrated facility (integrated pulp mill and paper mill). Alternatively, a selection of them could occur at a stand-alone paper mill or a stand-alone pulp mill (non-integrated facility). For example, a stand-alone paper mill could import pulp for the papermaking process (non-integrated paper mill), as illustrated in Figure 1-3.

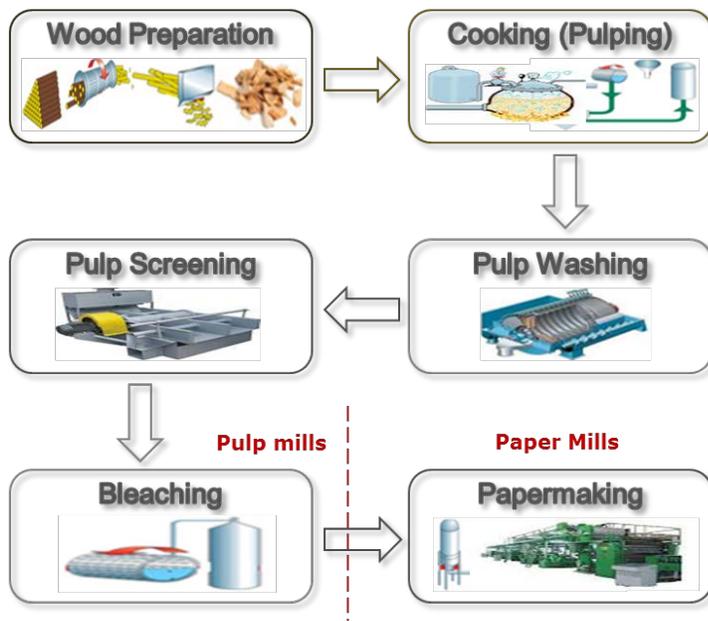


Figure 1-3. Schematic of the Integrated and Non-Integrated Processes

### 1.1.2. Chemical Pulping

In chemical pulping, wood chips are mixed with a chemical solution, heated under pressure to increase the reaction rate, and then disintegrated into fibers. The chemical recovery process involves evaporation, combustion, causticizing, and calcining. These processes are used to generate energy and recover cooking

chemicals. The weak black liquor from pulp washing is processed using a multiple-effect evaporator system to increase the black liquor solids content by removing water. This processing is done to improve the heating value of the liquor, because it will be burned in a recovery furnace to generate steam. The purpose of the recovery furnace is to burn the organics in the black liquor and recover the inorganics in molten form. These inorganics (known as smelt) are dissolved to create green liquor. Green liquor is then clarified and causticized using lime to create white liquor for the pulping process. Lime mud is collected from the white liquor clarifier and burned in a lime kiln to regenerate lime for the caustization process.

Kraft chemical recovery pulping is by far the most common pulping process used by plants in the US for virgin fiber and produced approximately 83 percent of all US virgin pulp tonnage during 2000 (USEPA, 2002). The kraft pulping process uses alkaline cooking liquor (called white liquor) of sodium hydroxide (NaOH) and sodium sulfide ( $\text{Na}_2\text{S}$ ) to digest wood, while the similar soda process uses only NaOH to digest the wood. The cooking liquor in the sulfite pulping process is an acidic mixture of sulfurous acid ( $\text{H}_2\text{SO}_3$ ) and salts of bisulfite ion ( $\text{HSO}_3^-$ ). The counter ion used in sulfite cooking liquor preparation is typically calcium, although historical counter ions also included ammonium, magnesium, and sodium.

### 1.1.3. Mechanical Pulping

Mechanical pulping is the oldest methodology used to separate pulp fibers from the wood matrix. The stone ground wood process was the most widely used mechanical pulping process until the 1990s. This method produces pulp by pressing a log against a rotating stone at atmospheric pressure. Fibers and fiber fragments are collected by washing the stone and are then processed. Pressurized ground wood, a similar process, uses the same technology, but grinds the logs at a temperature higher than 100 °C.

Mechanical pulping technology eventually shifted towards RMP, and by 1990, half of the mechanical pulp in the US was produced by this method. The advantage of RMP is that it uses wood chips instead of logs and refiner plates instead of stones. Three additional processes, thermo refiner mechanical pulp, pressure refiner mechanical pulp, and chemi-refiner mechanical pulp add pre-steaming of chips, increased refiner temperature, and chemical treatment, respectively. Finally, thermo-mechanical pulping (TMP) modified the RMP process by steaming chips under pressure prior to and during refining. Several variations of this process are utilized today, including pressure/pressure thermo-mechanical pulping, chemi-thermo-mechanical pulping (CTMP), thermo-mechanical-chemi pulping (TMCP), and long fiber chemi-mechanical pulping.

### 1.1.4. Semi-Chemical Pulping

Semi-chemical pulping utilizes both chemical and mechanical defibrillation methods. Examples of semi-chemical processes are neutral sulfite semi-chemical, high-yield kraft, and high-yield sulfite. The high-yield chemical processes utilize minimal kraft and sulfite chemical cooking followed by mechanical defibrillation. The neutral sulfite semi-chemical process is the most widely utilized semi-chemical process and is typically used to process hardwood. The liquor from these processes can be recovered in the kraft recovery furnace if they are collocated at a facility that uses kraft pulping, or a fluidized bed incinerator can be used.

### 1.1.5. Paper Recycling

In the fiber recycling process, pulp fiber is recovered from previously manufactured products such as cardboard or office paper. There are five basic grades of wastepaper that are commonly collected: mixed paper, old newsprint, old corrugated container, pulp substitutes, and high-grade de-inked. Mixed paper is the category that includes office waste, boxboard cuttings, and other grades. Pulp substitutes include unprinted and uncoated

paper and board. High-grade de-inked is printing and writing grades that have previously been printed (IPST, 2006).

These waste papers must be collected and transported to a processing facility, which can be expensive. Typically, plants that utilize wastepaper are located in urban areas where an abundant supply is available. After collection, waste papers are re-pulped using water and agitation. Contaminants are removed from the pulp through screening, de-inking, washing, and bleaching.

## 1.2. Energy Use in the Pulp and Paper Industry

Pulp and paper production is an energy intensive process. In 2002, the paper manufacturing industry consumed over 2.4 quads (quadrillion or  $10^{15}$  British thermal units [Btu]) of energy according to the Manufacturing Energy Consumption Survey, and represented over 15 percent of US manufacturing energy use (MECS, 2003; DOE, 2005). Large electricity losses are incurred at offsite utilities during generation and transmission of electricity; if these losses are included, the total energy associated with paper manufacturing reaches 2.8 quads (based on conversion factor of 10,500 Btu/kilowatt hour [kWh]).

Fuels comprise the bulk of the industry's primary energy use with only 7 percent of the energy use being purchased electricity. Nearly 55 percent of the energy demand is met by the use of biomass-based waste and byproduct fuels (e.g., wood, spent pulping liquors, chips, sawdust, and bark). Despite its large use of biomass-based fuels, the paper manufacturing industry is the fourth largest consumer of fossil energy, after chemicals, petroleum refining and steel. Energy intensity of various stages of production is given in Table 1-2. Process energy consumption can vary widely due to different technologies or variations in operating practices and feedstock composition. Energy demand among pulping processes can be quite different.

The industry relies on a diverse fuel mix. To supplement the use of fossil fuels, the industry self-generates electricity and heat using byproduct fuels such as wood, spent pulping liquors, chips, sawdust, and bark. In 2002, over 50 percent of the industry's energy demand was self-generated through the use of biomass-based fuels. The pulp and paper sector generates more electricity than any other manufacturing industry (51,208 kWh in 2002) (DOE, 2005).

Power boilers are often capable of being fired with multiple fuels. The design of power boilers varies with fuel type (e.g., oil, gas, coal, bark). Some are designed to process the so-called "hog fuel," a mixture of wood material generated onsite (e.g., bark, wood chips) that is constantly changing and is mill-dependent. Hog fuel boilers may be supplemented with oil, coal, or natural gas (e.g., if fuel moisture is too high, or during disturbances in solid fuel feeding). Non-integrated paper mills typically rely on fossil fuels because they do not produce wood byproducts.

Table 1-3 presents the various purchased and self-generated fuels used by the industry.

Table 1-2. Major Paper Manufacturing Processes (DOE, 2005)

Operation	Major Processes	Average energy (10 <sup>6</sup> Btu/ton pulp)	Average energy (10 <sup>6</sup> Btu/ton paper/paperboard) <sup>c</sup>
<b>Wood Preparation</b>	Debarking	0.10	n/a
	Chipping and conveying	0.35	
<b>Pulping</b>	Chemical pulping	2.68	n/a
	Kraft process	2.60	
	Sulfite process	5.38	
	Semi-chemical pulping	3.86	
	Mechanical pulping	7.68 <sup>b</sup>	
	Recycled paper re-pulping	1.30	
<b>Kraft Chemical Recovery</b>	Evaporation	3.86	n/a
	Recovery furnace	1.13 <sup>a</sup>	
	Re-causticizing	1.02	
	Lime kiln (calcining)	2.03	
<b>Bleaching</b>	Mechanical or chemical pulp bleaching	2.3	n/a
<b>Paper Making</b>	Paper refining and screening		0.84
	Forming, pressing, finishing and drying of:		
	Newsprint		5.61
	Tissue	n/a	9.77
	Uncoated paper		6.90
	Coated paper		7.10
	Linerboard		4.97

a. Does not reflect energy generated by the recovery furnace, which ranges from 4-20 million Btu/ton pulp.

b. Value for chemi-thermo-mechanical pulping.

c. Includes energy from steam and electricity for each product except tissue, which includes steam, electricity, and fuel.

n/a=not available in the report

**Table 1-3. Fuel Use for Pulp and Paper Production in 2000 (DOE, 2005)**

Fuel Source	Billion Btu Consumed	Percent of Total
Electricity	155,319.80	7
Steam	33,882.90	1.5
Coal	265,800.00	12
Petroleum Products	102,184.20	4.6
Natural Gas	395,611.00	17.7
Other	24,052.60	1.1
Excess Energy Sold	44,836.00	
Total Purchased	932,014.50	43.9
<b>SELF-GENERATED</b>		
Hog Fuel	327,359.00	14.7
Spent Liquor (solids)	894,985.90	40.3
Hydroelectric Power	4,989.70	0.2
Other	19,866.50	0.9
Total Self-Generated	1,247,201.10	56.1

Typically, a combustion unit (i.e., recovery furnace) is used to recover the cooking chemicals from spent cooking solutions (or liquors). Although the primary purpose of the recovery furnace (sometimes referred to as a recovery boiler) is to recover chemicals from spent pulping liquors (e.g., black liquor) for reuse, the recovery furnace also produces heat used to generate steam and electricity. Recovery furnaces at kraft pulp mills burn black liquor which has been concentrated through a multiple effect evaporator train and a direct contact or non-direct contact evaporator prior to being fired. Kraft and soda mills have an additional chemical recovery process in which a lime kiln is used to regenerate a portion of the chemical cooking solution.

Researchers are currently demonstrating gasification technologies that convert biomass and black liquor into a synthesis gas (syngas), which can be combusted in a gas turbine to generate electricity. In combined-cycle gasification, the gas turbine exhaust is then used to produce steam for generation of additional electricity or process heat (DOE, 2005). Currently, black liquor gasification technologies are in operation at three US pulp mills (two kraft mills and one stand-alone semi-chemical mill). Once black liquor gasification has been successfully introduced, adoption of biomass gasification will likely follow.

In addition, the forest product industry is still hopeful that technologies for conversion of biomass to biofuels, including gasification and hemicellulose conversion to ethanol, will continue to expand and will be able to extract more energy from the same amount of biomass and thereby reduce the use of fossil fuels and their emissions. Similarly, research continues on the production of renewable fuels at mills that could be used onsite to replace natural gas in equipment such as lime kilns. Widespread deployment is dependent upon many factors, particularly Federal research programs, the availability of capital, and successful scale-up from pilot operations to commercial facilities. A new technology for black liquor combustion in a dual-pressure recovery boiler promises significant improvement in steam generation and cogenerated electric power, which would reduce

fossil fuel demands at mills and utilities and the associated emissions. The dual pressure boiler technology is developed and waiting for full-scale commercial demonstration (AF&PA, 2009).

Table 1-4 provides a summary of the various pulp and papermaking processes and their relative energy intensities (energy consumed per ton of pulp).

**Table 1-4. General Classification of Pulping Processes (DOE, 2005)**

Pulping Process	Wood Pulp Production for 2001 (%)	Major Processes	Products	Average Energy Intensity* (10 <sup>6</sup> Btu/ton pulp)
Chemical	54	Kraft (sulfate)	Bags, wrapping paper, linerboard, newsprint, bleached pulp for white writing and printing papers	Electricity: 0.50 Steam: 2.10 Total: 2.60
		Sulfite	Fine paper, tissue, glassine, newsprint, dissolving pulp	Total: 5.38
Semi-chemical	4	Neutral sulfite semi- chemical High yield kraft High yield sulfite	Corrugated board, food packaging board, newsprint, magazine	Electricity: 1.56 Steam: 2.30 Total: 3.86
Mechanical	5	Stone ground wood Refiner mechanical pulp Thermo-mechanical pulp Chemi-thermo-mechanical pulp	Newsprint, magazine, catalogs, books, container board	Electricity: 6.08 Steam: 1.60 Total: 7.68
Recycled	37	N/A	Newsprint, printing/writing paper, tissue, packaging, containerboard, paperboard	Electricity: 0.50 Steam: 0.80 Total: 1.30

\* Electricity conversion factor of 3412 Btu/kWh.

### 1.3. Emissions from the US Pulp and Paper Industry

The environmental impacts from the pulp and paper industry can potentially come from hazardous chemicals, thermal loading to natural waterways, odor, combustion, and solid wastes. The industry is in the process of minimizing environmental impacts by increasing the use of recycled paper, improving energy efficiency, and making capital investments for effective compliance with regulations.

The pulp and paper industry generates more than 12 million tons per year of solid waste, consisting primarily of de-watered sludges. The standard treatment for these wastes in the past was to deposit them in landfills. Today they are more often being handled by incineration, conversion to useful products, and land application. Most solid waste from mills, such as sludge from de-inking plants, is non-hazardous and requires no special handling (Paperloop, 2003).

A survey study estimated that boilers are the dominant emission source, accounting for nearly 90 percent of the sulfur dioxide (SO<sub>2</sub>) and 70 percent of the nitrogen oxides (NO<sub>x</sub>) (NCASI, 2004).

Table 1-5 presents the 2005 SO<sub>2</sub> and NO<sub>x</sub> emissions results of the National Council for Air and Stream Improvement (NCASI) study (in tons per year). Kraft mill sources (primarily recovery furnaces) account for most

of the remaining nationwide SO<sub>2</sub> and NO<sub>x</sub> emissions from pulp and paper mills. Table 1-6 illustrates that the emissions from sulfite and semi-chemical pulping operations are minimal compared to the same from kraft mills.

Based on a survey of pulp and paper mills conducted by NCASI, there were approximately 425 pulp and paper mills that operated stationary combustion units (e.g., power boilers, recovery furnaces) in 2005 (NCASI, 2006). All of these 425 mills fall under NAICS code 3221. Of these 425 mills, 129 produced chemical pulp (including 108 integrated kraft /soda pulp mills, 8 sulfite pulp mills, and 13 stand-alone semi-chemical pulp mills) and 19 were mechanical pulp mills. The remainder of the mills operated combustion sources (e.g., power boilers) but did not produce pulp (Pinkerton, 2007).

**Table 1-5. Nationwide SO<sub>2</sub> and NO<sub>x</sub> Emissions from Pulp and Paper Mills (Pinkerton, 2007)**

Source	SO <sub>2</sub> (in thousands of tons per year)	NO <sub>x</sub> (in thousands of tons per year)
Boilers	293	153
Gas Turbines	-	3
Kraft Recovery Furnaces*	40	59
Kraft Smelt Dissolving Tanks*	1	1
Kraft Lime Kilns*	2	9
Kraft Thermal Oxidizers	2	1
Sulfite Pulp Mills	2	3
Semi-Chemical Pulp Mills	<1	1
<b>TOTAL</b>	<b>340</b>	<b>230</b>

\*Includes units at one soda pulp mill.

**Table 1-6. Trends in Nationwide SO<sub>2</sub> and NO<sub>x</sub> Emissions from Pulp and Paper Mills (AF&PA, 2009)**

	1980	1985	1990	1995	2000	2005
<b>SO<sub>2</sub> (in thousands of tons per year)</b>						
Boilers	730	523	461	393	351	<b>293</b>
Kraft pulping	122	153	96	86	57	<b>44</b>
Sulfite/Semi-chemical pulping	23	23	14	8	4	<b>3</b>
<b>TOTAL SO<sub>2</sub></b>	<b>875</b>	<b>699</b>	<b>571</b>	<b>487</b>	<b>412</b>	<b>340</b>
<b>NO<sub>x</sub> (in thousands of tons per year)</b>						
Boilers	207	231	231	233	199	<b>156</b>
Kraft pulping	66	73	69	76	76	<b>70</b>
Sulfite/Semi-chemical pulping	2	2	7	7	3	<b>4</b>
<b>TOTAL NO<sub>x</sub></b>	<b>275</b>	<b>306</b>	<b>307</b>	<b>316</b>	<b>278</b>	<b>230</b>

## 1.4. Overview of Universal ISIS-PNP

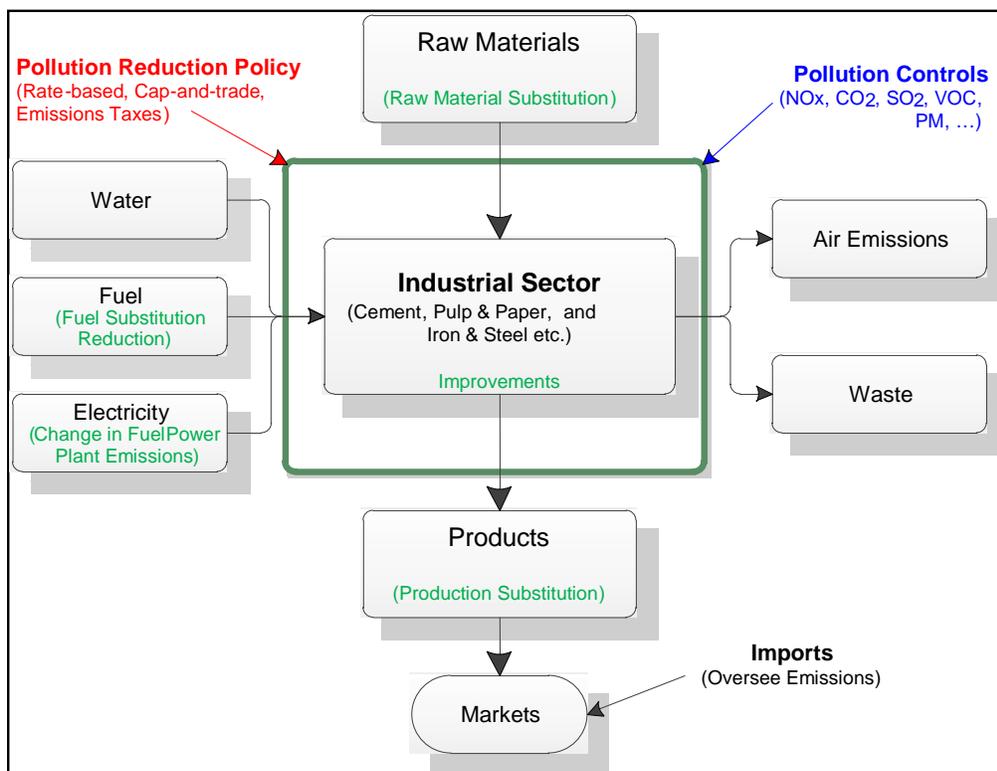
The Universal ISIS-PNP, a sector-based linear programming model, is designed to facilitate the analyses of emission reduction strategies for multiple pollutants while accounting for plant-level economic and technical factors such as the type of emission units (for pulp and paper – power boilers, hog fuel boilers, recovery furnaces and lime kilns), associated capacities, locations, costs of production, and applicable controls and costs. For each of the emission reduction strategies under consideration, the Universal ISIS-PNP is able to identify optimal (least cost) industry operation by selecting cost-effective controls to meet the demand for pulp and paper while complying with emission reduction requirements over the time period of interest.

The design of Universal ISIS-PNP allows for incorporating multiple industries within a multi-market, multi-product, multi-pollutant, and multi-region emissions trading framework. The objective function in Universal ISIS-PNP maximizes total (consumer and producer) surplus and uses an elastic formulation of the demand function to estimate area under the demand curve. The total surplus represents the difference between the cumulative amount that consumers value a product and the cumulative costs of producing the product. Total surplus is calculated for both Business as Usual (BAU) and policy cases. The change in total surplus between BAU and specific policy cases may be used to evaluate societal costs of policy implementation against societal benefits that may not be incorporated in the model. Emission reduction strategies are incorporated into the model through various constraints depending on the type of strategy.

The Universal ISIS code is written in GAMS language. Input data from Universal ISIS-PNP, organized in various spreadsheets of a Microsoft Excel workbook, are passed onto GAMS. These input data consist of an industry database, which provides unit-level production, capacity, production cost, and emissions information. A controls database provides information regarding applicable air pollution control technologies and their cost and emission control characteristics. A policy module is used to specify various parameters of interest to the policy analyst such as emissions cap, emission reduction scenarios, and discount rate. The input data, control data, and policy parameters are then transmitted to the optimization components of the Universal ISIS, where they are used to solve the selected baseline and policy cases. The results are post-processed to calculate values of various

outputs of interest. The output data are exported to Excel spreadsheets for further analyses and graphical representation of selected results.

Within an industrial sector, generally emissions arise from four pathways: (1) on-site emissions due to combustion of fossil fuels for energy at plants, (2) on-site emissions due to processing of certain raw materials (3) off-site emissions due to combustion of fossil fuels at power plants to generate the electricity needed by the industrial sector, and (4) overseas emissions associated with imports. These pathways are depicted in Figure 1-4.



**Figure 1-4. Integrated View of Pollution Generation Pathways, Emissions Abatement Approaches, and Multimedia Impacts for an Industrial Sector**

Also shown in Figure 1-4 are the potential options for abating emissions from industrial sectors and multimedia impacts. The options shown in green are pollution prevention measures, and the ones in red are mitigation measures. Clearly, the integrated picture presented in Figure 1-4 makes a compelling case for considering commodity production/supply activities along with emissions while developing holistic emission reduction strategies. While developing the Universal ISIS-PNP framework, care has been taken to build the emission pathways and abatement options shown in Figure 1-4. Example emission reduction policies that can be evaluated using Universal ISIS-PNP are:

- Criteria pollutants (NO<sub>x</sub>, SO<sub>2</sub>, particulate matter, carbon monoxide [CO]) –emission limits and/or cap-and-trade
- Hazardous Air Pollutants (e.g., total HAPs, benzene, hydrogen chloride) – emission limits

- Carbon dioxide (CO<sub>2</sub>) – cap-and-trade and/or emission taxes
- Long and short time horizons: CO<sub>2</sub> (decades), criteria pollutants (annual)

Policies may be simulated over long and short time horizons such as a CO<sub>2</sub> policy that occurs over a decadal time-frame and a criteria pollutant policy that occurs on an annual-time frame. The Universal ISIS model is also capable of evaluating requirements at a regional or national scale.

### 1.4.1. Pulp and Paper Modeling in Universal ISIS

The Universal ISIS-PNP modeling efforts for the pulp and paper sector are focused on the power boilers (including hog fuel boilers), recovery furnaces, and lime kilns at integrated and non-integrated mills. The industry database is comprised of 514 facilities, both integrated and non-integrated, populating US production capacity in 2007. Both the emissions information and the controls database focus on HAPs, criteria air pollutants, and greenhouse gases. Both databases can be updated as additional data are acquired and incorporated. An overview of the Universal ISIS-PNP framework for the pulp and paper industry is presented in Figure 1-5. Emissions related to pulping at non-integrated paper mills are incorporated as off-site emissions.

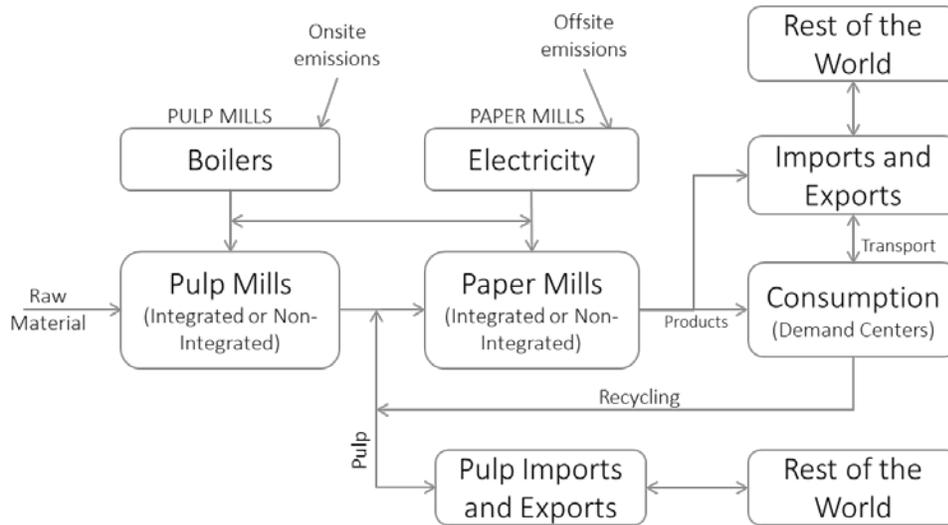


Figure 1-5. Universal ISIS-PNP Modeling Framework

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## 2. Emissions Sources

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### 2.1. Background

Pulp and paper manufacturing processes emit a variety of air pollutants that are regulated by federal air emission standards and permitting limitations. Emissions of total reduced sulfur (TRS), malodorous compounds characteristic of kraft pulp mills, are regulated under federal new source performance standards (NSPS) for kraft pulp mills and state limitations based on federal emission guidelines for kraft pulp mills. Emissions of particulate matter (PM) from kraft chemical recovery combustion sources - recovery furnaces, lime kilns, and smelt dissolving tanks - are also regulated under this NSPS.

HAPs from pulping process equipment (predominantly methanol and smaller quantities of additional organic compounds) are regulated by the US Environmental Protection Agency (USEPA) under the national emission standards for hazardous air pollutants (NESHAPs) for pulp and paper production. This NESHAP also regulates chlorinated compounds from bleaching processes at pulp and paper mills. A separate NESHAP regulates organic HAPs (predominantly methanol, plus other organic compounds) and metallic HAPs (regulated through a PM surrogate) from chemical recovery combustion sources at pulp mills. Federal NSPS regulate selected criteria pollutants--nitrogen oxides (NO<sub>x</sub>), SO<sub>2</sub>, and PM--from industrial boilers, and the recently promulgated NESHAP for industrial boilers and process heaters regulates HAPs from those sources.

Mill-specific criteria pollutant emission limits derived under USEPA's New Source Review and Prevention of Significant Deterioration pre-construction permitting programs and emission limits from state regulations are consolidated with these federal regulations in the title V operating permits of pulp and paper mills.

Over the past several decades, the pulp and paper industry has continually reduced its environmental impact by increasing the use of recycled paper, improving energy efficiency, and making capital investments for effective compliance with regulations. However, as noted in a 2009 document prepared by NCASI on the trade-offs and benefits accompanying NO<sub>x</sub> and SO<sub>2</sub> control (NCASI, 2009a), lingering environmental concerns associated with emissions of NO<sub>x</sub> and SO<sub>2</sub> have prompted continued pressure for further emissions reductions. These pollutants originate as products of combustion that accompany power generation and the processing of pulping chemicals.

The NCASI report noted that measures have been taken in North America over the last 25 years to reduce atmospheric emissions of NO<sub>x</sub> and SO<sub>2</sub> where levels contributed to impaired environmental quality, as well as in response to the aforementioned government-mandated performance standards. Nitrogen oxides and SO<sub>2</sub> together have been implicated in adverse respiratory effects where certain thresholds are exceeded, as well as acidic deposition thought to be of consequence to vegetation, soils and surface waters. Nitrogen oxide emissions are also known to contribute to ozone formation and deposition-related eutrophication of surface waters. Most recently, NO<sub>x</sub> and SO<sub>2</sub> emissions are being scrutinized because of their role in the formation of fine PM (PM<sub>2.5</sub>), which is an emerging health concern and a contributor to visibility impairment in certain geographic settings (NCASI, 2009a).

GHGs are another source of concern for a number of industries, including the pulp and paper sector. Greenhouse gas emissions from the pulp and paper sector are predominantly carbon dioxide (CO<sub>2</sub>), with smaller amounts of methane (CH<sub>4</sub>) and nitrous oxide (N<sub>2</sub>O). The majority of the CO<sub>2</sub> emissions from the pulp and paper industry are biogenic CO<sub>2</sub> emissions derived from the combustion of biomass fuels (e.g., bark and other wood residuals, black liquor) that are generated onsite as a byproduct of the pulping process. Many pulp and paper facilities generate

over half of their energy needs from biomass fuels recovered from the pulp and paper production process (USEPA, 2009).

A complex tool is needed to understand the technical and economic implications of applying process and emission control technologies to reduce the emissions of NO<sub>x</sub>, SO<sub>2</sub>, PM, and GHGs (particularly CO<sub>2</sub>). To facilitate the comprehensive analysis required to understand the complex interactions between economy and environment, the USEPA has developed the Universal ISIS model. The Universal ISIS model has been populated with data specific to the pulp and paper sector (Universal ISIS-PNP) to analyze the potential process and control technologies for reducing these emissions from the pulp and paper industry. This chapter discusses the major sources of NO<sub>x</sub>, SO<sub>2</sub>, PM, and CO<sub>2</sub> in the pulp and paper industry and potential technologies for reducing the emissions of these pollutants.

This chapter identifies emission reduction technologies, and, to the extent information is available in the literature reviewed, an approximate percent reduction in emissions expected to be achieved with each technology. When employing Universal ISIS-PNP for regulatory applications, users will be able to customize it with updated control efficiencies developed through a more rigorous analysis of actual emissions test data. The actual percent reduction that can be achieved with each technology depends on many factors, including process-specific characteristics and baseline control strategies already in use.

## 2.2. Air Emissions Sources

Paper production is an energy intensive process. Power boilers at pulp and paper mills generate electricity and process steam by combustion of fossil fuels and biomass. Some boilers fire so-called opportunity fuels such as process gases, wastewater treatment sludges, etc. Recovery furnaces (sometimes referred to as recovery boilers) at kraft pulp mills burn concentrated black liquor to recover cooking chemicals (specifically, Na<sub>2</sub>S) for reuse in subsequent pulping cycles. While the primary purpose of the recovery furnace is to recover cooking chemicals, the recovery furnace also produces heat used to generate steam and electricity for the mill. Kraft pulp mills use lime kilns to convert lime mud from the white liquor clarifier to lime, which is used in the causticizing process to recover additional pulping chemicals (specifically NaOH). Thermal oxidizers are used mostly for the destruction of malodorous organic compounds and other non-condensable gases from the pulping process. All of the above sources use fuel combustion for their operation and thus produce NO<sub>x</sub>, SO<sub>2</sub> (depending on fuel used), and PM.

A recent survey study by NCASI, which estimated emissions from US pulp and paper mills (NCASI, 2012), demonstrated that boilers are the dominant emission source of the NO<sub>x</sub>, SO<sub>2</sub>, and PM emissions in the sector, accounting for over 85 percent of the SO<sub>2</sub>, almost 65 percent of the NO<sub>x</sub>, and over 40 percent of the PM emissions, as shown in Table 2-1, below.

**Table 2-1. 2010 Emissions, 10<sup>3</sup> tons (NCASI, 2012)**

Process Unit	NO <sub>x</sub>	SO <sub>2</sub>	PM <sup>a</sup>
Boilers	124	205	17
Gas Turbines	2	-	-
Kraft Recovery Furnaces	55	29	12
Kraft Smelt Dissolving Tanks	-	1	6
Kraft Lime Kilns	8	2	4
Kraft Thermal Oxidizers	1	1	<1
Sulfite Pulp Mills	3	1	<1
Semi-Chemical Pulp Mills	1	<1	<1
<b>TOTAL</b>	<b>194</b>	<b>239</b>	<b>39</b>

<sup>a</sup> Filterable PM only.

Recovery furnaces and lime kilns are also major emission sources of these pollutants, together accounting for over 10 percent of the SO<sub>2</sub>, over 30 percent of the NO<sub>x</sub>, and over 40 percent of the PM emissions in the sector. Compared to emissions from boilers, kraft recovery furnaces, and kraft lime kilns, emissions from sulfite and semi-chemical mills (notably the chemical recovery combustion sources at these mills) are minimal, due to the small numbers of these mills.

Greenhouse gas emissions from the pulp and paper source category are predominantly CO<sub>2</sub> with smaller amounts of CH<sub>4</sub> and N<sub>2</sub>O. Fuel combustion is by far the largest source of GHG emissions emitted directly from pulp and paper mill operations. Other non-energy-related sources of GHG emissions from pulp and paper mills include use of carbonate-containing chemicals and CH<sub>4</sub> releases from industrial wastewater treatment and landfills. Table 2-2 summarizes the relative magnitude of nationwide GHG emissions (in million metric tons of CO<sub>2</sub> equivalents per year) reported to be emitted directly from stationary sources in the pulp and paper manufacturing sector in 2004 (USEPA, 2010a).

**Table 2-2. Nationwide GHG Emissions from the Pulp and Paper Manufacturing Industry**

Emission Source	Million metric tons of CO <sub>2</sub> e per year
Direct emissions associated with fuel combustion (excluding biomass CO <sub>2</sub> )	57.7
Wastewater treatment plant CH <sub>4</sub> releases	0.4
Forest products industry landfills	2.2
Use of carbonate make-up chemicals and flue gas desulfurization chemicals	0.39
Direct emissions of CO <sub>2</sub> from biomass fuel combustion (biogenic)	113

Note: In addition to GHG emissions directly from each pulp and paper plant site, there are indirect GHG emissions associated with off-site generation of steam and electricity that are purchased by or transferred to the mill. Indirect emissions have not been incorporated into the current version of the Universal ISIS-PNP and are not discussed further in this document.

Biogenic CO<sub>2</sub> emissions are of unique importance for the pulp and paper industry considering that the industry satisfies much of its energy requirements by burning large quantities of biomass fuels. Biogenic CO<sub>2</sub> emissions

result primarily from combustion of spent pulping liquor in chemical recovery furnaces and from combustion of woody biomass and other biogenic fuels in boilers and other combustion units. Biomass fuels have typically been considered to be carbon neutral (i.e., treated as zero emissions) due to their short-term renewable life cycle for purposes of emissions inventories; however, accounting methods for biogenic CO<sub>2</sub> emissions are currently under review by the USEPA. Once developed, USEPA’s accounting methodology for biogenic CO<sub>2</sub> emissions could be applied in different policy contexts that are yet to be determined. Given that it is unknown at this time how the biogenic CO<sub>2</sub> accounting methodology will affect future emission reduction policies, Universal ISIS-PNP considers the two extremes: (1) biogenic CO<sub>2</sub> emissions could be considered as zero under policies analyzed in Universal ISIS, or (2) biogenic CO<sub>2</sub> emissions could be treated the same as any other CO<sub>2</sub> emissions (e.g., derived from fossil fuel combustion). A third and in-between scenario is that biogenic CO<sub>2</sub> emissions could be discounted based on regional or biomass feedstock-specific biogenic accounting factors that might place biogenic emissions somewhere between zero and their full value.

Recent estimates of pulp and paper sector GHG emissions (excluding biogenic CO<sub>2</sub> emissions) from USEPA’s GHG Reporting Program are presented in Table 2-3 below (USEPA, 2013).

**Table 2-3. Pulp and Paper Sector — GHG Emissions Reported to the GHG Reporting Program for 2012**

Emissions by GHG	Reporting year 2012 million metric tons of CO <sub>2</sub> e per year*
Carbon dioxide (CO <sub>2</sub> )	39
Methane (CH <sub>4</sub> )	0.9
Nitrous oxide (N <sub>2</sub> O)	2
Total emissions (CO <sub>2</sub> e)	42

\* Biogenic CO<sub>2</sub> emissions are not included in emission totals provided above. Emissions from the industrial wastewater treatment and landfills are not included in Table 2-3. Biogenic CO<sub>2</sub> from the pulp and paper sector emissions were reported to be 121 million metric tons in 2012. The global warming potential factors used to arrive at the totals in Table 2-3 were 1 for CO<sub>2</sub>, 21 for CH<sub>4</sub>, and 310 for N<sub>2</sub>O.

The emissions in Table 2-3 are presented in CO<sub>2</sub> equivalents (CO<sub>2</sub>e), which are derived by multiplying each GHG by its respective global warming potential factor to place emissions on a common CO<sub>2</sub>e basis. Table 2-3 shows that CO<sub>2</sub>e emissions from fossil fuel combustion represent the majority of GHG emissions for the pulp and paper sector. Methane and N<sub>2</sub>O from fossil fuel combustion are usually very small compared to CO<sub>2</sub> emissions, even after conversion to CO<sub>2</sub>e. Thus, CO<sub>2</sub> emissions represent the largest potential for GHG emission reductions in the pulp and paper industry and, therefore, are the focus of GHG included in the Universal ISIS-PNP.

Further analysis of the 2012 GHG Reporting Program non-biogenic CO<sub>2</sub> emissions data reveals that emissions from boilers and pulp production (e.g., chemical recovery furnaces and lime kilns) represent the majority (95 %) of the non-biogenic CO<sub>2</sub> emissions from the pulp and paper industry. As shown in Figure 2-1, combustion turbines, process heaters, incinerator control devices (used to combust non-condensable gases [NCGs] for HAPs, volatile organic compounds [VOCs], and for TRS emissions control), and reciprocating internal combustion engines comprise less than 5 percent of the combustion-related CO<sub>2</sub> emissions. Figure 2-2 shows that, if biogenic CO<sub>2</sub> emissions were to be considered, then pulp production and boilers would account for nearly 99 percent of the CO<sub>2</sub> emissions. The Universal ISIS-PNP focuses on CO<sub>2</sub> emissions from boilers, chemical recovery furnaces, and lime kilns because these are the predominant GHG emission sources in the pulp and paper industry.

