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Universal industrial sectors integrated solutions module for the pulp and paper industry

Gurbakhash Bhandar and

Office of Research and Development, Air Pollution Prevention and Control Division, U.S.
Environmental Protection Agency, Research Triangle Park, NC 27711, USA

Wojciech Jozewicz

Arcadis US, Inc., Research Triangle Park, NC 27611, USA

Abstract

The U.S. is the world's second-leading producer of pulp and paper products after China. Boilers, recovery furnaces, and lime kilns are the dominant sources of emissions from pulp and paper mills, collectively accounting for more than 99 % of the SO₂, almost 96 % of the NO_x, and more than 85 % of the particulate matter (PM) emitted to the air from this sector in the U.S.

The process of developing industrial strategies for managing emissions can be made efficient, and the resulting strategies more cost-effective, through the application of modeling that accounts for relevant technical, environmental and economic factors. Accordingly, the United States Environmental Protection Agency is developing the Universal Industrial Sectors Integrated Solutions module for the Pulp and Paper Industry (UISIS-PNP). It can be applied to evaluate emissions and economic performance of pulp and paper mills separately under user-defined pollution control strategies.

In this paper, we discuss the UISIS-PNP module, the pulp and paper market and associated air emissions from the pulp and paper sector. After illustrating the sector-based multi-product modeling structure, a hypothetical example is presented to show the engineering and economic considerations involved in the emission-reduction modeling of the pulp and paper sector in the U.S.

Keywords

Pulp and paper sector; Emissions analysis; Modeling; Economic analysis; Mitigation options and Cost; Environmental analysis; Multi-pollutant assessment

Correspondence to: Gurbakhash Bhandar.

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Introduction

The U.S. is the world's second-leading producer of pulp and paper products after China (SFIF 2014). In 2011, the domestic production of paper and paperboard was approximately 83 million tons (Benway 2013), and this production amounted to almost 4 % of the manufacturing gross domestic product (GDP) in the U.S. in 2012 (AF&PA 2014). Over the past few decades, the pulp and paper industry has reduced its environmental impacts by increasing the use of recycled paper because of less virgin pulp production. The amount of paper recovered for recycling has increased by more than 70 % since 1990. In 2013, approximately 64 % of the raw material used by the pulp and paper industry was recycled paper which has exceeded 60 % for the past 5 years. Other developments include energy efficiency improvement and switching, to cleaner fuels. Based on these improvements, air pollutant emissions have been reduced considerably. In 2012, sulfur dioxide (SO₂) emissions were approximately 27 % lower than in 2008, and nitrogen oxide (NO_x) emissions were 12 % lower than in 2012. (AF&PA, 2014).

Greenhouse gas (GHG) emissions also have been reduced substantially, decreasing by approximately 56 % since 1972, approximately 23 % since 2000. Underlying this trend is a drop-in emissions intensity (CO₂eq per unit of product), driven by fuel switching, using biomass residuals and production improvements. The GHG emission intensity for the combination of pulp and paper mills and wood products facilities has decreased by approximately 23 % since 2000 compare to 2012. Between 2010 and 2012, this rate was reduced by approximately 4 % (AF&PA, 2014).

GHGs are produced in the combustion processes that accompany power generation and the processing of pulping chemicals. Pulp and paper sector GHGs are predominantly carbon dioxide (CO₂), with smaller amounts of methane (CH₄) and nitrous oxide (N₂O) (GHGRP 2017). The majority of these CO₂ emissions are biogenic CO₂ emissions, derived from the combustion of biomass fuels (e.g., bark, other wood residuals, and black liquor). Biogenic CO₂ emissions are generated onsite as a byproduct of the pulping process (RTI 2009). According to industry analysis, from 1972 through 2012 (40 years), use of biomass residuals for energy instead of fossil fuels reduced the sector's CO₂ emissions by approximately 218 million tons (AF&PA 2014).