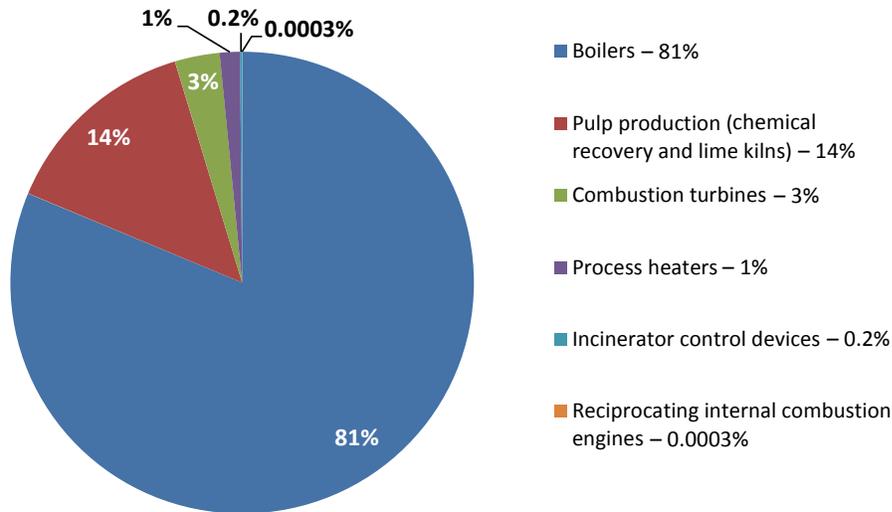


Figure 2-1. Stationary Combustion and Pulp Production Sources of Non-Biogenic CO<sub>2</sub> Emissions

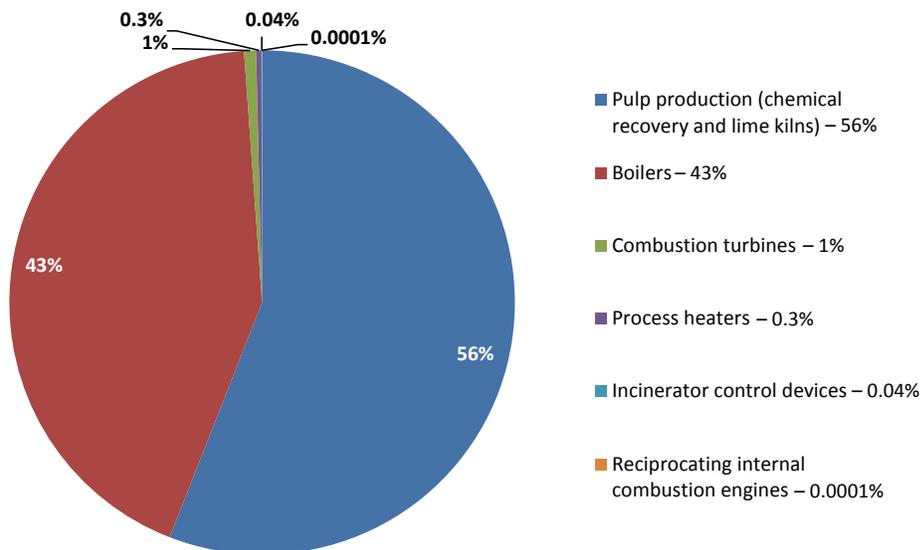


Figure 2-2. Stationary Combustion and Pulp Production Sources of Total CO<sub>2</sub> (biogenic and non-biogenic CO<sub>2</sub>)

## 2.3. Boilers

### 2.3.1. Boiler Design and Fuels

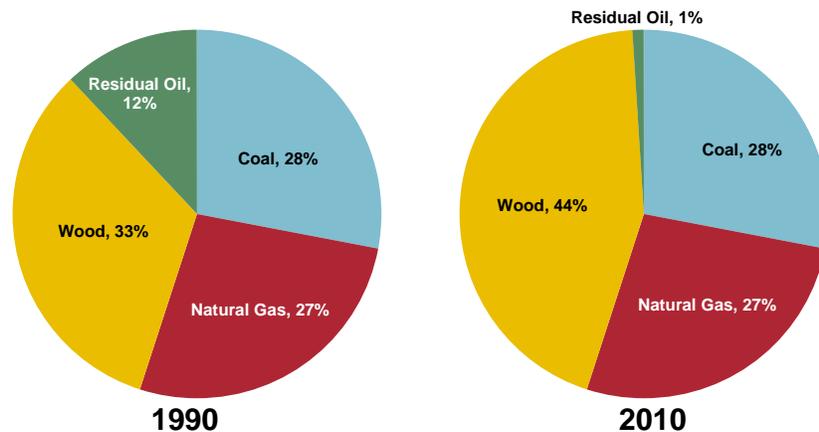
The pulp and paper sector uses power boilers (in addition to recovery furnaces) to produce the steam and electricity needed for the pulp and paper manufacturing process. According to NCASI study (NCASI, 2009a), the pulp and paper sector uses nearly 1,000 of these auxiliary power boilers, with the following attributes:

- Approximately 30 percent of these boilers are larger than 250 million Btu (MMBtu) per hour. Less than 20 of these boilers are larger than 1000 MMBtu/h. The largest boiler is 1400 MMBtu/h.

- Approximately 50 percent of the sector’s power boilers were installed prior to 1970. Nearly 30 percent were installed between 1971 and 1990. Approximately 20 percent were installed in 1991 or later.

The pulp and paper sector uses boilers with a variety of designs. Considering the design of heat exchange between combustion gases and water, boilers can be of watertube or firetube design. In the watertube design, the fuel is combusted in a central chamber and the combustion gases transfer heat to water circulating in metal tubes through radiation and convection. In the firetube design, water is stored in the main chamber of a boiler and combustion gases flow through metal tubes within the body of the boiler, allowing for heat to be transferred by conduction from the metal tubes to the surrounding water.

Boilers such as those described above for the pulp and paper sector have also been designed to operate with a variety of fuels. The fuel mix for boilers for 1990 and 2010 is shown in Figure 2-3 in terms of the percentage of total heat input. Coal, natural gas, wood, and residual oil are the primary fuels burned. The use of residual oil has decreased significantly from 1990 to 2010. The heat input from residual oil has been replaced by the heat input from wood. Boilers are commonly configured to burn multiple fuels to ensure that steam demands can be met at the most favorable fuel cost (NCASI, 2009a).



**Figure 2-3. Fuels Used by Boilers in Pulp and Paper Sector by Heat Input (NCASI, 2012)**

Coal-fired boilers most often use pulverized fuel and thus are known as pulverized-coal (PC) boilers. PC boilers are used in large industrial units. Smaller industrial units use stoker-fired boilers. In PC boilers, coal is pulverized to very small particle size in pulverizers or mills. These small coal particles are then blown with air into the boiler where they are burned in suspension. Heat is transferred from the combustion gases to watertubes on the walls of the boiler. PC boilers may be characterized by the burner configuration (wall, tangential, cyclone) and whether the bottom ash exits the boiler in solid or molten state (dry bottom vs. wet bottom). Another type of coal-fired boiler is a stoker boiler (stoker). In a stoker, the fuel is combusted in thin layers on top of a grate. Heat is transferred from the combustion gases to watertubes on the walls of the boiler. Depending on how coal is delivered to the grate, the stoker may be a spreader stoker (coal spread above the grate) or an underfeed stoker (coal pushed into the bottom of the fuel bed). Other less common stoker types include traveling-grate, chain-grate, and vibrating-grate.

Natural gas-fired boilers are typically smaller than coal-fired boilers and most often are package boilers. Based on information from USEPA's AP-42 section on natural gas combustion (USEPA, 1998a), package boilers are constructed off-site and shipped to the location where they are needed. While the heat input levels of packaged units may range up to 250 MMBtu/h, the physical size of these units is constrained by shipping considerations. The units generally have heat input levels less than 100 MMBtu/h. Package units are always wall-fired units with one or more individual burners. Given the size limitations imposed on package boilers, they have limited operational flexibility and cannot feasibly incorporate some NO<sub>x</sub> control options. Another type of natural gas-fired boiler is a field-erected boiler. Field erected boilers are constructed onsite and comprise the larger sized watertube boilers. Generally, boilers with heat input levels greater than 100 MMBtu/h are field-erected. Field-erected units usually have multiple burners and, given the customized nature of their construction, also have greater operational flexibility and NO<sub>x</sub> control options. Field-erected units can also be further categorized as wall-fired or tangential-fired. Wall-fired units are characterized by multiple individual burners located on a single wall or on opposing walls of the furnace, while tangential units have several rows of air and fuel nozzles located in each of the four corners of the boiler (USEPA, 1998a).

Residual oil-fired boilers typically use Number 6 fuel oil or other heavy fuel oil. These oil-fired boilers are available as package or field-erected units (USEPA, 2010b). In general, field-erected boilers are much more common than package units in the boiler size category above 100 MMBtu/h input capacity, whereas below this capacity, the boilers are usually package units. Field-erected boilers may be normal-fired or tangential-fired (NCASI, 2004).

Based on information from USEPA's AP-42 section on wood combustion (USEPA, 2003), wood or wood waste (hog fuel) boilers are typically grate fired, with a spreader stoker employed for wood-fired boilers with a steam generation rate larger than 100,000 lb/h. In this boiler type, wood enters the furnace through a fuel chute and is spread either pneumatically or mechanically across the furnace, where small pieces of the fuel burn while in suspension. Simultaneously, larger pieces of fuel are spread in a thin even bed on a stationary or moving grate. This type of boiler has a fast response to load changes, has improved combustion control, and can be operated with multiple fuels. Natural gas, oil, and/or coal are often fired in spreader stoker boilers as auxiliary fuels. The fossil fuels are fired to maintain constant steam production when the wood residue moisture content or mass rate fluctuates and/or to provide more steam than can be generated from the residue supply alone. Although spreader stokers are the most common stokers among larger wood-fired boilers, overfeed and underfeed stokers are also utilized for smaller units. Dutch ovens and fuel cell ovens are two other grate-fired units used in smaller operations. A later innovation in wood firing is the fluidized bed combustion boiler. A fluidized bed consists of inert particles through which air is blown so that the bed behaves as a fluid. Wood residue enters in the space above the bed and burns both in suspension and in the bed. Because of the large thermal mass represented by the hot inert bed particles, fluidized beds can handle fuels with moisture content up to near 70 percent (total basis). Fluidized beds can also handle dirty fuels (up to 30 % inert material) (USEPA, 2003). Despite their advantages, fluidized bed boilers represent only a small fraction of the population of boilers used in the pulp and paper industry.

To address the complexity of the design-fuel matrix, boilers were grouped by the type of fuel used. This approach will be used throughout the chapter to describe emissions from boilers and air pollution control technologies applicable to the sector and in Universal ISIS modeling of technology application scenario.

### 2.3.2. Source of Boiler Emissions

The most important determinant of NO<sub>x</sub>, SO<sub>2</sub>, and PM emissions from boilers is the choice of fuel (NCASI, 2009a). As noted in Figure 2-3, at pulp and paper mills in 2010, wood fuels accounted for 44 percent of the total fuel heat input to boilers, followed by coal (28 %), natural gas (27 %) and fuel oil (1 %). Wood is most often burned in combination with fossil fuels in these boilers (NCASI, 2009a). A comparison of the relative nitrogen and sulfur content of various fuels is shown in Table 2-4.

**Table 2-4. Relative Nitrogen and Sulfur Content of Fuels (NCASI, 2009a)**

Fuel	Nitrogen, %	Sulfur, %
Natural Gas	Insignificant	Insignificant
Distillate Oil	0.05 or less	0.05 or less
Residual Oil	0.1 to 1.0	0.3 to 3.0
Coal	0.5 to 2.0	0.4 to 4.0
Bark and Wood Residue	0.1 to 0.4	0.2 or less

Also influential on NO<sub>x</sub> and SO<sub>2</sub> emissions are features of the boiler's design (type, size) and the combustion conditions under which it can be operated (boiler load, firing conditions) (NCASI, 2009a).

#### 2.3.2.1. Boiler NO<sub>x</sub> Emissions

The principal sources of NO<sub>x</sub> emissions from boilers are "thermal" NO<sub>x</sub> (formed from the thermal conversion of nitrogen in the combustion air) and "fuel" NO<sub>x</sub> (formed from the nitrogen in the fuel) (NCASI, 2009a). Based on information from an NCASI technical bulletin on criteria pollutant emissions from pulp and paper mills (NCASI 2004), the principal mechanism of NO<sub>x</sub> formation in natural gas combustion is the thermal NO<sub>x</sub> mechanism, while NO<sub>x</sub> emissions from residual oil combustion arise from both fuel NO<sub>x</sub> and from thermal NO<sub>x</sub>. Fuel NO<sub>x</sub> can account for 60 to 80 percent of the total NO<sub>x</sub> formation in residual oil combustion (NCASI, 2004).

NO<sub>x</sub> emissions from coal combustion (thermal and fuel NO<sub>x</sub>) are considerably higher than the NO<sub>x</sub> emissions from gas or oil. Fuel NO<sub>x</sub> can account for up to 80 percent of the total NO<sub>x</sub> formed. Coal nitrogen content ranges from 0.5 to 2 percent. Emissions of NO<sub>x</sub> are highest for cyclone boilers, followed by pulverized coal, stokers, and mass feed units (NCASI, 2004).

Nitrogen oxide emissions from wood combustion are mainly the result of fuel NO<sub>x</sub>, with bark nitrogen contents typically ranging from 0.1 to 0.2 percent. Average NO<sub>x</sub> emissions from wood combustion in typical pulp mill boilers are lower than average NO<sub>x</sub> emissions from coal or residual oil combustion and slightly higher than average NO<sub>x</sub> emissions from natural gas burning (NCASI, 2004).

#### 2.3.2.2. Boiler SO<sub>2</sub> Emissions

Sulfur dioxide emissions are driven by fuel sulfur content, which is highest in coal and negligible in natural gas (NCASI, 2009a). The average sulfur content of coal used in pulp and paper boilers was 1.27 percent for coals used in 2010 (NCASI, 2012). Small amounts of other sulfur-containing fuels are burned in boilers, including tire-derived fuel (TDF) and petroleum coke. TDF sulfur content is normally about 1.5 percent. Petroleum coke sulfur content ranges from 4 to 6 percent.

The incineration of NCG streams containing TRS in mill combustion devices creates the potential for emissions of SO<sub>2</sub> (NCASI, 2009a). The potential for SO<sub>2</sub> emissions from this practice is relatively small compared with overall mill emissions and varies with the combustion devices chosen (boiler, lime kiln, recovery furnace, or stand-alone incineration device). Power boilers are the most versatile of the combustion devices used to incinerate NCG. Approximately one-third of kraft mill power boilers are used to manage TRS gas streams because the relatively large size of boilers accommodates high-volume, low-concentration and low-volume, high-concentration gas streams. There is a potential increase of boiler SO<sub>2</sub> emissions. However, SO<sub>2</sub> can be absorbed by the alkaline dust in wood and combination fuel boilers (NCASI, 2009a).

### *2.3.2.3. Boiler PM Emissions*

The determinants of PM emissions from pulp and paper boilers depend on a variety of factors, as outlined below based on PM emissions information for each boiler type from USEPA's AP-42.

Because natural gas is a gaseous fuel, filterable PM emissions from natural gas boilers are typically low. Particulate matter in natural gas combustion is usually higher molecular weight hydrocarbons that have not been fully combusted. Increased PM emissions may result from poor air/fuel mixing or maintenance problems (USEPA, 1998a).

PM emissions from residual oil burning are related to the oil sulfur content. Boiler load can also affect filterable PM emissions in units firing residual oil, with low load conditions reducing emissions by 30 to 40 percent from larger boilers and as much as 60 percent from smaller boilers. Under very low load conditions, proper combustion conditions may be difficult to maintain, and PM emissions may increase significantly (USEPA, 2010b).

In coal-fired boilers, PM composition and emission levels are a complex function of boiler firing configuration, boiler operation, pollution control equipment, and coal properties. Uncontrolled PM emissions from coal-fired boilers include the ash from combustion of the fuel as well as unburned carbon resulting from incomplete combustion. In pulverized coal systems, combustion is almost complete; thus, the PM emitted is composed primarily of inorganic ash residues. Coal ash may either settle out in the boiler (bottom ash) or be entrained in the flue gas (fly ash). The distribution of ash between the bottom ash and fly ash fractions directly affects the PM emission rate and depends on the boiler firing method and furnace type (wet or dry bottom). Boiler load also affects the PM emissions, as decreasing load tends to reduce PM emissions. However, the magnitude of the reduction varies considerably depending on boiler type, fuel, and boiler operation (USEPA, 1998b).

In bark/wood combustion, PM emissions result from inorganic materials contained in the bark and wood itself and from carbonaceous material resulting from incomplete combustion (NCASI, 2004).

### *2.3.2.4. Boiler GHG Emissions*

The paragraphs below summarize available information from USEPA's AP-42 on the sources of emissions of the GHGs CO<sub>2</sub>, CH<sub>4</sub>, and N<sub>2</sub>O from boilers. These pollutants are all produced during combustion of natural gas, residual oil, coal, and wood residues. Nearly all of the fuel carbon (99 % or more) is converted to CO<sub>2</sub> during the combustion process. This conversion is relatively independent of firing configuration. The majority of the fuel carbon not converted to CO<sub>2</sub> is due to incomplete combustion in the fuel stream. In natural gas and fuel oil combustion, fuel carbon not converted to CO<sub>2</sub> results in CH<sub>4</sub>, CO, and/or VOC emissions. In coal and wood combustion, the majority of unconverted fuel carbon is entrained in bottom ash. Even in boilers operating with poor combustion efficiency, the amount of CH<sub>4</sub>, CO, and VOC produced is insignificant compared to CO<sub>2</sub> levels. Carbon dioxide emissions from coal combustion vary with carbon content, and carbon content varies between

the classes of bituminous and subbituminous coals. Further, carbon content also varies within each class of coal based on the geographical location of the mine. Biogenic CO<sub>2</sub> emitted from wood combustion has generally not been counted as GHG emissions because of its role in the short-term CO<sub>2</sub> cycle of the biosphere (USEPA, 1998a, 1998b, 2003, 2010b).

The formation of N<sub>2</sub>O during the combustion process is governed by a complex series of reactions, and its formation is dependent upon many factors. Formation of N<sub>2</sub>O is minimized when combustion temperatures are kept high (above 1475 °F), and excess air is kept to a minimum (less than 1 %). Nitrous oxide emissions for coal combustion are not significant except for fluidized bed boilers, where the emissions are typically two orders of magnitude higher than all other types of coal firing due to areas of low-temperature combustion in the fuel bed (USEPA 1998a, 1998b, 2003, 2010b).

Methane emissions vary with the type of fuel and firing configuration, but are highest during periods of incomplete combustion or low-temperature combustion such as the start-up or shut-down cycle for boilers. Typically, conditions that favor formation of N<sub>2</sub>O also favor emissions of CH<sub>4</sub> (USEPA, 1998a, 1998b, 2003, 2010b).

### 2.3.3. Boiler Emission Reduction Strategies

#### 2.3.3.1. Boiler NO<sub>x</sub> Reduction

As noted previously, NO<sub>x</sub> is formed in boilers mostly through the oxidation of nitrogen in the combustion air (thermal NO<sub>x</sub>) and through oxidation of fuel nitrogen (fuel NO<sub>x</sub>). According to NCASI 2009a, the firing of natural gas typifies the former, whereas the firing of coal and oil typifies the latter. Fuel NO<sub>x</sub> represents approximately 50 percent of the total uncontrolled emissions when firing residual oil and more than 80 percent when firing coal (NCASI, 2009a).

NCASI 2009a indicated that fuel switching is an attractive option for reducing boiler NO<sub>x</sub> emissions, but cautioned that its application cannot be considered in isolation from a host of site-specific factors of importance to boiler performance, boiler integrity and overall emissions control capability. For example, biomass and wood are favorable fuels from the standpoint of NO<sub>x</sub> emissions, but firing them has been observed to lead to accelerated corrosion of boiler components. Fuel properties are best taken into account at the time of boiler design (NCASI, 2009a).

Apart from choice of fuel, control technologies exist that can reduce boiler NO<sub>x</sub> emissions. These technologies can be divided into primary and secondary control technologies. Primary control technologies seek to limit the formation of thermal NO<sub>x</sub> by manipulation of combustion conditions, while secondary control technologies aim to remove the NO<sub>x</sub> from the flue gas by treatment of flue gas in the post-combustion regions of the furnace (NCASI, 2009a). Various approaches for NO<sub>x</sub> control are characterized in Table 2-5. According to NCASI 2009a, the applicability of individual options and performance will depend upon boiler design and configuration, fuels being burned, and the dynamic character of boiler loading. Greater opportunity for NO<sub>x</sub> reduction exists when the capability is designed into newly constructed boilers as opposed to retrofitting existing boilers (NCASI, 2009a).

Table 2-5. Boiler NO<sub>x</sub> Control Technologies (NCASI, 2009a)

Control Option	Description	Performance	Application
Combustion Modifications			

Control Option	Description	Performance	Application
<b>Low-NO<sub>x</sub> Burner (LNB)</b>	Burners designed to mix fuel and air in a controlled pattern that sustains local fuel-rich regions, keeps the temperatures down and dissipates heat quickly	Approximately 50 % NO <sub>x</sub> reduction	Used in both gas/oil-fired and coal-fired units. Elongated flame configuration limits application in smaller boilers
<b>Ultra Low-NO<sub>x</sub> Burner (ULNB)</b>	For gaseous fuel burners, ULNBs often use air staging and internal flue gas recirculation (FGR) (no external ductwork needed), or they may alternatively use lean-premixed combustion with FGR for lower emissions than possible with LNB alone. ULNB is also a term used for some second-generation coal-fired LNBs that are installed in combination with overfire air (OFA) (Andover 2010).	In the range of 75 % NO <sub>x</sub> reduction (Andover, 2010)	Used in gas-fired and coal-fired units (Andover, 2010)
<b>Flue Gas Recirculation (FGR)</b>	Up to 20 % of the combustion flue gas is brought into the combustion zone, acting as a heat sink, lowering combustion zone temperature	20 -30 % NO <sub>x</sub> reduction	Because only thermal NO <sub>x</sub> formation can be controlled by this technique, it is especially effective only in oil- and gas-fired boilers. Most effective when used in conjunction with air and/or fuel staging. More adaptable to new designs than as a retrofit application. Capital intensity and high operating and maintenance (O&M) costs are prejudicial for use on industrial-scale boilers
<b>Overfire Air (OFA)</b>	Diversion of 10-20 % of combustion air downstream of burners	15-30 % NO <sub>x</sub> reduction	More attractive for new units than retrofit applications. May be used with all fuels and most combustion systems; Can decrease energy efficiency
<b>Biased Burner Firing</b>	The furnace is divided into a lower, fuel-rich zone and an upper fuel-lean zone to complete the burnout	20 % NO <sub>x</sub> reduction	Proven only for oil/gas-fired utility boilers

Control Option	Description	Performance	Application
<b>Low Excess Air</b>	Reducing excess air in the combustion flame zone reduces fuel and thermal NO <sub>x</sub> formation	<ul style="list-style-type: none"> <li>- <u>Dry bottom</u>: 50-70% NO<sub>x</sub> reduction</li> <li>- <u>Wet bottom</u>: 30-70 % NO<sub>x</sub> reduction</li> <li>- <u>Fluidized bed</u>: no data</li> <li>- <u>Traveling grate stoker</u>: 35-50 % NO<sub>x</sub> reduction</li> <li>- <u>Spreader grate stoker</u>: 50-65 % NO<sub>x</sub> reduction (USEPA 1999)</li> </ul>	Limited by production of smoke, high CO emissions, and increased fouling and corrosion in boiler. Applied for energy efficiency.
<b>Fuel Staging</b>	10-20 % of the total fuel input is diverted to a second combustion zone downstream of the primary zone. Combustion of fuel in the fuel-rich secondary zone reduces nitric oxide (NO) formed in the primary zone to nitrogen (N <sub>2</sub> ). Low nitrogen-containing fuels such as natural gas and distillate oil are typically used for reburning to minimize further NO <sub>x</sub> formation.	Claims of NO <sub>x</sub> reductions from 50-70 % when combining this approach with overfire air and flue gas recirculation	Limited application in the US
<b>Burners Out of Service</b>	In multiple burner systems, fuel flow is blocked to upper burners allowing only air to pass	50-70 % NO <sub>x</sub> reduction for dry bottom boilers (USEPA 1999)	Useful in retrofit situations involving suspension-fired coal and oil/gas-fired boilers. Operational problems can include soot/slag formation
<b>Reduced Air Preheat</b>	Lowers the primary combustion zone peak temperature through reduced preheating of the combustion air	<ul style="list-style-type: none"> <li>- <u>Dry bottom</u>: 50-70 % NO<sub>x</sub> reduction</li> <li>- <u>Wet bottom</u>: 30-70 % NO<sub>x</sub> reduction</li> <li>- <u>Fluidized bed</u>: no data</li> <li>- <u>Traveling grate stoker</u>: 35-50 % NO<sub>x</sub> reduction</li> <li>- <u>Spreader grate stoker</u>: 50-65 % NO<sub>x</sub> reduction (USEPA 1999)</li> </ul>	Reduced air preheat lowers only thermal NO <sub>x</sub> , and thus is economically attractive only for natural gas and distillate fuel oil combustion. The energy penalty usually makes this option unfavorable.
<b>Steam &amp; Water Injection</b>	Flame quenching by the addition of steam or water in the combustion zone	<ul style="list-style-type: none"> <li>- <u>Dry bottom</u>: 50-70 % NO<sub>x</sub> reduction</li> <li>- <u>Wet bottom</u>: 30-70 % NO<sub>x</sub> reduction</li> <li>- <u>Traveling grate stoker</u>: 35-50 % NO<sub>x</sub> reduction</li> <li>- <u>Spreader grate stoker</u>: 50-65 % NO<sub>x</sub> reduction (USEPA 1999)</li> </ul>	An effective control technology for oil/gas-fired burners, but one with a potentially significant energy penalty
<b>Load Reduction</b>	Reducing boiler capacity lowers flame temperatures and reduces thermal NO <sub>x</sub> formation	NO <sub>x</sub> reduction specific to boiler capacity	Can cause improper fuel-air mixing during combustion, creating carbon monoxide (CO) and soot emissions

Control Option	Description	Performance	Application
<b>Post-Combustion/Flue Gas Treatments</b>			
<b>Selective Non-Catalytic Reduction (SNCR)</b>	Involves the injection of urea, ammonium hydroxide, anhydrous ammonia, or aqueous ammonia into the furnace exit region where the flue gas is in the range of 900 to 1,150 °C. Nitrogen oxide is reduced to N <sub>2</sub> and water. Performance affected by inlet NO <sub>x</sub> level, temperature, mixing, residence time, reagent-to-NO <sub>x</sub> ratio, and fuel sulfur content.	NO <sub>x</sub> reduction as high as 60-70 %	A portion of the NO reduction (about 5 %) is due to formation of N <sub>2</sub> O, a potent GHG. Process complexity prompts concern about ability to perform adequately under changing load and fuel conditions. Operating problems include optimizing chemical addition to prevent ammonia emissions in the flue gas and, with higher sulfur fuels, salt deposits on downstream components that contribute to plugging and reduced heat transfer.
<b>Selective Catalytic Reduction (SCR)</b>	NO <sub>x</sub> is reduced to N <sub>2</sub> and water by the injection of ammonia into the flue gas at temperatures between 350 and 400 °C in the presence of a catalyst. Performance is affected by NO <sub>x</sub> level at SCR inlet, flue gas temperature, ammonia-to-NO <sub>x</sub> ratio, fuel sulfur content, gas flow rate, and catalyst condition.	70-90 % NO <sub>x</sub> reduction	A proven technology, but not often applied to smaller industrial-scale boilers. Major problems with SCR processes include corrosion, formation of solid ammonium sulfate, and formation of salt deposits in high sulfur oil-fired or coal-fired boilers that reduce heat transfer efficiencies. Ammonia slippage* is also a potential problem. Catalysts lose activity over time due to poisoning by trace metals or erosion by fly ash.
<b>Regenerative SCR (RSCR)</b>	RSCR applies SCR in combination with regenerative thermal oxidizer technology to more efficiently reheat cleaned gas to SCR operating temperatures than possible in previous "tail end" SCR designs. RSCR is a recently-developed technology that has been used on biomass-fired boilers (Andover, 2010).	>75 % NO <sub>x</sub> reduction (Andover 2010)	Used on biomass boilers downstream of PM removal devices to reduce NO <sub>x</sub> . Therefore, RSCR is well suited for many pulp and paper mills. RSCR has the advantage of being installed near the end of the process and requires less fuel to reheat the gas than traditional "tail end" SCR systems. As a result, RSCR may be an attractive retrofit option. RSCR may be limited by the available space near the existing chimney (Andover, 2010).
<b>Low-Temperature Oxidation (LoTOx)</b>	LoTOx is a process whereby the NO <sub>x</sub> compounds are oxidized to water-soluble forms, which are subsequently captured in a downstream wet scrubber (Andover, 2010).	>90 % NO <sub>x</sub> reduction (Andover, 2010)	This process can perform only in combination with a downstream wet scrubber (Andover, 2010).

\* When ammonia passes through the SCR unreacted, it is known as "slippage." Slippage can result from over-injection into the gas stream, catalyst degradation, or if the temperature is not high enough for the ammonia to react.

Note: all data from (NCASI, 2009a), except where otherwise indicated.

Thermal NO<sub>x</sub> formation is commonly controlled by reducing peak and average flame temperatures, an approach contrary to measures typically employed to ensure complete fuel combustion. A compromise is therefore exacted between effective combustion and NO<sub>x</sub> formation. Conversion of fuel-bound nitrogen is more dependent upon fuel-air proportions than variations in combustion zone temperatures. NO<sub>x</sub> control involves a

delicate balance of air distribution and combustion temperature control that invites a risk of combustion inefficiency and potential release of pollutants associated with incomplete combustion (NCASI, 2009a).

Post-combustion flue gas controls involve chemical reduction of NO<sub>x</sub> to nitrogen (N<sub>2</sub>), entailing the injection of ammonia-based compounds under suitable temperature conditions where flue gas exits the furnace (NCASI 2009a). Because of the relatively narrow temperature windows required and reaction chemistry sensitivity to flue gas flow rates, NCASI concluded that these control options are ill-suited for application to industrial scale boilers that are subject to highly variable loads and fuel combinations (NCASI, 2009a).

LNB/FGR. Low-NO<sub>x</sub> burners (LNBs), as well as FGR, are the most widely applied primary technologies for boiler NO<sub>x</sub> reduction (NCASI, 2009a). LNB limits NO<sub>x</sub> formation by controlling the stoichiometry and temperature of combustion. LNBs may use staged combustion to slow complete fuel-air mixing or lean-premixed combustion (mostly for gas fuel). This staged combustion reduces both flame temperature and oxygen concentration during some phases of combustion, lowering both thermal NO<sub>x</sub> and fuel NO<sub>x</sub> formation (NCASI, 2009a). NO<sub>x</sub> reductions up to approximately 50 percent may be achieved by LNBs. The extent of reduction depends on fuel preparation and local conditions in the furnace. Flue gas recirculation reduces thermal NO<sub>x</sub> formation by reducing peak temperatures and limiting oxygen availability. Taken together, NCASI indicated that NO<sub>x</sub> reductions of 60 to 90 percent are achievable. However, the report concluded that flue gas recirculation is better suited to new boilers rather than retrofits, can reduce boiler heating capacity, and is difficult to justify economically for industrial-scale boilers (NCASI, 2009a).

ULNB. Ultra low-NO<sub>x</sub> burners (ULNB) often use air staging and internal FGR (no external ductwork needed), or they may alternatively use lean-premixed combustion with FGR for lower emissions than possible with LNB alone. ULNB is also a term used for some second-generation coal-fired LNBs that are installed in combination with OFA. ULNBs offer in the range of 75-percent reduction from uncontrolled levels (Andover, 2010).

OFA. Another commonly used primary technology is OFA, which is a form of air staging in which a fraction (typically 10-20 %) of combustion air is injected downstream of the burner. OFA is often used in conjunction with LNBs to increase NO<sub>x</sub> reduction by an additional 15 to 30 percent. Use of OFA can result in reduced boiler efficiency manifested by increased CO concentration and loss on ignition in the flue gas.

SCR/SNCR. Two of the secondary technologies that could be used to reduce NO<sub>x</sub> emissions include selective non-catalytic reduction (SNCR) and selective catalytic reduction (SCR). Both SNCR and SCR involve injection of a reducing agent such as ammonia or urea into the flue gas under conditions where the reagent can react with NO<sub>x</sub> to form N<sub>2</sub> and water (NCASI 2009a). In SNCR, the reducing agent reacts with NO<sub>x</sub> at about 900 to 1150 °C, while in SCR, the reduction reaction occurs at around 350 to 400 °C and for this reason requires a catalyst. The catalyst is typically installed between the boiler economizer and air preheater (known as a hot side or high-dust installation). Sometimes the SCR reactor can be placed after the air preheater (known as the low-dust SCR). The catalyst needs to be replaced periodically because of its sensitivity to impurities in the flue gas, resulting in catalyst poisoning and/or blinding. Catalysts have been found to remain active much longer in flue gas from the combustion of natural gas than from the combustion of coal.

In SNCR, a stoichiometric excess of reducing agent is needed for the reaction to proceed effectively, creating the operational requirement to limit the so-called ammonia slip (unreacted agent that exits with the flue gas) that can impact plume visibility and make fly ash difficult to dispose of. SNCR has been widely used on boilers and

has a proven NO<sub>x</sub> reduction of over 60 percent. SCR has also been widely used and has achieved NO<sub>x</sub> reductions in excess of 90 percent.

According to NCASI 2009a, the retrofitting of SCR on industrial boilers has been found to be difficult and costly, indicating that, in retrofit application, capital costs are estimated to be 30 to 50 percent higher. Moreover, SCR systems are not very tolerant of constantly changing conditions, as a stable window of operation is required for optimum efficiency. Load swings make it particularly difficult to retrofit boilers with SCR or SCNR, as appropriate temperature windows are hard to maintain. Urea- or ammonia-handling systems are an added complication for boiler operations. In addition, associated salt deposition on downstream boiler components contributes to plugging and reduced heat transfer efficiencies (NCASI, 2009a).

NCASI 2009a further noted that secondary emissions that can result with SNCR include such intermediate reaction products as N<sub>2</sub>O, a potent GHG. Nitrous oxide levels have been observed to equal up to 4 percent of the NO<sub>x</sub> reduction with ammonia injection, while urea injection yielded N<sub>2</sub>O levels up to 25 percent of the NO<sub>x</sub> reduced. However, the report noted that SCR has been found to enhance mercury removal (NCASI, 2009a).

The use of SCRs is often limited by the available space to install the catalyst reactor at the correct temperature that exists in the process, which may require significant changes to the existing equipment unless a “tail end” SCR is installed, where the gas is reheated to the correct temperature. However, “tail end” SCR units are unattractive due to the additional fuel necessary for reheating the gas. An alternative to a traditional “tail end” SCR is a regenerative SCR (RSCR). RSCR applies SCR in combination with regenerative thermal oxidizer technology to more efficiently reheat cleaned gas to SCR operating temperatures than possible in a previous “tail end” SCR designs. RSCR is a recently-developed technology that has been used on biomass-fired boilers downstream of PM removal devices to reduce NO<sub>x</sub> by over 75 percent. Therefore, RSCR is well suited for many pulp and paper mills. RSCR has the advantage of being installed near the end of the process and requires less fuel to reheat the gas than traditional “tail end” SCR systems. As a result, it may be an attractive retrofit option. RSCR may be limited by the available space near the existing chimney (Andover, 2010).

Multi-pollutant reduction. One example of this type of emission control involves the use of SCR followed by wet flue gas desulfurization (FGD), which has gained credence as a potential means of reducing not only NO<sub>x</sub> and SO<sub>2</sub>, but also mercury emissions (NCASI, 2009a). The contribution of SCR technology to mercury reduction comes from the fact that SCRs have been shown to oxidize elemental mercury. Wet scrubbers, in turn, have been shown to be effective in removing oxidized mercury (NCASI, 2009a). Another example involves the use of low temperature oxidation (LoTOx), whereby the NO<sub>x</sub> compounds are oxidized to water-soluble forms that are subsequently captured in a downstream wet scrubber. The oxidizer used to convert NO<sub>x</sub> in the LoTOx process may also help remove SO<sub>2</sub> by oxidizing it to sulfur trioxide (SO<sub>3</sub>). Nitrogen oxide emission reductions higher than 90 percent may be achievable using the LoTOx process. However, this process can perform only in combination with a downstream wet scrubber (Andover, 2010).

Applicability of NO<sub>x</sub> control technologies. As noted above, the applicability of individual NO<sub>x</sub> control options and performance will depend upon boiler design and configuration, fuels being burned, and the dynamic character of boiler loading. The following paragraphs review the applicability of the primary and secondary NO<sub>x</sub> control technologies for the different boiler types at pulp and paper mills, summarized in Table 2-6, below.

**Table 2-6. Applicability of NO<sub>x</sub> Control Technologies (Andover, 2010)**

Boiler Type	Wood/Hog Fuel	Coal	Natural Gas	Residual Oil
LNB	No	Yes (50) <sup>b</sup>	Yes (50)	Yes (50)
ULNB	No	No	Yes (75)	No
OFA	Yes (25)	Yes (25)	No	Yes (25)
SNCR	Yes (50)	Yes (50)	No <sup>c</sup>	Yes (25)
SCR	Yes (75) <sup>a</sup>	Yes (90)	Yes (90) <sup>d</sup>	Yes (90)
RSCR	Yes (75)	Yes (75)	Yes (75) <sup>d</sup>	Yes (75)
LoTO <sub>x</sub> <sup>e</sup>	Yes (90)	Yes (90)	Yes (90)	Yes (90)

Note: percent NO<sub>x</sub> reduction in parentheses.

<sup>a</sup> Tail-end configuration.

<sup>b</sup> Pulverized coal only.

<sup>c</sup> Retrofit possible; not on new units.

<sup>d</sup> New units possible; not on retrofits.

<sup>e</sup> Requires downstream wet scrubber.

Wood and hog fuel boilers are typically grate-fired, possibly fluid- or bubbling bed-fired, and are not amenable to traditional low-NO<sub>x</sub> burners. Wood and hog fuel boilers may use any of the post-combustion NO<sub>x</sub> control methods described above. However, for SCR application, only a tail-end SCR configuration would be applicable because of the need to avoid catalyst poisons. SNCR could be used and would be expected to provide approximately 50-percent reduction of NO<sub>x</sub>.

RSCR has been used on biomass boilers downstream of PM removal devices to reduce NO<sub>x</sub>, so RSCR is well suited for many pulp and paper mills. As noted previously, RSCR has the advantage of being installed near the end of the process and requires less fuel to reheat the gas than traditional “tail end” SCR systems. As a result, RSCR may be an attractive retrofit option. RSCR may be limited by the available space near the existing chimney, however. SCR and RSCR are not likely to be used for retrofit of gas-fired boilers due to low NO<sub>x</sub> levels that are achievable with combustion controls. However, SCR and RSCR are an option for new gas boiler installations. Application of LoTO<sub>x</sub> would likely be limited because this process would require a downstream wet scrubber (Andover, 2010).

Pulverized coal-fired boilers can use combustion modifications such as low-NO<sub>x</sub> burners and OFA. Grate-fired boilers would not use low NO<sub>x</sub> burners and would instead use air staging similar to OFA. Any post-combustion NO<sub>x</sub> control technology could be used on coal-fired boilers (pulverized or grate), and the selection would depend on the desired level of NO<sub>x</sub> control and on the size of the facility. SNCR would typically provide up to approximately 50-percent reduction. Because smaller boilers (<100 MW) would typically be expected at pulp and paper facilities, there might be space limitation and thus tail-end SCR would be likely for smaller boilers. For utility-size coal-fired boilers, conventional high-dust SCR would be expected.

Natural gas boilers typically have their NO<sub>x</sub> emissions most effectively controlled with combustion modification controls such as low-NO<sub>x</sub> burners or flue gas recirculation. As far as post-combustion controls, SNCR is not likely to be used on natural gas boilers with low-NO<sub>x</sub> burners. SCR would likely be installed on most new facilities. Retrofit of the SCR into the required temperature zone on natural gas boilers could be difficult and might require

either reheat or the use of a low-temperature SCR. However, SCR would not likely be a good retrofit candidate since combustion modifications would bring NO<sub>x</sub> emissions to low levels on their own.

Residual oil is burned in numerous boilers at pulp and paper mills. They typically can use LNB and OFA for combustion modifications and may use any of the post-combustion control methods. If an SCR system is installed, a tail-end SCR may be necessary for these boilers for the reasons explained earlier for coal-fired boilers.

### *2.3.3.2. Boiler SO<sub>2</sub> Reduction*

Based on information from NCASI, fuel switching is an attractive option for reducing boiler SO<sub>2</sub> emissions, but the report cautioned that its application cannot be considered in isolation from a host of site-specific factors of importance to boiler performance, boiler integrity and overall emissions control capability. The report stated that switching to lower sulfur fuels can be an effective way to reduce SO<sub>2</sub> emissions but pointed out that lower sulfur fuels are typically more expensive and indicated that there is a question of compatibility with the design of the existing boiler system and related equipment. The report further cautioned that fuel changes may also compromise boiler efficiency and emissions control capability. To illustrate, the report cited an example of a boiler switching from (1) eastern bituminous coal, with a high heat value and low ash content, to (2) a low-sulfur western sub-bituminous coal with a lower heating value and high ash content. Though such a change may be beneficial for reducing SO<sub>2</sub> emissions, the report noted that it comes with the following potentially adverse effects (NCASI, 2009a):

- Flame stability impacts consequential to boiler efficiency and pollutant emissions
- Diminished energy efficiency due to deposition and slagging on heat transfer surfaces
- Increased ash loading
- Unsatisfactory performance of emissions control equipment.

According to the report, natural gas is recognized as a clean burning fuel, but its higher hydrogen content yields water vapor during combustion that contributes to greater heat loss out the stack. The report noted that biomass and wood are favorable fuels from the standpoint of SO<sub>2</sub> emissions, but firing these fuels has been observed to lead to accelerated corrosion of boiler components. The report suggested that fuel properties are best taken into account at the time of boiler design (NCASI, 2009a).

NCASI 2009a noted that post-combustion FGD techniques can be used to remove SO<sub>2</sub> formed during combustion of sulfur-bearing fuels (e.g., coal). FGD involves injection of an alkaline sorbent into the flue gas stream that reacts with SO<sub>2</sub> to form liquid or solid sulfur-bearing compounds that are subsequently separated; SO<sub>2</sub> FGD scrubber systems are characterized as either wet, dry, or semi-dry, as well as non-regenerable or regenerable in terms of whether the end products have viable commercial use (NCASI, 2009a). Attributes of various SO<sub>2</sub> control technologies are summarized in Table 2-7.

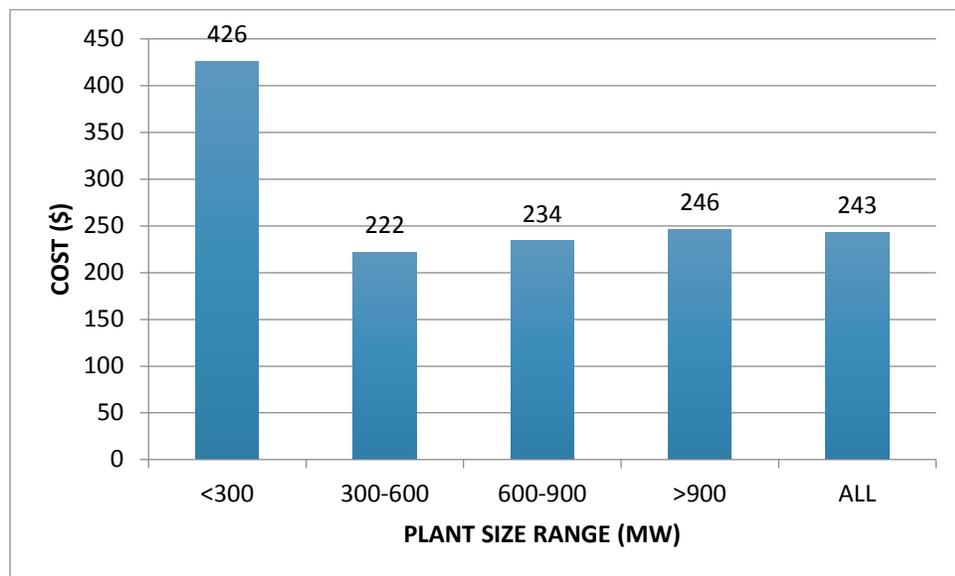
**Table 2-7. Boiler SO<sub>2</sub> Control Technologies (NCASI, 2009a)**

Control Option	Description	Performance	Application
<b>Wet Systems</b>			
Lime/Limestone Wet Scrubbing (LWS)	Aqueous slurry of the sorbent is injected into the flue gas, saturating the gas stream. Sulfur dioxide dissolves into slurry droplets and reacts with alkaline particles. The slurry falls to the bottom of the reactor, is collected, and sent to a reaction tank to complete conversion to a neutral salt.	80 to 90 % SO <sub>2</sub> removal with limestone; up to 95 % removal with lime	Wet systems are applicable to high sulfur fuels and produce a wet sludge byproduct requiring management and disposal. Though high in capital and operating cost, wet limestone scrubbing is the preferred process for coal-fired electric utility plants.
Sodium Carbonate, Hydroxide or Bicarbonate Wet Scrubbing		80% to 98% reduction	High reagent cost a disadvantage
Magnesium Oxide/Hydroxide Wet Scrubbing		80% to 95+% reduction	Sorbent can be regenerated
Dual Alkali Wet Scrubbing		90% to 96% reduction	Uses lime to regenerate sodium-based scrubbing liquid
<b>Semi-Dry Systems (Spray Dryer Absorber [SDA])</b>			
Calcium Hydroxide Slurry Sorbent	As with wet systems, aqueous sorbent slurry is injected into the flue gas stream. The sorbent is more concentrated in semi-dry system slurries, however. Hot flue gas evaporates water in the slurry, but sufficient water remains on the solid sorbent to enhance SO <sub>2</sub> removal. The resulting dried waste product is subsequently captured with a standard particulate collection device.	70 % to 90 % SO <sub>2</sub> reduction	Applicable to low- and medium-sulfur fuels; produces a dry residual byproduct that is less difficult to manage than wet residuals. Performance is sensitive to operating conditions due to potential for wet solids to deposit on the absorber and downstream equipment. High temperatures and high SO <sub>2</sub> concentrations degrade performance. Typical applications are utility and industrial boilers burning low to medium sulfur coal and requiring 80 % SO <sub>2</sub> control.
<b>Dry Systems</b>			
Dry Calcium Carbonate/Hydrate Injected in Upper Furnace Cavity	Powdered sorbent is injected directly into the furnace. The waste product is removed with standard particulate control equipment.	50-60 % SO <sub>2</sub> reduction	Even distribution of sorbent and adequate residence time within narrow temperature bands is critical for high SO <sub>2</sub> removal. Dry systems are less costly than wet systems, use less space, and are thought more suitable for retrofit applications. The technique is viewed as an emerging technology for medium-to-small industrial boiler applications.
Dry Sorbent Injection into Ductwork	Powdered sorbent is injected directly into downstream ductwork. Water can be injected to enhance SO <sub>2</sub> removal. The waste product is removed with standard particulate control equipment.	50-80 % SO <sub>2</sub> reduction with sodium-based sorbent.	

Wet FGD. Wet systems, the most commonly employed technique, achieve the greatest removals, with SO<sub>2</sub> reductions of 95 percent and more (NCASI 2009a). The wet scrubbing process most commonly used to treat boiler flue gas is limestone wet scrubbing (LWS). Occasionally, lime wet scrubbing or sodium wet scrubbing may be used. LWS uses a low cost reagent and can capture up to 90 percent of SO<sub>2</sub> (depending upon inlet SO<sub>2</sub> levels). In addition, LWS generates a byproduct that can be disposed or reused. LWS is most often used for high SO<sub>2</sub>

concentration applications. Lime wet scrubbers are similar in operation to LWS. The slurry is more reactive than limestone slurry, allowing for the same level of SO<sub>2</sub> removal in a smaller scrubber (lower capital costs) as LWS, but lime is more expensive than limestone. The use of dolomitic lime allows for further decrease in the size of the wet scrubber compared to conventional lime reagent. When sodium is used as a reagent for wet scrubbing of SO<sub>2</sub>, no solid waste is produced. The byproduct from the sodium wet scrubber can be converted to Na<sub>2</sub>S in the recovery furnace, and this conversion may create the potential to mitigate the cost of chemicals used in the pulping process.

NCASI 2009a noted that wet FGD using lime/limestone is used primarily for reducing SO<sub>2</sub> emissions for large electric utility boilers and concluded that the technology cannot be cost-justified for industrial-scale boilers. The report cited a cost survey carried out by the EUCG (formerly known as the Electric Utility Cost Group) that documented the sensitivity of cost to boiler size. As shown in Figure 2-4, costs for FGD systems for boilers smaller than 300 MW are nearly double the costs for boilers greater than 300 MW. Most boilers in the pulp and paper sector are significantly smaller than 300 MW, with the average size being equivalent to roughly 25 MW. These small boilers would be subject to disproportionate costs were they to adopt this control technique (NCASI, 2009a).



**Figure 2-4. FGD-Only Costs among 49 FGD Systems (NCASI 2009a)**

Space availability is another aspect that can skew the costs of FGD system installation (NCASI, 2009a). Pulp and paper mills house a vast array of large-scale process equipment concentrated in a relatively small footprint. Accommodating an FGD system would incur disproportionate construction costs. Such space constraints might favor a dry FGD system. Dry systems have been characterized as an emerging technology for industrial-scale boilers. However, the dynamic nature of mill boiler loadings would jeopardize performance, given the sensitivity of dry systems to operating conditions (NCASI, 2009a).

The report noted that, within the pulp and paper industry there are numerous fluidized-bed boilers with lime injection for SO<sub>2</sub> removal, plus many more boilers with wet control devices (venturi scrubbers, wet electrostatic

precipitators [ESPs], spray towers) and alkali addition for SO<sub>2</sub> removal. There are no lime/limestone wet FGD systems of the type that dominate coal-fired electric utility boiler systems (NCASI, 2009a).

Semi-dry FGD. Both wet and semi-dry FGD approaches impose water demand ranging from 0.5 to 1.5 tons of water per ton of coal burned (NCASI, 2009a). Heating and evaporation of that water also impose a significant energy demand. The need to reheat flue gas to preserve plume buoyancy poses an additional drain. The electrical energy required to drive process equipment has been estimated to range from 1 to 2.5 percent of boiler capacity. The report noted that schemes exist to regenerate the chemical absorbent, but stated that the regeneration schemes are very energy-intensive. The report also noted that once-through systems are most common, but stated that the once-through systems generate a large quantity of solid wastes. The report further noted that, while the accumulation of metals, including mercury, in wastewaters and sludges of FGD systems is of benefit to air emissions, it is problematic with regard to the management of those waste streams. Removal of mercury from flue gas, however, is a co-benefit (NCASI, 2009a).

The report pointed out the following from the comparisons of wet and semi-dry approaches (NCASI, 2009a):

- The non-air quality environmental impacts and negative energy impacts are significantly greater for the wet FGD control technology, since it generates a visible plume, consumes more water, generates a wastewater stream requiring treatment and disposal, generates slightly more solid byproducts for landfill, and because the wet FGD requires significantly more auxiliary power consumption during operation.
- Compared to wet lime/limestone scrubbing technology, the spray dryer absorber (SDA) has the reported advantages of fewer major equipment items and thus lower capital cost, high reliability, lower space requirements, lower potential for corrosion, potential for lower energy consumption, absence of a wastewater stream, lower water consumption, and less sensitive and simpler process chemistry.

Dry FGD. Dry scrubbers typically do not achieve the SO<sub>2</sub> reduction levels associated with their wetter counterparts but stated that the technology does offer other relative advantages. Specifically, the dry scrubbers have significantly lower capital and operating costs because they are simpler, demand less water, and involve less complex waste disposal (NCASI, 2009a).

Multi-pollutant reduction. One example of this type of emission control involves the use of SCR followed by wet FGD, which has gained credence as a potential means of reducing not only NO<sub>x</sub> and SO<sub>2</sub> but also mercury emissions (NCASI, 2009a). The contribution of SCR technology to mercury reduction is that SCRs have been shown to oxidize elemental mercury; wet scrubbers, in turn, have been shown to be effective in removing oxidized mercury (NCASI, 2009a). Another example involves the use of low temperature oxidation (LoTOx), where the NO<sub>x</sub> compounds are oxidized to water-soluble forms that are subsequently captured in a downstream wet scrubber. The oxidizer used to convert NO<sub>x</sub> in the LoTOx process may also help remove SO<sub>2</sub> by oxidizing it to SO<sub>3</sub>. Nitrogen oxide emission reductions higher than 90 percent may be achievable using the LoTOx process. However, this process can perform only in combination with a downstream wet scrubber (Andover, 2010).

### *2.3.3.3. Boiler PM Reduction*

The following paragraphs summarize available information on various control technologies for reducing PM emissions, based on information provided in USEPA's AP-42.

As with NO<sub>x</sub> and SO<sub>2</sub>, fuel switching is an attractive option for reducing boiler PM emissions. For example, PM will generally be reduced when a lighter grade of fuel oil is burned. Fuel alteration of heavy oil by mixing with water and an emulsifying agent has also reduced PM emissions significantly in controlled tests (USEPA, 2010b).

Apart from choice of fuel, the principal PM control techniques for industrial size boilers are post-combustion methods, including ESP, fabric filter (or baghouse), wet scrubber, or mechanical collector (USEPA, 1998b, 2003, 2010b). Attributes of these PM control technologies are summarized in Table 2-8 and discussed in the paragraphs below.

ESP. Electrostatic precipitation technology is applicable to a variety of coal combustion sources. Because of their modular design, ESPs can be applied to a wide range of system sizes and should have no adverse effect on combustion system performance. The operating parameters that influence ESP performance include fly ash mass loading, particle size distribution, fly ash electrical resistivity, and precipitator voltage and current. Other factors that determine ESP collection efficiency are collection plate area, gas flow velocity, and cleaning cycle. Data for ESPs applied to coal-fired sources show fractional collection efficiencies greater than 99 percent for fine (less than 0.1 micrometer) and coarse (greater than 10 micrometers) particles. These data show a reduction in collection efficiency for particle diameters between 0.1 and 10 micrometers (USEPA, 1998b).

Atmospheric fluidized bed combustion (AFBC) boilers may tax conventional particulate control systems. The particulate mass concentration exiting AFBC boilers is typically 2 to 4 times higher than the particulate mass concentration exiting pulverized coal boilers. AFBC particles are also, on average, smaller in size and irregularly shaped with higher surface area and porosity relative to pulverized coal ash. The effect is a higher pressure drop. The AFBC ash is more difficult to collect in ESPs than pulverized coal ash because AFBC ash has a higher electrical resistivity, and the use of multiclones for recycling, inherent with the AFBC process, tends to reduce the exit gas stream particulate size (USEPA, 1998b).

Electrostatic precipitators are commonly used in oil-fired power plants. Older precipitators, usually small, typically remove 40 to 60 percent of the emitted PM. Because of the low ash content of the oil, greater collection efficiency may not be required. Currently, new or rebuilt ESPs can achieve collection efficiencies of up to 90 percent (USEPA, 2010b).

Electrostatic precipitators are employed with wood-fired boilers when collection efficiencies above 90 percent are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector pre-cleaners that remove larger-sized particles. Collection efficiencies of 90 to 99 percent for PM have been observed for ESPs operating on wood-fired boilers (USEPA, 2003).

A variation of the ESP is the electrostatic gravel bed filter. In this device, PM in flue gases is removed by impaction with gravel media inside a packed bed. Collection is augmented by an electrically charged grid within the bed. Particulate collection efficiencies are typically over 80 percent (USEPA, 2003).

**Table 2-8. Boiler PM Emission Control Technologies**

Control Option	Description	Performance	Application
Electrostatic Precipitator (ESP)	Uses electrical forces to move the particles out of the gas stream and onto collector plates. Once the particles are collected on the plates, they are typically removed from the plates by knocking, allowing the collected layer of particles to slide down into a hopper, which is later emptied.	- <u>Coal</u> : >99 % PM reduction - <u>Oil</u> : 40-60 % with older ESPs; up to 90 % with new or rebuilt ESPs - <u>Wood</u> : 90 % PM reduction	ESP technology is applicable to a variety of coal combustion sources. Because of their modular design, ESPs can be applied to a wide range of system sizes and should have no adverse effect on combustion system performance. ESPs are commonly used in oil-fired power plants and in wood-fired boilers when collection efficiencies above 90 % are required. When applied to wood-fired boilers, ESPs are often used downstream of mechanical collector pre-cleaners which remove larger-sized particles.
Fabric Filter (or baghouse)	Consists of a number of filtering elements (bags) along with a bag cleaning system contained in a main shell structure incorporating dust hoppers.	- <u>Coal</u> : ≤99.9 % PM reduction - <u>Oil</u> : > 99 % PM reduction - <u>Wood</u> : ≥80 % PM reduction	Fabric filtration has been widely applied to coal combustion sources since the 1970s. Fabric filters have had limited applications to wood-fired boilers. Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood.
Wet Scrubber	Includes venturi and flooded disc scrubbers, tray or tower units, turbulent contact absorbers, and high-pressure spray impingement scrubbers.	<u>Coal</u> : 95-99 % PM reduction <u>Oil</u> : 50-60 % PM reduction <u>Wood</u> : ≥85 % PM reduction	Wet scrubbers are applicable for PM as well as SO <sub>2</sub> control on coal- and oil-fired combustion sources. The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers.
Mechanical Collector	Cyclone separators can be installed singly, in series, or grouped as in a multicyclone or multiclone collector. These devices are referred to as mechanical collectors.	<u>Coal</u> : 90-95 % PM reduction <u>Oil</u> : ≤85 % PM reduction <u>Wood</u> : 25-65 % PM reduction	These devices are often used as a pre-collector upstream of an ESP, fabric filter, or wet scrubber so that these devices can be specified for lower particle loadings to reduce capital and/or operating costs. For oil combustion, mechanical collectors are primarily useful in controlling particulates generated during soot blowing, during upset conditions, or when very dirty heavy oil is fired. Mechanical collectors also provide particulate control for many wood-fired boilers. Often, two multiclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles.

Note: data from (USEPA, 1998b, 2002, 2003, and 2010b)

Fabric filter. Fabric filtration has been widely applied to coal combustion sources since the early 1970s and consists of a number of filtering elements (bags) along with a bag cleaning system contained in a main shell structure incorporating dust hoppers. The particulate removal efficiency of fabric filters is dependent on a variety of particle and operational characteristics. Particle characteristics that affect the collection efficiency include particle size distribution, particle cohesion characteristics, and particle electrical resistivity. Operational parameters that affect fabric filter collection efficiency include air-to-cloth ratio, operating pressure loss, cleaning sequence, interval between cleanings, cleaning method, and cleaning intensity. In addition, the particle collection efficiency and size distribution can be affected by certain fabric properties (e.g., structure of fabric, fiber composition, and bag properties). Collection efficiencies of fabric filters can be as high as 99.9 percent for coal combustion and more than 99 percent for fuel oil combustion (USEPA, 1998b, 2010b).

Fabric filters have had limited application to wood-fired boilers. The principal drawback to fabric filtration, as perceived by potential users, is a fire danger arising from the collection of combustible carbonaceous fly ash. Steps can be taken to reduce this hazard, including the installation of a mechanical collector upstream of the fabric filter to remove large burning particles of fly ash (i.e., "sparklers"). Despite complications, fabric filters are generally preferred for boilers firing salt-laden wood. This fuel produces fine particulates with a high salt content having a quenching effect, thereby reducing fire hazards. Particle collection efficiencies are typically 80 percent or higher (USEPA, 2003).

Wet scrubber. Wet scrubbers, including venturi and flooded disc scrubbers, tray or tower units, turbulent contact absorbers, or high-pressure spray impingement scrubbers are applicable for PM as well as SO<sub>2</sub> control on coal-fired combustion sources. Scrubber collection efficiency depends on particle size distribution, gas side pressure drop through the scrubber, and water (or scrubbing liquor) pressure, and can range between 95 and 99 percent for a 2-micron particle (USEPA, 1998b).

Scrubbing systems have also been installed on oil-fired boilers to control both SO<sub>2</sub> and PM. These systems can achieve SO<sub>2</sub> removal efficiencies of 90 to 95 percent and particulate control efficiencies of 50 to 60 percent on oil-fired boilers (USEPA, 2010b).

The most widely used wet scrubbers for wood-fired boilers are venturi scrubbers. With gas-side pressure drops exceeding 15 inches of water, particulate collection efficiencies of 85 percent or greater have been reported for venturi scrubbers operating on wood-fired boilers (USEPA, 2003).

Mechanical collector. Cyclone separators can be installed singly, in series, or grouped as in a multicyclone collector. These devices are referred to as mechanical collectors and are often used as a pre-collector upstream of an ESP, fabric filter, or wet scrubber so that these devices can be specified for lower particle loadings to reduce capital and/or operating costs. The collection efficiency of a mechanical collector depends strongly on the effective aerodynamic particle diameter. Although these devices will reduce PM emissions from coal combustion, they are relatively ineffective for collection of particles less than 10 microns (PM<sub>10</sub>). The typical overall collection efficiency for mechanical collectors ranges from 90 to 95 percent for coal combustion (USEPA, 1998b).

For oil combustion, mechanical collectors are useful primarily in controlling particulates generated during soot blowing, during upset conditions, or when dirty heavy oil is fired. For these situations, high-efficiency cyclonic collectors can achieve up to 85-percent control of particulate. Under normal firing conditions, or when clean oil is combusted, cyclonic collectors are not nearly so effective because of the high percentage of small particles (less than 3 micrometers in diameter) emitted (USEPA, 2010b).

Mechanical collectors also provide particulate control for many wood-fired boilers. Often, two multiclones are used in series, allowing the first collector to remove the bulk of the dust and the second to remove smaller particles. The efficiency of this arrangement varies from 25 to 65 percent (USEPA, 2003).

#### 2.3.3.4. Boiler CO<sub>2</sub> Reduction

Carbon is a basic component of fossil fuels, not an impurity (like sulfur) or a byproduct of combustion (like NO<sub>x</sub>). Removing carbon from flue gases after combustion is therefore energy intensive and extremely expensive. Thus, for the foreseeable future, there are only two practical ways to reduce CO<sub>2</sub> emissions cost effectively from fossil-fueled combustion: switch to a lower-carbon fuel or increase process energy efficiency so that less fuel is combusted (STAPPA, 1999). These operational changes often also result in reductions of other air pollutants such as SO<sub>2</sub>, NO<sub>x</sub>, and PM, particularly when GHG emissions are reduced by reducing energy consumption.

Fuel Switching. According to NCASI 2009b, reducing GHG emissions by changing fuels can have significant effects on SO<sub>2</sub>, NO<sub>x</sub>, and PM emissions because the fossil fuels that tend to have the highest sulfur content (coal and fuel oil) are also the most GHG-intensive. Switching from these fuels to natural gas or biomass would be expected to reduce SO<sub>2</sub> emissions. The effects of fuel selection on NO<sub>x</sub> emissions are more complex because NO<sub>x</sub> emissions are affected not only by fuel type but also by the combustion conditions. Though a significant portion of the fuel nitrogen can be converted to NO<sub>x</sub> during combustion, the amount of nitrogen available in the fuel is relatively small compared with the amount of nitrogen available for conversion in the combustion air. Peak combustion temperatures influence the magnitude of that conversion (NCASI, 2009b). Some general information on the GHG intensity relative to the potential for formation of SO<sub>2</sub> and NO<sub>x</sub> emissions associated with different fuels is presented in Table 2-9.

**Table 2-9. Representative Boiler Efficiency and GHG Emission Factors**

Fuel	Boiler efficiency (% of fuel energy [HHV]* transferred into steam)	CO <sub>2</sub> Emissions kg CO <sub>2</sub> /MMBtu
Natural Gas	80	53.02
Distillate Oil (no. 2)	not provided	73.96
Residual Oil (no. 6)	82	75.10
Coal (bituminous)	84	93.4
Bark and Wood Residue	65	93.8 <sup>a</sup>

<sup>a</sup> Alternatively, zero if credit given for biogenic emissions of CO<sub>2</sub>.

\*Higher Heating Value

Reducing GHG emissions by selecting low GHG-intensity fuels can affect PM emissions, with the effect ranging from strong co-benefits to strong trade-offs. In general, although solid fuels are associated with higher PM emissions than liquid and gaseous fuels, the emissions are also highly dependent on the type and efficiency of the device used to control PM emissions. In the US, the two solid fuels used most by the industry, coal and wood-derived biomass fuels, are at the opposite end of the range of GHG emission factors (assuming that biomass is treated as carbon neutral). Therefore, fuel switching from coal to biomass, which would greatly reduce GHG emissions (assuming that biomass is treated as carbon neutral), may not significantly affect PM emissions. Switching from coal to natural gas would accomplish reductions in both PM emissions and GHGs. At the other end of the spectrum, switching from natural gas to solid biomass would significantly reduce GHG emissions

(assuming that biomass is treated as carbon neutral), but in all likelihood, significantly increase PM emissions (NCASI, 2009b).

Reducing energy-related GHG emissions by fuel switching can affect energy consumption. The amounts of usable energy obtained from fuels are more or less inversely related to the GHG emissions of the fuel, as shown in Table 2-9. For example, a change from coal to bark will accomplish a very large reduction in GHG emissions (assuming biomass is considered carbon neutral) but will require more total energy consumption because more bark is required to produce the same amount of usable energy (due to its high moisture content). Switching to less GHG-intensive fuels seldom reduces total energy consumption, although it can significantly reduce non-renewable energy consumption if the change involves switching from a fossil fuel to biomass.

A 2001 report by NCASI describes the applicability and limitations of switching a power boiler from fossil fuel to wood fuel, or to build a new boiler to utilize available biomass fuel. Fuel switching of fossil fuel-fired power boilers to biomass would reduce on-site CO<sub>2</sub> generation, given that biomass fuels are considered to have a net zero CO<sub>2</sub> emission factor. Separately, the NCASI report presents details on switching a power boiler from coal or oil to natural gas (NCASI, 2001).

Energy Efficiency Measures. Numerous energy efficiency measures may be applicable for steam and power supply systems in pulp and paper plants (Andover, 2010; NCASI, 2001; USEPA, 2010). Some measures such as the ones given below require capital investment.

- Replacing low pressure boilers and installing turbogenerator capacity
- Replacing burners
- Preheating demineralized water with secondary heat before steam heating
- Rebuilding or replacing low efficiency boilers
- Installing a steam accumulator to facilitate efficient control of steam header pressures
- Installing an ash reinjection system in the hog fuel boiler
- Installing a bark press or bark dryer to increase utilization of biofuels
- Installing additional heat recovery systems on boilers to lower losses with flue gases
- Installing a gas turbine cogeneration system for electrical power and steam generation
- Installing flue gas heat recovery systems
- Improving boiler insulation
- Implementing condensate return

Other measures mostly require improved operation and maintenance practices such as:

- Implementing energy management program for current and reliable information on energy use
- Improved boiler and process control and maintenance
- Steam trap maintenance and automatic steam trap monitoring

- Leak repair (LR)
- Minimizing boiler blow down, and blow down steam recovery
- Reducing of excess air amount and flue gas quantities

The above information could be reviewed further to determine appropriate energy efficiency measures for inclusion in the Universal ISIS-PNP for purposes of assessing CO<sub>2</sub> emission reductions and their associated costs.

## 2.4. Recovery Furnaces

### 2.4.1. Recovery Furnace Design and Fuels

Chemical recovery is the heart of the kraft mill that allows the kraft mill to operate as an essentially closed operation with recovery of spent cooking chemicals to produce fresh cooking liquor (Na<sub>2</sub>S and NaOH) (NCASI, 2009a). See Figure 2-5 for an illustration of the chemical recovery process. Further information about the process is provided below, based on a background document developed by USEPA in support of the chemical recovery combustion sources NESHAP (USEPA, 1996).

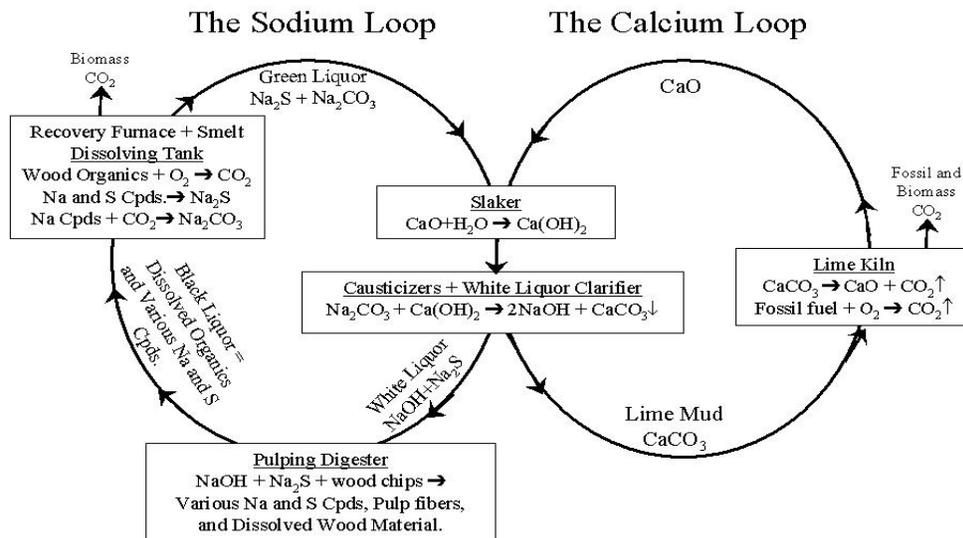


Figure 2-5. Simplified Representation of the Kraft Pulping and Chemical Recovery System (USEPA, 2010a)

In the chemical recovery process, weak black liquor from pulp washing is first directed through a series of multiple-effect evaporators to increase the solids content to approximately 50 percent. The strong black liquor from the multiple-effect evaporators system is then either oxidized in the black liquor oxidation system, it is further concentrated in a direct contact evaporator, or routed to a non-direct contact evaporator, also called a concentrator. Oxidation of the black liquor in the black liquor oxidation system stabilizes the sulfur compounds in the black liquor by converting the Na<sub>2</sub>S in the liquor to nonvolatile sodium thiosulfate, thereby reducing emissions of TRS compounds, which are stripped from the black liquor in the direct contact evaporator when it contacts hot flue gases from the recovery furnace. Black liquor that is concentrated in non-direct contact evaporators does not contact the hot flue gases and, therefore, does not require oxidation. The solids content of the black liquor following the final evaporator/concentrator is 65 percent or higher (USEPA, 1996).

The concentrated black liquor is then fired into the recovery furnace (sometimes referred to as a “recovery boiler”), where organic compounds are combusted, and the sodium sulfate ( $\text{Na}_2\text{SO}_4$ ) in the black liquor is reduced to  $\text{Na}_2\text{S}$ . Since the 1970s, most new recovery furnaces have been designed with non-direct contact evaporators (USEPA, 1996). Over 70 percent of recovery furnaces currently in operation are non-direct contact evaporator furnaces, and less than 30 percent are direct contact evaporator furnaces, based on the latest inventory information (RTI, 2013a).

The black liquor burned in the recovery furnace has a high energy content, which is recovered as steam for process requirements such as cooking wood chips, heating and evaporating black liquor, preheating combustion air, and drying the pulp or paper products. When necessary, natural gas or distillate oil is used as an auxiliary fuel (usually for furnace startup and shutdown). Particulate matter (primarily  $\text{Na}_2\text{SO}_4$  and sodium carbonate [ $\text{Na}_2\text{CO}_3$ ]) exiting the recovery furnace with the hot flue gases is collected in an ESP and added to the black liquor to be fired in the furnace. Additional makeup  $\text{Na}_2\text{SO}_4$ , or “salt cake,” may also be added to the black liquor prior to firing. Molten inorganic salts, referred to as “smelt,” are one of the main products from the combustion of black liquor, and they collect in a char bed at the bottom of the recovery furnace. Smelt is drawn off and dissolved in weak wash water in the smelt dissolving tank associated with the furnace to form a solution of carbonate salts called “green liquor,” which is primarily  $\text{Na}_2\text{S}$  and  $\text{Na}_2\text{CO}_3$ . Reprocessing of the green liquor into cooking liquor continues after the smelt dissolving tank (USEPA, 1996).

#### 2.4.2. Source of Recovery Furnace Emissions

A background discussion of the  $\text{NO}_x$ ,  $\text{SO}_2$ , and PM emissions from kraft recovery furnaces is provided in the paragraphs below, based on information from two NCASI reports (NCASI, 2004, 2009a).

The basic elements of pulping chemicals are sulfur and sodium. The recovery furnace is designed and must be operated to maximize capture of these substances, as well as separate and burn the organic substances dissolved from wood chips during pulping. The chemistry progresses through a series of complex reactions responsive to temperatures and the staged addition of combustion air that regulates available oxygen levels over the height of the furnace. The furnace environment is non-uniform (NCASI, 2009a).

Temperatures and oxygen-deficient reducing conditions at the base of the furnace produce molten  $\text{Na}_2\text{S}$ . Sodium fumes released in that region of the furnace react with  $\text{SO}_2$  formed higher in the furnace, where excess oxygen levels are conducive to oxidation of hydrogen sulfide ( $\text{H}_2\text{S}$ ) that also originates in the furnace reducing zone. Emissions of sulfur are related to the composition of the spent pulping liquor being recovered and the staged combustion conditions in the furnace. Nitrogen compounds will also be liberated from the liquor in the lower furnace and, depending upon temperatures, may take a form that contributes to greater formation of  $\text{NO}_x$  in the furnace. Except for very limited circumstances, recovery furnace temperatures do not reach levels that support the oxidation of combustion air nitrogen to form  $\text{NO}_x$ . Thus, emissions of  $\text{NO}_x$  are related to the composition of the spent pulping liquor being recovered and the staged combustion conditions in the furnace (NCASI, 2009a).

The above description of recovery furnace chemical reactions illustrates circumstances that contribute to emissions of  $\text{NO}_x$  and  $\text{SO}_2$ . A host of other chemical reactions occur as combustion gases rise through the various zones of the furnace. The conditions under which these reactions occur influence emissions of not only  $\text{NO}_x$ , but also odorous reduced sulfur gases, carbon monoxide (CO), VOCs, and other compounds of environmental interest. The emission levels of these various substances are inter-related and cannot all be simultaneously

controlled to low levels by manipulation of combustion conditions. Nor can sight be lost of the purpose of the furnace in the closed-loop recovery of pulping chemicals (NCASI, 2009a).

#### *2.4.2.1. Recovery Furnace NO<sub>x</sub> Emissions*

Recovery furnace NO<sub>x</sub> emissions are influenced by pulping liquor nitrogen content, combustion temperatures in the reducing zone of the furnace, and excess oxygen in the zone where most of the liquor combustion occurs. Recovery furnace SO<sub>2</sub> emissions are a function of liquor properties such as sulfidity (sulfur-to-sodium ratio), solids content and associated heat value; combustion air and liquor firing patterns; furnace design features; furnace load; auxiliary fuel use; and stack gas oxygen content. None of these factors, however, exhibit a consistent relationship with SO<sub>2</sub> emissions (NCASI, 2009a).

Kraft recovery furnaces typically have inherently low NO<sub>x</sub> emissions due to the following factors (NCASI, 2009a):

- Low nitrogen (N<sub>2</sub>) concentrations in most “as-fired” black liquor solids (< 0.2 %)
- Low overall conversions of liquor N<sub>2</sub> to NO<sub>x</sub> by the fuel NO<sub>x</sub> formation pathway
- Insufficient temperatures for thermal NO<sub>x</sub> formation, and perhaps
- Highly staged combustion design of recovery furnaces
- Existence of sodium fumes that might promote “in-furnace” NO<sub>x</sub> reduction or removal.

Overall conversions of black liquor nitrogen to nitric oxide (NO) are quite low compared with other fuels, ranging from 10 to approximately 25 percent. Emission levels for individual furnaces do not vary greatly. However, there can be wide differences from one furnace to another, reinforcing the observation that each recovery furnace is an individual and that optimum conditions for process and emission performance must be carefully sought (NCASI, 2009a).

#### *2.4.2.2. Recovery Furnace SO<sub>2</sub> Emissions*

Conditions involving liquor quality (such as high Btu, high solids content, and sulfidity), liquor firing patterns, and conditions related to furnace operations (air distribution, auxiliary fuel, etc.) that lead to maximizing temperatures in the lower furnace generally result in minimizing SO<sub>2</sub> emissions from kraft recovery furnaces. Emissions of SO<sub>2</sub> are typically less than 100 parts per million (ppm) and are extremely variable, a measure of the dynamic nature of furnace operations (NCASI, 2009a).

In general, recovery furnaces are not used to incinerate waste streams generated in other parts of the mill, with the exception of some recovery furnaces that receive high-volume, low-concentration NCG containing TRS from the pulping area of the mill. Because of the importance of the recovery furnace to the chemical recovery cycle and the potential for catastrophic explosion (due to water entering the furnace during operation), the industry’s Black Liquor Recovery Boiler Advisory Committee has recommended that the recovery furnace not be used for NCG incineration (NCASI, 2009a). Thus, the contribution of TRS-containing NCG streams to SO<sub>2</sub> formation is not a consideration for most recovery boilers.

#### *2.4.2.3. Recovery Furnace PM Emissions*

Recovery furnaces are designed and operated to ensure the presence of high levels of sodium fumes to capture the SO<sub>2</sub> produced as a result of oxidation of reduced sulfur compounds. Consequently, recovery furnace flue gases contain high levels of PM. The uncontrolled PM load from recovery furnaces is highly variable and has

been reported to range from 100 to 250 pounds per oven-dried ton of pulp for direct contact evaporator furnaces and 200 to 450 pounds per oven-dried ton of pulp for non-direct contact evaporator furnaces. The lower particulate loading from direct contact evaporator furnaces is due to the capture of some PM in it (NCASI, 2004). However, use of direct contact evaporator recovery furnaces is being phased out in favor of more energy efficient non-direct contact evaporator systems that produce fewer emissions of pollutants such as TRS, VOCs, and HAPs.

Particulates generated in the recovery furnace are comprised mainly of  $\text{Na}_2\text{SO}_4$ , with lesser amounts of  $\text{Na}_2\text{CO}_3$  and sodium chloride (NaCl). Similar potassium compounds are also generated, but in much lower amounts. Trace amounts of other metal compounds, e.g., magnesium, calcium, and zinc, can be present. A significant portion of the particulate material is sub-micron in size, which makes removal with add-on control devices more difficult (NCASI, 2004).

Increasing liquor firing density (ton/day/square foot) has been reported to increase recovery furnace particulate loading. Other factors such as bed and furnace temperature, liquor solids, liquor composition, and air distribution also affect uncontrolled particulate emissions from recovery furnaces (NCASI, 2004).

#### *2.4.2.4. Recovery Furnace GHG Emissions*

Concentrated spent pulping liquors generated as a byproduct of chemical pulping are burned in chemical recovery furnaces (or other types of chemical recovery combustion units) to produce steam for use in facility processes and to recover chemicals for reuse in the pulping process. Carbon dioxide emissions associated with combustion of spent pulping liquor (e.g., black liquor at kraft mills) in chemical recovery furnaces are biomass-derived  $\text{CO}_2$  because the carbon originates from the wood or other cellulosic materials. The carbon in the spent pulping liquor exits the recovery furnace in two forms: (1) as  $\text{CO}_2$  emissions from the recovery furnace stack, and (2) as carbonates in the smelt flowing from the bottom of the recovery furnace (which eventually makes its way to the lime kiln) (USEPA, 2009).

Small amounts of supplemental fossil fuels (e.g., oil or natural gas) are also fired in the furnace, usually during startup or shutdown conditions. Therefore, chemical recovery furnaces are sources of both biogenic and fossil fuel-based  $\text{CO}_2$  as well as small amounts of  $\text{CH}_4$  and  $\text{N}_2\text{O}$ . National statistics indicated that 98 percent of the annual heat input to chemical recovery furnaces originated from biomass in 2005 (USEPA, 2009). Thus, Universal ISIS-PNP could focus on biogenic  $\text{CO}_2$  emissions from the recovery furnace (from combustion of spent liquor) or exclude recovery furnace  $\text{CO}_2$  reduction measures from consideration until future Universal ISIS versions are developed to utilize an accounting methodology that does not consider biogenic  $\text{CO}_2$  emissions to be zero.

### *2.4.3. Recovery Furnace Emission Reduction Strategies*

The subsections below discuss measures for reducing emissions of  $\text{NO}_x$ ,  $\text{SO}_2$ , PM, and GHG (predominantly  $\text{CO}_2$ ) from recovery furnaces. Distinctions in recovery furnace type (direct versus non-direct contact evaporator) are made where appropriate. As was mentioned previously, that non-direct contact evaporator recovery furnaces do not appear to significantly reduce PM,  $\text{SO}_2$  or  $\text{NO}_x$  emissions, but that they are preferred over direct contact evaporators because of their impact on TRS (STAPP, 2006).

#### *2.4.3.1. Recovery Furnace $\text{NO}_x$ Reduction*

According to NCASI 2009a, optimization of staged combustion within a large existing kraft recovery furnace to obtain from 20- to 40-percent reduction in prevailing  $\text{NO}_x$  emissions is the only technologically feasible reduction measure that has been demonstrated at the present time. However, the report cautioned that the effects of

such air staging on emissions of other pollutants, mainly TRS, SO<sub>2</sub>, and CO, and on other furnace operational characteristics, including fouling, plugging, and chloride buildup, need to be examined with longer-term data. In addition, lower furnace temperature conditions conducive to low NO<sub>x</sub> formation aggravate SO<sub>2</sub> emissions (NCASI, 2009a). The report concluded that many of the commonly cited NO<sub>x</sub> control options (such as low NO<sub>x</sub> burners or SNCR) can be dismissed either because they are inappropriate for the nature of recovery furnace NO<sub>x</sub> formation or incompatible with recovery furnace chemistry and operational integrity (NCASI, 2009a). SNCR and SCR technologies for recovery furnaces have been investigated but have been determined not to be technically feasible. Low-NO<sub>x</sub> burners appear to affect efficiency and energy usage adversely; staged combustion has been determined to be best available control technology (BACT) in at least one state (STAPPA, 2006). Attributes of potential recovery furnace NO<sub>x</sub> control technology options are summarized in Table 2-10.