In general, there are four potential primary sources of direct and indirect emissions in the pulp and paper sector: 1) direct emissions (onsite) due to the combustion of fossil fuels and biomass in power boilers; 2) direct emissions (onsite) due to the processing of certain raw materials, the combustion of black liquor in recovery furnaces, and the combustion of lime mud waste in lime kilns; 3) indirect emissions (off-site) due to the combustion of fossil fuels at power plants to generate the electricity required by the pulp and paper industrial sector and bringing other materials (e.g., wood, chemicals, etc.) to the mill; and (4) overseas emissions (indirect) associated with imports. The latest available survey that estimated the emissions from U.S. pulp and paper mills demonstrated that the combination of boilers, recovery furnaces, and lime kilns is the dominant emissions source. This combination of sources collectively accounts for approximately 99 % of the SO₂, 96 % of the NO_x, and

85 % of the filterable particulate matter (PM) emissions of the pulp and paper sector (NCASI 2012).

Because of the variety of different processes and fuels used by the sector to produce various products, a multi-faceted tool is required to help understand the technical and economic implications of applying different process and emission control technologies to reduce the emissions of NO_x, SO₂, PM, and GHGs.

To understand these complexities more fully, EPA has developed a module of the Universal Industrial Sectors Integrated Solutions model for the pulp and paper sector (UISIS-PNP). The benefits of the sector-based multi-pollutant analysis approach utilized by UISIS-PNP include the ability for a user or decision maker to consider the feasibility, costs, and benefits across various pollutant types, including the criteria air pollutants (CAPs), hazardous air pollutants (HAPs) and GHGs. UISIS-PNP provides an innovative and comprehensive analysis of the pulp and paper sector in an integrated fashion, and the module framework is designed with the knowledge that decision makers must balance multiple objectives that may vary from community to community. The module identifies cost-minimizing strategies to meet alternative emission requirements by analyzing the interplay between emission reduction targets, environmental implications of reduction options, cost of technology, costs of products, regional differences in markets, and imports and exports. UISIS-PNP can aid plant operators, decision makers, researchers, and analysts to develop innovative emission reduction technologies and strategies (EPA 2013, Bhander 2015). The module can:

- Evaluate GHG and other pollutant emission reduction requirements for PNP on a regional or national scale
- Assess the environmental benefits and economic costs associated with different fuels used in the PNP sector
- Identify cost-effective emission control technologies needed to meet emission scenarios
- Consider energy efficiency, and other pollution prevention options for multi-pollutant emission reductions.

The following sections of the paper discuss the U.S. pulp and paper sector air emissions and applicable emission control technologies. Next, the data collection and processing methodologies utilized in UISIS-PNP are explained, followed by the description of UISIS-PNP structure and mathematical foundation. The illustrative analysis of cap-and-trade emission reduction strategy for the pulp and paper sector is presented to demonstrate the capability of UISIS-PNP module to analyze hypothetical emission reduction strategies. The analysis presented in this paper was conducted to verify the functionality of UISIS-PNP and has not been used to develop or recommend any emission reduction scenario.

Air Emissions and Control Technologies

The most recent survey of emissions from boilers, recovery furnaces, and lime kilns installed throughout the pulp and paper mills in the U.S. estimated that, in 2010, these emission sources produced 236, 187, and 33 thousand metric tons of SO₂, NO_x, and PM emissions,

respectively. Boilers produced the majority of these emissions (NCASI, 2012, Bhander, Jozewicz 2017).

Greenhouse gas emissions from the pulp and paper source category consist predominantly of CO₂ from fuel combustion. The pulp and paper sector generates significant emissions of both biogenic and non-biogenic CO₂. Biogenic CO₂ comes from combustion of spent pulping liquors (i.e., biomass) in chemical recovery combustion units and from the combustion of wood fuels in other stationary fuel combustion units. Non-biogenic CO₂ comes from fossil fuel combustion in chemical recovery systems, lime kilns, and other fuel combustion sources; and from the addition of carbonaceous makeup chemicals in chemical recovery systems. Table 1 summarizes the relative magnitude of nationwide GHGs emissions (in million metric tons of CO₂ equivalents per year [mtCO₂e/year]) reported to be emitted directly from stationary sources in the pulp and paper manufacturing sector in 2004 (EPA 2010a).

As discussed above, emissions of NO_x and SO₂ from pulp and paper mill operations have decreased significantly over the last two decades. Increasingly, industrial boilers are being designed to accommodate various fuels. This flexibility provides the advantage of being able to satisfy energy demand with low cost, locally available fuels (EPA 2009).

However, because different fuels produce flue gases with varying properties and compositions, certain NO_x emission control technologies may not be applicable for all fuels, as shown in Table 2.

Flue gas desulfurization (FGD) technologies can be used to remove SO₂ from flue gas. FGD technologies can be divided into wet, semi-dry, and dry systems. Wet limestone FGD systems, which use water to enhance performance, are the most common and achieve the highest SO₂ removal. Semi-dry FGD, which uses spray drying, is applied when low-to medium-sulfur fuels are being burned. Dry FGD (sorbent injection) typically does not achieve the SO₂ removal levels of wet or semi-dry FGD. Unlike NO_x controls, generally, any type of FGD can be used for any flue gas. The selection criteria and limiting factors include the desired level of SO₂ removal, water availability, waste handling preference, and the need for the co-benefit of removal of mercury.

Similarly, PM emission control equipment can generally be used on any flue gas. However, depending on the fuel and the properties of the resulting PM, removal efficiencies may vary. Certain properties of PM (e.g. high resistivity ash, soot particles etc.) may require special handling at the PM control equipment.

Data Collection and Processing

The UISIS-PNP modeling approach is focused on representing the entire population of integrated and non-integrated pulp and paper mills (approx. 663 mills) and their products in the U.S. To facilitate the analysis, all paper products in the modeling framework are grouped into eight major categories: 1) containerboard, 2) boxboard and other board, 3) packaging and industrial paper, 4) corrugating medium, 5) newsprint, 6) tissue, 7) coated printing and writing paper, and 8) uncoated printing and writing paper. Also, to facilitate the analysis,

two major categories of pulp products were established in the module, i.e., 1) softwood and 2) hardwood pulp. Nearly all pulp and paper production mills, as well as the demand centers (DCs), are located in three regions in the U.S., i.e., the North, South, and West, where pulp is supplied from pulp mill centers (PCs) to paper mill centers (SCs), and paper products are supplied from SCs to demand centers (DCs). DC is a distribution location where the product is sold to a consumer. Also, the import and export terminals are assumed to be located in the same three regions (North, South, and West). Imported pulp products are transported to PCs, and paper products are transported to the DCs. Pulp is transported from the PCs to the export terminals, and paper products are transported from the DCs to export terminals. Fig 1 shows how input and output data are grouped and managed in UISIS-PNP module. The inputs to UISIS-PNP module contain industry-specific data, market-specific data, and optimization parameters. Data outputs include optimized mitigation options and optimized economic parameters of products. The input data that are specific to the pulp and paper industry characterize the following aspects of individual facilities: unit-level production for each category of products, capacity, production cost (material, operations, and maintenance costs) (RISI 2011), capital cost, fuel types and cost, information about emissions sources (boilers, recovery furnaces, and lime kilns) (EPA 2002; EPA 2012a; EPA 2012b), mitigation technologies (emission controls), energy efficiency measures, and fuel emission intensities (EPA 2003; GHGRP 2017; ERG 2002; EPA 2010a). The data related to mitigation technologies provide information regarding applicable air pollution control technologies, their costs, and their emission control characteristics (EPA 2003; GHGRP 2017; ERG 2002; EIA 2015; Holloway 2016; Smook, 2002). Similarly, data related to measures intended to increase energy efficiency provide information regarding applicable energy efficiency measures, their costs, and their characteristics (EPA 2009; EPA 2010a).

The market data consist of historical and projected nationwide commodity consumption, discount rates, cost of electricity, escalation rates, economic life of technologies, and import and export quantities and prices (RISI, 2011). User-defined scenario choices related to optimization parameters provide information concerning emissions caps, emission reduction percentages, taxes, emissions abatements, banking options, and allowance options.