Table 2-10. Recovery Furnace NO<sub>x</sub> Control Technologies

Control Option	Description	Performance	Application
<b>Combustion Modifications</b>			
Overfire Air (OFA)	Optimizing staged combustion in the upper furnace reduces availability of oxygen for oxidation of nitrogen compounds originating in the pulping liquor. Limited short-term experience after installing “quaternary” air ports (overfire air) in two US furnaces showed that a 20-40 % reduction in baseline NO <sub>x</sub> levels is feasible. Comparable performance has been reported abroad. The practice would be limited to large furnaces. The reduction of NO <sub>x</sub> emissions is variable, dependent on the furnace type and design and the method of OFA application. OFA has to be adapted to the specific conditions of recovery furnaces.	20-40 % NO <sub>x</sub> reduction	The application of this technique may result in increases in CO and unburned carbon emissions if not well controlled. The effect of such air staging on emissions of other pollutants, chiefly SO <sub>2</sub> , CO, and TRS, and other furnace operational characteristics needs to be examined with longer-term data on North American furnaces.  Direct contact evaporator recovery furnaces are smaller and may not have room for additional levels of air (USEPA, 2012).
Low-NO <sub>x</sub> Burners (LNB)	The highly staged combustion design of recovery furnaces, the inherent low reducing zone oxygen concentrations needed for efficient recovery of chemicals, and the dominance of temperature-sensitive fuel nitrogen precursors of NO <sub>x</sub> combine to render low-NO <sub>x</sub> burners unproductive.	Infeasible	
Oxygen Trim and Water Injection	Neither option is appropriate for kraft recovery furnaces since: (a) any injection of water into the furnace would lead to an unacceptable explosive condition; and (b) the oxygen trim technique would have marginal effect due to the already existing highly staged combustion air configuration in recovery furnaces.	Infeasible	
Flue Gas Recirculation (FGR)	In FGR, a portion of the uncontrolled flue gases is routed back to the combustion zone, primarily with the intention of reducing thermal NO <sub>x</sub> . Recovery furnace NO <sub>x</sub> emissions are dominated by nitrogen that originates in the black liquor, not the oxidation of nitrogen in combustion air. Operational handicaps and other means for reducing fuel-related NO <sub>x</sub> erode the viability of FGR on recovery furnaces.	Infeasible	FGR would add additional gas volume in the furnace, increasing velocities and potentially causing more liquor carryover, which would result in increased fouling of the recovery furnace tubes.
<b>Post-Combustion/Flue Gas Treatments</b>			
Selective Catalytic Reduction (SCR)	The use of SCR on a kraft recovery furnace has never been demonstrated, even on a short-term basis. The impact on catalyst effectiveness of high PM concentrations in the economizer region of the furnace and fine dust particles is a major impediment to the application of this technology ahead of PM control. Installation after the PM control device would render the gas stream too cold for effective reaction with the NO <sub>x</sub> . Catalyst poisoning by soluble alkali metals in the gas stream is also problematic (NCASI 2009a).  Consequently, it would be necessary to install the SCR after removal of catalyst poisons from the gas stream,	Traditional SCR: infeasible (STAPPA, 2006)  Tail-end SCR: unattractive due to additional fuel requirements (Andover, 2010)  RSCR: recently developed, >75 %	Reheating the flue gas after the particulate control device and ahead of the SCR section would incur a substantial energy penalty, which could be reduced by using a RSCR to more efficiently reheat the gas (Andover, 2010).

Control Option	Description	Performance	Application
	suggesting that a tail-end SCR would be needed. However, tail-end SCRs are unattractive due to the additional fuel necessary for reheating the gas. An alternative to a traditional “tail end” SCR is a RSCR, which applies SCR in combination with regenerative thermal oxidizer technology to reheat cleaned gas to SCR operating temperatures more efficiently. RSCR is a recently-developed technology that has been used on biomass-fired boilers downstream of PM removal devices to reduce NO <sub>x</sub> by over 75 % (Andover 2010).	NO <sub>x</sub> reduction for biomass boilers (Andover, 2010), but not currently demonstrated for recovery furnaces	
Selective Non-Catalytic Reduction (SNCR)	SNCR, which uses the injection of urea or ammonia into a high temperature location in the furnace, is not considered technologically feasible for recovery boiler applications because of the risk of disrupting the complex chemistry of the unit. Trials with ammonia injection in Europe indicate a 30 % NO <sub>x</sub> removal capability.	Infeasible (STAPPA, 2006)	Because the use of urea can eventually cause corrosion problems due to the possible formation of corrosive byproducts, safety concerns discourage, if not preclude, its use in recovery boilers.
Low-Temperature Oxidation (LoTOx)	LoTOx is a process whereby the NO <sub>x</sub> compounds are oxidized to water-soluble forms, which are subsequently captured in a downstream wet scrubber. Can achieve higher than 90 % NO <sub>x</sub> reduction (Andover, 2010).	Potentially >90 % NO <sub>x</sub> reduction (Andover, 2010), but not currently demonstrated for recovery furnaces	This process can only perform in combination with a downstream wet scrubber (Andover, 2010).

Note: all data from NCASI 2009a, except where otherwise indicated.

### 2.4.3.2. Recovery Furnace SO<sub>2</sub> Reduction

According to NCASI 2009a, firing more concentrated black liquor is conducive to reduced SO<sub>2</sub> emissions, but the report cautioned that this increases NO<sub>x</sub> formation and particulate emissions, requiring additional control. The report concluded that alkaline scrubbing is the most viable post-combustion control option, with reported removals up to 90 percent (NCASI, 2009a). However, the report cautioned that conducting alkaline scrubbing with the many furnaces that emit low levels of SO<sub>2</sub> (20 ppm and less) would be very difficult and extremely expensive due to the large gas volumes involved. The report concluded that scrubbing would not be a realistic alternative for those recovery furnaces, nor would 90-percent reductions be achievable in that circumstance. The report noted that flue gas treatment for SO<sub>2</sub> reduction has been applied abroad but not in North America (NCASI, 2009a).

NCASI 2009a noted that potential dividends associated with alkaline scrubbing include increased retention of process sulfur and heat recovery, in cases where it can be used. However, the report indicated that any associated capture of process sulfur and heat, as well as avoidance of a wastewater stream, would depend upon the available capacity of equipment components associated with the pulping liquor recovery process (NCASI, 2009a).

Attributes of potential recovery furnace SO<sub>2</sub> control technology options are summarized in Table 2-11.

**Table 2-11. Recovery Furnace SO<sub>2</sub> Control Technologies**

Control Option	Description	Performance	Application
Increasing Black Liquor Concentration	Maximizing temperatures in the lower furnace by combustion of more concentrated liquor enhances the formation of Na <sub>2</sub> SO <sub>4</sub> , with a concurrent gaseous SO <sub>2</sub> reduction.	SO <sub>2</sub> reduction site-specific	Increased lower furnace temperatures associated with more concentrated liquor firing increase conversion of fuel nitrogen to NO. That phenomenon, combined with a possible greater tendency for the creation of thermal NO <sub>x</sub> and diminished capability for internal alkaline fume capture of NO <sub>x</sub> , results in greater furnace NO <sub>x</sub> emissions. Increasing black liquor dissolved solids content from a common 65 % up to 75 % may increase NO <sub>x</sub> emissions by up to 20 %.  Firing more concentrated liquor increases the emissions of particulates prior to flue gas cleaning. To compensate, a more efficient and expensive electrostatic precipitator has to be installed.  Concentrating solids may liberate sulfur compounds, requiring collection and incineration, producing SO <sub>2</sub> .
Scrubber	The few scrubbers that exist on recovery furnaces in the US pulp and paper industry were installed for purposes other than SO <sub>2</sub> control and do not reflect the range of capability. Experience abroad indicates removal efficiency for SO <sub>2</sub> in excess of 90 %.	Greater than 90 % SO <sub>2</sub> reduction (outside US); 90 % reduction not expected to be achievable for furnaces with low SO <sub>2</sub> levels	The scrubber requires alkali in the form of oxidized white liquor, weak liquor or NaOH, which can increase the capacity demands on other components of the chemical recovery process.

Note: all data from NCASI 2009a.

#### 2.4.3.3. Recovery Furnace PM Reduction

The following paragraphs summarize available information on PM control technologies for kraft recovery furnaces from USEPA's background document for the chemical recovery combustion sources NESHAP (USEPA, 1996).

Due to State and Federal regulations regarding PM emissions and the economic benefits of recycling PM captured from the recovery furnace flue gases, all recovery furnaces are equipped with add-on PM control devices as baseline controls. Electrostatic precipitators are a demonstrated control technique for reducing PM emissions from recovery furnaces. Particulate matter emissions from approximately 96 percent of all recovery furnaces are controlled with an ESP alone. The remaining furnaces are controlled with ESPs followed by wet scrubbers (3 %) or with wet scrubbers alone (USEPA, 1996; RTI, 2013a).

Properly designed and operated ESPs used on recovery furnaces routinely achieve PM removal efficiencies of 99 percent or greater. The ESPs used to control PM emissions from recovery furnaces are generally classified as plate-wire ESPs where the flue gas flows between parallel sheet metal plates and high-voltage electrodes. Each paired set of electrodes and plates forms a separate electrostatic field within the ESP. The ESPs used to control

recovery furnace PM emissions typically have two parallel precipitator chambers (i.e., flue gas passages) with three or four electrostatic fields per chamber (USEPA, 1996).

The PM recovered in the ESP ( $\text{Na}_2\text{SO}_4$ , with lesser amounts of  $\text{Na}_2\text{CO}_3$  and  $\text{NaCl}$ ) is subsequently recycled to the black liquor. The ESPs used on recovery furnaces may be designed with either a wet or dry bottom. In wet-bottom ESPs, the collected PM falls directly into a pool of liquid, which may be black liquor or water, in the bottom of the ESP. In dry-bottom ESPs, the collected PM falls to the (dry) bottom of the ESP and is transferred from the ESP bottom to a mix tank (containing black liquor) via drag-chain or screw conveyors. Black liquor is sometimes used to transport the dry collected PM to the mix tank. More recent ESP installations employ a dry PM return system to transport the PM to the mix tank. Because the PM removed by the ESP is recycled to the black liquor in the mix tank, the ESP is an integral part of the chemical recovery loop as well as an air pollution control device (USEPA, 1996).

The two recovery furnace types often differ in the types of ESPs that are used to control PM emissions from the furnace. For example, the ESPs that control PM emissions from direct contact evaporator recovery furnaces tend to be wet-bottom ESPs, whereas ESPs on non-direct contact evaporator recovery furnaces tend to be dry-bottom ESPs, with wet or dry PM return systems (USEPA, 1996).

The average lifetime of an ESP in service on a recovery furnace varies depending upon the type of ESP bottom (i.e., wet vs. dry), the inlet temperature of the gases, and maintenance practices. The lifetime of ESPs used to control PM emissions from recovery furnaces with non-direct contact evaporators, which tend to operate with dry-bottom ESPs, typically ranges from 12 to 15 years. After that point, major repairs or a rebuild may be required. Recovery furnaces with direct contact evaporators tend to have cooler inlet gases and wet-bottom ESPs; these two factors promote corrosion through condensation of acid gases and shorten the life of the ESP to from 7 to 10 years (USEPA, 1996).

Opportunities may exist to reduce current PM emissions levels by upgrading or replacing older ESPs or adding a wet scrubber after the ESP. For example, a STAPPA 2006 document noted that, on recovery furnaces, older model ESPs have collection efficiencies close to 90 percent, while newer model ESPs have collection efficiencies greater than 99 percent. The STAPPA 2006 document further stated that the cost of retrofitting a recovery furnace with an ESP is heavily influenced by site-specific factors (STAPPA, 2006).

A few recovery furnaces currently employ both an ESP and wet scrubber, which can simultaneously reduce emissions of sulfur compounds ( $\text{SO}_2$ , TRS) and PM. A review of available PM emissions data for these recovery furnaces suggests that wet scrubbing of recovery furnace exhaust gases (either alone or in conjunction with an ESP) does not necessarily improve filterable PM removal. The wet scrubbers installed following recovery furnace ESPs are typically designed for  $\text{SO}_2$  removal rather than for removal of PM (RTI, 2013a).

Attributes of potential recovery furnace PM control technology options are summarized in Table 2-12.

**Table 2-12. Recovery Furnace PM Control Technologies**

Control Option	Description	Performance	Application
ESP Upgrade/ Replacement	Upgrading existing ESP or replacing older ESP with new ESP	Could increase PM control from 90 to 99 % (STAPPA 2006)	The cost of retrofitting a recovery furnace with an ESP is heavily influenced by site-specific factors including the age and design of the ESP already in place.
Addition of Wet Scrubber	Adding a new wet scrubber after an existing recovery furnace ESP	No improvement in PM control found. A review of the available PM data showed an overlap in PM control efficiencies and PM emissions for recovery furnaces equipped with an ESP and those equipped with an ESP + wet scrubber. Also, the best-performing ESP-wet scrubber (99 %) is less efficient than the best-performing ESP alone (99.96 %) (RTI 2013b).	Some recovery furnaces equipped with a wet scrubber alone or with a wet scrubber in combination with an ESP exhibited PM emissions above the NESHAP new source PM limit of 0.015 grains per dry standard cubic foot (gr/dscf), but below the NESHAP existing source PM limit of 0.044 gr/dscf, suggesting that wet scrubbing of recovery furnace exhaust gases (either alone or in conjunction with an ESP) does not necessarily improve filterable PM removal. The wet scrubbers installed following recovery furnace ESPs are typically designed for SO <sub>2</sub> removal rather than for removal of PM (RTI 2013a).

Note: The PM emissions and control efficiencies for best-performing ESP and ESP-wet scrubber from (RTI 2013b).

#### 2.4.3.4. Recovery Furnace CO<sub>2</sub> Reduction

Unlike the situation in boilers, fuel switching is generally not an option of significance for recovery furnaces because spent pulping liquor comprises most of the heat input. Only small amounts of supplemental fossil fuels (e.g., oil or natural gas) are fired in the furnace. Energy efficiency measures for recovery furnaces are described below (USEPA, 2010a).

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

In a submerged tube concentrator, black liquor is circulated in submerged tubes, where it is heated but not evaporated; the liquor is then flashed to the concentrator vapor space, causing evaporation. One study estimated that, for a 1,000 ton per day pulp mill, increasing the solids content in the black liquor from 66 to 80 percent would lead to fuel savings of 30 MMBtu/h, or approximately \$550,000. Capital costs of the high solids concentrator would include concentrator bodies, piping for liquor and steam supplies, and pumps.

A tube-type falling film evaporator operates almost exactly the same way as a more traditional rising film evaporator, except that the black liquor flow is reversed. The falling film evaporator is more resistant to fouling because the liquor is flowing faster, and the bubbles flow in the opposite direction of the liquor. This resistance to fouling allows the evaporator to produce black liquor with considerably higher solids content (up to 70 % solids, rather than the traditional 50 %), thus eliminating the need for a final concentrator. One study estimated a steam savings of 0.76 MMBtu per ton of pulp with this type of concentrator.

According to another study, a 900-ton-per day-pulp and paper mill that installed a liquor concentrator increased its solids content from 73 to 80 percent and reduced annual energy usage by about 110,000 MMBtu. Cost savings for the mill were approximately \$900,000 per year, with an estimated payback period of four years (USEPA, 2010a).

Additional information on the costs and CO<sub>2</sub> reductions associated with installing a high solids concentrator to maximize steam generation with black liquor is provided in NCASI 2001. This report notes that high-solids firing is applicable only for the non-direct contact evaporator recovery furnaces. The report also describes the impact of converting a recovery furnace from direct to a non-direct contact evaporator furnace along with implementation of high solids firing (NCASI, 2001).

Improved composite tubes for recovery furnaces. Recovery furnaces consist of tubes that circulate pressurized water to permit steam generation. These tubes are normally made of carbon steel, but severe corrosion thinning and occasional tube failure has led to the research and development of more advanced tube alloys, including new weld overlay and co-extruded tubing alloys. Replacing carbon steel tubes in the recovery furnace with these composite alloy tubes allows the use of black liquor with higher dry solids content, which increases the thermal efficiency of the recovery furnace and decreases the number of furnace shutdowns. Improved composite tubes have been installed in more than 18 kraft recovery furnaces in the US, leading to a cumulative energy savings of 4.6 trillion Btu since their commercialization in 1996 (USEPA, 2010a).

Recovery furnace deposition monitoring. Better control of deposits on heat transfer surfaces in recovery furnaces can lead to higher operating efficiency, reduced downtime (by avoiding plugging), and more predictable shutdown schedules. A handheld infrared inspection system is currently available that can provide early detection of defective fixtures (tube leaks or damaged soot blower) and slag formation, preventing impact damage and enabling cleaning before deposits harden. The system can reportedly provide clear images in highly particle-laden boiler interiors and enable inspection anywhere in the combustion chamber. As of 2005, 69 units were in use in the US, generating 1.4 trillion Btu in energy savings since their introduction in 2002 (energy savings are attributable to reduced soot blower steam use) (USEPA, 2010a).

Quaternary air injection. Most recovery furnaces in the US have three stages of air injection but use the third stage in a limited fashion. Using the third stage fully and adding a fourth air injection port can reduce carryover and tube fouling, thereby reducing the frequency of recovery furnace washing, which will lead to energy savings because boiler shutdowns and reheating can be reduced. One estimate indicated each boiler reheat cycle will consume approximately 10 MMBtu at a cost of approximately \$50,000. Capital costs for this measure are estimated at \$300,000 to \$500,000 (USEPA, 2010a).

## 2.5. Lime Kilns

### 2.5.1. Design and Fuels

A background discussion of lime kilns is provided in the paragraphs below based on information from NCASI 2009a. The report noted that the smelt that flows from the recovery furnace consists principally of Na<sub>2</sub>S and Na<sub>2</sub>CO<sub>3</sub>. The smelt is combined with wash water to form an intermediate solution known as green liquor, which requires further chemical processing (or recausticizing) to regenerate pulping liquor. Recaucsticizing involves the slaking of quicklime (CaO) into the green liquor to form a solution of Na<sub>2</sub>S and NaOH known as white liquor. The

chemical reaction leaves a suspension of calcium carbonate ( $\text{CaCO}_3$ ) that is subsequently separated from the white liquor to complete the liquor recovery cycle (NCASI, 2009a). See Figure 2-5, above, for details.

The separated  $\text{CaCO}_3$ , known as lime mud, is washed and filtered and reprocessed through the lime kiln to form  $\text{CaO}$  to be used again in the recausticizing cycle. The conversion to quicklime involves the burning of lime mud most often in a rotary lime kiln. Fuels most commonly employed for lime kilns include oil and natural gas, which may be supplemented by other fuels such as petroleum coke, a carbonaceous byproduct of the oil refining coking process, or tire-derived fuel.

Rotary lime kilns are large refractory-lined steel cylinders that are slightly inclined from the horizontal and are slowly rotated. Lime mud is introduced at the higher end and slowly makes its way to the lower discharge end due to the inclination and rotation. Lime mud and combustion gases flow in opposite directions. The burner is installed at the discharge end of the kiln. Heat transfer from this flame and the hot combustion gases that flow up the kiln dry, heat, and calcine the counter-flowing lime solids (NCASI, 2009a).

In the kiln, the temperature profile from the inlet to the outlet is an important variable that must be controlled properly to ensure consistent lime quality and reduce operational problems in reaction chemistry. Solids temperatures range from 80 °C in the drying zone at the feed inlet end of the kiln to higher than 870 °C in the calcining zone toward the outlet end of the kiln. Primary air flow, apart from supporting combustion, is important for effective heat transfer in the kiln (NCASI, 2009a).

## 2.5.2. Sources of Emissions

The following paragraphs discuss the sources of lime kiln  $\text{NO}_x$ ,  $\text{SO}_2$ , and PM emissions, based on information from NCASI 2009a and other sources.

Emissions of  $\text{NO}_x$  and  $\text{SO}_2$  from lime kilns are relatively low. The  $\text{NO}_x$  and  $\text{SO}_2$  emissions are influenced by fuel choice, the composition of materials fed to the kiln, chemical reactions that accompany lime mud calcination, and choice of external control approaches for PM emissions. The report stated that combustion process modifications may be useful, but cautioned that they are limited by site-specific considerations and product quality impact (NCASI, 2009a).

### 2.5.2.1. Lime Kiln $\text{NO}_x$ Emissions

Though the mechanisms differ,  $\text{NO}_x$  produced in the kraft lime kiln originates from the combustion of fossil fuels. The formation of  $\text{NO}_x$  is related to the nitrogen content of the fuel. Burner design and flame temperature are also prominent factors in  $\text{NO}_x$  emissions due to the need to attain a high flame temperature for good heat radiation to the bed of lime (NCASI, 2009a).

Natural gas and fuel oil, either alone or in combination, are the most common fuels currently used in lime kilns (RTI 2013a). According to NCASI 2009a, the range of  $\text{NO}_x$  emissions is wide, and data are unclear as to whether gas or oil is associated with the greater level. The introduction of other fuels (e.g., solid petroleum coke) and process streams bearing reduced sulfur compounds such as stripper off-gases, which are relatively rich in nitrogen content, increases the potential for  $\text{NO}_x$  emissions (NCASI, 2009a).

Petroleum coke has between 1.0- and 2.6-percent nitrogen ( $\text{N}_2$ ) compared with approximately 0.1- 1.0-percent  $\text{N}_2$  for residual fuel oil. The nitrogen content of natural gas is considered insignificant. Thus, there would appear to be significant potential for fuel  $\text{NO}_x$  formation from petroleum coke combustion. However, observed levels of  $\text{NO}_x$  emissions from burning petroleum coke in lime kilns suggest that less than 10 percent of the  $\text{N}_2$  in

petroleum coke converts to NO<sub>x</sub>, a level even lower than typical fuel nitrogen conversions for residual fuel oil. Thus, the report concludes that firing petroleum coke contributes little, if any, increase in NO<sub>x</sub> emissions (NCASI, 2009a).

Lime kiln SO<sub>2</sub> is formed from the combustion of fuel oil, residual sulfide in the lime mud, or other gaseous streams (NCGs, stripper off-gases) that may be burned in the kiln for purposes of TRS emissions control. According to NCASI 2009a, kiln chemistry provides a built-in mechanism for SO<sub>2</sub> control. The report noted that sodium liberated from the residual Na<sub>2</sub>CO<sub>3</sub> in the lime mud combines with SO<sub>2</sub> to form Na<sub>2</sub>SO<sub>4</sub> that is captured in the kiln particulate control device or retained by the solids in the kiln. The report cautioned that the potential of this mechanism is not unbounded, however; SO<sub>2</sub> reduction will cease once the Na<sub>2</sub>CO<sub>3</sub> capacity of the mud is exhausted. Moreover, if the lime mud contains excessive sodium, impaired kiln operation can occur due to severe ring formation that obstructs kiln operation. Ring formation is a consequence of Na<sub>2</sub>SO<sub>4</sub> formation in the kiln lime bed. The control of kiln particulate emissions by wet scrubbers can contribute additional SO<sub>2</sub> control attributable to the alkaline nature of the particulate catch. Consequently, lime kiln SO<sub>2</sub> emissions, on average, are very low (about 50 ppm) (NCASI, 2009a).

#### *2.5.2.2. Lime Kiln SO<sub>2</sub> Emissions*

According to NCASI 2009a, the impact of petroleum coke burning on SO<sub>2</sub> emissions from lime kilns can be insignificant in spite of the relatively high levels of sulfur (S) in petroleum coke, 4.9 percent on average. As with other kiln sulfur inputs, the report indicated that this outcome is also attributable to the high degree of in situ SO<sub>2</sub> capture capability of lime kilns (NCASI, 2009a).

#### *2.5.2.3. Lime Kiln PM Emissions*

While passing through the kiln, the combustion gases pick up a significant amount of PM both from lime mud dust formation and from alkali vaporization (NCASI, 2004). Particulate matter in the exhaust gas is mainly sodium salts (Na<sub>2</sub>SO<sub>4</sub> and Na<sub>2</sub>CO<sub>3</sub>), CaCO<sub>3</sub>, and CaO (USEPA, 1996).

#### *2.5.2.4. Lime Kiln GHG Emissions*

As mentioned previously, in the kraft pulping and chemical recovery process, biomass carbon from the wood is dissolved and either emitted as biomass CO<sub>2</sub> from the recovery furnace or captured in Na<sub>2</sub>CO<sub>3</sub> exiting in the smelt from the recovery furnace. In the process of converting the Na<sub>2</sub>CO<sub>3</sub> into new pulping chemicals, this biomass carbon (i.e., the carbonate ion) is transferred to CaCO<sub>3</sub> in the causticizing process. In the lime kiln, the CaCO<sub>3</sub> is converted to CaO (i.e., lime material used in the chemical recovery process) and biomass CO<sub>2</sub> originating from the wood residuals contained in black liquor is released to the atmosphere. Unlike lime kilns used at lime production facilities, where CO<sub>2</sub> emissions are entirely fossil in nature, the CO<sub>2</sub> emitted from kraft mill lime kilns originates from two sources: 1) fossil fuels burned in the kiln, and 2) conversion of CaCO<sub>3</sub> (or “lime mud”) generated in the recovery process to CaO (lime). The CaCO<sub>3</sub>-derived CO<sub>2</sub> emissions almost exclusively originate from biomass and are accounted for in recovery furnace emission factor calculations (because recovery furnace emission factors are based on the carbon content of spent pulping liquor, and this biogenic carbon eventually exits the chemical recovery process from either the recovery furnace or lime kiln) (USEPA, 2010a).

The lime kiln typically produces about 95 percent of the lime needed for the causticizing reaction. Either make-up lime or limestone is purchased to account for losses (USEPA 2010a). Emissions associated with carbonated makeup chemicals are typically included in emissions inventories. Therefore, the Universal ISIS-PNP does not include CO<sub>2</sub> emissions associated with makeup chemicals.

Several pulp mills pipe stack gas from lime kilns or calciners to adjacent precipitated calcium carbonate plants for use as a raw material. Precipitated calcium carbonate is sometimes used as an inorganic filler or coating material in paper and paperboard products (USEPA, 2010a). This practice is not accounted for in the Universal ISIS-PNP because it transfers emissions offsite rather than reducing them through implementation of emission reduction measures.

In addition to CO<sub>2</sub> emissions, lime kilns emit CH<sub>4</sub> and N<sub>2</sub>O from combustion of fossil fuels. According to the International Council of Forest and Paper Associations GHG Emissions Estimation Protocol (NCASI 2005), the operating temperatures in rotary lime kilns (the predominant design for pulp mill lime kilns) appear to be too high to allow significant generation of N<sub>2</sub>O. Therefore, it is reasonable to assume that N<sub>2</sub>O emissions from rotary lime kilns are negligible (USEPA, 2009).

### 2.5.3. Lime Kiln Emission Reduction Strategies

#### 2.5.3.1. Lime Kiln NO<sub>x</sub> Reduction

This section discusses the applicable controls for reducing lime kiln NO<sub>x</sub> emissions, based on information from NCASI 2009a. According to the report, combustion modifications are the best prospect for altering NO<sub>x</sub> emissions from lime kilns. The report indicated that NO<sub>x</sub> control in newer lime kilns may be achieved mainly by minimizing the hot end temperatures in gas-fired kilns and by reducing the available oxygen in the combustion zone in oil-fired kilns. However, these combustion-related modifications may be difficult to achieve in certain existing kilns due to their inherent design and the implications for product quality. The report stated that there are combustion conditions that must be sustained to efficiently produce an end product (CaO) of consistently acceptable quality and that implications for adversely affecting emissions of other pollutants also need to be considered. As a result, attempts to modify NO<sub>x</sub> formation by adjusting the kiln operating parameters, flame shape, air distribution and excess oxygen have not been very successful (NCASI, 2009a).

According to NCASI 2009a, NO<sub>x</sub> control strategies for each kiln must be evaluated on a case-by-case basis because mechanisms of formation and control are not well understood (NCASI, 2009a). To illustrate, the report pointed out that techniques to minimize the hot end temperatures in gas-fired kilns, while potentially helpful in reducing NO<sub>x</sub> emissions, must be balanced with the simultaneous need to address emission levels of TRS compounds and to sustain the necessary calcining capacity, which would otherwise be reduced under this option. The report stated that there is also an energy penalty associated with the need for greater heat input per ton of lime mud processed. The report further stated that, while reducing available oxygen in the kiln combustion zone may be useful for NO<sub>x</sub> reduction in oil-fired kilns, altering the air supply also affects combustion efficiency, resulting in excessively high emissions of TRS compounds and CO. Whatever combustion modifications are made may be limited by kiln configuration and geometry, as well as by impacts on process performance, stability, and control (NCASI, 2009a).

A report by STAPPA referred to a BACT analysis performed in 2003 for a proposed lime kiln. The BACT analysis evaluated the feasibility of low-NO<sub>x</sub> burners, flue gas recirculation, oxidation/reduction scrubbing, SCR, SNCR and non-selective catalytic reduction, and concluded that none of these options is technically feasible for lime kiln NO<sub>x</sub> emissions control. Rather, the regulatory agency concluded that “good design and operation practices” constitute BACT, and established a NO<sub>x</sub> limit of 175 ppm at 10-percent oxygen (STAPPA, 2006).

Table 2-13 presents lime kiln NO<sub>x</sub> control technology options and the impact of this technology.

**Table 2-13. Lime Kiln NO<sub>x</sub> Control Technologies**

Control Option	Description	Performance	Application
Combustion Air Control	Combustion zone availability of oxygen is a key factor in NO <sub>x</sub> formation, especially in oil-fired kilns. Primary air feed is driven by flame control requirements, limiting the opportunity for staging combustion air. Air supply must be sufficient to sustain oxidizing conditions throughout the kiln.	NO <sub>x</sub> reduction is site-specific since mechanisms of formation and control not well understood	Detuning a burner from optimized combustion incurs an energy penalty by virtue of requiring greater heat input per ton of product. Inadequate air supply contributes to excessively high emissions of TRS and CO, as well as excessive carbon deposits in the lime.  More applicable for new kilns, not retrofit of existing kilns.
Burner Design	Low NO <sub>x</sub> burners are technically infeasible due to complex factors that result in poor efficiency, increased energy usage, and decreased calcining capacity of the lime kiln. Reduced flame temperature, however, could be conducive to diminished thermal NO <sub>x</sub> formation, especially in gas-fired kilns.	LNB infeasible; NO <sub>x</sub> reduction unknown for reduced flame temperature option	Reducing flame temperature in gas-fired kilns can reduce NO <sub>x</sub> , but that reduction comes with a cost of reduced kiln capacity or an energy penalty associated with the need for greater heat input per ton of lime mud processed.  More applicable for new kilns, not retrofit of existing kilns.
Fuel Selection	Fuel nitrogen is the principal source of NO <sub>x</sub> in oil-fired kilns, unlike gas-fired kilns where thermal NO <sub>x</sub> formation is prevalent. There is typically little difference in reported emissions between oil and gas.	NO <sub>x</sub> reduction fuel-specific	
Flue Gas Recirculation (FGR)	A possibly promising but untested approach.	NO <sub>x</sub> reduction unknown; untested approach for lime kilns	Altering kiln temperature profiles with FGR would possibly adversely affect calcining efficiency.
SCR	Infeasible due to kraft lime kiln configuration. High particulate loadings preclude SCR prior to particulate control and temperature requirements are not met after particulate control.	Infeasible	Reheating the flue gas after the particulate control device and ahead of the SCR section would incur a substantial energy penalty.
SNCR	Infeasible due to kraft lime kiln configuration. The necessary elevated temperature regime required for SNCR is unavailable in kilns.	Infeasible	

Note: all data from (NCASI 2009a).

### 2.5.3.2. Lime Kiln SO<sub>2</sub> Reduction

According to NCASI 2009a, combustion modifications, as a practical matter, provide little opportunity for beneficial reduction of SO<sub>2</sub> emissions originating in fuels or raw material (lime mud) fed to the kiln. However, the regenerated quicklime in the kiln acts as an excellent in situ scrubbing agent for reducing SO<sub>2</sub> emissions. Post-combustion controls can provide additional SO<sub>2</sub> control. Nearly 70 percent of lime kilns in the US are equipped with wet scrubbers, over 20 percent are equipped with ESPs, and less than 10 percent are equipped

with ESPs followed by scrubbers. While the wet scrubbers are primarily venturi scrubbers designed for PM control and not normally conducive to the gas absorption needed for reduction of SO<sub>2</sub>, wet scrubbers can augment the SO<sub>2</sub> removal process because the scrubbing solution becomes alkaline from the captured lime dust. Between the in situ scrubbing and venturi scrubber, approximately 95 percent of the SO<sub>2</sub> formed within the kiln is captured prior to release, typically resulting in low SO<sub>2</sub> emissions (approximately 50 ppm) (NCASI, 2009a).

While most lime kilns are equipped with wet scrubbers, installing ESPs to control PM from lime kilns has become more widespread in recent years (USEPA, 1996). However, according to NCASI 2009a, emissions of SO<sub>2</sub> are higher when ESPs are used for PM control instead of scrubbers. Sulfur dioxide emissions are also affected by the relative magnitude of sulfur input to the kiln and the sodium content of the lime mud. The improved collection of fine PM with ESPs and improved lime mud washing contribute to potentially greater SO<sub>2</sub> emissions reductions. The report pointed out that these examples illustrate the compromises that must be struck to balance environmentally sensitive manufacturing process improvements with collateral changes in other measures of environmental interest, as well as choosing among emissions control options that may favor one pollutant over another (e.g., PM vs. SO<sub>2</sub>) (NCASI, 2009a).

Table 2-14 presents lime kiln SO<sub>2</sub> control technology options and their impacts.

**Table 2-14. Lime Kiln SO<sub>2</sub> Control Technologies**

Control Option	Description	Performance	Applicability
Fuel Selection	Using fuel with lower sulfur content	SO <sub>2</sub> reduction fuel-specific	SO <sub>2</sub> formation not only dependent upon fuel sulfur content but also lime mud sulfur content and sulfur-bearing NCGs or stripper off-gases that may be burned in the kiln.
Scrubber	The majority of kilns are equipped with wet scrubbers for particulate control. Alkaline conditions accompanying lime dust capture contribute additional control of SO <sub>2</sub> not otherwise retained within the kiln.	Combined with in situ SO <sub>2</sub> removal, typically, >95 % of SO <sub>2</sub> is captured	Particulate scrubbers are designed and optimized for particulates. Associated high velocities are not conducive to gas absorption; SO <sub>2</sub> removal would not likely equal what might be achievable with a scrubber designed for that purpose.  Some kilns use ESPs followed by wet scrubbers.

Note: all data from (NCASI 2009a).

### 2.5.3.3. Lime Kiln PM Reduction

The following paragraphs summarize available information on PM control technologies for kraft lime kilns from USEPA's background document for the chemical recovery combustion sources NESHAP (USEPA, 1996).

Due to State and Federal regulations for PM emissions, all lime kilns are equipped with add-on PM control devices. As noted previously, as a baseline, nearly 70 percent of lime kilns are currently equipped with wet scrubbers, over 20 percent are equipped with ESPs, and less than 10 percent are equipped with ESPs followed by scrubbers. If a wet scrubber is used, a mechanical collector (e.g., cyclone separator) may be installed upstream. The mechanical collector is generally used to remove larger particles, which are mainly calcium-

containing ( $\text{CaCO}_3$ ,  $\text{CaO}$ ). The dust collected by the mechanical collector is returned directly to the lime kiln. A wet scrubber or ESP follows for removal of smaller particulates, which are mainly sodium salts ( $\text{Na}_2\text{SO}_4$  and  $\text{Na}_2\text{CO}_3$ ) and have aerodynamic diameters less than or equal to  $10\ \mu\text{m}$  (USEPA, 1996; RTI, 2013a; NCASI, 2004).

Venturi scrubbers are the most commonly used type of wet scrubber for lime kilns. Water is the typical scrubbing fluid, but caustic and weak wash are also used. The scrubbing fluid is recirculated, and the scrubber blowdown is recycled to the lime mud washer. Venturi scrubbers are designed to remove PM primarily by impaction through high-energy contact between the scrubbing liquid and suspended PM in the gas stream. A venturi scrubbing system typically consists of a venturi scrubbing vessel and cyclonic separator. The venturi scrubbing vessel has a converging section, a throat section, and diverging section (USEPA, 1996).

The performance of the scrubber in terms of PM collection is strongly affected by the pressure drop across the scrubber throat, the liquid-to-gas ratio, and the particle size distribution. Particulate matter collection efficiency generally increases as the throat velocity and turbulence of the gas stream increase, as indicated by an increased pressure drop across the scrubber. For lime kiln applications, PM collection efficiencies for venturi scrubbers average 99 percent (USEPA, 1996).

Although venturi scrubbers have traditionally been the most common PM control device used on lime kilns, the use of ESPs to control PM emissions from lime kilns has steadily increased since about 1980. The expected lifetime of a lime kiln ESP is typically more than 15 years (USEPA, 1996).

The ESP is generally mounted on top of the lime kiln feed building, and the captured dry PM is rerouted to the kiln by gravity feed. The trend towards ESPs as PM control devices at newer lime kiln installations and as replacement control devices for older scrubbers is primarily related to the lower energy costs, reduced maintenance, and increased reliability of the ESPs in comparison to venturi scrubbers that provide equivalent control. An added benefit is that an ESP installed on a lime kiln produces a dry product that can be recycled directly to the kiln. The wastewater produced by the venturi scrubber is typically recycled to the mud washers before the kiln to recover the lime particulate in the spent scrubbing fluid. Additional energy is needed to remove the excess water in the lime mud filter and to complete evaporation in the kiln. Properly designed and operated ESPs used on lime kilns routinely achieve PM removal efficiencies of 99 percent or greater (USEPA, 1996).

However, as noted in the previous section, emissions of  $\text{SO}_2$  are higher when ESPs are used for PM control instead of scrubbers, illustrating the compromises that must be struck in choosing among emissions control options that may favor one pollutant over another (e.g., PM vs.  $\text{SO}_2$ ) (NCASI 2009a). Based on a review of available lime kiln PM data that show that ESP-scrubber combinations do not necessarily outperform ESPs on PM, adding a scrubber to an existing ESP (or vice versa) may not necessarily improve lime kiln PM control (RTI, 2013a).

Potential control technology options for reducing lime kiln PM emissions involve replacing the existing scrubber with an ESP, upgrading or replacing the existing ESP, upgrading the existing scrubber, and adding a second PM control device (i.e., adding ESP before existing scrubber, or adding scrubber after existing ESP). Attributes of potential lime kiln PM control technology options are summarized in Table 2-15.

**Table 2-15. Lime Kiln PM Control Technologies**

Control Option	Description	Performance	Applicability
Replacing Scrubber with ESP	The use of ESPs to control PM emissions from lime kilns has steadily increased since the 1980s, due to lower energy costs, reduced maintenance, and increased reliability; also, lime kiln ESPs produce a dry product that can be recycled directly to the kiln. Particulate matter removal efficiencies of 99 % or greater can be achieved with properly designed and operated ESPs (USEPA, 1996).	Could increase PM control from 99 % (scrubber) up to 99.97 % (best-performing ESP)	Emissions of SO <sub>2</sub> are higher when ESPs are used for PM control instead of scrubbers (NCASI, 2009a).
ESP Upgrade or Replacement	Upgrading existing ESP or replacing older ESP with new ESP.	Could increase PM control from 99 % up to 99.97 % (best-performing ESP)	The cost of retrofitting a lime kiln with an ESP is heavily influenced by site-specific factors including the age and design of the ESP already in place (NCASI, 2009a).
Scrubber Upgrade	The majority of kilns are equipped with wet scrubbers for particulate control, obtaining PM reductions of approximately 99 % (NCASI, 2009a).	Could increase PM control from 99 % up to 99.88 % (best-performing scrubber)	Alkaline conditions accompanying lime dust capture contribute additional control of SO <sub>2</sub> not otherwise retained within the kiln.
ESP + Scrubber	An estimated 10 lime kilns are equipped with both a wet scrubber and ESP for particulate control, obtaining PM reductions of approximately 99 % on average (best-performing unit is 99.8 %) (RTI, 2013b).	Could increase PM control from 99 % (baseline scrubber or ESP) up to 99.8 % (ESP + scrubber)	However, a review of available lime kiln PM data shows that ESP-scrubber combinations do not necessarily outperform ESPs on PM, so adding a scrubber to an existing ESP (or vice versa) may not necessarily improve lime kiln PM control (RTI, 2013a).

Note: PM control performance data based on (RTI, 2013b).

#### 2.5.3.4. Lime Kiln CO<sub>2</sub> Reduction

The USEPA is presently unaware of control measures to reduce fossil-related GHG from pulp mill lime kilns other than process changes or energy efficiency measures. Process changes and energy efficiency measures are described below.

Lime kiln oxygen enrichment. Oxygen enrichment is an established technology for increasing the efficiency of combustion and has been adopted in various forms by a number of industries with high-temperature combustion processes (e.g., glass manufacturing). According to one study, oxygen enrichment of lime kilns can reduce fuel requirements by approximately 7 to 12 percent. Reportedly, capital investments for oxygen enrichment are negligible compared to other recausticizing plant upgrades, requiring relatively simple equipment, including feed piping, an injection lance, and controls. Payback periods have been estimated between one and three years (USEPA, 2010a).