UISIS-PNP Module Formulation

UISIS-PNP is a dynamic, linear-modeling foundation that analyzes and evaluates the optimal industry-level and plant-level economic and environmental performance with and without the constraints imposed by the requirements of environmental compliance (Bhander 2015). The module considers complex plant-level economic and technical factors (inputs) as well as elasticity of demand, interest rates, import quantities and export demand, discount rate, and taxes on emissions. For each emission reduction strategy that is being considered, the module can identify optimal (least-cost) industry operation, cost-effective controls to meet market demand, and emission reduction strategies over the time period of interest. In this fashion, the extent of emission reduction and the cost to the industry to achieve the desired level of reduction can be calculated. The UISIS-PNP module treats the pulp mill and the paper mill as two separate mills rather than as one integrated mill. This approach gives the user the ability to evaluate the economic impact of emission constraints that are exclusively applicable to each of the mills. Optimal solutions for the baseline case (without

emission constraints or Business as Usual (BAU)) and the emission reduction strategy case (with emission constraints) are obtained by using a solver application embedded in the UISIS-PNP Optimization Engine.

It is developed in such a way as to help the user understand the required inputs when modeling the pulp and paper industry and to assist with entering the baseline BAU data for the pulp and paper sector. In this fashion, the extent of emission reduction and the cost to the industry to achieve the desired level of reduction can be calculated.

UISIS-PNP Modelling Structure

Fig 2 shows the general structure of UISIS-PNP module. As can be seen in Fig 2, the module treats the pulp mill and the paper mill as two independent mills rather than as one integrated mill. This approach gives the user the ability to evaluate the economic impact of emission constraints that are exclusively applicable to each of the mills.

The UISIS-PNP module addresses five types of mills: 1) existing mills that are currently operational and producing different categories of products, 2) expansion mills that are additions to existing mills to increase their production capacity, 3) replacement mills that are new production mills built to replace existing production mills as they are retired from service, 4) new production mills built or under construction that represent entirely new production capacity, and 5) projected production mills that represent entirely-new production capacity projected for the future.

The UISIS-PNP module is a stand-alone, mathematical modeling framework coded into General Algebraic Modeling system (GAMS) solves (optimizes) the model by choosing decision variables for the optimal levels of production, imports, and controls required to meet the demand and the emissions constraints resulting from emission reduction strategy inputs. GAMS software is a frequently used optimization software package that can be download from the website: www.gams.com including user manuals. Optimal solutions for the baseline case (without emission constraints or Business as Usual (BAU)) and the emission reduction strategy case (with emission constraints) are obtained by using a solver application (e.g. CPLEX) embedded in the UISIS-PNP Optimization Structure. The optimized results are transferred into the database and presented with the outputs interface to illustrate results in the format of interest. The user-defined inputs data includes the time horizon (simulation period), reference year, discount rate, commodity characteristics, emissions types, fuel types, and plant types. The graphical interface functions as an intermediate facilitator between the optimization engine and an interface that assists users with exchanging data and manipulating results. The interface allows the user to enter the BAU industrial sector data, which include historical and projected nationwide commodity consumption, commodity imports, number of production facilities, distance from production facilities to demand center, production capacity, associated costs (e.g., material, operations, and maintenance), fuel types and costs, emissions sources and intensities, and other data.

Mathematical Framework of UISIS-PNP

The mathematical framework of UISIS-PNP is centered on its objective to minimize the difference between the consumer's price and the producer's price such that you achieve equilibrium between both. The cumulative amount that consumers pay is integrated over existing demand centers to yield a demand curve. To satisfy market demand, the model performs multiple iterations to balance domestic production and import quantities. Demand is satisfied when the marginal demand price no longer exceeds the marginal supply cost. Once the quantities are determined, the module optimizes the total cost by solving the objective function of minimizing the total cost of the production that is required to meet the demand (Srivastava et al. 2011; EPA 2013).

The user chooses a range of interest centered on the expected demand for demand center and production year (default value 0.5 – 1.5). Demand in this range is divided into a user defined number of steps or intervals (default 100 steps). The inverse demand curve is used to determine the demand price ($P(D)$) at the midpoint of each demand step using a constant elasticity (default $\sigma = 0.88$) of demand model for each region (D_0 and P_0 are the initially-specified demand quantity and price):

$$P(D) = P \left(\frac{D}{D_0} \right)^{\frac{1}{\sigma}} \quad [1]$$

The demand for a product in a market can be met by the sum of domestic production (sum of Units (PRQ_{Unit})) and sum of foreign imports from terminals (IPR_{Ter}) decreased by the total amount of exports (EPR_{Ter}), as shown in the equation below:

$$\sum_{Unit} PRQ_{Unit} + \sum_{Ter} IPR_{Ter} - \sum_{Ter} EPR_{Ter} \geq \sum_{STEP} DEMAND_{Step} \quad [2]$$

Changes required in the domestic production capacity to satisfy demand are determined within the module as a function of total production-related costs.

The total cost is determined from the available producer's cost data when the pulp and paper production by individual mills is integrated, beginning from the least-expensive plants (and including imports) until the demand has been satisfied. The total cost for each plant includes costs associated with production, import-export, transportation, emission control, and energy efficiency improvement costs. These costs are discussed below. Emission control and energy efficiency improvement costs are discussed in more detail than other costs listed above because they affect UISIS-PNP's hypothetical scenarios presented in this paper (Bhander 2015).

The production-related cost component includes electricity production and consumption, heat production, and waste paper recycling. Heat in the form of steam is required for pulp and paper production. There are two main sources that can provide heat: power boilers and recovery furnaces. Burning black liquor in recovery furnaces supplements the heat produced

with fossil fuel-fired and wood-fired power boilers. Heat produced from boilers can also be used for the generation of electricity that can be used to satisfy the mill's own demand for electricity, or it can be sold to a grid. A modern Kraft pulp mill is more than self-sufficient in its generation of electricity and normally can provide electricity to other industries or the local community. Waste paper products are recycled and serve as feedstock to produce paper products. In UISIS-PNP, plants are classified as to whether or not they could purchase recycled fiber or purchase both market pulp and recycled fiber.

The cost of imports to each import district is a function of the quantity of pulp or paper that is imported and the cost of importing the products. The quantity imported is assumed to be the average quantity imported over the last five years of the modelled period. The terminals' default capacities are assumed to be 20 % more than the average quantity imported (default value can be adjusted by the user). The cost of imports is the sum of the import price times quantity delivered to the import district, the costs of insurance and freight to the import terminal, and the handling costs at each import terminal. The cost of exports to each export terminal is the product of the quantity exported and the cost per unit of product exported. The total cost of exports is the sum of the export price times quantity delivered to the export terminal, the costs for insurance and freight to the export terminal, and the handling costs at each export terminal. The quantity of exports is assumed to be the average quantity exported over the last 5 years, and it is assumed to be equal to the capacities of the terminals. The user can define the percentage increase in the quantity exported annually (e.g., three percent increase per year).

Costs for domestic transportation of paper are the costs associated with moving paper products from supply centers (paper mills) to demand centers. Costs for transporting pulp are the costs associated with moving pulp products from pulp supply centers to paper supply centers. Based on the transportation costs associated with alternative routes, the module determines the optimal transportation route between the supply centers and the demand centers. All transport data are adapted from NAPAP report/documentation (Timber Outlook 1993). In the NAPAP report, the exact transport cost from one region to another region was not given but only from a given region to the entire USA was given. This has led us to assign the lowest cost to be the transport cost between the like regions. For instance, for the Container Board product the transport cost from North to North is the lowest value of the three values for import districts. The same rule applies to all the products. It is assumed that the transport cost from North to South or from South to North to be the intermediate cost, and either from North or South to West to be the most expensive one. We have also assumed the transport cost from a given region to another given region to be same as reverse. For instance, the transport cost from North to South is the same as from South to North for all the products. For the pulp products, where there was more than one subcategory available, we took the respective average. For instance, for pulp and paper product there were cost listed for the Specialty Packaging and the Kraft Packaging. For this particular case, we entered the average transport cost from a given region to another given region.