Lime kiln modification. Several other modifications are possible to reduce energy consumption in lime kilns. High-efficiency filters can be installed to reduce the water content of the kiln inputs, thereby reducing the required evaporative energy. Higher efficiency refractory insulation brick can be installed to reduce heat losses

from the kiln. One estimate indicated that newer high-performance refractory can lead to lime kiln energy savings of up to 5 percent. Heat can also be recovered from the lime and from kiln exhaust gases to pre-heat incoming lime and combustion air. According to one estimate, the energy savings achievable from implementing all of these measures is approximately 0.47 MMBtu per ton of production. Such improvements may also improve the rate of recovery of lime from green liquor, thereby reducing a mill's requirement for additional purchased lime (USEPA, 2010a).

Lime kiln electrostatic precipitators. Electrostatic precipitators can replace wet scrubbers on lime kilns and lead to energy and water savings. Electrostatic precipitators can collect kiln dust as a dry material and return the kiln dust directly to the kiln feed without unnecessarily loading the lime mud filter. In contrast, wet scrubbers require effluent recycling via the lime mud filter and are significant consumers of water. One estimate indicated that, for every one-percent reduction in lime mud feed moisture content (through the addition of dry dust), lime kiln energy consumption is reduced by approximately 46 MMBtu. Another analysis found that increasing mud dryness from 70 to 75 percent would reduce fuel consumption by 0.4 MMBtu per ton of lime (USEPA, 2010a).

Install a biofuel gasifier to use low-Btu gas in the lime kiln. Biofuels such as hog fuel generated on site can be gasified resulting in low-Btu gas that can be substituted for fossil fuel in the lime kiln. The gasification process is usually carried out in a fluidized bed reactor to promote a high rate of heat transfer. The biofuel is injected into the fluidized bed, where high turbulence causes rapid combustion and gasification of the char. Low Btu gases generated in the reactor are withdrawn, cooled, scrubbed if needed to remove moisture or pollutants, and can then be fired in the lime kiln to displace fossil fuel.

Both direct firing of hog fuel (dried to a minimum of 85 % dryness) and hog fuel gasification and low Btu gas incineration in the lime kiln have been practiced in the Nordic countries since the late 1970s. The technology is viable, but it may not be economically attractive unless free hog fuel is in excess at the site (NCASI, 2001). A biofuel gasifier will reduce CO<sub>2</sub> emissions from fossil fuel combustion in the lime kiln, replacing them with biogenic CO<sub>2</sub> emissions.

Fossil fuel switching. Similar to fuel switching in boilers, switching from oil firing to natural gas firing in the lime kiln, or discontinuing use of supplemental fossil fuels with high carbon content (e.g., petroleum coke) could potentially reduce lime kiln CO<sub>2</sub> emissions. Additional literature could be identified and reviewed to determine the applicability and limitations and CO<sub>2</sub>-reduction potential from fuel switching.

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## 3. Universal ISIS-PNP Modeling Framework

### 3.1. Introduction

Universal ISIS-PNP is a sector-based linear programming model that can help analyze optimal pulp and paper sector operations for meeting demand and pollution reduction requirements over specified time periods. The objective in a Universal ISIS-PNP simulation is to maximize total surplus over a time horizon of interest for the pulp and paper sector. The total surplus (consumer surplus plus producer surplus) concept has long been a mainstay of social welfare economics because it takes into account the interests of both consumers and of producers (Nordhaus and Heyden, 1977).

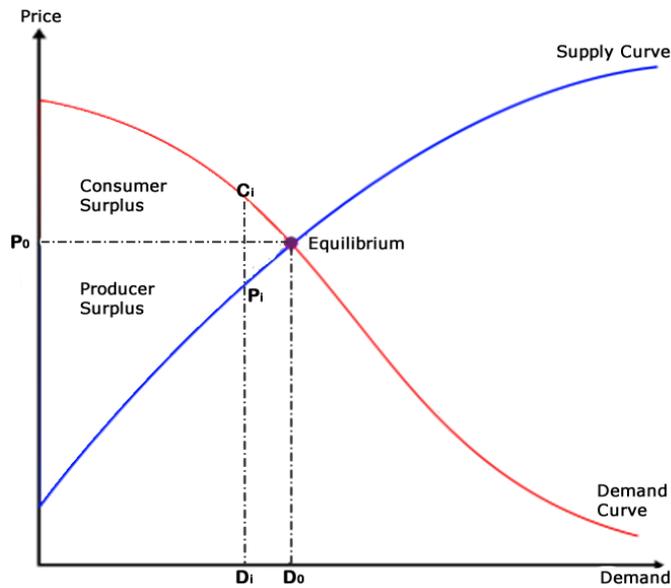


Figure 3-1. Total Surplus in a Market

In a market at competitive equilibrium, the total surplus can be thought of as composed of producer surplus and consumer surplus. As shown conceptually in Figure 3-1, the producer surplus corresponding to a quantity  $Q$  of a commodity is the difference between the gross revenue and the inverse supply curve (blue area). Gross revenue is the result of the price and the quantity consumed. Similarly, the consumer surplus corresponding to a quantity  $Q$  is given by the area under the inverse demand curve up to that quantity minus the gross revenue (pink area).

It is evident from Figure 3-1 that the total surplus is maximized exactly when quantity  $Q$  is equal to the equilibrium quantity  $Q_E$ . When the quantity consumed is less than the optimum  $Q_E$ , e.g.  $Q_i$ , the consumer pays a higher price  $C_i$  resulting in reduction in consumer surplus. At a new equilibrium, the marginal total cost will increase from  $P_i$  of the base case to  $C_i$  at the lower quantity  $Q_i$ . The total surplus shrinks, as depicted by the green area in Figure 3-1. The producer surplus changes from the equilibrium case as a portion of the total surplus. However, the framework of the Universal ISIS-PNP does not proportion the total surplus into consumer and producer surplus. Instead, Universal ISIS-PNP calculates the total surplus as the difference between the total area under the inverse demand curve less the area under the inverse supply curve.

Universal ISIS-PNP utilizes the general concept of “spatial price equilibrium” in a network when analyzing the balance of supply, demand, and trade. In spatial price equilibrium network models, interregional economies are simulated by finding the balance of demand, supply, and trade that will result in competitive market equilibrium among the regions.

## 3.2. Objective Function

The objective function of Universal ISIS-PNP is to maximize the total surplus for the pulp and paper sector over the selected time horizon. By the equivalent function, the objective is to minimize the total discounted cost over the same time horizon while meeting the demand. Components of total cost include production cost, transportation cost, import cost, control cost and energy efficiency cost, as well as emission charge. Each element of cost is corrected to net present value (discounted) by applying a discount factor for each year within the time horizon based on a user supplied discount rate.

Individual cost elements of total cost are treated by Universal ISIS-PNP as described below:

- 1 Production cost - Obtained for each pulp and paper production unit. The production cost of each unit takes into account the factor input costs of raw material, labor, energy, and other cost components.
- 2 Transportation cost - cost of transport from supply center to the demand center. Production from each supply center may be transported to any demand center. Distance from each supply center to each demand center is incorporated into the industry inputs.
- 3 Import cost - calculated by multiplying the quantity of imported goods by the import price for each country of origin and adding any handling and other associated costs. All imports arrive at the import terminals and incur transportation costs to reach each demand center; distances from import terminals to each demand center are incorporated into the industry inputs.
- 4 Control and energy efficiency costs - Include the capital and variable costs of installing controls and energy efficiency options to achieve any emission reduction targets governed by the constraints.
- 5 Emission charge - Added if any allowance price is given for the pollutants.

Thus, the objective function is defined as follows (Eq. 3-1):

$$\begin{aligned}
\text{Minimize } z = & \sum_{t,i} \text{discount factor}(\text{time}) \bullet \text{production cost}(\text{time, production unit}) + \\
& \sum_{t,dc} \text{discount factor}(\text{time}) \bullet \text{transportation cost}(\text{time, demand center}) + \\
& \sum_{t,id} \text{discount factor}(\text{time}) \bullet \text{import cost}(\text{time, import district}) + \\
& \sum_{t,i,k} \text{discount factor}(\text{time}) \bullet \text{control cost}(\text{time, production unit, control option}) + \\
& \sum_{t,i,ee} \text{discount factor}(\text{time}) \bullet \text{energy efficiency cost}(\text{time, unit, efficiency option}) + \\
& \sum_{t,f} \text{discount factor}(\text{time}) \bullet \text{allowance price}(\text{time, fuel}) \bullet \text{total emissions}(\text{time, fuel}) - \\
& \sum_t [\text{discount factor}(\text{time}) \bullet \text{total benefit}(\text{time, demand center})]
\end{aligned} \tag{3-1}$$

where :

$z$  is the additive inverse of the total surplus,

$t$  is the time period of interest,

$i$  is the production unit of interest,

$id$  is the import district of interest,

$k$  is the control option of interest,

$ee$  is the energy efficiency measure of interest, and

$f$  is the fuel of interest

Total cost approximates the inverse supply curve by filling demand from the lowest cost product through consecutively higher cost products until demand is satisfied. Demand is satisfied when the demand price no longer exceeds the supply cost. The user chooses a range of interest centered on the expected demand for demand center and production year, model default is 0.5 to 1.5 times the expected demand. Demand in this range is divided into a user defined number of steps or intervals; the model default is 100 steps. The inverse demand curve is used to determine the demand price at the midpoint of each demand step using a constant elasticity of demand model for each region (Eq. 3-2):

$$P(D) = P0 \left( \frac{D}{D0} \right)^{\frac{1}{\sigma}} \tag{3-2}$$

where:

$D$  is the demand for the product with corresponding price  $P(D)$ ,

$\sigma$  is the elasticity of demand relative to price, and

$D0$  and  $P0$  are the initially-specified demand quantity and price, respectively

The total surplus is calculated based on a constant elasticity of demand model in the stepwise integration fashion, as illustrated in Figure 3-2. The surplus within the demand range considered by the user, from  $D_{\min}$  to the final demand quantity, is estimated by the product of price at the midpoint of each step and the width of the step. The benefit associated with demand from zero to  $D_{\min}$  is estimated by the product of  $D_{\min}$  and the demand price of the first step of the range.

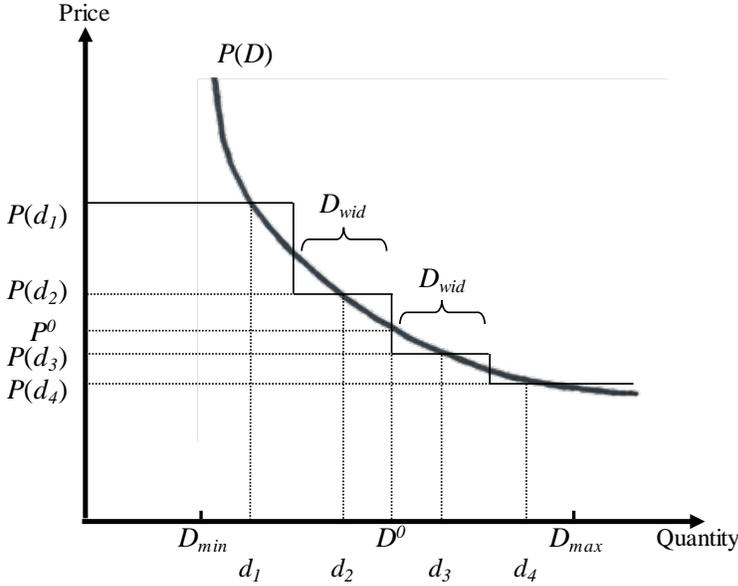


Figure 3-2 Stepwise Integration of the Inverse Demand Curve

### 3.3. Production and Costs in Universal ISIS-PNP

The demand for a product in a market can be satisfied by the sum of domestic production (sum of  $PRQ_{Unit}$ ) and foreign imports (sum of  $IPR_{Terminals}$ ) decreased by the amount of exports (sum of  $EPR_{Terminals}$ ), as shown in Equation 3-3:

$$\sum_{Unit} PRQ_{Unit} + \sum_{Terminals} IPR_{Terminals} - \sum_{Terminals} EPR_{Terminals} \geq \sum_{Steps} DEMAND_{Steps} \quad (3-3)$$

The domestic production capacity changes (to satisfy the demand) take place in the Universal ISIS-PNP modeling framework based on the treatment of total production-related costs. Total pulp ( $Z_{PULPCOST}$ ) or paper ( $Z_{PAPERCOST}$ ) production-related costs are a sum of production costs ( $Z_{PCost}$ ), imports costs ( $Z_{ICost}$ ), export costs ( $Z_{ECost}$ ), associated export/import transportation costs ( $Z_{TCost}$ ), and recycling cost of paper products ( $Z_{RCost}$ ), as shown in Equations 3-4 and 3-5 below:

$$Z_{PULPCOST} = \sum Z_{PCost} + \sum Z_{ICost} + \sum Z_{ECost} + \sum Z_{TCost} \quad (3-4)$$

$$Z_{PAPERCOST} = \sum Z_{PCost} + \sum Z_{ICost} + \sum Z_{ECost} + \sum Z_{TCost} + \sum Z_{RCost} \quad (3-5)$$

Production-related costs include capital costs as well as fixed and variable costs. Fixed costs are in the form of capital recovery costs. Capital recovery usually depreciates the cost of a new production capacity over the economic life of the additional capacity using a user defined interest rate for capital expenses. However, user has the option to add fixed costs, if any, for the existing production units. Variable production costs include raw material costs, labor costs, operation and maintenance cost, fuel costs, water costs, wastewater costs, electricity

consumption costs, solid waste costs, controls costs, and energy efficiency costs provided by the user on a unit of production basis.

Universal ISIS-PNP includes constraints for ensuring that production capacity changes occur in a realistic way. Production is modeled for five types of units: existing production units, expansion units, replacement units, projected units and new production units. Existing production units are units currently installed and capable of producing product. Expansion units are the units associated with increasing production capacity at an existing production unit. Replacement units are production units built to retire existing production units and replace with new production units. New production and projected units represent entirely new production capacity. Production capacity changes occur in Universal ISIS-PNP by analysis of production-related cost components. These production-related cost components are explained in more detail below.

*Electricity production/consumption:* Heat produced from boilers can also be used for electricity generation which can be used to satisfy a mill's own electricity demand or be sold to a grid. A modern kraft pulp mill is more than self-sufficient in its electrical generation and normally can provide energy for use by other industries or to the local community. Thus, electricity consumption/production and its cost are formulated in Universal ISIS as follows (Eq. 3-6 and 3-7):

$$EL_{unit} = \sum_{product} PRQ_{unit,product} * \{(ELC_{intensity}) - (ELP_{intensity})\} \quad (3-6)$$

$$Z_{ELC} = ELC_{Cost} * \sum_{unit} EL_{unit} \quad (3-7)$$

where  $EL_{unit}$  is the electricity consumption/production (kilowatt hours, kWh) per unit,  $ELC_{intensity}$  is the electricity intensity consumed (kWh/ton of product) by a mill,  $ELP_{intensity}$  is the electricity intensity produced (kWh/ton of product), and  $PRQ_{unit,product}$  is the production quantity (tons of product) of all products in a pulp or paper mill. Thus,  $EL_{unit}$  is the net demand for electricity in a mill. When a mill produces more electricity than it needs to meet its demand,  $EL_{unit}$  becomes negative and represents a profit for a mill. Total electricity cost,  $Z_{ELC}$  (\$) is calculated by multiplying cost per unit,  $ELC_{Cost}$  (\$/kWh) by total kWh of electricity used by a unit,  $EL_{unit}$  across the entire sector.

*Heat production:* Heat in the form of steam is required for pulp and paper production. Two main sources can provide heat: power boilers and recovery furnaces. Burning black liquor in recovery furnaces supplements the heat produced with fossil fuel-fired and/or wood-fired power boilers. The heat requirement is modeled as follows (Eq. 3-8):

$$HEAT_{Required(unit)} = \sum_{product} EI_{unit,product} * PRQ_{unit,product} + \sum_{product} PRQ_{unit,product} * ELC_{Q_{unit}} * C_{Factor} \quad (3-8)$$

where  $EI_{unit,product}$  is the energy intensity required to produce one ton of product (MMBtu/ton).  $PRQ_{unit,product}$  is the production quantity of all products in a mill.  $ELC_{Q_{unit}}$  is the electricity production quantity from each pulp or paper mill.  $C_{Factor}$  is the conversion coefficient to convert electricity to heat. For a paper mill, the total heat production is the sum of heat required for production and heat required for electricity generation from power boilers (Eq. 3-9):

$$HEAT_{RF} + HEAT_{PWRBLR} = HEAT_{Required(Pulp\ unit)} \quad (3-9)$$

For a pulp mill with a recovery furnace, the heat required for pulp and electricity production is the sum of heat produced from a recovery furnace burning black liquor and heat produced from power boilers. Approximately 70 percent of products (130 % of black liquor per ton of product) are assumed to be produced from black liquor and burned. Because of no cost for black liquor, the Universal ISIS-PNP uses 100 percent of the heat from the recovery furnace and produces the rest of the required heat from the power boilers (Eq. 3-10):

$$Z_{FUEL} = HEAT_{BLR} * FUEL_{COST} \quad (3-10)$$

Lime mud, referred to  $CaCO_3$  precipitate, is produced in causticizing and calcining processes in a pulp mill. The production of lime mud and emissions is formulated as follows (Eq. 3-11):

$$LMQ = \left( \sum_{product} PL_{product} \right) * LM_{Intensity} \quad (3-11)$$

where  $LM_{Intensity}$  is the lime mud intensity from each product (tons lime mud/ton product) and  $PL_{product}$  refers to the quantity of a product (tons) produced by a mill.  $LMQ$  is the total production quantity of lime mud in tons from a pulp mill. Emissions quantities are calculated by multiplying of emissions intensity (lb/ton lime mud) with mud quantity in tons.

Waste paper products are recycled and used as feedstock to produce paper products. Increasing the use of recycled paper product has continually reduced the environmental impacts of the sector. The recovery rate of boxboard and other board (BXT) is 91.2 percent, container board (CNT) is 50 percent, corrugating medium (COR) is 91.2 percent, coated printing and writing paper (CPW) is 56.8 percent, newsprint is 73 percent, packaging and industrial paper (PIP) is 50 percent, and uncoated printing and writing paper (UPW) is 56.8 percent. In the Universal ISIS-PNP, mills (facilities) are classified according to whether or not they could purchase recycled fiber or purchase both market pulp and recycled fiber. Total recycling pulp is calculated based on purchase of recycled fiber for each unit (Eq. 3-12):

$$PLP_{RECYCLE} = \sum_{product} PRQ_{unit,product} * PLP_{REP} \quad (3-12)$$

where  $PRQ_{unit,product}$  is the production quantity of each product and  $PLP_{REP}$  is the percentage of recycled fiber purchased to manufacture each product. Recycling fiber transportation cost is calculated similarly to domestic transport. Three recycle fiber collection locations are assumed in the United States and collected fibers are assumed to be transported to a products supply center (SC).

*Domestic Transportation:* Paper products are transported from SC to demand center. However, all paper production mills are grouped in three supply centers, North, West and South. Similarly, on the domestic demand side, Universal ISIS-PNP considers domestic demands from three demand centers (North, South, and West) within the United States. Paper transportation costs are the costs associated with moving paper products from paper mills to the demand centers. For pulp transportation, all pulp production mills are grouped into three pulp supply centers (PSCs) in the United States. Pulp transportation costs are the costs associated with moving pulp products from PSCs to SCs. Unit transportation costs for each product is a function of location of the supply and demand centers. Domestic transportation costs between the supply and demand centers are adopted from the North American Pulp and Paper model (Ince et al., 1994). Each facility (regardless of its regional location) is allowed to transport paper products to any of the demand centers. However, the model determines the optimal

transportation route between supply centers and demand centers depending on the transportation cost. Total cost of domestic transport for pulp products is expressed as (Eq. 3-13):

$$Z_{T_{Cost}} = \sum_{PC} TQPL_{PC} * PLQ_{PC} \quad (3-13)$$

where  $TQPL_{SC}$  is the cost (\$/year) of transporting a unit of domestic quantity from each pulp supply center to each paper supply center.  $PLQ_{PC}$  is the pulp quantity (tons/year) transported from each pulp supply center to each paper mill. For the integrated pulp and paper mill, the  $Z_{T_{Cost}}$  equals zero. Pulp quantity at a pulp supply center is the total sum of pulp products produced from each pulp unit ( $ip$ ) in that region and is expressed as (Eq. 3-14):

$$TPL_{PC} = \sum_{ip} PLQ_{ip} \quad (3-14)$$

Similarly, total cost of domestic transport for paper products is expressed as (Eq. 3-15):

$$Z_{T_{Cost}} = \sum_{SC} TPR_{SC} * PRQ_{SC} \quad (3-15)$$

where  $TPR_{SC}$  is the cost (\$/year) of transporting a unit of domestic quantity from the paper products supply center to domestic demand centers.  $PRQ_{SC}$  is the paper products quantity transported from each paper supply center. Paper products quantity at supply center is the total sum of paper products produced from each paper unit ( $ir$ ) in a region and it is expressed as (Eq. 3-16):

$$TPR_{SC} = \sum_{ir} PRQ_{ir} \quad (3-16)$$

*Imports:* Import costs ( $Z_{I_{Cost}}$ ) to each import district are the product (of pulp or paper) of the imported quantity and the cost of importing product. The quantity imported to each import district is iteratively determined from the marginal cost of domestic production, at the high cost production facility, and the total cost associated with the imports inclusive of transportation. Cost of imports is the sum of the import price to the import district, insurance and freight to the import district and handling costs at each import district. The import price is determined from a constant elasticity of supply curve for each import district based on user supplied information.

In the current version of the model, the import cost function includes two origins of imports (Canada and the Rest of the World) and three import districts within United States (North, West, and South). Total cost of import is expressed as (Eq. 3-17):

$$Z_{I_{Cost}} = \sum_{id} IQ_{id} * ICOST_{id} \quad (3-17)$$

where  $ICOST_{id}$  is the import cost including import cost (from Canada and ROW), insurance, freight, customs, and handling, and associated cost of transporting a unit of imported quantity from the import districts ( $id$ ) to pulp or paper demand centers.  $IQ_{id}$  is the quantity imported from each origin of import to each import district ( $id$ ).

*Exports:* Pulp and paper product are exported to Canada and the Rest of the World from each demand center and pulp supply centers. Exports quantity is assumed to be the average exported quantity for the last ten years,

and it is assumed to be terminal capacity. User can define yearly quantity increase percentage (e.g., 3 % per year, etc.) Exports cost ( $Z_{E_{Cost}}$ ) to each export district is the product of exported quantity and the cost of exporting product. Costs of exports is the sum of the export price to the export district, insurance and freight to the export district and handling costs at each export district.

*Controls:* A controls database provides information regarding applicable air pollution control technologies and their cost and emission control characteristics. In general, the costs associated with controls comprise the following components: (1) capital and fixed operation and maintenance costs, (2) costs associated with any reagent and/or catalyst consumption, (3) costs associated with any reduction in fuel and/or raw material use, (4) costs associated with electricity consumption, (5) costs associated with byproduct(s), and (6) costs associated with water use, if any. Various cost elements are escalated appropriately to use values in years of interest (Eq. 3-18 and 3-19):

$$CC_{unit} = \sum_{pollutant} (CC_{pollutant} * POLQ_{pollutant}) \quad (3-18)$$

$$Z_{Cc} = \sum_{unit} CC_{unit} \quad (3-19)$$

where  $CC_{unit}$  is the control cost (\$/year) of installing controls on an industrial boiler,  $CC_{pollutant}$  (\$/ton pollutant) is the cost of control per ton of the pollutant it is controlling,  $POLQ_{pollutant}$  is total tons of pollutant produced by a unit. Note that  $Z_{Cc}$  is total control costs (\$/year) for the entire sector calculated by adding  $CC_{unit}$  (control costs) of each unit.

*Energy Efficiency Costs:* Some of the most commonly used measures include good O&M measures, air preheaters and economizers, boiler insulation, minimization of inleakage, and steam line maintenance. The majority of measures are common, such as burner retrofit capable of substantial CO<sub>2</sub> emission reduction. For example, the replacement of conventional LNB with ULNB is capable of reducing NO<sub>x</sub> and CO<sub>2</sub> emissions by 75 percent (NCASI, 2009) and 6 percent (USEPA, 2010), respectively, compared to uncontrolled case.

The cost elements associated with energy efficiency measures are specific to each mill and individual costs to upgrade a mill (Eq. 3-20).  $Z_{upgrade, unit}$  can be added to estimate total cost, Z (Eq. 3-21).

$$E_{upgrade, unit} = E_{old, unit} (1 - \text{Percent reduction}) \quad (3-20)$$

$$Z = \sum_{unit} Z_{upgrade, unit} \quad (3-21)$$

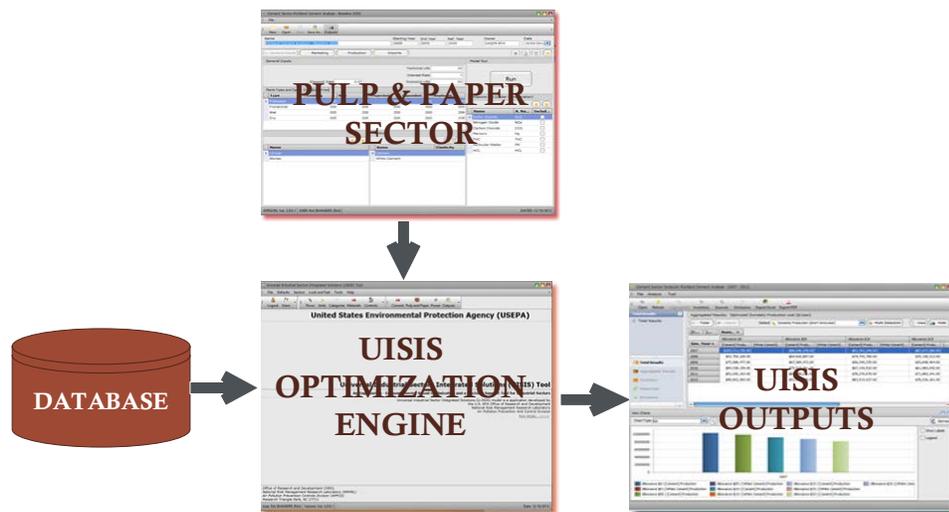
where  $E_{upgrade}$  is emission of a unit after energy efficient measures have been taken, and  $E_{old, unit}$  is the emission of a unit before the measures.

### 3.4. Modeling Framework Architecture

The Universal ISIS is developed in GAMS language and has a modular architecture as shown in Figure 3-3 for the PNP sector.

The inputs from Universal ISIS-PNP are transmitted to the optimization part of the Universal ISIS via the interface, where the inputs from Universal ISIS-PNP are used to solve the selected cases. The Universal ISIS-PNP interface is a single personal-computer-based executable tool that provides a user-friendly tool for exploring and

comparing various scenarios of meeting product demand and pollution reduction requirements for an industrial sector of interest over specified time periods. The Universal ISIS interface allows the user to develop, edit, or delete scenarios for an industrial sector of interest. The functionality of the interface ensures that users are allowed to use individually chosen general inputs as well as policy inputs and are able to access the USEPA-hosted database and Universal ISIS optimization engine to produce output for the desired type of analysis for the industrial sector of interest (in this case the PNP sector). The interface is a web-based application and is programmed in C++ Builder and web development programming software in a graphical web-based layout. The features of the user interface include pull-down menus, mouse support, and point click activation of many of the features. The Universal ISIS database is fully secured and protected, so that each user's scenario option will be evaluated individually.



**Figure 3-3. Modular Architecture of Universal ISIS-PNP**

The Universal ISIS-PNP interface communicates with the Microsoft SQL database, generates input data sheets, and transmits to the Universal ISIS-PNP for optimization. The general input interface helps the user to develop/modify the required modeling framework of the industrial sector of interest which includes time horizon (simulation period) to be used for the model runs, reference year, discount rate, time blocks, commodity characteristics, emission types, fuel types, plant types and characteristics, as well as imports and exports. The interface allows users to define policy-related parameters such as number of mitigation options, types of policy pollutants, emission reduction targets and emission reduction percentages, etc. The user can specify the emission reduction percentage of interest, allowance, banking or non-banking, taxes, minimum reduction levels and policy horizon (time period) to be used for the model runs. Selected data are then pre-processed in the Universal ISIS model to arrive at suitable input parameters for use in equations. After pre-processing the data, Universal ISIS solves for the appropriate levels of production, imports, and controls required for meeting the constraints associated with commodity demand and emissions, while maximizing total surplus. The outputs are transferred into a Microsoft SQL database. The interface then helps the user to interpret these outputs in the desired format (tables, graphs, etc.).

Architecture of an individual module is shown in Figure 3-4 below, using the example of the Universal ISIS-PNP. Figure 3-4 shows inputs containing industry-specific data, market data, and optimization parameters. The industry-specific input data characterize unit-level production, capacity, production cost, capital cost, as well as

fuel types and cost. Input data also provide information about emissions sources, mitigation technologies, energy efficiency measures, and emissions/fuel intensities. The market input data consist of historical and projected nationwide consumption, discount rates, cost of electricity, escalation rates, economic life of technologies, and import and export quantities and prices. Data related to optimization parameters provide information concerning emissions caps, emission reduction percentages, taxes, emission abatements, banking options, and allowance options.

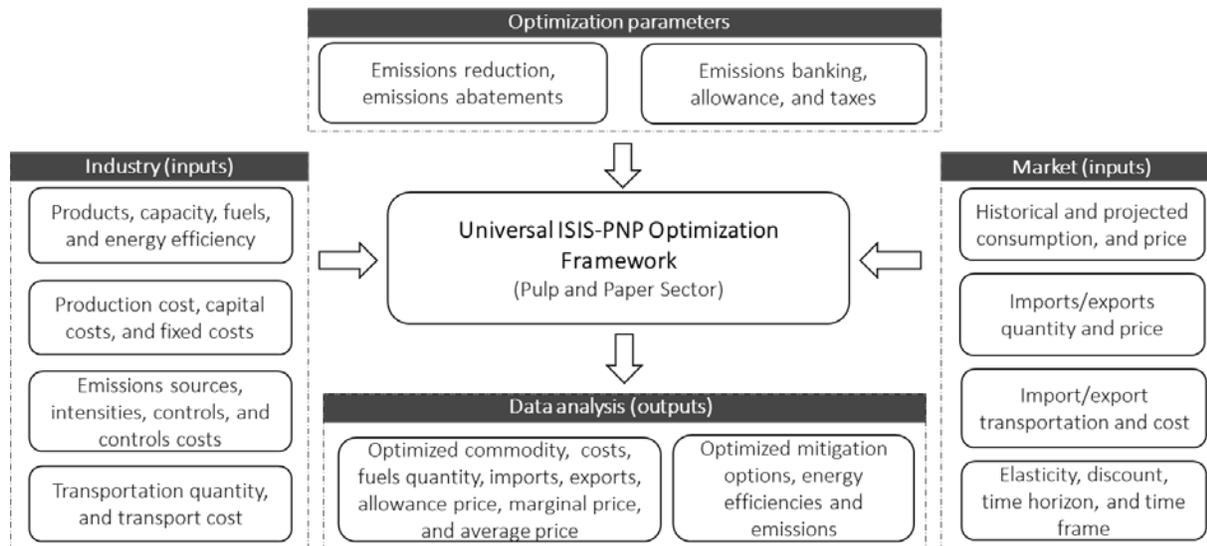


Figure 3-4. Input and Output Data Management in Universal ISIS-PNP

### 3.5. Constraints and Limitations

The Universal ISIS-PNP includes constraints and limitations for ensuring that production capacity changes occur in a realistic way. Constraints include production, consumption-supply, and emissions. Limitations include transportation and terminal capacities.

Production of a commodity is limited to the availability of the plants. Plant availability can be restricted by resource availability such as fuel or raw materials availability and by capacity. For instance, energy consumption by a plant can only be selected from the fuels available at the location of production. The total supply for each demand center has to be greater than or equal to consumption in the given time period. Supply can be comprised of local production, import from other regions, and foreign import. Universal ISIS-PNP provides full flexibility to determine demand centers, imports and exports terminals, commodities quantity and price, and associated domestic and exports/imports transportation costs.

Emissions abatement approaches in Universal ISIS are categorized in three abatement approaches: process modifications and upgrades, raw material and/or fuel substitution, and emission mitigation technologies. For each emission abatement approach, where possible, information on capital cost, fixed operating cost, variable operating cost, emission reduction performance for all of the pollutants, impacts on fuel and/or raw material use, impact on electricity consumption, byproduct generation and cost, and impact on water use is included in the Universal ISIS. The Universal ISIS-PNP framework includes algorithms to account for tracking multiple pollutant streams associated with uncontrolled emissions, controlled emissions, pollution prevention from

process modifications and energy efficiency measures, and any controls-related effects. For a given pollutant, total emissions have to be limited to emission limits specified by the exogenous policy constraints on emissions. If the policy being analyzed allows for banking of emissions, then the banking equation enables banking of allowances for future use.

Transportation of goods and commodities from a supply center is limited by lower of the production capacity of the supply center and the transportation capacity from a supply center to all demand centers, if specified. Imports quantity at each terminal is limited by the terminal capacity. However, Universal ISIS-PNP provides full flexibility to customize assumptions including changes in quantity (e.g., percentage increase per year), changes in import prices and terminal locations.

The objective function of Universal ISIS-PNP is minimized with regard to the constraints described above to arrive at the optimal solution.

### 3.6. Optimization and Post-Processing

In Universal ISIS-PNP, the input data are pre-processed to arrive at suitable input parameters for use in the model equations explained earlier in this chapter. Once the data have been pre-processed, Universal ISIS-PNP solves for the appropriate levels of production, imports, and controls required to meet the constraints associated with product demand and emissions while maximizing total surplus. Once the surplus maximization problem has been solved, the results are post-processed to obtain parameters and level values of the variables of interest. The key variables of interest are: production level of each production unit to meet regional demand, level of imports in each region, installation of various controls, emissions, and various costs. Output data are written in appropriate worksheets in an Excel workbook and further linked to various plots to enable visual presentation and analyses of the results. The Universal ISIS-PNP modeling framework is designed to accommodate the analyses of emission reduction technologies for multiple pollutants. For a particular emission control strategy under consideration, the Universal ISIS-PNP can estimate the amount of emission reductions and associated costs. Universal ISIS-PNP may analyze a number of emissions reduction options including fuel exchange, cap-and-trade, emission taxes, emissions limits, and target emissions reduction. Additionally, appropriate combinations of these options can also be evaluated.

The fuel switching option offers substantial reductions of emissions from the pulp and paper sector. Fuel switching is an attractive option for reducing boiler emissions because these emissions are a function of fuel consumption. For example, combustion of natural gas produces far less SO<sub>2</sub> emissions than coal because of its significantly lower sulfur content. Natural gas and oil are favorable fuels from the standpoint of NO<sub>x</sub> emissions compared to coal and wood. These examples of different fuel switching scenarios can be analyzed by Universal ISIS-PNP and an optimum fuel switching for minimal emissions can be selected.

In the cap-and-trade option, an emissions cap is set on the amount of a pollutant that can be emitted by the sector considered. Sources are issued emission permits (allowances) that represent the right to emit a specific amount of the pollutant. Allowances may be banked for use in future. The total amount of allowances available in the current period and those banked in previous periods cannot exceed the cap in the current period. Sources or companies that need to increase their emissions may buy allowances from those who pollute less. This transfer of allowances is referred to as an allowance trade. In effect, the buyer pays a charge for polluting, while the seller is rewarded for having reduced emissions by more than was needed. Thus, in theory, those that can reduce emissions least expensively will do so, achieving the pollution reduction at the lowest possible cost to

the sector. The Universal ISIS-PNP framework allows the user to select an allowance price to determine the level of emission reduction achieved by the sector corresponding to this selected allowance price. The cost of emissions is determined for each pollutant as the product of the emission and allowance price for the emission considered.

Universal ISIS-PNP framework allows also for evaluation of costs and emission reductions associated with emission reduction programs utilizing unit-specific rate-based emission limits. This is accomplished by imposing the rate-based emission limit for pollutant emitted by any specific unit.

### 3.7. References

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## 4. Pulp and Paper Data

A significant amount of data is required for the Universal ISIS-PNP, including mill-level data, sector data, policy information, and economic parameters. The Universal ISIS-PNP models the pulping and papermaking processes separately to represent the various types of facilities found in the sector (i.e., integrated facilities, non-integrated pulp mills, and non-integrated paper mills) more accurately. The Universal ISIS-PNP focuses on the combustion sources located at pulp and papermaking facilities. These combustion sources include recovery furnaces, lime kilns, and boilers. Recovery furnaces are used to recover valuable pulping chemicals for re-use in the process. Lime kilns are used to convert the recovered pulping chemicals into fresh pulping chemicals. Boilers, often capable of being fired with multiple fuels, are used to generate steam and electricity for the facility and its processes.

Boilers, recovery furnaces, and lime kilns do not produce paper products but are supporting equipment in a larger production process that encompasses a variety of equipment. The onsite production of steam for electricity generation and process heating is a major supporting operation in paper manufacturing. Production of steam is accomplished by utilizing renewable energy sources, primarily byproducts of wood preparation and virgin pulping processes. On average, more than 40 percent of electricity is produced onsite along with cogeneration of steam. Process energy consumption can vary widely due to facility-specific operations. Boilers are fired with a diverse range of fuels and exhibit varying boiler efficiencies as shown in Table 4-1 (DOE, 2005).

**Table 4-1. Boiler Fuel Efficiency**

Fuel Type	Boiler Fuel Efficiency (%)
Oil	83
Gas	82
Coal	81
Bark	64
Black Liquor	65

In 2002, the pulp and paper sector generated 51,208 million kWh, which represented 38 percent of total US industry onsite generation (USDOE, 2005). Table 4-2 lists statistics on fuel and energy use by the pulp and paper sector in 2000, based on data compiled by an industry trade organization (AF&PA, 2002). In 2000, the energy use mix was dominated by the use of self-generated renewable energy (56 %) and purchased natural gas (18 %).

Table 4-2. US PNP Sector Energy Use in 2000

Fuel Source	Billion Btu	% of Total
<b>PURCHASED</b>		
Electricity	155,319.80	7
Steam	33,882.90	1.5
Coal	265,800.00	12
Petroleum Products	102,184.20	4.6
Natural Gas	395,611.00	17.7
Other	24,052.60	1.1
Excess Energy Sold	44,836.00	
Total Purchased	932,014.50	43.9
<b>SELF-GENERATED</b>		
Hogged Fuel	327,359.00	14.7
Spent Liquor (solids)	894,985.90	40.3
Hydroelectric Power	4,989.70	0.2
Other	19,866.50	0.9
Total Self-Generated	1,247,201.10	56.1

The data inputs to the Universal ISIS-PNP can be broadly categorized into the following main components:

- Finished product data
- Mill level data
- Cost data
- Emissions and controls data
- Import modeling data
- Policy and economic parameters

This chapter discusses the data collection methodology as well as the components of Universal ISIS-PNP input data.

## 4.1. Data Collection Methodology

Data to assist in characterizing individual facilities and the collective industry were purchased from Resource Information Systems, Inc. (RISI) for facilities with available data. The RISI data included information on pulp and paper production, cost, facility characterization, product composition, and import-export. The data sets purchased from RISI and a description of each set are given below:

- North American Graphic Paper Capacity Report 2011– this report summarizes the current, planned, and future capacity for the North American printing and writing paper market
- North American Graphic Paper Historical Data – this report contains 17 years of historical data (annual basis), including production, consumption, imports, exports, capacity, prices, and costs for the graphic papers, recovered paper, and pulpwood markets
- World Recovered Paper Annual Historical Data – this report contains 17 years of historical data (annual basis) for supply, demand, and price for recovered paper
- North American Paper Packaging Capacity Report 2011 – this report summarizes the current, planned, and future capacity for the North American paper packaging market
- North American Paper Packaging Annual Historical Data – this report contains 17 years of historical data (annual basis), including production, consumption, imports, exports, capacity, prices, and costs for corrugated box, containerboard, boxboard, packaging and industrial papers, and recovered paper and pulpwood
- World Market Pulp Capacity Report 2011 – this report contains current, historical, and future capacity for the world paper grade market pulp industry
- World Pulp Annual Historical Data – this report contains 17 years of historical data (annual basis) for the world market pulp industry
- World Tissue Capacity Report 2011 – this report contains current, historical, and future capacity of the world tissue market
- United States Mill Asset Database – this database provides process flow diagrams for US pulp and paper facilities

The 2011 Lockwood-Post, a directory of the North, Central, and South American pulp and paper mills, was also purchased from RISI. This directory is a compilation of survey information obtained annually from many of the mills and companies listed in the directory, supplemented with data from other sources. The data in the directory included facility locations, process types, product types, and production capacities. Only facilities operating in 2011 and those that closed in 2010 were included in the directory, i.e., facilities that were idle or closed prior to 2010 were not included and neither were facilities idled in 2011 but expected to reopen in 2012.