Available emission control technologies and their characteristics are recorded in a database that contains the inputs. UISIS-PNP selects the least-cost control technology from the inputs and assumes that it is installed on a unit to acquire the reduction in pollutant emissions

required by the emission-reduction scenario under consideration. It should be clarified that UISIS-PNP imposes the constraint of a control from one vintage on a unit for the period starting when the control of that vintage comes online and ending when the lifecycle of the control ends. After the lifecycle of the control of that vintage ends, the control technology can no longer be used. In general, the costs associated with controls comprise the capital, fixed operation and maintenance costs, costs associated with the consumption of any reagents and/or catalyst, cost savings associated with any reduction in the use of fuels and/or raw materials associated with electricity consumption, cost(s) associated with byproduct(s), and cost associated with the use of water. Various cost elements are escalated appropriately to use values in the years of interest, as show< below:

$$CC_{unit} = \sum_{poll} (CC_{poll} \cdot POLQ_{poll}) \quad [3]$$

$$Z_{CC} = \sum_{unit} CC_{unit} \quad [4]$$

where CC_{unit} is the control cost (\$/year) of installing control on an industrial boiler, CC_{poll} (\$/ton of pollutant) is the cost of control per ton of the pollutant being controlled, and $POLQ_{poll}$ is the total tons of the pollutant produced by a unit. Note that Z_{CC} is total control costs (\$/year) for the entire sector calculated by summing the CC_{unit} (control costs) of each unit.

Energy efficiency measures are treated in UISIS-PNP in a way similar to the treatment of emission control technologies. Similarly, to previously described constraints, it is assumed that only an energy efficiency measure of one vintage is possible on a unit for the period starting when the measure of that vintage comes online and ending when its technical life ends (EPA, 2010a). Costs for controls and energy efficiency options consist of both capital recovery cost and variable costs to achieve any emission reduction targets governed by the constraints. Both measures are amortized over the expected lifetime of the modification. Control technologies further modify the energy intensity of production and, therefore, the fuel cost as well. Some of the most commonly used measures include good operation and maintenance practices, air preheaters and economizers, boiler insulation, minimization of leakage, and steam-line maintenance are in common use and are capable of substantial reductions of CO₂ emissions. The cost elements associated with these measures are specific to each plant. Individual costs to upgrade a plant, can be added to estimate the total cost, Z , for a plant:

$$Z = \sum_{unit} E_{old,unit} (1 - e_{fraction}) \quad [5]$$

where $E_{old,unit}$ is the emissions of a unit before the upgrade measures have been implemented. The emission reduction fraction ($e_{fraction}$) is the target fractional reduction of emissions (control emission reduction capacity).

Constraints within UISIS-PNP

UISIS-PNP was developed to determine the optimal (least-cost) operation of the pulp and paper sector to achieve onsite emission reductions over the time period of interest. UISIS-PNP includes constraints for ensuring that changes in the production capacity occur in a realistic way. For example, when considering consumption and supply for each demand center, the total supply must be greater than or equal to consumption in the given time period. Supply for each demand center can be comprised of local production, imports from other demand centers, and foreign imports. UISIS-PNP provides the user with the flexibility to determine demand centers, import and export terminals, the quantities and prices of commodities, and the associated domestic and export/import transportation costs. These constraints are discussed in more detail below.

Production of a commodity is limited by the availability of the plant, which can be restricted by the availability of resources (fuel and raw materials) and the capacity of the plant. For example, energy consumption by a plant can only be associated with the fuels that are available at the plant site.

UISIS-PNP includes algorithms to account for multiple pollutant streams associated with uncontrolled emissions, controlled emissions, pollution prevention from process modifications or implementation of energy efficiency measures, and any emission control-related effects (co-benefits, when applicable) (Bhander 2015). The total emissions of any given pollutant are limited to the emission limits specified by the emission-reduction strategy selected by the user. In cases in which the strategy being analyzed allows for the banking of emissions, the banking equation enables the banking of allowances for future use (EPA 2013; Bhander 2015).