Emissions and controls data were obtained from an information collection request (ICR) survey sent to the pulp and paper industry by the USEPA in 2011. This survey collected information for use in regulatory reviews, i.e., the review of the National Emission Standards for Hazardous Air Pollutants (NESHAP) for pulp and papermaking sources and the NESHAP for chemical combustion sources at pulp mills, as well as the review of the NSPS for kraft pulp mills. Only major source facilities (i.e., those that produce more than 25 tons per year of hazardous air pollutants) in operation during base-year 2009 were required to complete the ICR survey. Data for area source facilities (typically stand-alone paper mills) were not collected.

Historical mill information was obtained from the “Mills Online” database (<http://www.cpbis.gatech.edu/data/mills-online-new>) maintained by the Center for Paper Business and Industry Studies at the Georgia Institute of Technology. This database provides historical mill data for all facilities which

have operated in the US since 1970. The data included mill location, number of products produced, and whether or not a facility was an integrated facility. The website also tracks company announcements such as capacity expansions, closures, and acquisitions.

Supplemental data for facilities were obtained from company websites, news websites, and trade organization websites, including the mill curtailments and closures spreadsheet maintained by the Pulp & Paper-workers Resource Council (<http://www.pprc.info/html/millclosures.htm>). These data were used to determine if facilities were closed and to determine product composition (e.g., recycled material content).

## 4.2. Finished Product Data

Finished product data were purchased from RISI to provide 10 years of historical information for the Universal ISIS-PNP. This section discusses the processing of the purchased data and a summary of the final data used for the Universal ISIS-PNP.

### 4.2.1. Data Processing

Universal ISIS-PNP modeling efforts were focused on representing the entire population of US integrated and non-integrated pulp and paper mills and their products. The pulp and paper sector produces a wide variety of products, e.g., printing and writing papers, sanitary tissue, industrial-type papers, containerboard, boxboard, newspaper, etc. Therefore, it becomes essential to aggregate products into product categories to make modeling more manageable and to develop benchmark products that are capable of describing the industry. Paper products were aggregated into eight major product categories. Similarly, pulp products there were aggregated into two major product categories: softwood pulp and hardwood pulp. Table 4-3 lists the major product categories for paper products and pulp products utilized in the model. At the same time, the assumption was made that products of similar functionality, i.e., belonging to the same major product category, will share the same demand variables.

The methodology of similar product aggregation into product category is illustrated in Figure 4-1 for the boxboard group of products.

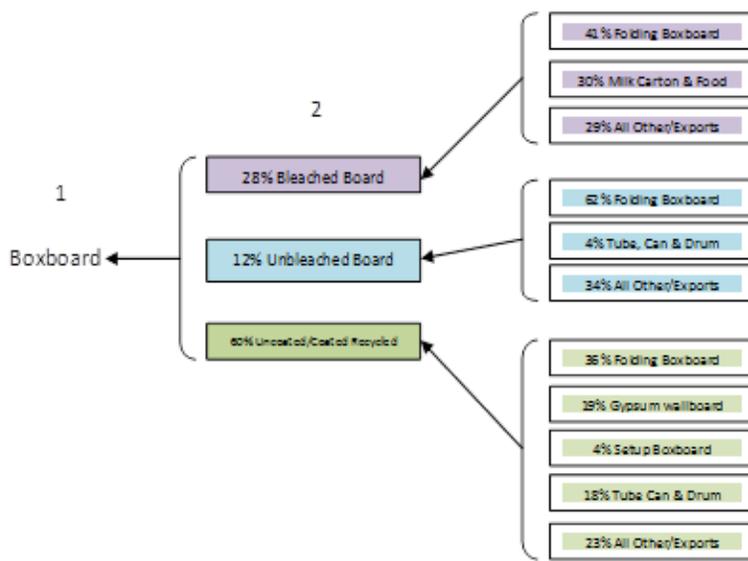


Figure 4-1. Methodology of Product Aggregation into Product Categories

Table 4-3. Universal ISIS Product Categories for the US Pulp and Paper Market

Paper		
Categories	Subcategories	
1. Containerboard (CNT)	Bleached Kraftliner Unbleached Kraftliner White-top Kraftliner Semi-chemical Medium	Recycled Medium Recycled Liner-board White-top Recycled Liner
2. Boxboard and Other Board (BXT)	Bleached Boxboard Unbleached Boxboard Folding Cartonboard Liquid Packaging board Food Service Folding Boxboard Other Unbleached Boxboard Recycled Boxboard Other Recycled Board	Coated Cartonboard Uncoated Cartonboard Gypsum Wallboard Facings Tube, Can, Core, and Drum Multi-ply/Multi-furnish Boxboard White-lined Chipboard Liquid Packaging Board Bleached Kraft Board
3. Packaging and Industrial Paper (PIP)	Kraft Wrapping Paper Unbleached Kraft Paper Bleached Kraft Paper	Unbleached Packaging Paper Bleached Packaging Paper Specialty and Industrial Paper
4. Corrugating Medium (COR)	Semi-chemical Medium Recycled Medium	
5. Newsprint		
6. Tissue		
7. Coated Printing and Writing Paper (CPW)	Coated Free-sheet Coated Bristol Coated Free-sheet including coated Bristol	Coated Mechanical Coated Groundwood
8. Uncoated Printing and Writing Paper (UPW)	Uncoated Freesheet Uncoated Bristol Cotton Fiber Papers	Uncoated Freesheet including Uncoated Bristol and Cotton Fiber Paper Uncoated Mechanical Uncoated Groundwood
Pulp		
1. Hardwood Pulp (HWP)	Bleached Hardwood Kraft Unbleached Hardwood Kraft	Mechanical Hardwood
2. Softwood Pulp (SWP)	Bleached Softwood Kraft Unbleached Softwood Kraft	Mechanical Softwood

Boxboard comes in various forms, may be bleached or unbleached, and may also be recycled. Furthermore, many boxboard products serve a similar purpose but have slightly different characteristics to meet niche needs. Boxboard, a thick, paper-based material that is generally thicker than regular paper, is used for products such as

milk cartons, cereal boxes, shoe boxes, or frozen food packaging. In general, boxboard is used for the packaging of non-durable consumer goods. However, the functionality of these different boxboard products, the driver of consumer demand, remains similar. Therefore, because Universal ISIS-PNP models demand, these similar boxboard products were aggregated (by weighted mean approach) into one product category to arrive at the total demand for the product category as well as weighted prices and costs.

#### 4.2.2. Data Summary

Final product data were collected for 514 facilities and 37 product subcategories. Many facilities produce more than one subcategory of each grade of paper, and as a result, a total of 908 sets of 10-year data were available for the eight major paper products and the two major pulp products. The Uncoated Printing and Writing Paper category had the most information with 211 data sets at 146 facilities and contained subcategories such as uncoated mechanical, uncoated free-sheet, uncoated ground-wood, uncoated Bristol, and cotton fiber papers. The Boxboard and Other Board category was the second largest category with 170 data sets for 135 facilities. The Boxboard and Other Board category contained subcategories such as uncoated carton-board, recycled board, folding carton-board, food service, liquid packaging, bleached kraft board, coated carton-board, other unbleached board, and other recycled board. The remaining categories can be found in Table 4-4, which summarizes the number of data sets available for analysis and the number of facilities producing each product.

**Table 4-4. Summary of Facilities Producing Each Major Product Category**

Major Category	Number of Data Sets	Number of Facilities
Containerboard	77	73
Boxboard and Other Board	170	135
Packaging and Industrial Paper	143	34
Corrugating Medium	70	66
Newsprint	24	24
Tissue	86	86
Coated Printing and Writing Paper	68	58
Uncoated Printing and Writing Paper	211	146
Hardwood Pulp	20	20
Softwood Pulp	39	39
<b>TOTAL Number of Records</b>	<b>908</b>	<b>N/A</b>

Production for the major paper products for 2000 and 2010 is shown in Table 4-5. All of the products except for tissue experienced a decline during this time period. Newsprint experienced the largest decline with production dropping from 7,463 tons to 3,588 tons, a decrease of 51.9 percent. Overall industry production declined from 105,030 tons to 89,939 tons, a reduction of 14.4 percent.

**Table 4-5. Summary of Production by Major Product Category**

Major Category	2000 Production (1000 tons/year)	2010 Production (1000 tons/year)	Change (%)
Containerboard	26,377	25,556	-3.1
Boxboard and Other Board	17,400	14,826	-14.8
Packaging and Industrial Paper	6,197	5,637	-9.0
Corrugating Medium	10,953	10,415	-4.9
Newsprint	7,463	3,588	-51.9
Tissue	7,359*	7,628	3.7
Coated Printing and Writing Paper	11,126	8,814	-20.8
Uncoated Printing and Writing Paper	18,155	13,475	-25.8
<b>TOTAL</b>	<b>105,030</b>	<b>89,939</b>	<b>-14.4</b>

\*This value is for 2005, the first year of available data for tissue in the RISI report.

### 4.3. Mill Data

Mill level data utilized in the Universal ISIS-PNP were purchased from RISI, collected through the ICR, and obtained from researching the internet. This section discusses the processing of the mill level data and a summary of the final data used for the model. This section focuses on the currently operating US facilities as well as those that have closed since 2000. The Universal ISIS-PNP does not project new mills or options for the addition of new production capacity by region because no new facilities have been built since 1990, and the current trend is to reopen closed mills (i.e., International Paper in Franklin, VA). Each mill facility modeled was characterized by its location, pulping process, facility equipment availability, annual product capacities, and retirement information, when applicable. In addition, each facility was characterized by its average variable cost components. This information is discussed further in the following sections.

#### 4.3.1. Data Processing

The number of mills in the Universal ISIS-PNP database and their locations were determined using the North American Graphic Paper Capacity Report, the North American Paper Packaging Capacity Report, and the World Tissue Capacity Report purchased from RISI. The mill types (integrated or non-integrated) were determined using the ICR and Center for Paper Business and Industry Studies' "Mills Online" database. For mills that are currently closed, a retirement date was determined using the Pulp & Paper Resource Council's website and the capacity report (i.e., facilities with "0" capacities were assigned the first year of "0" capacity as their retirement year). Facilities in the Universal ISIS-PNP database were identified based on a plant type and a Universal ISIS-PNP ID number. These values were concatenated to form mill identification numbers and were then used to identify the facilities in each data table (e.g., market pulp production, paper production, etc.).

As mentioned previously, the pulp and paper industry is regional in nature. In Universal ISIS-PNP, each facility modeled is located in one of three regional markets (USDOA, 1994) and shown in Figure 4-2.

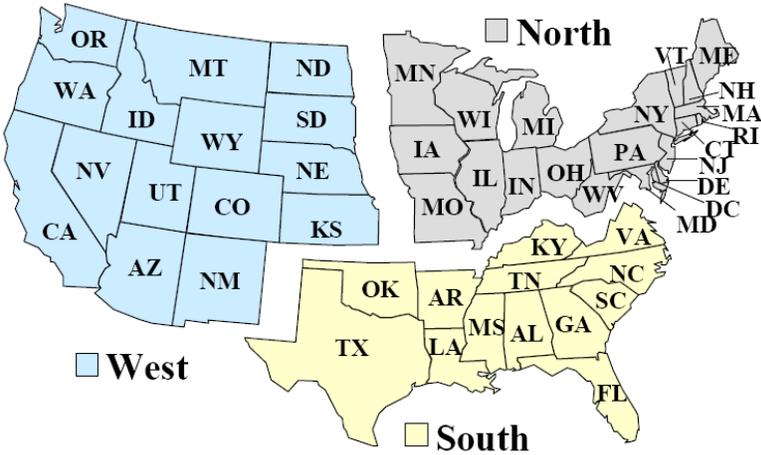


Figure 4-2. Mill Capacity Regions in the US (USDA, 1994)

Although the US market for pulp and paper products exhibits regional behavior, the Universal ISIS-PNP allows for all modeled facilities to supply demand in any region, subject to transport costs as discussed later. It is important to note that the purchased RISI data divided the market into two regional markets (north and south) as opposed to the three regional markets shown in Figure 4-2. However, considering the variation in regional behavior, we decided that three regional markets would be a better representation of the US market for pulp and paper. Data for the mills that belonged to the northwest and southwest regions in the RISI database were assigned to the mills located in the west region of the Universal ISIS-PNP database. Table 4-6 shows the states in each Universal ISIS-PNP and RISI region for comparison.

Table 4-6. Universal ISIS-PNP and RISI Region Comparison

RISI Region North		RISI Region South	
State	Universal ISIS-PNP Region	State	Universal ISIS-PNP Region
CT	North	AL	South
DE	North	AR	South
IA	North	FL	South
IL	North	GA	South
IN	North	KY	South
MA	North	LA	South
MD	North	MS	South
ME	North	NC	South
MI	North	OK	South
MN	North	SC	South
MO	North	TN	South
NH	North	TX	South
NJ	North	VA	South
NY	North	AZ	West
OH	North	CA	West
PA	North	NM	West
VT	North	NV	West
WI	North	UT	West
WV	North		
CO	West		
KS	West		
MT	West		
OR	West		
WA	West		
ID	West		

### 4.3.2. Process Characterization

The United States Mill Asset Database, a collection of process flow diagrams (PFDs) for 231 mill facilities, was used to extract process and production information. The data extracted included pulp production, product composition, facility type, whether or not the facility could purchase market pulp and/or recycled pulp, number of boilers and recovery furnaces, fuels utilized, steam and electricity generation, and electricity utilization. These data were extrapolated to the remaining 283 mill facilities that did not have PFDs available. Production process information for facilities without PFDs (e.g., the ability to process recycled fiber) was determined using public information on company websites.

Production process characteristics for the facilities such as capacity, product recipe, electricity usage, pulp mill type, equipment classification, controls, and lime mud and black liquor production were determined using the PFDs purchased from RISI (the United States Mill Asset Database), the ICR, and company websites. These parameters were used in Universal ISIS-PNP to represent production processes at the modeled facilities more accurately.

The final product capacity for each product for each facility was determined using the maximum production value for the 10-year period for which data were purchased. A facility was assumed to be operating at 85-percent capacity in the year with the highest production. This value represents the maximum amount of each product a facility can make without making a process change or upgrading equipment. Capacity for a facility was reported as "0" for years which production values were "0." An example is shown in Table 4-7 below.

**Table 4-7. Production Capacity Example**

Values (in thousands of tons/year)	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	MAX
<b>Production</b>	5.5	7.5	6.0	8.5	10.5	7.5	5.5	5.0	2.5	0	0	10.5
<b>Capacity</b>	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	12.4	0	0	12.4

For integrated facilities, pulp production and pulp capacity were calculated using the PFDs for those with available data. For pulp production, pre-digester and post-digester pulp values were extracted from the PFDs and used to calculate pulping yield. For example, a pre-digester value of 2,400 bone dry short tons (BDST) per day of softwood chips and a post-digester value of 1,170 BDST per day of softwood pulp indicate a pulping yield of 48.75 percent. This pulping yield was then used in conjunction with the values in the product summary table (such as Table 4-7) on the PFD for the amount of wood used for each product to determine the amount of pulp needed for each product. For example, if a ton of finished product requires 1.411 BDST of wood, the product requires 0.361 BDST of pulp ( $1.411 \times 0.4875 = 0.361$ ). This value was then multiplied by the yearly production value for the product to determine the amount of pulp produced. These calculations were repeated for all products produced at a mill and then summed to obtain the final pulp production value. Final pulp values were averaged based on the major product category produced, and tons of pulp needed per ton of product values were assigned to similar facilities where PFDs were unavailable. Pulp mill capacity was determined using the maximum production year and a utilization factor of 85 percent, the same method used to calculate final product capacity in Table 4-8.

**Table 4-8. Example Product Summary Table for an Integrated Facility**

Category	Units	Product Grade	
		PIP	CNT
SWRW	BDST/FST	1.411	1.286
SW Chips	BDST/FST	0.734	0.669
Starch	BDST/FST	0.015	0.010
Hog fuel	BDST/FST	0.165	0.169
Coal	Short ton/FST	0.155	0.159
Oil	BBL/FST	0.309	0.288
Electricity	kWh/FST	428	423

BDST = bone dry short ton FST = finished short ton

BBL = barrel SW = softwood

SWRW = softwood/roundwood

PIP = Packaging and Industrial Paper CNT = Containerboard

Product recipes were determined using the product summary table on the PFD for facilities where PFDs were available. These values represent the amount of softwood pulp, hardwood pulp, additives, and recycled pulp in the final product. In the case of integrated facilities, the pulping yield, as calculated for the pulp mill production and capacity values, was also used to determine product composition. This calculated value and the values for SWRW (softwood, roundwood), HWRW (hardwood roundwood), SW Chips (softwood chips), and HW Chips (hardwood chips) were used to determine the amount of virgin pulp in the final product. Values for starch and filler from the summary table were also accounted for to calculate an accurate composition. For non-integrated facilities, values for pulps and recycled papers from the product summary table (such as Table 4-9) were used to calculate product composition. All recycled paper values (e.g., de-inked pulp, pulp substitutes, old corrugated containers, old newsprint, and mixed paper) were summed up to create one “recycled pulp” value for each product. Market pulp values (e.g., northern bleached softwood kraft pulp and northern bleached hardwood kraft pulp) were maintained as separate values to determine softwood and hardwood percentages. Average product compositions were determined based on final product and mill classification (e.g., non-integrated vs. integrated, recycle mill vs. virgin mill) and assigned to facilities without PFDs.

**Table 4-9. Example Product Summary Table for a Non-Integrated Facility**

Category	Units	Grade: UPW
Northern Bleached Hardwood Kraft Pulp	ADMT/FST	0.335
Northern Bleached Softwood Kraft Pulp	ADMT/FST	0.211
De-inked pulp/pulp waste	ADMT/FST	0.094
Pulp Subs	ADST/FST	0.156
Starch	BDST/FST	0.026
Filler	BDST/FST	0.188
Natural Gas	MCF/FST	13.11
Electricity	kWh/FST	610

ADMT = air-dried metric ton

ADST = air dried short ton

MCF = million cubic feet

FST = finished short ton

BDST = bone dry short ton

UPW = Uncoated Printing and Writing Paper

The paper grade recipes were confirmed to match the classification of the facility. For example, a facility producing boxboard from 100-percent recycled material was confirmed to be represented by a “1” in the “facility can purchase recycled pulp” column. We also confirmed, for example, that a facility producing tissue from 50-percent hardwood pulp and 50-percent softwood pulp could produce the pulp (indicated by a “Y” in the “integrated facility” column) or could purchase the pulp (indicated by a “1” in the “can purchase market pulp” column) for use in the final product. In cases where these conditions were not met, product recipes were adjusted accordingly; that is, if a product composition was assumed for a facility, and that facility could not produce or purchase virgin pulp but could purchase recycled pulp, the product composition was changed to 100-percent recycled. Some facilities produced products from both recycled pulp and from virgin pulp. In these cases, all products were compared to the mill classification to confirm that the facility was capable of making all of the products based on their characterization. We also confirmed that all pulp mills had corresponding pulp production data. For example, an integrated facility producing hardwood pulp and making containerboard from hardwood and softwood pulp was confirmed to be represented by “Y” in the “integrated facility” column and a “1” in the “facility can purchase pulp” column. For the integrated mills, we confirmed that hardwood pulp production and/or softwood pulp production values were available. If all years were reported as zero for both pulp types, the pulp mill classification was removed.

Pulp mill type was determined for the 163 pulp mills in the database. This information dictated the type of equipment utilized at the facility, as well as the type and quantity of emissions. Pulp mills were classified as mechanical or chemical based on the PFDs, ICR information, and company websites. Chemical pulp mills were further classified as sulfate (kraft pulping) or other.

Equipment information was determined using the ICR, the boiler Maximum Achievable Control Technology (MACT) database, and the PFDs. For integrated facilities, boilers were assigned to paper mills, while lime kilns and recovery furnaces were assigned to pulp mills. The average number of boilers, lime kilns, and recovery furnaces (3, 1, and 2, respectively) was determined for integrated facilities with data and were assigned to those without data. The average number of boilers (2) for stand-alone paper mills was assigned to facilities without

PFDs. Lime kilns and recovery furnaces were not assigned to facilities using chemical pulping methods other than sulfate (kraft), unless ICR data showed that the facility had one or both.

Existing controls for the assigned equipment were determined based on the ICR and the boiler MACT database for those with data available. Boiler controls were assigned based on fuel type and products produced at similar facilities with data. Lime kiln controls were assumed to be scrubbers for all kilns without data, and recovery furnace controls were assumed to be dry-bottom electrostatic precipitators (DBESPs), both based on the representative control for the majority of emission units with data.

Lime mud production and black liquor production were calculated using information collected in the ICR. Values in the ICR for lime mud production were on the basis of a ton of CaO produced per day, and a recovery rate of 90 percent was assumed to calculate the amount of lime mud burned per day. This value was then combined with the previously calculated daily pulp production for 2009, resulting in a ton of lime mud produced per ton of pulp produced value. An average value of 0.270 ton of lime mud produced per ton of pulp produced was assigned to mills without ICR data (this value was the average of all available data). Black liquor values in the ICR were based on million pounds of solids per day. This value was combined with the previously calculated daily pulp production for 2009, resulting in tons of black liquor solids produced per ton of pulp produced. An average value of 1.49 tons of black liquor solids produced per ton of pulp produced was assigned to mills without ICR data (this value was the average of all available data).

Landfill data were provided in the summary table of the PFDs in the form of waste ton per ton of final product. For facilities without a PFD, a landfill value was assigned based on mills with data with of similar mill type and final product type.

### 4.3.3. Boiler and Fuel Characterization

Electricity data were extracted from the boiler section of the PFDs for the available facilities. In this section, the number of power boilers was indicated for each plant, as well as the amount of electricity generated, used, purchased, and sold. These values were combined with the daily production values to determine the electricity values (i.e., generated, used, purchased, and sold) per ton of finished product. Facilities with electricity values were averaged based on all of the products produced at each facility, as well as the facility type, and then applied to similar facilities producing similar products without PFDs.

Boiler data were extracted from the boiler section of the PFDs for available facilities. The number of power boilers and the fuel used for each facility were extracted. Fuel intensities, or amounts of each fuel used per ton of production were also extracted from the PFD summary table. Some boilers had input fuels that were not assigned to product intensities. These fuel intensities were not populated; however, the fuel intensities were included as fuels available for use by the facility. An example of this scenario is shown in Figure 4-3. Fuel intensities were averaged per product and assigned to facilities without PFDs. Controls and boiler fuel types were assigned based on the most frequently used for each product in the database. Boiler fuel data as well as the number of boilers were also extracted from the boiler MACT database and compared to the PFD results. These additional data assisted in populating values for facilities without PFDs.

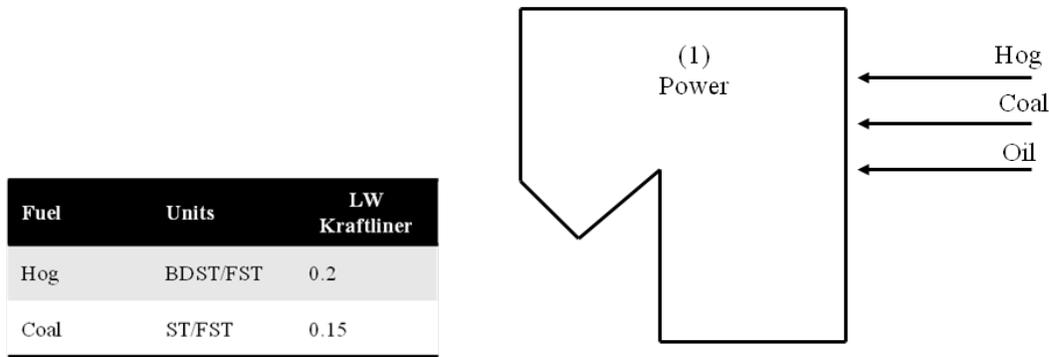


Figure 4-3. Example Boiler Data

Facility fuel availability was assigned to each facility based on fuel intensities from the PFD summary table and boiler input fuels (PFD and boiler MACT). These values were assigned to facilities without PFDs based on final products produced and facility type.

#### 4.3.4. Data Summary

The total number of facilities represented in Universal ISIS-PNP was 514, which consisted of 151 integrated facilities, 12 stand-alone pulp mills, and 351 stand-alone paper mills. Individually, there were 163 pulp mills and 502 paper mills represented in the model. These facilities were located in 43 states, divided into three regions. There were 63 facilities located in the west region, 160 facilities in the south, and 291 facilities in the north. Of the 163 pulp mills, 145 were classified as chemical pulp mills and 18 were classified as mechanical pulp mills. According to the populated retirement dates, 346 of the facilities were operating in 2012.

Facilities were classified as to whether or not they could purchase recycled fiber and produce or purchase market pulp. Of the 163 pulp mills, 49 mills were able to produce market pulp. Many facilities (322) were able to purchase recycled fiber, and 193 were able to purchase market pulp. Recovery rates for recycled fiber were estimated for each major product and are shown in Table 4-10.

Table 4-10. Recycled Fiber Recovery Rates for Major Product Grades

Grade	Recovery Rate (%)
Boxboard and Other Board	91.2
Containerboard	50.0
Corrugating Medium	91.2
Coated Printing and Writing Paper	56.8
Newsprint	73.0
Packaging and Industrial Paper	50.0
Uncoated Printing and Writing Paper	56.8

The electricity data showed that 513 facilities consume electricity. The remaining facility utilized only steam according to the RISI data. Many facilities (391) were able to produce electricity, and 19 of those facilities produced a surplus of electricity and sold the excess to the grid. A total of 490 facilities purchased electricity.

Facilities consuming electricity used an average of 899 kWh/ton product. Facilities producing electricity made on the average 597 kWh/ton and facilities selling electricity made on the average 829 kWh/ton.

Fuel availability was determined for all facilities so that fuel switching could be utilized as an emission reduction strategy. Fuels such as coal and natural gas may be available to a facility even if those fuels are not currently in use. Table 4-11 shows the number of facilities with the option to use each type of fuel assessed.

**Table 4-11. Fuel Availability Summary**

Fuel	Number of Facilities
Coal	210
Natural Gas	488
Oil	335
Hog	171
Free hog	142
Sludge	34
Tire-derived fuel	19
Pet-coke	14

Boilers were assigned to paper mills and stand-alone pulp mills in the model to prevent duplicate counting. All of the facilities in the database except for two had at least one boiler and a total of 1,196 were characterized for the model. Of the 163 pulp mills, 128 were assigned at least one recovery furnace and 124 were assigned at least one lime kiln. A total of 217 recovery furnaces and 162 lime kilns were characterized for the model.

Existing controls were assigned to the boilers, recovery furnaces, and lime kilns based on ICR data and assumptions previously discussed. As shown in Table 4-12, DBESPs were the most commonly utilized air pollution control device for recovery furnaces (155 units). Wet-bottom ESPs were second most common, utilized on 40 recovery furnaces. As shown in Table 4-13, scrubber was the most commonly used air pollution control device for lime kilns, followed by an ESP at 27 units. Boiler controls were specific to fuel type and are shown in Table 4-14.

**Table 4-12. Recovery Furnace Controls Summary**

Control Device	Number of Emission Units
DBESP	155
Wet-bottom ESP	40
DBESP-WPR	16
DBESP and Wet-bottom ESP	1
DBESP and SCBR	1
Wet-bottom ESP and SCBR	1
SCBR	2
DBESP and DBESP-WPR	1
<b>Total</b>	<b>217</b>

WPR = wet particulate matter removal      SCBR = scrubber  
 DBESP = dry bottom electrostatic precipitator      ESP = electrostatic precipitator

**Table 4-13. Lime Kiln Controls Summary**

Control Device	Number of Emission Units
SCBR	121
ESP	27
ESP and SCBR	8
CYC and SCBR	4
CYC and ESP	1
MC and SCBR	1
<b>Total</b>	<b>162</b>

CYC = cyclone      MC = multicyclone      SCBR = scrubber  
 ESP = electrostatic precipitator

**Table 4-14. Boiler Controls Summary**

<b>Fuel</b>	<b>Control Device</b>	<b>Number of Emission Units</b>
Coal (total: 248)	Scrubber - Electrostatic precipitator	19
	Electrostatic precipitator	107
	Fabric Filter	118
	Scrubber	1
	Furnace sorbent injection - Electrostatic precipitator	1
	Fabric Filter - Dry sorbent injection	2
	Low NO <sub>x</sub> burners	27
Gas (total: 596)	Venturi Scrubber	2
	No Control	588
	Fabric Filter	1
	Cyclone or Multi- Cyclone	5
	Low NO <sub>x</sub> burners	270
Dry Biomass (total: 51)	Scrubber	16
	Venturi Scrubber - Electrostatic precipitator	1
	Fabric Filter	1
	Fabric Filter - Dry Sorbent Injection	2
	Electrostatic precipitator	22
	Dry sorbent injection and Electrostatic precipitator	1
	Duct sorbent injection and Electrostatic precipitator	1
	Dry Scrubber - Cyclone	1
	Cyclone or Multi- Cyclone - electrified filter bed	2
	Cyclone or Multi- Cyclone	4
	Low NO <sub>x</sub> burners	13
Heavy Liquid (total: 47)	No control	41
	Scrubber	4
	Spray dryer absorber	2
	Low NO <sub>x</sub> burners	21
Light Liquid (total: 84)	Scrubber	1
	No Control	81
	Electrostatic precipitator	2
	Low NO <sub>x</sub> burners	6

Fuel	Control Device	Number of Emission Units
Wet Biomass (total: 170)	Wet Scrubber - Electrostatic precipitator	4
	Scrubber	63
	No control	1
	Spray dryer - Fabric filter	1
	Fabric Filter	2
	Electrostatic precipitator	95
	Dry sorbent injection - Electrostatic precipitator	1
	Dry sorbent injection – Cyclone or Multi- Cyclone	1
	Cyclone or Multi- Cyclone	1
	Dry Scrubber - limestone injection - Electrostatic precipitator	1
	Low NO <sub>x</sub> burners	48

### 4.4. Cost Data

Cost data were obtained from RISI or calculated for six primary cost functions in the model. The primary cost functions were raw material cost, maintenance and repair cost, labor cost, fuel cost, electricity cost, and solid waste disposal cost. The development of these functions is discussed in this section.

#### 4.4.1. Raw Material

Hardwood and softwood logs and chips serve as raw materials for integrated facilities and non-integrated pulp mills, whereas market pulp serves as the feed for non-integrated paper mills. The Universal ISIS-PNP identifies paper mills and pulp mills as two separate entities, however, regardless of whether or not the facility is integrated. As a result, the raw material cost was divided between pulp mills and paper mills. Raw material cost for pulp mills included the cost of raw wood, pulping chemicals and wastewater treatment, whereas paper mill raw material cost would represent the cost of papermaking chemicals and purchased fiber (i.e., recycled fiber and market pulp). Raw material costs (\$/short ton of finished product) for each major product category were obtained from the RISI database for a period of 11 years (2000 to 2010), and the final raw material cost for each major product was calculated by summing the weighted average (based on the capacity in the respective year) of each year’s raw materials cost.

#### 4.4.2. Maintenance and Repair

Repair and maintenance are required for periodic upkeep of facilities. Maintenance and repair costs (\$/short ton of finished product) for each major product category were obtained from the RISI database for a period of 11 years (2000 to 2010). RISI reported the maintenance costs for integrated mills only. Fifty percent of the reported maintenance costs were considered to make up the maintenance cost of the stand-alone facilities to conform to the design framework of the Universal ISIS-PNP. Final maintenance and repair cost for each major product was calculated by adding the weighted average (based on the capacity in respective year) of each year’s maintenance and repair cost.

### 4.4.3. Labor

Labor costs were obtained by adding operating labor cost and mill-salaried labor costs. Labor costs were calculated based on the data reported by RISI Inc. for a period of 11 years (2000 to 2010). However, the RISI database represented the labor costs for integrated mills only. Therefore, 48 percent of the total labor costs was used for the non-integrated paper mills, and 52 percent was used for the non-integrated pulp mills. Final labor cost for each major product was calculated by adding the weighted average (based on the capacity in respective year) of each year's labor cost.

### 4.4.4. Fuel

Coal, oil, natural gas, black liquor, biomass, hog-fuel sludge, bark, and TDF are primary fuels used in the pulp and paper industry. Coal, oil, natural gas, biomass, hog fuel, bark, sludge, and TDF are largely consumed in the boiler, whereas black liquor is used primarily in the recovery furnace. The Universal ISIS-PNP database gives a detailed description of the types of fuels used in each pulp and paper mill in the United States. The fuel database of Universal ISIS-PNP was constructed based on the information collected from the RISI and ICR databases. Fuel cost (\$/MMBtu) in each state for each fuel type has been collected from US Energy Information Administration website ([http://www.eia.gov/state/seds/sep\\_fuel/html/pdf/fuel\\_pr\\_wv.pdf](http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_pr_wv.pdf))

### 4.4.5. Electricity

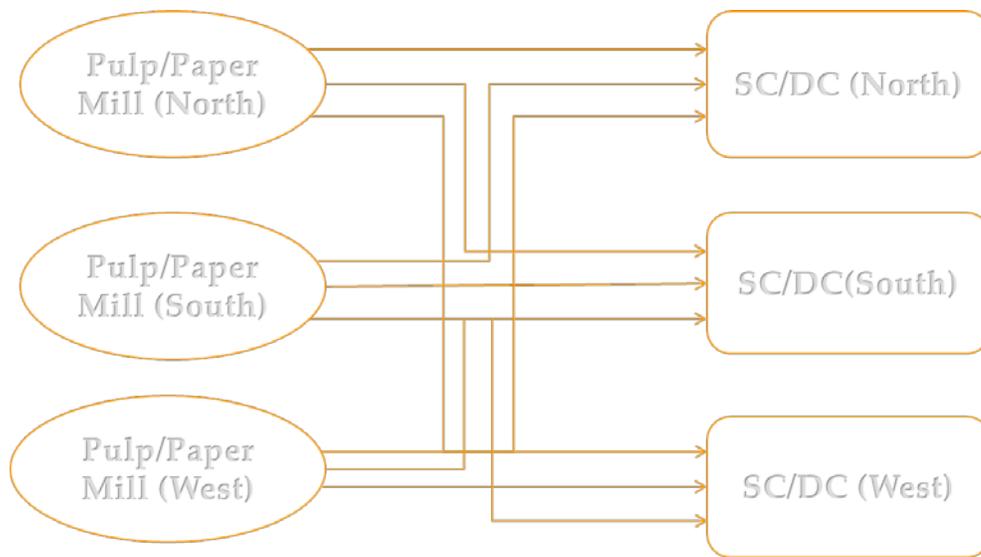
Electricity is consumed primarily by the auxiliary equipment and paper machine(s). Integrated facilities often produce more electric power than required and sell extra electricity to the power grid. The Universal ISIS-PNP database reported the amount of electricity sold, produced and/or purchased with respect to each mill in the United States. Electricity cost (cents/Kwh) in each state for was collected from National Public Radio website (<http://www.npr.org/blogs/money/2011/10/27/141766341/the-price-of-electricity-in-your-state>)

### 4.4.6. Solid Waste Disposal

Facilities must dispose of production process waste materials. Many of the facilities dispose of waste materials by utilizing a private landfill. The amount of waste generated per ton of finished product was calculated as discussed previously and a value of \$50 per waste ton was assigned as the disposal cost.

### 4.4.7. Transportation and Interregional Trade

In the Universal ISIS-PNP, a domestic transportation matrix was used to describe the costs for transporting pulp from pulp mills to paper mills, and from paper mills to demand centers (the US market for paper products). Figure 4-4 illustrates the Universal ISIS-PNP network of domestic transport of pulp from pulp mills to paper mills in three regions within the United States.



**Figure 4-4. Domestic Transport of Pulp from Pulp Mills to Paper Mills**

Transportation costs were calculated by adapting the methodology for the North American Pulp and Paper modeling framework (USDOA, 1994). However, transportation costs reported in the United States Department of Agriculture report were adjusted by the consumer price index published by the Bureau of Labor Statistics <http://www.bls.gov/cpi/> to obtain real 2010 dollar values.

## 4.5. Emissions and Controls Data

The design of the Universal ISIS-PNP can accommodate any number of pollutants of interest. In the model, each boiler, recovery furnace, and lime kiln were characterized by their NO<sub>x</sub>, SO<sub>2</sub>, PM, and CO<sub>2</sub> emissions.

### 4.5.1. NO<sub>x</sub>

In the Universal ISIS-PNP, pollution control technologies are normally related to boiler, recovery furnace, and lime kiln heat inputs and/or furnace gas flow rate. NO<sub>x</sub> emissions from the pulp and paper industry result primarily from boilers and recovery furnaces. NO<sub>x</sub> emission reduction methods in the Universal ISIS-PNP may be divided into combustion and post-combustion methods. Different types of applicable NO<sub>x</sub> reduction technologies for recovery furnaces and boilers available in Universal ISIS-PNP are described briefly below and summarized in Table 4-15, giving NO<sub>x</sub> control technologies for different types of fuel. Because of different designs and types of fuels used, not all controls may be feasible for any combustion source in the pulp and paper sector, as discussed below.

*Recovery furnaces* – Recovery furnaces are not amenable to low NO<sub>x</sub> burners because the fuel is not admitted in a manner where low NO<sub>x</sub> burners can be applied. However, recovery furnaces can use air staging techniques in the form of OFA. This type of staging technique would typically be called a “Quaternary” air system, since air is already admitted in three stages in many recovery furnaces (primary, secondary and tertiary air). Recovery furnaces are also capable of using post combustion NO<sub>x</sub> control methods. However, because of the presence of alkali compounds that would likely poison the catalyst, for SCR it would be necessary to install the SCR after removal of catalyst poisons from the gas stream.

**Table 4-15. Applicability of NO<sub>x</sub> Reduction Technologies**

NO <sub>x</sub> Technology	Byproduct Liquor	Biomass	Coal	Fuel Oil	Natural Gas
LNB	No	No	Yes (PC, 50 %) ** No (grate/stoker)	Yes (50 %)	Yes (50 %)
ULNB	No	No	No	No	Yes (75 %) *
OFA	Yes (25%)	Yes (25%)	Yes (25%)	Yes (25%)	No *
FGR	No	No	No	No	Yes *
SNCR	Yes (50 %)	Yes (50 %)	Yes (PC 25 %) Other (50 %)	Yes (25 %)	No
SCR	No	No	Yes (80 %+)	Yes (80 %+)	Yes (80 %+ ) ***
RSCR (or tail end)	Yes (75 %)	Yes (75 %)	Yes (75 %)	Yes (75 %)	Yes (75 %)
Lo Temp SCR	No	No	No	No	Yes (90 %)
LoTOx****	Yes (90 %)	Yes (90 %)	Yes (90 %)	Yes (90 %)	Yes (90%)

\*OFA is generally not an option on package boilers. Since most gas-fired boilers are package boilers, OFA is not generally applicable. FGR, however, is used but typically in combination with ULNBs.

\*\*Note: expected percent reduction shown in parentheses.

\*\*\*SCR is not likely to be used for retrofit of gas fired boilers due to low NO<sub>x</sub> levels that are achievable with combustion controls. However, SCR is an option for new installations.

\*\*\*\*LoTOx requires a downstream scrubber.

*Hog fuel boilers* – Hog fuel boilers are typically grate-fired or possibly fluid or bubbling bed and are not amenable to traditional low NO<sub>x</sub> burners. Hog fuel boilers are also capable of using post-combustion NO<sub>x</sub> control methods; however, for SCR it would be necessary to install the SCR after removal of compounds that could poison the catalyst.

*Coal fired boilers* – If firing PC, these boilers can use low NO<sub>x</sub> burners and OFA. Grate- or stoker-fired boilers would not use low NO<sub>x</sub> burners, and would instead use air staging similar to OFA. However, coal fired boilers are also capable of using any post-combustion NO<sub>x</sub> control method. SNCR would provide about 25-percent reduction on PC boilers, while higher NO<sub>x</sub> reductions approaching 50 percent might be achieved in grate or stoker or fluid/bubbling bed boilers. In principle, a high dust SCR can be installed on any coal-fired boiler, and hundreds of utility coal-fired boilers employ SCR in a high-dust arrangement.

*Heavy Oil-Fired boilers* – Number 6 fuel oil or other heavy fuel oil is burned in many pulp and paper mill power boilers. These boilers typically can use LNB and OFA and any of the post-combustion control methods. Like the coal-fired boilers, many oil-fired power boilers at pulp and paper mills are not likely to have adequate space after the economizer for a typical SCR. As a result, a tail-end SCR may be necessary at these locations if SCR is applied.