Transportation of goods and commodities from a supply center is limited by the lower of two values: 1) the production capacity of the supply center and 2) the transportation capacity from a supply center to all demand centers. The quantity of imports for each terminal is limited by its capacity. However, UISIS-PNP provides the user with full flexibility to customize assumptions, including changes in the quantity of imports at the terminal (e.g., percentage increase per year) or changes in the prices of the imports or the locations of the terminals. The quantity of exports for each terminal is limited by a user-defined limit.

UISIS-PNP Applications

The Clean Air Act (CAA) requires EPA to review the new source performance standards (NSPS) and the national emission standards for hazardous air pollutants (NESHAP) for pulp and paper production every eight years. The NSPS regulate selected criteria pollutants—nitrogen oxides (NO_x), sulfur dioxide (SO_2), and PM from industrial boilers and the NESHAP also regulates chlorinated compounds from bleaching processes at pulp and paper mills. A separate NESHAP regulates organic HAP (predominantly methanol, plus other

organic compounds) and metallic HAP (regulated through a PM surrogate) from chemical recovery combustion sources at pulp mills. The hypothetical analysis is presented to show how the module would assist EPA in determining the impacts of revised federal regulations, as well as obtaining an estimate of how mills might comply with the new standards (e.g., reduced production, process changes, add-on controls, fuel switching, equipment upgrades, or mill closure).

As mentioned above, the UISIS-PNP module treats the pulp mill and the paper mill as two independent mills rather than as one integrated mill that provides the user the ability to evaluate the economic impact of emission constraints. Optimal solutions for the baseline case (without emission constraints or Business as Usual (BAU)) and the emission reduction strategy case (with emission constraints) are obtained by using a solver application embedded in the UISIS-PNP Optimization Engine. The key inputs of interest to the user when establishing the BAU may be grouped into variables that describe production and demand, unit characterization, emission control costs, and other costs. The input variables that describe production and demand include:

- production level of each production unit to meet regional demand
- product demand by product category and by market region, and
- quantities of imports and exports in each market region.

The input variables for individual unit characterization include:

- existing installation of emission controls
- existing application of energy efficiency measures
- efficiency of the existing energy efficiency measures and emission controls
- emissions of multiple pollutants
- fuel availability by production unit (coal, natural gas, oil, byproduct liquor, biomass)
- emission control type - primary fuel mapping, and
- emission control type - boiler type mapping.

The input variables that describe emission control costs and other costs for an individual unit include:

- capital cost, fixed cost, and variable cost components for emission controls
- capital cost, fixed cost, variable cost components for energy efficiency measures
- transportation cost, and
- fuel cost for the types of fuel available at the unit.

To illustrate the utility of UISIS-PNP in pulp and paper sector, a pollution reduction (mitigation) scenario including the possible outputs of UISIS-PNP when conducting the analysis of the cap-and-trade emission reduction scenario for SO₂ is demonstrated. This following example identifies the practical range of options available for the reduction of SO₂

emissions in the time scenario considered and the features of the PNP sector in the selected range of options.

Hypothetical Cap-and-Trade Scenario

Methodology

Under the cap-and-trade emission reduction scenario, an emissions cap is set on the amount of a pollutant that can be emitted (EPA, 2017). Sources, companies, or other groups are issued emission permits (allowances) that represent the right to emit a specific amount of the pollutant. Sources or companies that need to decrease their emissions must either buy allowances from those who pollute less or install emission reduction technology. The transfer of allowances is referred to as a trade. In effect, the buyer is paying a charge for polluting, while the seller is being 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.

UISIS-PNP module allows the user to select an allowance price to determine the level of emission reduction achieved by the sector that corresponds to the selected allowance price. The user can select from an input menu including cap-and-trade with or without de minimis requirements and can specify separate caps on pollutants of interest (emissions include SO₂, NO_x, PM, and VOC). The user has the option to run a cap-and-trade scenario with or without banking (or saving emission credits) of emissions if the user decides to analyze a cap-and-trade scenario with the de minimis requirements, the user defines a minimum level of emission reduction required for each emission unit (single pulp and paper plant). If the emission tax scenario is of interest, the user may input an amount of emission tax for pollutants of interest. The user also can specify the scenario's horizon (time period) to be used for the model runs.