*Natural gas boilers* – These boilers are usually most effectively controlled with combustion controls. Natural gas boilers may use low NO<sub>x</sub> burners, ultra-low NO<sub>x</sub> burners, and sometimes flue gas recirculation for control of NO<sub>x</sub>. OFA is not likely to be used since most of these boilers are package boilers. SNCR is not likely to be effective on natural gas fired boilers due to the low NO<sub>x</sub> levels on gas fired boilers equipped with low NO<sub>x</sub> burners. SCR would not be likely to be retrofit on this application because combustion controls tend to be effective at reducing NO<sub>x</sub> emissions to low levels. SCR would likely be installed on most new facilities.

### 4.5.2. SO<sub>2</sub>

SO<sub>2</sub> emissions from a recovery furnace are the product of sulfur in the smelt. SO<sub>2</sub> emissions from power boilers, especially those firing coal or residual fuel oil, are directly related to the sulfur content of the fuel. State of the art recovery furnaces and power boilers maintain efficient SO<sub>2</sub> emission controls. Wet and dry scrubbing technologies may be applied to control SO<sub>2</sub> emissions. Wet scrubbing systems capture SO<sub>2</sub> in an aqueous reaction within an absorption vessel. The wet scrubbing processes most commonly used in industrial boilers such as these in the pulp and paper sector are Limestone Wet Scrubbing, Ammonia Wet Scrubbing, or Sodium Wet Scrubbing.

The most common form of dry scrubber is an SDA. In an SDA, hydrated lime slurry is introduced into an absorption vessel to react with the SO<sub>2</sub> to form calcium sulfate and calcium sulfite. In all SDA systems, a particulate matter control device follows the SDA vessel to capture the solids formed in the SDA. In most cases, the particulate control device is a fabric filter because the filter cake improves SO<sub>2</sub> removal performance of the system.

### 4.5.3. CO<sub>2</sub> and Energy Efficiency

The net CO<sub>2</sub> emissions from boilers and recovery furnaces are emitted only from combustion processes. Net CO<sub>2</sub> emissions include CO<sub>2</sub> emissions from fossil-fuel sources and biogenic CO<sub>2</sub> that is absorbed during biomass growth. Burning biomass in hog fuel boilers produces CO<sub>2</sub> emissions from biomass, which equals the total CO<sub>2</sub> emissions from the hog fuel boiler minus CO<sub>2</sub> absorption during the growth of the biomass. In general, plants absorb carbon dioxide during their growth (life cycle). Short rotation woody crop biomass can absorb 1.88 kg/kg biomass (0.244 lb/MMBtu) in its life cycle, which is assumed to be 15 years (Department of Conservation, 2009). Burning biomass produces 31.34 kg CO<sub>2</sub> per kg biomass. Thus, net CO<sub>2</sub> emission to the atmosphere is 31.34 – 1.88 = 29.46 kg CO<sub>2</sub>/kg biomass. CO<sub>2</sub> emissions from combustion of fuels used in the pulp and paper sector are shown in Table 4-16, and resulting emission factors are given in Table 4-17.

**Table 4-16. CO<sub>2</sub> Production from Combustion of Various Fuels (lb/MMBtu)**

	Coal	NG	Oil	Byproduct Liquor	Biomass
Power Boilers	204.7	123.4	169.1		
Recovery Furnace				207.2	
Hog Fuel Boilers					241

**Table 4-17. CO<sub>2</sub> Emission Factors for Combustion Sources at Pulp and Paper Mills (USEPA, 2009)**

Fuel	Emission factor <sup>1</sup> (kg CO <sub>2</sub> /MMBtu HHV)	Emission factor <sup>1</sup> (lb CO <sub>2</sub> /MMBtu HHV <sup>4</sup> )
<b>Recovery furnaces/black liquor gasification units<sup>2</sup></b>		
North American softwood	94.4	208.1
North American hardwood	93.7	206.6
North American (average) <sup>3</sup>	94.1	207.3
<b>Boilers</b>		
Biomass (wood and wood residuals) <sup>2</sup>	93.80	206.8
Coal (mixed – industrial sector) <sup>4</sup>	93.91	207.0
Natural gas	53.02	116.9
<b>Distillate oil</b>		
No. 1 distillate oil	73.25	161.5
No. 2 distillate oil	73.96	163.1
Distillate oil (average)	73.61	162.3
Residual oil (No. 6)	75.10	165.6
Propane	61.46	135.5
Coke oven gas	46.85	103.3

Notes:

1. Emission factor: to obtain emission factor in lb CO<sub>2</sub>/MMBtu, multiply emission factor in kg CO<sub>2</sub>/MMBtu HHV by 2.204623 lb/kg.
2. Combustion of black liquor in recovery furnaces and black liquor gasification units and combustion of biomass in boilers is considered carbon neutral with regard to CO<sub>2</sub> in GHG reporting protocols. Therefore, CO<sub>2</sub> emissions are reported as zero in Universal ISIS-PNP.
3. The average emission factor for recovery furnace was developed; the same emission factor was used for the black liquor gasification unit.
4. For coal-fired boilers, emission factors for mixed coals used (industrial sector) were used to reflect mixtures included in pulp and paper inventory.

Replacement of an existing boiler or a recovery furnace is one possibility for improvement of efficiency and reduction in fuel inputs and emissions outputs as well as O&M costs for pulp and paper facilities. A furnace/boiler system replacement may require replacing more than the combustion unit to maximize benefit. Because modern boilers are capable of operating under higher pressure conditions for more efficient steam cycles than older systems, it is sometimes necessary to replace the steam plant and turbine generator as well as the boiler to realize the full benefit of the new boiler. Air pollution control equipment will also need to be installed on the new boiler. Furthermore, a significant improvement in efficiency may result in the paper mill becoming a net generator, which would require a modification to switchgear and the electrical connection to the electric grid.

Modern recovery furnaces are more efficient than the general majority of existing installed recovery furnaces due, in part, to the ability of modern furnaces to fire liquor with a higher concentration of black liquor solids (BLS) and to operate at higher steam pressures and, therefore, more efficient steam cycles. Modern furnaces also use air preheaters, hot condensate return, flue gas cooling, and other system enhancements that improve efficiency. Therefore, to realize the full benefits of replacing existing recovery furnaces with new furnaces, it is generally necessary to modernize the steam plant and to include a new steam turbine generator. The improvements enable fossil fuel use in the recovery furnace to be relied upon only during startup and shutdown, thereby increasing power production and reducing CO<sub>2</sub> emissions from fossil fuels to near zero.

Energy efficiency improvement options generally entail an up-front capital cost to install or modify equipment. The up-front investment is recovered over time through the reductions realized in fuel or electricity costs. In effect, the variable operating costs are usually negative for these technologies. In most cases, installation of these technologies will not change the fixed operating costs of the plant. Assuming similar year-to-year facility operation, the energy savings should be similar from year-to-year. Hence, these methods lend themselves to being represented economically in terms of simple payback, or how many years of savings required to recover the cost of the initial investment. A shorter payback period (typically represented in years) implies an economically more attractive energy savings approach – at least from the perspective of the measure of payback period.

Capital costs of efficiency improvement methods applied in the pulp and paper industry in 1994 were reported in terms of \$ per ton of paper produced per year (Worrell, 2001). Summary of these energy efficiency measures and their capital costs escalated to 2008 dollars per MMBtu/hour are shown in Table 4-18 along with fuel savings.

**Table 4-18. Energy Efficiency Measures for Pulp and Paper Industry Boilers**

Energy Efficiency Measure	Capital Cost (\$/MMBtu/h)	Fuel Saving (%)	Applicable Share of Production (%)
Efficient Steam Production and Distribution Boiler Maintenance	0	6.50	20
Improved Process Control	242	2.8	50
Flue Gas Heat Recovery	424	1.3	50
Blowdown Steam Recovery	484	1.2	41
Steam Trap Maintenance	727	9.2	50
Automatic Steam Trap Monitoring	727	4.6	50
Leak Repair	182	2.8	12
Condensate RReturn	2301	13.8	2

Notes: Capital cost in 2008 dollars. No electricity savings projected for any measure in Table 4-18.

## 4.6. Import Modeling Data

US pulp and paper markets receive imported quantities of pulp from a number of countries. However, the US imports a significant amount of pulp and paper products from Canada. Considering Canada’s role in the US import market, the entire import region Universal ISIS-PNP has been divided into two markets: 1) Canada, and 2) ROW. These imports arrive at three import districts: North, South and West. Figure 4-5 illustrates the import dynamics of Universal ISIS-PNP framework, outlining the import of pulp from world market to the US via import districts.

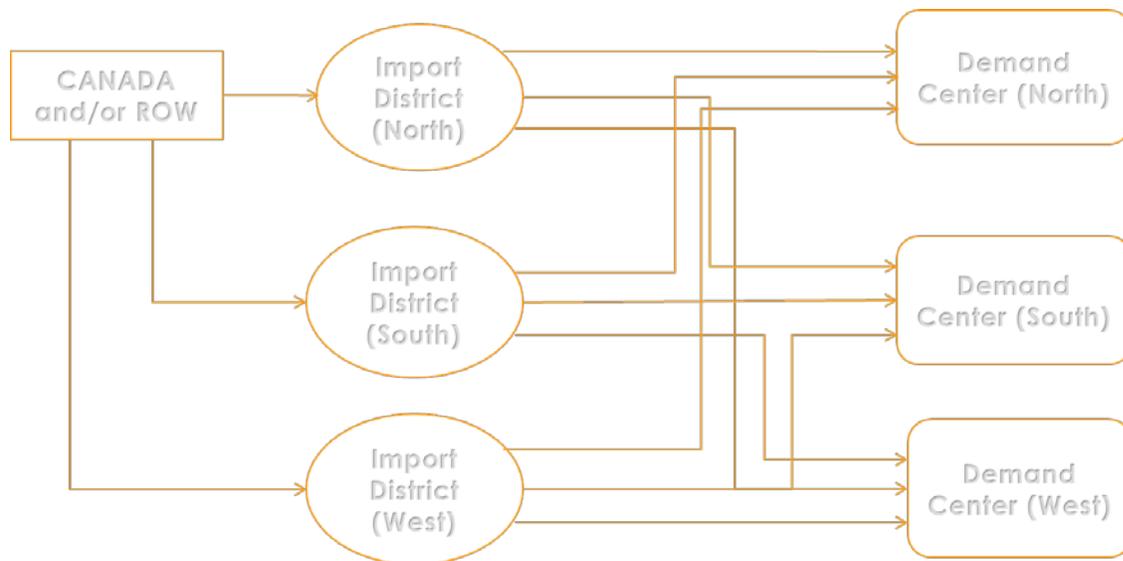


Figure 4-5. Import Network of Pulp from Canada and/or ROW to the US

## 4.7. Scenario Parameters

The Universal ISIS-PNP framework allows the user to select a variety of potential emission reduction scenario options for evaluation. The user can select from cap-and-trade (with or without *de minimis* requirements), emissions charge, or rate-based scenario. In a cap-and-trade scenario, separate caps on pollutants of interest can be specified. The user has the option to run a cap-and-trade scenario with or without banking of emissions. Further, a cap-and-trade scenario can include *de minimis* requirements, where the user defines a minimum level of emission reduction required for each emission unit. As previously mentioned, the user can input an emission charge for the pollutants of interest. Furthermore, rate-based scenarios with unit specific emission reduction requirements specified by the user can be modeled in Universal ISIS-PNP. The user can specify the scenario horizon (time period) to be used for the model runs.

## 4.8. References

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## 5. Model Calibration

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Large techno-economic models of Universal ISIS-PNP framework size require model calibration as they utilize an extensive amount of data which comes from different sources. This chapter outlines calibration methodology that was used, discusses data used for calibration, presents calibration results, and gives further recommendations.

### 5.1. Methodology

The model calibration method utilizes the concept of the calibration constant. The calibration constant has been developed to account for possible errors in production, imports and costs. The value of calibration constant,  $calconst(i)$ , is set by trial and error during calibration. The objective of the trial and error approach is to minimize the absolute difference in the reported and model-predicted pulp and paper prices (which are marginal values of the supply equation) for each USGS district.

In the first step of calibration, the Universal ISIS-PNP is set to run for 2007-2009 by making appropriate changes in the input worksheet and GAMS input files. The import quantities and prices are then adjusted to be equal to the reported import quantity for each of the import products.

In the next step, the impact of changing the calibration constant is monitored. This impact of the calibration constant is assessed on estimated production quantities of CNT, BXT, UPW, PIP, and COR products. The difference between reported and model-predicted production values of all five products should be within reasonable limits.<sup>1</sup> The calibration constant modifies the variable cost of production of each product. The “Calibration\_PnP” worksheet within the “Inputs” workbook has values of the calibration constant assigned for each product. Finally, in the input GAMS file, the values are assigned for all five products produced from different units.

The model is first calibrated for the year 2007, to obtain values of the calibration parameter  $calconst\_PnP(i)$  for the year. Next, these values are used to validate production and predicted prices against known values of these parameters for years 2008 and 2009. If there is an acceptable level of difference in the reported and model-predicted values, the  $calconst\_PnP(i)$  values for 2007 are used for all future-year predictions. However, if there is significant disagreement in reported and predicted values, then values for 2007 are used as starting point to obtain values for the same parameter for 2008. Similarly, the process is repeated to obtain the values for 2009. Then, an average of the  $calconst\_PnP(i)$  values over the three years is taken and used for the future model runs. Current values of the parameter  $Calconst\_PnP(i)$  being used in the model runs can be found in the worksheet “Calibration\_PnP” of the “ISIS\_Inputs.xls” workbook. In the case of the Pulp and Paper model, calibration constant values for 2007 resulted in an acceptable level of agreement between reported and predicted values for 2008 and 2009 (discussed in section 5.3, below).

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<sup>1</sup> There is no standard method to guide the user in determining the acceptable level of “error” in the reported and predicted values for the purpose of calibration. In this work, we have set an acceptable level for the absolute gap between the individual reported and the predicted values to  $\pm 15\%$ , although an effort has been made to keep this level below 10% for most of the quantities. However, due to discontinuities in the transportation matrix, errors in the reported data, or other unknowns, the gap in the estimated and reported values may be higher in certain markets.

Calibration is a dynamic process; it is recommended that model calibration be performed periodically. In this fashion, any available new production, imports, or price data could be utilized in the model.

## 5.2. Data Used

Annual production quantities, annual demand, annual imports and reported annual paper prices for the United States for linerboard, coated free sheet, uncoated free sheet, corrugating medium and solid bleached board products are the key quantities used for calibration of the Universal ISIS-PNP. Reported data for years 2007, 2008, and 2009 were used to calibrate the model and to obtain values of appropriate calibration parameters.

### 5.2.1. Prices

Reported annual paper product prices for the United States are shown in Table 5-1. For any given year, the reported prices for paper products show a wide price-range among product categories.

**Table 5-1. Reported Annual Prices of Paper Products**

Product	2007 (\$/ton)	2008 (\$/ton)	2009 (\$/ton)
CNT	495	528	497
BXT	711	745	762
UPW	796	840	822
PIP	659	697	663
COR	464	496	469

### 5.2.2. Production

Reported annual paper products production levels are shown in Table 5-2. Generally production has decreased from 2007 to 2009, due to a decrease in demand resulting from the economic downturn.

**Table 5-2. Reported Paper Products Annual Production**

Product	2007	2008	2009
	Thousand Tons		
CNT	20,812	20,329	20,772
BXT	12,910	12,745	12,744
UPW	13,033	12,300	12,244
PIP	2,244	2,113	1,975
COR	9,709	9,561	9,619

### 5.2.3. Demand

Reported annual linerboard, coated free sheet, uncoated free sheet, corrugating medium and solid bleached board domestic demand is shown in Table 5-3.

**Table 5-3. Reported Annual Paper Products Demand**

Product	2007	2008	2009
	Thousand Tons		
CNT	20,497	19,973	20,376
BXT	12,989	12,796	12,768
UPW	17,409	16,675	16,618
PIP	2,878	2,737	2,590
COR	10,047	9,896	9,951

### 5.2.4. Imports to the United States

Reported annual import quantities of paper products to the US are shown in Table 5-4.

**Table 5-4. Reported Annual Import Quantities of Paper Products**

Product	2007	2008	2009
	Thousand Tons		
CNT	1089	1089	1089
BXT	1027	1027	1027
UPW	4424	4424	4424
PIP	941	941	941
COR	443	443	443

## 5.3. Results

Reported and calculated values of annual prices as well as the difference between the two values for five paper products are shown for years 2007, 2008, and 2009 in Table 5-5, 5-6, and 5-7, respectively. As can be seen from these tables, the majority of differences between reported and calculated product prices are within  $\pm 5$  percent. In general, the price differentials are smaller in the year 2007 and have increased in 2009. Generally, model-predicted market prices are within the criteria specified in the QA document, and the aberrations are explained by the demand-supply gap and transportation cost.

The current set of calibration constant values are averaged over the years of calibration and are available in the "Calibration\_PnP" worksheet in the "ISIS\_Inputs.xls" workbook.

**Table 5-5. Reported and Calculated Prices of Products for 2007**

Product	Reported	Calculated	% $\Delta$
CNT	495	488	0.01
BXT	711	705	0.01
UPW	796	757	0.05
PIP	659	708	-0.07
COR	464	451	0.03

**Table 5-6. Reported and Calculated Prices of Products for 2008**

Product	Reported	Calculated	%Δ
CNT	528	500	0.05
BXT	745	723	0.03
UPW	840	767	0.09
PIP	697	726	-0.04
COR	496	462	0.07

**Table 5-7. Reported and Calculated Prices of Products for 2009**

Product	Reported	Calculated	%Δ
CNT	497	489	0.02
BXT	762	715	0.06
UPW	822	748	0.09
PIP	663	715	-0.08
COR	469	457	0.03

## 5.4. Recommendations

The Universal ISIS-PNP should be re-calibrated each time modifications or refinements are made. For example, transportation matrix, modes, and cost of transportation all have significant impact on the behavior of production distribution and prices across the demand centers. Therefore, following any changes to the transportation matrix, the model needs to be re-calibrated. In addition, if any of the key input parameters such as those relating to production quantities and costs are refined or otherwise modified or additional observed data become available, the calibration of the model should be repeated.

At the time of calibration of the model, production, import, and price values for only 2007 to 2009 were available. As discussed above, when the new values become available, the model should be calibrated again. Calibration of the model should be repeated as soon as new information or new observed data become available. Due to practical limitations, it is recommended that the calibration of the model be repeated every two years. Further, since the calibration data are available only for three years, equal weight was given to the parameters obtained for each year. Once larger data set is available, a modified weighing system can be adopted to give highest weight to the data from the most recent year.

## 6. Illustrative Analysis

The Universal ISIS-PNP is designed to show the impact of emission reduction policies on fuel consumption, fuel and production costs across the pulp and paper sector. The model assists in the analyses of emission reduction strategies for multiple pollutants: NO<sub>x</sub>, SO<sub>2</sub> and CO<sub>2</sub>. In this chapter, results of three illustrative scenarios for reduction of NO<sub>x</sub> emissions from the pulp and paper sector are presented and discussed. The model-generated emissions in 2009 are used as reference emissions for each scenario. The emission reduction scenarios presented here do not reflect any actual USEPA considerations and are used only to familiarize the reader with the capability of the Universal ISIS-PNP. The following three illustrative examples will be presented below.

1. **Fuel substitution:** The first illustrative example for reducing NO<sub>x</sub> emissions is examined for the year 2010. In the initial step, the model calculates emissions for the year 2010 based on the emissions in reference year 2009. The emissions cap for NO<sub>x</sub> is set at 50 percent of the emissions generated by the model in 2010 based on the reference 2009 year emissions, thereby requiring industry-wide reductions of 50 percent in NO<sub>x</sub> from the reference year-based emissions in 2010. The impact of this reduction in NO<sub>x</sub> is observed on other pollutants (SO<sub>x</sub> and PM), fuel switching and fuel costs across the sector. The model chooses from various fuels of varying cost (coal, natural gas, hog fuel, oil, and black liquor) to minimize operating costs of the pulp and paper mills while meeting the regional demands and capacity constraints. Low NO<sub>x</sub> generating fuels may replace the fuels that emit higher NO<sub>x</sub> levels. For example, natural gas that has an emission intensity of 0.19 lb/MMBtu will replace coal with an intensity of 0.64 lb/MMBtu.
2. **Installation of controls:** The second illustrative example demonstrates how Universal ISIS-PNP can be used to analyze the effect of installation of an SCR on the operation of a specific pulp and paper plant. The boilers in some plants are built for specific fuels, thereby constraining them from switching fuels to aid in NO<sub>x</sub> reduction. In other words, it may not be possible for some mills to replace their coal fired power boilers with natural gas fired boilers. In this case, control technologies can be installed on boiler equipment to reduce NO<sub>x</sub> emission levels.
3. **Implementation of energy efficiency measures:** The third illustrative example describes how Universal ISIS-PNP could assess the impact of good O&M practices, specifically of replacing or retrofitting burners on emissions of NO<sub>x</sub> and CO<sub>2</sub>. For this example, the same hypothetical plant as the one used in the second illustrative scenario was used.

### 6.1. Fuel Substitution

Fuel substitution may be a viable option to reduce NO<sub>x</sub> emissions from pulp and paper operations because different fuels have different emission intensities, as shown in Table 6-1, giving emission intensities of different fuels in lb/MMBtu.

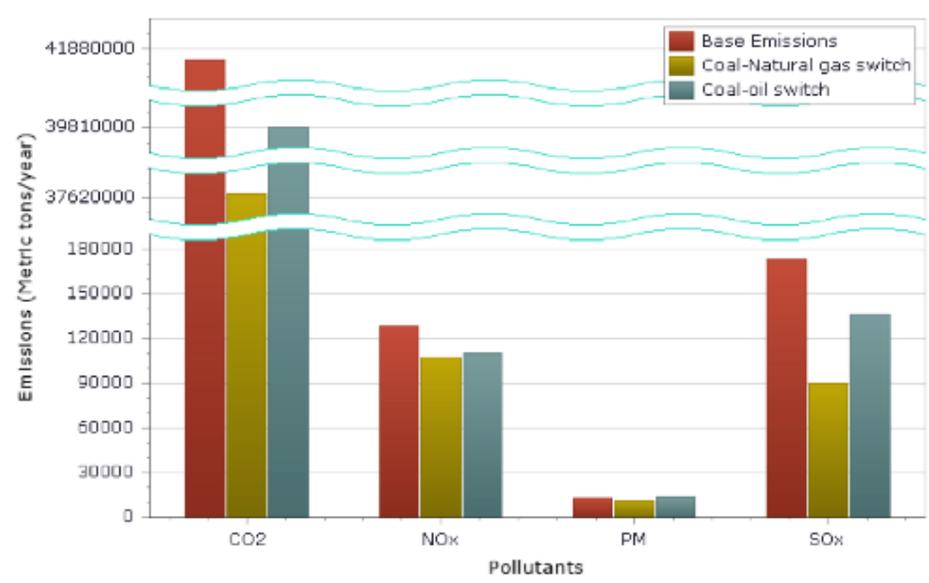
**Table 6-1. Emission Intensity of Fuels**

	Coal	NG	Oil	Hog	BLS
NO <sub>x</sub>	0.64	0.19	0.24	0.22	1.40
SO <sub>2</sub>	1.7653	0.00059	0.998	0.025	1.13
CO <sub>2</sub>	208	117	164	4.35	0.75
PM	0.0298785	0.0019	0.062	0.060	0.68

BLS= Black Liquor Solids

Table 6-1 shows that NO<sub>x</sub> emissions from BLS and coal combustion are higher than the emissions from natural gas, oil, and hog boilers. Thus, the use of natural gas offers the opportunity of lowest NO<sub>x</sub> emissions on an uncontrolled basis.

Figure 6-1 shows the NO<sub>x</sub> emissions from the pulp and paper industry in the base case (BAU scenario without emission reduction requirements) compared with the NO<sub>x</sub> emissions after applying the 50-percent policy reduction. The emission reduction requirements may be satisfied either by switching from coal to natural gas or from coal to oil. The effect of fuel substitution on reducing NO<sub>x</sub> emissions is also seen on SO<sub>2</sub>, CO<sub>2</sub>, and PM emissions. Figure 6-1 shows that under the emission reduction scenario, the SO<sub>2</sub>, CO<sub>2</sub>, and PM emissions are lower than the BAU case as a result of a different fuel consumption profile. To achieve NO<sub>x</sub> emission reductions, the model is constrained to choose a combination of fuels different from the base case. The new fuel combination ensures that the industry production meets demands with cleaner fuels. However, these new fuels with lower emission intensities may be more expensive, which may result in an increase in fuel costs and in turn production costs.



**Figure 6-1. Comparison of Base Emissions with Projected Emissions after Fuel Substitution**

The impact of fuel substitution on the annual fuel cost can be seen in Figure 6-2, presenting the modeling results for base case and 50-percent coal substitution scenarios. The 50-percent substitution of coal with either natural gas or oil has resulted in a predicted increase of annual fuel cost. Substitution of coal with hog fuel resulted in a predicted decrease of annual fuel cost.

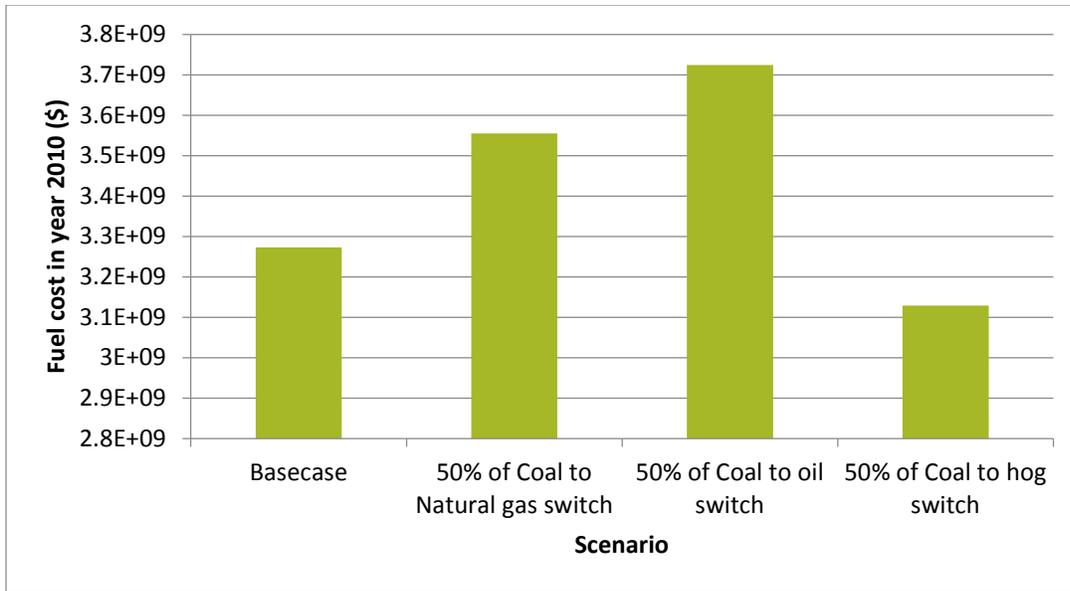


Figure 6-2. Fuel Cost in Base Case and Fuel Substitution Scenarios

## 6.2. Installation of Controls

This scenario illustrates how Universal ISIS-PNP could be used to analyze the effect of installation of an SCR on the operation of a specific pulp and paper plant. Boilers deployed in the pulp and paper sector typically use LNB and OFA. However, the boilers are also capable of using any post-combustion NO<sub>x</sub> control method. In principle, a high dust SCR (SCR installed upstream of PM control device) can be installed on any industrial boiler. For this scenario, a hypothetical plant located in the southern supply center with a different annual production capacity for each of its four products (CNT, newsprint, PIP, and UPW) was selected. The plant uses 6 percent coal, 68 percent natural gas, 11 percent oil, and 15 percent hog fuels to produce the required products. To calculate NO<sub>x</sub>, SO<sub>2</sub>, PM, and CO<sub>2</sub> emissions from each of these fuels, the energy intensity (ton of fuel used per ton of product) and production capacity (tons of product per year) were taken to calculate the amount of fuel (tons of fuel used per year) used to produce the specific product. The heat produced by each fuel can be calculated by multiplying the amount of fuel in tons by its corresponding fuel intensity (MMBtu/ton). The emissions (lb/MMBtu) associated with each fuel are different based on the emission intensity of that fuel. Each fuel will therefore have its own NO<sub>x</sub>, SO<sub>2</sub>, PM, and CO<sub>2</sub> emissions (lb/year). The NO<sub>x</sub> emissions from all fuel types are added to obtain total NO<sub>x</sub> emissions.

To reduce NO<sub>x</sub> emissions from this hypothetical plant, one could install SCR at the plant. The SCR technology is capable of 75 percent reduction in NO<sub>x</sub> emissions from hog fuel and 90 percent emission reduction each from coal, natural gas, and residual oil. The total NO<sub>x</sub> emissions (lb/year) as calculated by Universal ISIS-PNP after applying these percentages of NO<sub>x</sub> reductions to each fuel results in 85.6 percent overall NO<sub>x</sub> emission reduction. However, there is no change in SO<sub>2</sub>, PM, and CO<sub>2</sub> emissions, as can be seen in Figure 6-3.

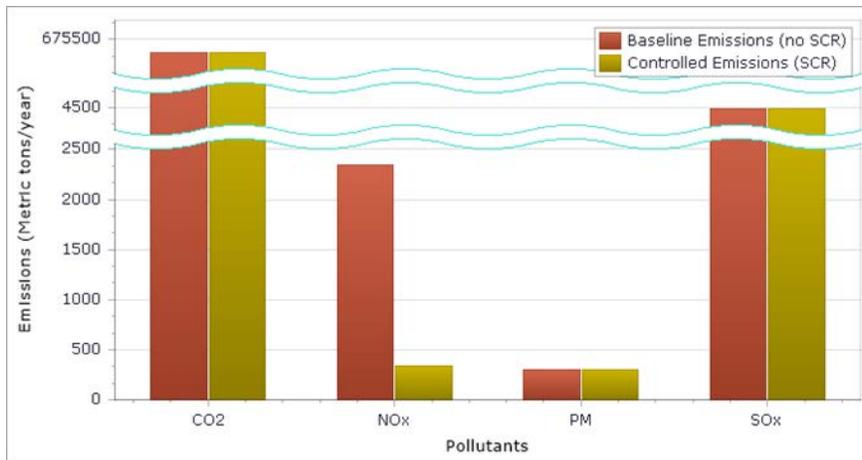


Figure 6-3. The effect of SCR technology on reduction in emissions of NO<sub>x</sub>, SO<sub>2</sub>, and CO<sub>2</sub>

### 6.3. Implementation of Energy Efficiency Measures

Energy efficiency measures for industrial boilers used in the pulp and paper sector may vary from operation and maintenance improvements to repowering. The third illustrative scenario describes how Universal ISIS-PNP could assess the impact of good O&M practices, specifically of replacing or retrofitting burners, on emissions of NO<sub>x</sub> and CO<sub>2</sub>. For this scenario, the same hypothetical plant, used before in the second scenario (located in the southern supply center) was selected. The plant uses coal and has conventional LNB installed. This scenario describes the effect of replacement of conventional LNB with ULNB. The ULNB is capable of reducing NO<sub>x</sub> and CO<sub>2</sub> emissions by 75 (NCASI, 2009) and 6 percent (USEPA, 2010), respectively, compared to the uncontrolled case. With conventional LNB installed, emissions of NO<sub>x</sub> and CO<sub>2</sub> were assumed to be reduced by 50 and 2 percent, respectively compared to the identical plant without LNB. Baseline emissions of NO<sub>x</sub> and CO<sub>2</sub> for the plant with LNB were taken as 2,340 and 675,369 metric tons/year, respectively. Next, installation of ULNB was considered in the third scenario as a replacement for conventional LNB already in place in this plant. As a result of this LNB-to-ULNB upgrade, emissions of NO<sub>x</sub> and CO<sub>2</sub> decreased to 1,170 and 647,803 metric tons/year for this plant, as shown in Figure 6-4.

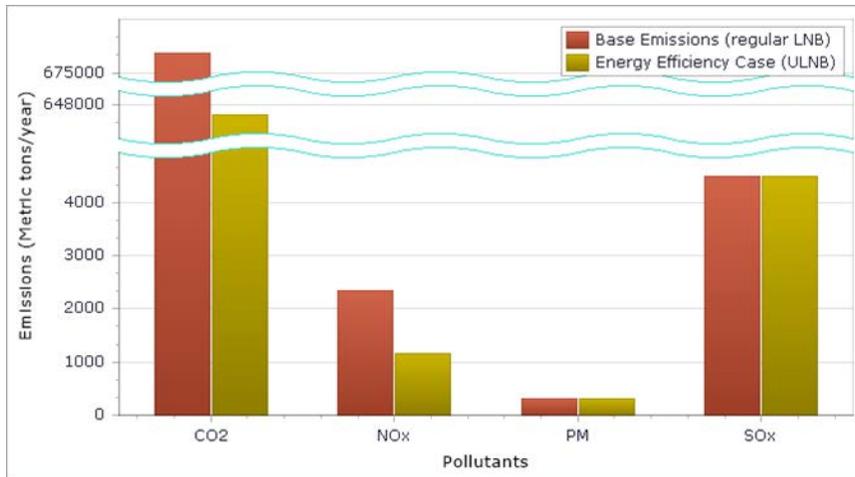


Figure 6-4. The emission reduction of NO<sub>x</sub> and CO<sub>2</sub> as an effect of LNB to ULNB upgrade.

## 6.4. Summary

The Universal ISIS-PNP was used to describe three illustrative scenarios of emissions from boilers in the US pulp and paper sector under the regime of fuel switching, installation of air pollution equipment, and implementation of energy efficiency measures. The objective of the analysis was to gain insights relative to broad questions on the range of practical SO<sub>2</sub>, NO<sub>x</sub>, and CO<sub>2</sub> reduction options in the US pulp and paper industry.

As illustrated by the first scenario, fuel switching offers substantial reductions of SO<sub>2</sub>, NO<sub>x</sub>, CO<sub>2</sub>, and PM emissions for the sector. Fuel switching is an attractive option for reducing boiler SO<sub>2</sub> emissions because these emissions are a function of fuel sulfur content. For example, combustion of natural gas produces far less SO<sub>2</sub> emission than coal because of the significantly lower sulfur content of natural gas. Natural gas and oil are favorable fuels from the standpoint of NO<sub>x</sub> emissions compared to coal and wood. As the availability of natural gas in the US is increasing, more business owners may decide to switch their boilers to natural gas. Universal ISIS-PNP is a useful tool to predict the extent of emission reduction resulting from the coal-to-natural gas switch. As with NO<sub>x</sub> and SO<sub>2</sub>, fuel switching is an attractive option for reducing boiler PM emissions. For example, PM will generally be reduced when a lighter grade of fuel oil is burned or when coal is replaced with natural gas. Similarly, fuel switching may reduce CO<sub>2</sub> emissions significantly because of varying emission intensities of fuels. For example, CO<sub>2</sub> intensity of coal and natural gas is approximately 93 and 53 kg CO<sub>2</sub>/MMBtu, respectively. Thus, switching from coal to natural gas would accomplish reductions in SO<sub>2</sub>, PM, and CO<sub>2</sub> emissions. Switching from natural gas to solid biomass would significantly reduce GHG emissions but would likely increase PM emissions. These different fuel switching scenarios can be analyzed by Universal ISIS-PNP, and an optimum fuel switching strategy for minimal emissions can be selected either for an individual boiler or for the sector.

Installation of air pollution control equipment assures reduction of emissions from the plant, as shown in the second scenario. While over 80 percent emission reduction of a single pollutant from the plant was achieved, emissions of other pollutants were unaffected. However, Universal ISIS-PNP provides the capability to analyze emission reduction on a sectoral scale. In this way, the user could implement SCR for plants with the highest NO<sub>x</sub> emissions and wet FGD for plants burning fuels with high sulfur content (e.g., high sulfur coal). For example, utilizing the Universal ISIS-PNP database, a user could discern the type of boiler used at the plant and, in turn,

infer flow mixing conditions in the boiler. For boilers with favorable mixing conditions, the user may analyze application of SNCR in lieu of more expensive SCR. By comparing plants with boilers of different sizes, a user can understand the economy of scale for wet FGD installation. Understanding the economy of scale may result in installation of SDA rather than wet FGD for plants burning mid-sulfur fuels. Utilizing the Universal ISIS-PNP database, the user can analyze reduction of emissions of other pollutants such as mercury since fuel properties and installed air pollution control technologies are known at plant level.

Similarly, PM control technology applications could be analyzed to accomplish maximum PM emission reduction. For example, a plant with excessive PM emissions despite having an ESP installed could have a fabric filter added based on results from the Universal ISIS-PNP database that determined high resistivity PM (function of fuel use) was limiting the performance of the ESP. This selective application of efficient air pollution control technologies to plants with the highest emissions of a specific pollutant could then be analyzed by Universal ISIS-PNP to understand how the cost impact of equipment installation could be minimized across the sector.

There is a menu of GHG emission reduction measures for existing boilers (USEPA, 2010). Some of the most commonly used measures include good O&M measures, air preheaters and economizers, boiler insulation, minimization of inleakage, and steam line maintenance. The majority of measures are common, such as the burner retrofit discussed above, yet capable of substantial CO<sub>2</sub> emission reduction. In the example discussed above, simple replacement/retrofit of burners was capable of approximately 6 percent CO<sub>2</sub> emission reduction. Other measures may be complex and may require site reconfiguration, such as, for example, combined heat and power or repowering. Impacts of any measure are highly site-specific in terms of energy efficiency gain. In turn, CO<sub>2</sub> emission reduction corresponds to actual percent efficiency gain realized as the effect of measure implementation. Using the Universal ISIS-PNP database and the menu of GHG emission measures, the user is able to optimize technology solutions that may be applied to specific boilers to reduce overall GHG emissions from the sector. As illustrated by the cases above, simultaneous reductions of GHG and other pollutants may be accomplished by measures such as fuel switching or energy efficiency improvements. Similar analyses can be made for pollutants other than GHG, utilizing a menu of SO<sub>2</sub>, NO<sub>x</sub> and other emission control technologies built into Universal ISIS-PNP.

## 6.5. References

NCASI (2009). National Council for Air and Stream Improvement. Environmental Footprint Comparison Tool: Trade-Offs and Co-Benefits Accompanying SO<sub>x</sub> and NO<sub>x</sub> Control. 2009.

USEPA (2010). US Environmental Protection Agency. Available and Emerging Technologies for Reducing Greenhouse Gas Emissions from the Pulp and Paper Manufacturing Industry. Available at: <http://www.epa.gov/nsr/ghgdocs/pulpandpaper.pdf>. Last accessed on October 31, 2014.

# 7. Universal ISIS-PNP Manual

The objective of this chapter is to demonstrate various aspects of running the Universal ISIS-PNP by introducing the user to the model’s user interface. The manual discusses the user’s personal computer hardware/software requirements for installing Universal ISIS-PNP. Usage instructions are given for opening and running the model. Model input data requirements, data processing, and output are discussed. To familiarize user with the Universal ISIS-PNP, examples of running different scenarios are given. Troubleshooting is also explained in the manual.

## 7.1. Hardware/Software Requirements of Universal ISIS-PNP

An overview of hardware requirements for the installation and simulation runs using the Universal ISIS-PNP software package is given below in Table 7-1. The software package containing the database and executable files can be downloaded from the USEPA website.

**Table 7-1. System Requirements for Software Installation**

Component	Requirements
Processor	i7-XXX (4 <sup>th</sup> Generation)
Operating System	Windows 7 or Higher
Memory	Minimum 8 GB RAM
Support Software	GAMS-IDE Microsoft Office 2007 or Higher Latest Version of Adobe Acrobat Reader
Support Documents	GAMS Tutorial and User Manual: <a href="http://gams.com/docs/document.htm">http://gams.com/docs/document.htm</a>

## 7.2. Installation of GAMS (Supporting Software)

GAMS is a user interface to the UISIS\_PNP model that facilitates the running of the model, thereby allowing the user to solve mathematical equations in the model to get optimized results. The aforementioned hardware and software requirements of Universal ISIS-PNP apply to GAMS. The user should read the GAMS tutorial and user manual document available on GAMS website ([www.gams.com](http://www.gams.com)) to get an overview of the installation process.

1. Depending on the computer configuration (32-bit or 64-bit), select the appropriate GAMS executable program file from the GAMS Website: <http://www.gams.com/download/>.
2. Download the executable GAMS program file windows\_x86\_32.exe (for 32-bit) or windows\_x86\_64.exe (for 64-bit).
3. Double click on the file to install and run the setup.
4. Check the “Use advanced installation mode” box as shown in Figure 7-1.

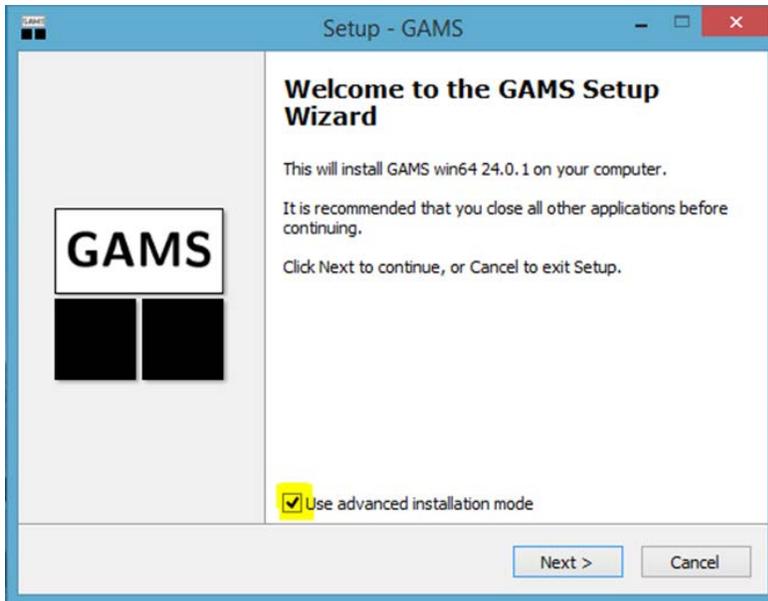


Figure 7-1. GAMS Setup Wizard

5. Select a folder where GAMS will be installed. To carry out a Universal ISIS-PNP model run, ensure that GAMS is installed in the PATH that includes GAMS installation directory as shown in Figure 7-2.

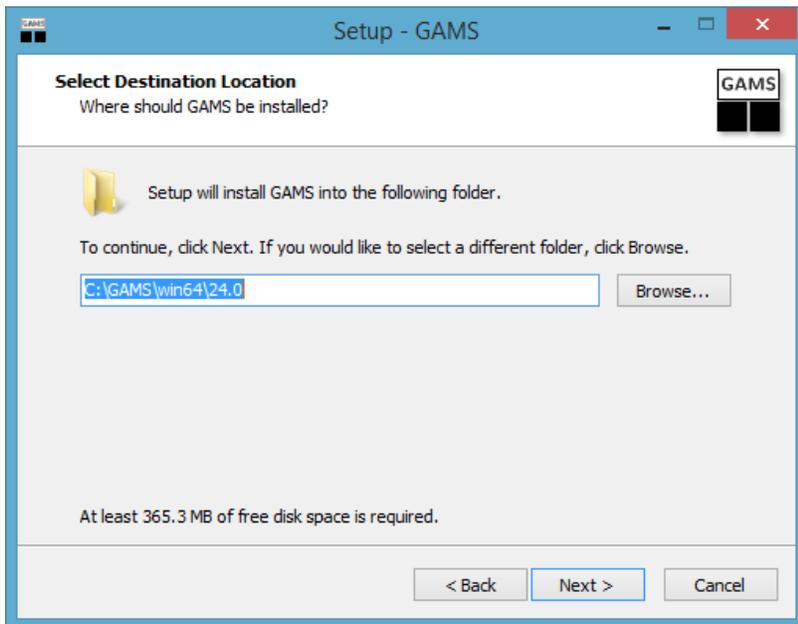


Figure 7-2. Select Destination Location

6. In "Advanced options," check all three boxes including "Add GAMS directory to PATH Environment variable" as highlighted in Figure 7-3.

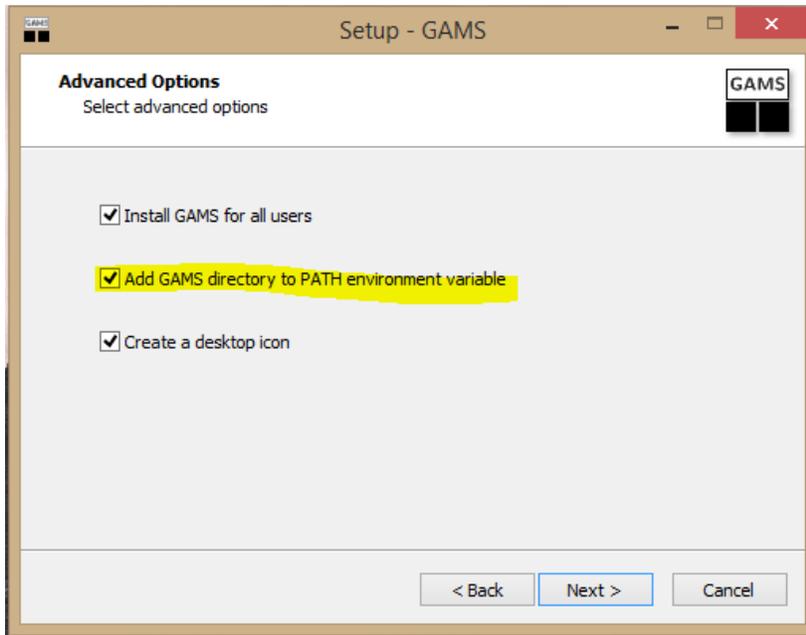


Figure 7-3. GAMS Setup

7. Select the gamslice.txt file and select “open” to perform copy. Copy the GAMS license file (gamslice.txt) and choose the “Copy license file” option, as shown in Figure 7-4.

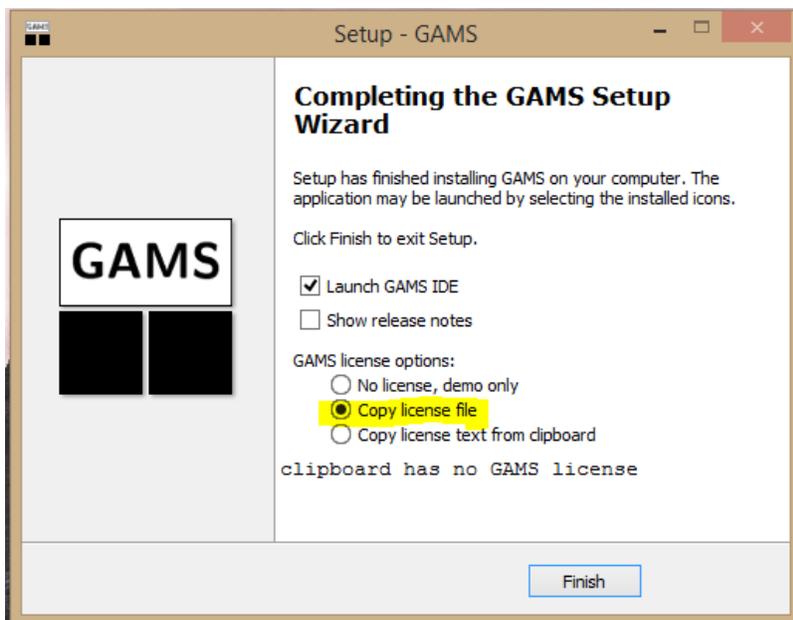


Figure 7-4. GAMS Setup

### 7.3. Opening and Running Universal ISIS-PNP

Download the Universal ISIS-PNP zipped file (containing the database and the executable files) from the USEPA website. Folder contains:

- 1) Database (input and output Excel files)
- 2) Universal ISIS-PNP (GAMS format)
- 3) Model Interface

**Note:** Do not change the names of the Input and Output Microsoft Excel files because Universal ISIS-PNP GAMS project file code will then become invalid and non-executable. It is also important to note that the Input and Output Excel files should be stored in the same folder for GAMS to produce comprehensible results.

### 7.3.1. Open Project

To open a project, the steps are as follows:

- 1) Open the GAMS-IDE program from the directory it has been installed in. For example, if the GAMS-IDE program is installed in program files, click the following: Go to Start → All Programs → GAMS → GAMSIDE.
- 2) To open Universal ISIS-PNP project, click on **[File]** at the top left of the GAMS toolbar and choose **[Project]** → **[Open Project]**.
- 3) The Universal ISIS-PNP project file will appear automatically on GAMS home screen and will have the extension “.gpr” as shown in the Figure 7-5.

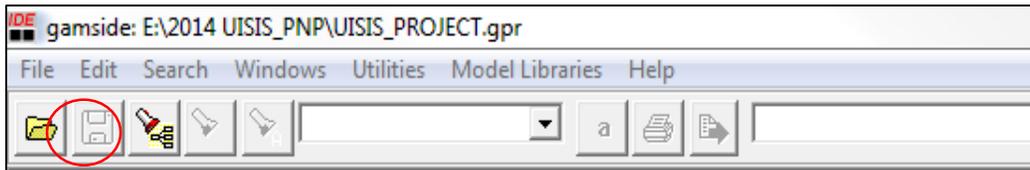


Figure 7-5. Universal ISIS-PNP Project Opens on GAMS

### 7.3.2. Open and Run Database

To open and run the database, the steps are as follows:

- 1) To open UISIS\_PNP database, click on the open folder shown circled in red in the figure above and choose GAMS file DATABASE with extension \*.gms from 2014 UISIS\_PNP folder, as shown in Figure 7-6.

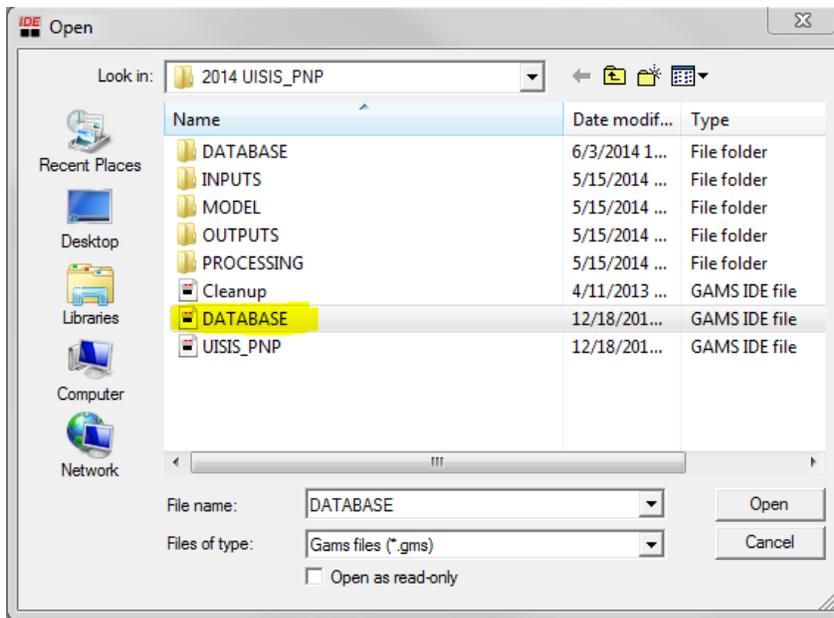


Figure 7-6. Database GAMS File in Universal ISIS-PNP Folder

- Once the user clicks on the DATABASE file, the file opens with title bar reading **[s=Database]**, as shown in Figure 7-7, indicating that the database will be saved by GAMS and will get ready to be processed. An empty title bar indicates that the database will not be saved for the model to process it. To avoid this issue, user can manually type **s=Database** in the empty space.



Figure 7-7. GAMS Title Window before Running Database

- Click on the **[Run]**  button to run the database. Once user hits run, a new window titled "1 active process" should open. This signifies that GAMS is actively running on code file.
- The active process window indicates the status of the program's run and if any troubleshooting is required. When the status reads **[Normal Completion]**, as shown in Figure 7-8, the GAMS file has run successfully.

**Note:** GAMS generates a new window for database.lst file. The Extension ".lst" stands for Data list file. One can expand the "display" button in database.lst to see a list of input parameters and variables.

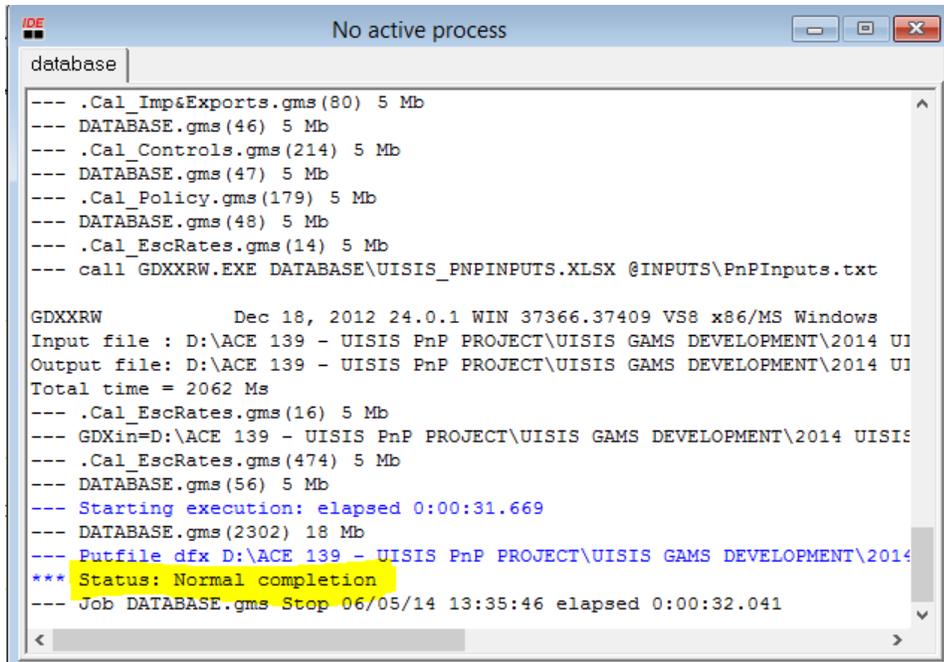


Figure 7-8. Model Run Status

### 7.3.3. Open and Run Model

- 1) Click on [OPEN] folder icon to choose UISIS\_PNP GAMS file from the UISIS\_PNP folder, as shown in Figure 7-9.

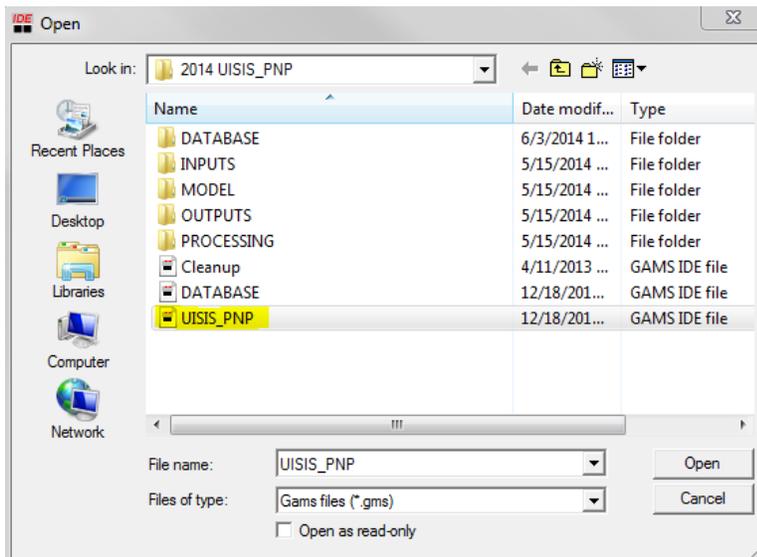


Figure 7-9. Choosing Universal ISIS-PNP GAMS File

- 2) The file opens with the title bar reading **[r=Database]**, as shown in Figure 7-10.



Figure 7-10: GAMS title window before running the model

- 3) This means the database that was saved earlier is ready to be run through the mathematical equations of the model. An empty title bar indicates that the database will not run. To avoid this issue, user can manually type **r=Database** in the empty space.
- 4) At this point, both the model and database in GAMS format are displayed next to each other as shown in Figure 7-11.

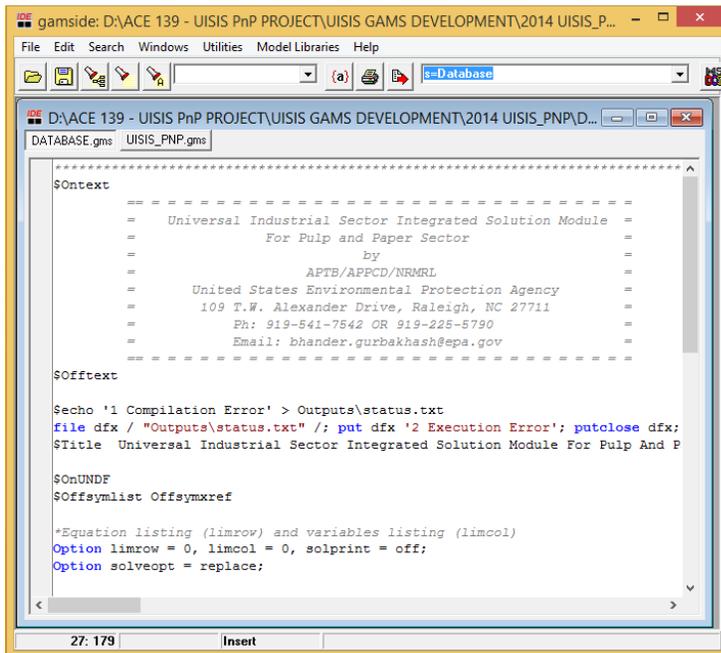


Figure 7-11: Database and Universal ISIS-PNP GAMS files

- 5) After making sure **r=Database** shows up on the screen, click on **[Run]**  button.
- 6) Check the status of completion at the bottom of the window. A successful UISIS\_PNP model run should display 'Normal Execution' status and the numbers for **[MIP Solution]**, **[Final Solve]** and **[Best possible]** should match as shown in Figure 7-12.
- 7) Take note of location of the output file marked in yellow in the figure below. All results are displayed in the excel sheet at this location.

```

database uisis_pnp

MIP Solution: -731372892.664440 (21899 iterations, 0 nodes)
Final Solve: -731372892.664437 (16094 iterations)

Best possible: -731372892.664440
Absolute gap: 0.000000
Relative gap: 0.000000

--- Restarting execution
--- UISIS_PNP.gms(4483) 611 Mb
--- Reading solution for model UISIS_ElPnP
***
*** Reading with solveopt=REPLACE (0)
***
--- UISIS_PNP.gms(4483) 612 Mb
--- Executing after solve: elapsed 0:01:18.222
--- UISIS_PNP.gms(4484) 613 Mb
--- UISIS_PNP.gms(5066) 619 Mb

GDXXRW Dec 18, 2012 24.0.1 WIN 37366.37409 VS8 x86/MS Windows
Input file : D:\ACE 139 - UISIS PnP PROJECT\UISIS GAMS DEVELOPMENT\2014 UI
Output file: D:\ACE 139 - UISIS PnP PROJECT\UISIS GAMS DEVELOPMENT\2014 UI
Total time = 23140 Ms
--- UISIS_PNP.gms(5130) 625 Mb

```

Figure 7-12. Universal ISIS-PNP Output File Location

## 7.4. Model Input Requirements

The database was organized in Microsoft SQL database and an Excel Workbook was developed based on information derived from the 2002 U.S Economic Census of pulp, paper and paperboard mills (North American Industry Classification system (NAICS) Code 3221) and data obtained from RISI and boiler MACT. The interface allows the user to enter the data, which include historical and projected nationwide commodity consumption, imports, exports, number of production facilities, distance from production facilities to the demand centers, production capacity, associated costs (e.g., material, operations, and maintenance), fuel types and costs, emissions sources and intensities, and other data.

Various tabs in the input Excel sheet of this data set are explained in the table below to familiarize the user with location of desirable inputs.

<b>POLICY</b>	Policy parameters for reduction of emissions such as, for example, target year, percentage emission reduction, etc., can be defined here
<b>CONSUMPTION</b>	Product demand in all three regions (North, South, and West) from 2007 to 2020
<b>PLUNITS</b>	Unit level data for integrated and non-integrated pulp mills. Information includes plant location, cost of raw materials, labor, repair and maintenance, total electricity produced and consumed, black liquor and lime mud quantity produced by mill. Production capacity, types of fuel and boiler availability by production unit.
<b>PRUNITS</b>	Unit level data for integrated and non-integrated paper mills. Information includes plant location, cost of raw materials, labor, repair and maintenance and total electricity produced and consumed by product in each mill. Production capacity, hardwood, softwood, recycling, additive pulp consumption percentage by product and types of fuel and boiler availability by production unit.

<b>BLRSCAP</b>	Boiler data for pulp and paper mills. The data include boiler capacity, type of fuel burned, type of control installed on the boiler.
<b>RMT&amp;RECYCLING</b>	Recycling and Transportation costs from demand centers to supply centers
<b>ENERGY</b>	Fuel cost for North, South, and West regions. The data also include 2011 electricity price by State.
<b>ENGINTENSITY</b>	Fuel/Energy data by mill
<b>INTENSITY</b>	Emissions data by fuel and heat intensity of individual fuels
<b>TRANS&amp;IMPORTS</b>	Product transportation costs, import quantity and price by North, West, and South regions
<b>EXPORTS</b>	Product transportation costs, export quantity and price by North, West, and South regions
<b>ESCALATIONRATES</b>	Escalation rates for all costs used in the model
<b>WASTEWATER</b>	Wastewater and landfill quantity and costs by mill
<b>CONTROLS</b>	Control availability, capacity, capital costs and compatibility with boilers and fuels
<b>PLCONTROLS</b>	Control data for pulp mills
<b>PRCONTROLS</b>	Control data for paper mills
<b>CALIBRATION</b>	Model Calibration adjustments

## 7.5. Pre-Processing of Data

- 1) Input data for the Universal ISIS-PNP are organized in a Microsoft Excel spreadsheet and in a Microsoft SQL database.
- 2) This user-defined input spreadsheet includes the time horizon (simulation period), reference year, discount rate, time blocks, commodity characteristics, emissions types, fuel types, and plant types.
- 3) GAMS communicates with this input data Excel sheet via GDX (GAMS Data Exchange) files. The mathematical modeling framework coded into GAMS optimizes the input data for the optimal levels of production, imports, and controls required to meet the demand.
- 4) The optimized input data are exported to Microsoft SQL database (through Excel spreadsheets) for further analyses.

Data processing is shown schematically in Figure 7-13, below.

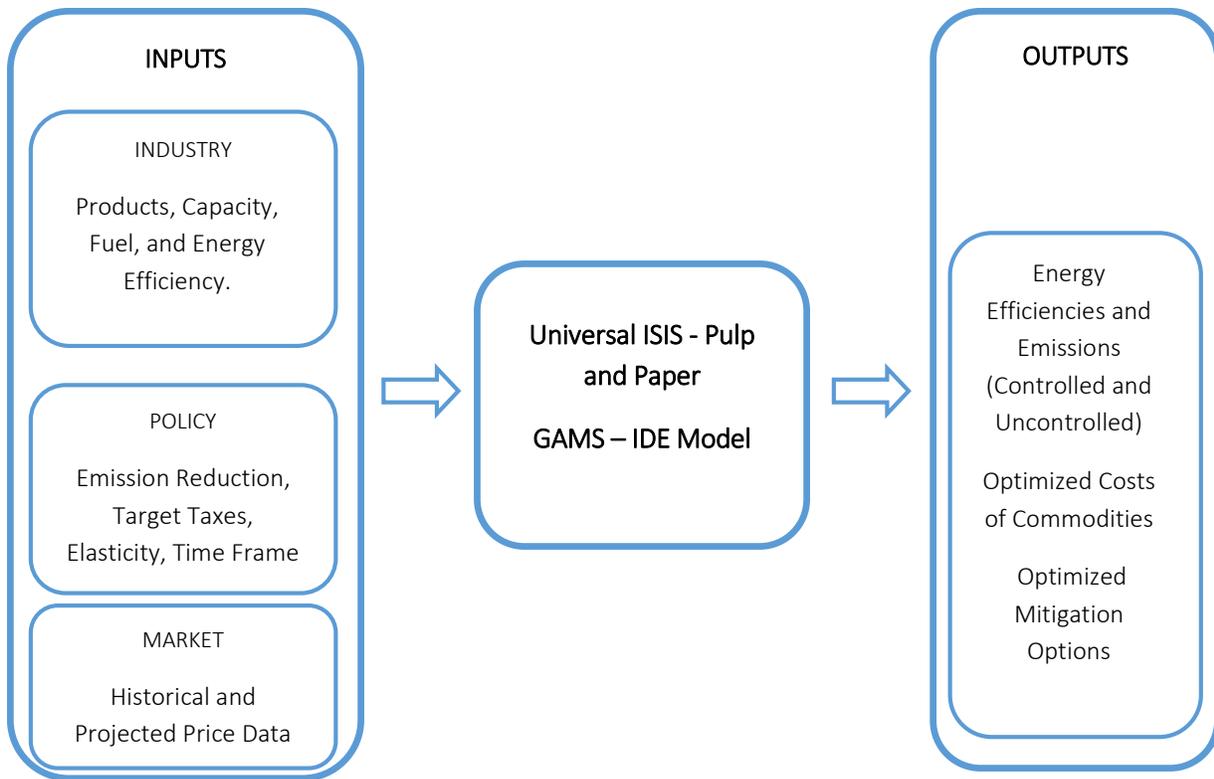


Figure 7-13. Universal ISIS-PNP Data Structure

## 7.6. Output Database

The desirable outputs which include optimized production level of each production unit by product, imports in each region, fuel requirements, controls, boiler emissions, and costs may be selected by the user. The resulting computations are exported to the PnPOUTPUTS.gdx file or into the Excel file, UISIS\_PNPOUTPUT.xlsx stored in the same folder as the input file. Various tabs in the output Excel sheet of this data set are explained in the table below to familiarize the user with location of desirable outputs.

<b>AGGREGATE RESULTS</b>	Optimized quantity and costs of total production and imports for both pulp and paper products for all mills combined.
<b>PRICES</b>	Average and Marginal prices for all paper products
<b>COSTS</b>	Fuel, raw material, labor, operation and maintenance, domestic transportation, and annual costs of production
<b>PLPPRODN</b>	Optimized quantity and costs of pulp products by mill
<b>FUELS</b>	Optimized quantity and costs of fuel by mill for both pulp and paper mills.
<b>PRPPRODN</b>	Optimized quantity and costs of paper products by mill
<b>DOMTRANSPORT</b>	Optimized domestic transport quantity and costs by product for both pulp and paper mills

PLP_BOILERS	Total heat and fuel required by mill for pulp mills
PR_BOILERS	Total heat and fuel required by mill for paper mills
BLS&MUD	Black liquor solids and lime mud quantity by mill for pulp mills
PRIMP&EXPORTS	Annual imports and export quantity by product
EMISSIONS	Annual domestic emissions by mill for both pulp and paper mills
RECYCLE	Amount of recycled material used

## 7.7. Running a Scenario in Universal ISIS-PNP

The model evaluates environmental and economic impacts of emission reduction scenarios by comparing the scenario case with business as usual case. Three cases are presented in this manual to make the user conversant with manipulating input data to obtain desired results from the model:

- BAU
- Scenario I – Emission constraints
- Scenario II – Fuel constraints

### 7.7.1. Business as Usual (BAU)

**Step 1:** Open Universal ISIS-PNP project (See section 7.3.1)

**Step 2:** Open UISIS\_PNPINPUTS excel sheet in DATABASE sub-folder of 2014 Universal ISIS-PNP folder, as shown in Figure 7-14.

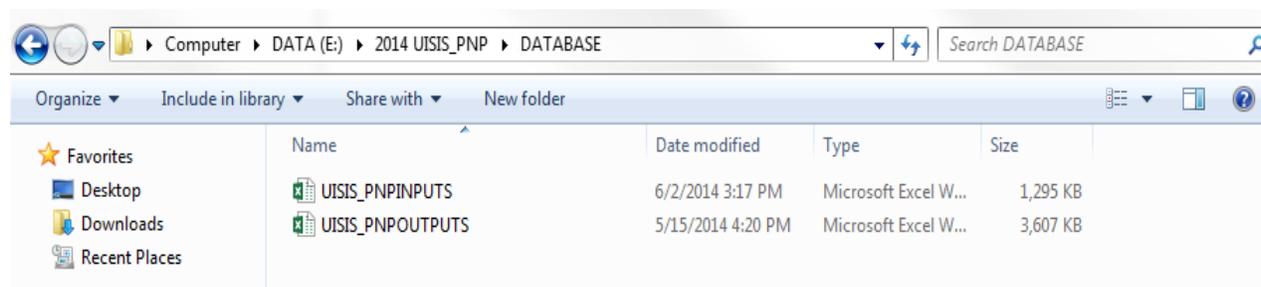


Figure 7-14. Input and Output Database Files of Universal ISIS-PNP

**Step 3:** Go to GENERALS tab to define the time period of simulation under **General Inputs (Pulp and paper mills)**. The cost data in the model were populated for the reference year 2009, and the simulation starts in 2010. To change the reference year to something other than 2009, the data in the input sheet have to be updated to reflect costs for that year. The user can choose to change the last year of simulation (e.g., **lastsimyear**, as shown in Figure 7-15). The optimized results will be projected until this last year. For this example, 2020 is chosen as the target year. In this case, the model will run simulations for a ten-year period (2010-2020).

Time	
simrefyear	2009
1stsimyear	2010
lastsimyear	2020
timeblock	1

Figure 7-15: Choosing time period of simulation in input file

**Step 4:** Go to POLICY tab of the spreadsheet to manipulate policy parameters for reduction of emissions (see section 7.4). For BAU scenario, scenario parameters should not be applied (“0” in Figure 7-16). Save and close the Excel file.

Allowances Auctioned at Fixed Allowance Price	1
Allowances Grandfathered	0
Allowance Trading with Output-Based Rebating	0
Apply Policy Parameters (Important: Apply Policy = 1, BAU = 0)	0

Figure 8-16: Applying business as usual parameters in input file

**Step 5:** Open and run DATABASE (See section 4.2).

**Step 6:** Open and run the model (See section 4.3).

**Step 7:** Open Universal ISIS-PNPOUTPUTS excel sheet in DATABASE sub-folder of 2014 Universal ISIS-PNP folder. The results are displayed in this output file. See Section 7 for location of desirable outputs.

## 7.7.2. Scenario I - Emission Constraints

**Step 1:** Open Universal ISIS-PNP project (See section 4.1).

**Step 2:** Open Universal ISIS-PNPINPUTS excel sheet in DATABASE sub-folder of 2014 Universal ISIS-PNP folder. Go to GENERALS tab to define the time period of simulation under **General Inputs (Pulp and paper mills)**. See Step 3 of Section 7.7.1.

**Step 3:** Go to POLICY tab of the spreadsheet to change to “Apply Policy Parameters” (“1” in Figure 7-17).

Allowances Auctioned at Fixed Allowance Price	1
Allowances Grandfathered	0
Allowance Trading with Output-Based Rebating	0
Apply Policy Parameters (Important: Apply Policy = 1, BAU = 0)	1

Figure 7-17. Applying Policy Parameters in Input File

**Step 4:** Set emission reduction constraints on POLICY tab under EMISSION INTENSITY TARGETS for target year, as shown in Figure 7-18. For example, **Pollutants in consideration** column gives values of NO<sub>x</sub> pollutant in BAU scenario between 2010 and 2020. To achieve 50-percent reduction of NO<sub>x</sub> by target year 2020, value of NO<sub>x</sub> in **Emissions Intensity Targets** column should be half of its 2010 value in **Pollutants in consideration** column. User can choose to change the target year to the year by which you want to meet the emission reductions. Save and close the UISIS\_PNPINPUTS Excel file after having specified the policy parameters.

Target Year	2020		
<b>Emissions Intensity Targets</b>			
EMISSION	Value		
NO <sub>x</sub>	=0.5*44468		
CO <sub>2</sub>			
SO <sub>2</sub>			
PM			
TRS			
VOC			
HAP			
<b>Pollutants in Consideration (S.Tons/year)</b>			
	NO <sub>x</sub>	CO <sub>2</sub>	SO <sub>2</sub>
2010	44,468	12,387,683	77,017

Figure 7-18. Target Emissions Constraint in Input File

**Step 5:** Open and run DATABASE (See section 4.2).

**Step 6:** Open and run the model (See section 4.3).

**Step 7:** Open UISIS\_PNPOUTPUTS excel sheet in DATABASE sub-folder of 2014 UISIS\_PNP folder. The results are displayed in this output file. See section 7 for location of desirable outputs.

### 7.7.3. Scenario II- Fuel Constraints

**Step 1:** Open Universal ISIS-PNP project (See section 4.1).

**Step 2:** Follow Step 2 and 3 of Section 8.2.

**Step 3:** Set fuel constraints on POLICY tab under **Pulp Mills Fuel Constraints** and **Paper Mills Fuel Constraints** columns for fuels, as shown in Figure 7-19. For example: - To make the model satisfy market demand without use of coal, set the value of 0.000001 for coal under “Fuel Constraints (=>) Note: Cheap fuel constraints must be less than or equal to” column for both pulp and paper mills fuel constraints. Save and close the UISIS\_PNPINPUTS Excel file after you have specified the policy parameters.

*Note:* If user wants the model not to utilize coal, user cannot enter “0” value for coal because the model is coded to read “0” as an empty box/no value. Entering a negligible value like 0.0000001 is understood by the model as constraint and it limits the use of coal. Entering “0” will make the model fully ignore the constraint resulting in the same results as BAU scenario.

Pulp Mills Fuel Constraints			
Fuel Constraints (=>) Note: Cheap fuel constraints must be less than or equal to			
Coal	NG	Oil	Hog
0.0000001			

Fuel Constraints (<=) Note: Expensive fuel constraints must be greater than or equal to			
Coal	NG	Oil	Hog

Paper Mills Fuel Constraints			
Fuel Constraints (=>) Note: Cheap fuel constraints must be less than or equal to			
Coal	NG	Oil	Hog
0.0000001			

Fuel Constraints (<=) Note: Expensive fuel constraints must be greater than or equal to			
Coal	NG	Oil	Hog

Figure 7-19. Fuel Constraints in Input File for both Pulp and Paper Mills

**Step 4:** Open and run DATABASE (See section 4.2).

**Step 5:** Open and run the model (See section 4.3).

**Step 6:** Open UISIS\_PNPOUTPUTS Excel sheet in DATABASE sub-folder of 2014 Universal ISIS-PNP folder. The results are displayed in this output file. See section 7.6 for location of desirable outputs.

## 7.8. Troubleshooting

GAMS error messages can be broadly classified into two types – compilation errors and execution errors.

### 7.8.1. Compilation Errors

The most common errors encountered when using GAMS-IDE are the compilation errors. Compilation errors arise due to errors in the syntax of the GAMS code. Common compilation errors include:

- Forgetting to end a statement or operation line with a “;”.

- Misspelled words or commands
- Using a parameter or variable before defining the parameter or variable.

Compilation error messages are outlined in red in the active process window. Click on these messages to be navigated to where the error was noticed. The Data list file contains markers for compilation errors as well. A text set marked by “\*\*\*\*” in the beginning of the line signals compilation errors. Error messages at the end of the Data list file provide more detail on these errors.

## 7.8.2. Execution Errors

Execution errors are more complex and difficult to decipher than compilation errors. Execution errors may include incorrect equation specification, insufficient memory, or infeasibility error.

### Incorrect equation specification

Execution errors often arise from incorrectly specified equations and models or unrecoverable constraints such as dividing by zero. Expanding on display statements and checking on defined parameters and variables to check on output values may prove useful in trying to single out the sources of executable errors.

### Insufficient memory

Another common execution error is caused by insufficient memory. When this error is encountered the user should try to install GAMS on a machine with higher memory (4 GB RAM (64-bit)). Alternatively, the user may choose to use an extended virtual memory to solve this problem although it will slow down the GAMS program. The insufficient memory error display is shown in Figure 7-20.

```

iOE 1 active process
uisis_pnp |
Iteration: 13097 Dual objective = -1063112914.612150
Elapsed time = 327.93 sec. (381244.74 ticks, 15051 iterations)
Elapsed time = 337.55 sec. (392603.98 ticks, 15288 iterations)
Iteration: 15975 Dual objective = -1048174272.772749
Elapsed time = 346.10 sec. (402639.86 ticks, 16318 iterations)
Elapsed time = 354.28 sec. (412775.01 ticks, 16708 iterations)
Elapsed time = 362.62 sec. (422936.69 ticks, 17403 iterations)
Elapsed time = 371.14 sec. (433298.19 ticks, 17633 iterations)
Iteration: 18609 Dual objective = -1010150231.220840
Elapsed time = 379.21 sec. (443376.93 ticks, 18828 iterations)
Elapsed time = 392.56 sec. (460021.76 ticks, 18872 iterations)
Removing perturbation.
Root relaxation solution time = 400.36 sec. (469234.56 ticks)
Root node processing (before b&ic):
  Real time = 632.43 sec. (522275.29 ticks)
Sequential b&ic:
  Real time = 0.00 sec. (0.00 ticks)
-----
Total (root+branch&cut) = 632.43 sec. (522275.29 ticks)
MIP status(107): time limit exceeded
Cplex Time: 1007.64sec (det. 555849.14 ticks)
Fixing integer variables, and solving final LP...
Presolve time = 1.44 sec. (12.22 ticks)
Insufficient memory for presolve.
CPLEX Error 1001: Out of memory.
Fixed MIP status(0):
Cplex Time: 3.25sec (det. 655.02 ticks)
*** CPLEX Error 1001: Out of memory.

*** CPLEX Error 1001: Out of memory.
Interrupt Stop  Summary only  Update

```

Figure 7-20. Insufficient Memory Error in Universal ISIS-PNP Run

### Infeasibility Error

The Universal ISIS-PNP utilizes several mathematical equations to satisfy a known demand at least cost while applying emission constraint inputs by the user. When the applied user constraints curb the ability of the model

to balance both the left and right hand side of the equations, the model fails to execute normal completion and displays an infeasible solution error. For example: The user puts a restriction on coal to get the demand met by other fuels like natural gas, etc., but the model requires energy from coal along with other fuels to satisfy heat balance equations. The model runs in two parts, general and elastic run. Even if the running status shows normal completion at the end of the Universal ISIS-PNP GAMS window, the user must check individual solutions of both models to check infeasibility error in each of them. The infeasibility error display is shown in Figure 7-21.

```
IDE No active process
database uisis_pnp
Starting Cplex...
Row 'EQPRDEMAND(2010.North.CNT)' infeasible, all entries at implied bounds.
Presolve time = 1.44 sec. (680.91 ticks)
MIP status(103): integer infeasible
Cplex Time: 1.56sec (det. 772.50 ticks)
CPLEX Error 1217: No solution exists.
Problem is integer infeasible.
--- Restarting execution
--- UISIS_PNP.gms(4392) 167 Mb
--- Reading solution for model UISIS_PnP
***
*** Reading with solveopt=REPLACE (0)
***
--- Executing after solve: elapsed 0:00:24.473
--- UISIS_PNP.gms(4394) 168 Mb
--- UISIS_PNP.gms(4395) 168 Mb
--- UISIS_PNP.gms(4455) 168 Mb

GDXXRW      Dec 18, 2012 24.0.1 WIN 37366.37409 VS8 x86/MS Windows
Input file : E:\2014 UISIS_PNP\EMISSIONS.GDX
Output file: E:\2014 UISIS_PNP\DATABASE\UISIS_PNPINPUTS.XLSX
Total time = 2309 Ms
--- UISIS_PNP.gms(4482) 168 Mb
--- Generating MIP model UISIS_ElPnP
--- UISIS_PNP.gms(4483) 681 Mb
--- 1,530,141 rows 3,160,488 columns 7,861,007 non-zeroes
--- 1,225,884 discrete-columns
--- Executing CPLEX: elapsed 0:00:38.410

IBM ILOG CPLEX Dec 18, 2012 24.0.1 WEX 37366.37409 WEI x86_6
--- GAMS/Cplex licensed for continuous and discrete problems.
Cplex 12.5.0.0

Reading data...
Starting Cplex...
Row 'EQPRELDEMAND(2010.North.CNT)' infeasible, all entries at implied bounds.
Presolve time = 1.86 sec. (1082.41 ticks)
MIP status(103): integer infeasible
Cplex Time: 1.96sec (det. 1174.77 ticks)
CPLEX Error 1217: No solution exists.
Problem is integer infeasible.
--- Restarting execution
```

Figure 7-21. Infeasibility Error in Universal ISIS-PNP Run

For more information on troubleshooting, licensing questions or other general queries, please refer to the GAMS tutorial and User Guide - <http://www.gams.com/docs/document.htm>

## Appendices

Appendix A RTI International Draft Memo for Pulp and Paper Industry January 16, 2009

Appendix B Andover Technology Partners Memo March 15, 2010

Appendix C RTI International Memos for Paper Machine November 16, 2011 and March 29, 2013