For cap-and-trade analysis, the inputs that can be set by the user include:

- emission reduction required (sector based), %
- minimum emission reduction required for a unit, %
- banking option, yes/no
- amount of emission tax, \$/ton of pollutant
- emission allowance price, \$/ton of pollutant
- scenario's horizon, years.

The emission reduction requirements that result from the cap-and-trade scenario may be satisfied by fuel switching, installation of energy-efficient improvement measures, installation of emission controls, or by the combination of these.

Different fuel-switching scenarios can be analyzed by UISIS-PNP, and an optimum scenario of fuel switching can be selected to minimize emissions. Given the availability of various fuels and boiler type-fuel type matches, the fuel-switching option may offer substantial reductions of emissions from the pulp and paper sector since boiler emissions are a function

of the type and amount of the fuel that is used. For example, the combustion of natural gas produces far less SO₂ emissions than the combustion of coal because the sulfur content of the gas is significantly lower than the sulfur content of coal. Similarly, fuels that produce high amounts of NO_x emissions could be replaced with fuels that generate lower NO_x emissions. For example, natural gas and oil are more favorable fuels from the standpoint of NO_x emissions than coal and wood. Thus, natural gas may replace coal.

To demonstrate the application, a constraint is added to reduce the use of coal in the PNP sector by 50 % relative to 2010 (EIA 2014). No energy efficiency measures were applied across the PNP sector. Constraining 50 % coal supply may affect the commodity production of a coal-based plant because coal boiler may not be able to produce enough heat to satisfy production-demand. The module then compensated for the coal constraint by increasing the use of other fuels based on fuel costs, fuel availability and fuel emission factors. In addition, 2010 PNP boiler inputs of coal, wood, natural gas, and residual oil use are combined with their respective air pollutant emission factors (lbs. of pollutant/MMBtu of heat input) to estimate 2010 NO_x, SO₂, PM, and GHG emissions by fuel type.

Results

Fig 3 shows the extent of the reductions of CO₂, NO_x, and SO₂ emissions obtainable in the pulp and paper sector resulting from switching from coal to various other fuels. In this illustrative scenario, half of the coal that was used (by heat input) was replaced with natural gas, oil, or biomass. As can be seen in Fig 3, coal-to-natural gas switch was the most effective option as far as the amount of NO_x emission reduction resulting from fuel switch. NO_x emissions were reduced significantly from about 128,241 metric tons to 107,350 metric tons because the coal fuel was constrained and the module used the natural gas (natural gas next low cost) to satisfy production to meet demand. Furthermore, the switching from coal to either natural gas or biomass approximately halved SO₂ emissions because there are typically negligible amounts of S in these fuels. The substitution with biomass provided an additional benefit of reduced emissions of non-biogenic CO₂.

Discussion

The main problems that should be analyzed by the user in this example are the determination of the practical range of options available for the reduction of SO₂ emissions in the time scenario considered and what the features of the PNP sector will be for the selected range of options. Once the practical range of emission reductions has been determined, the user can analyze the PNP industry revenue and the price of the PNP product categories under the scenario considered.

For a chosen range of SO₂ reduction levels, first, UISIS-PNP determines the predicted allowance price (\$/ton of SO₂) under the cap-and-trade scenario by conducting UISIS-PNP module runs for the BAU case and separately for each of the caps selected for analysis by the user. Based on this allowance price information from these initial runs, the user can select an economically viable range of emission reductions.

To satisfy demand without disturbing production, the module requires input of all available fuels for every plant. Fuel prices are also required because the module replaces fuels beginning with the least expensive (linear modeling). In this way, while choosing from various fuels, the module is capable of minimizing the operating costs of the pulp and paper mills while meeting the emission reduction scenario under consideration, regional demands, and capacity constraints.

For cases in which deployment of energy efficiency improvement measures or installation of additional emission control technology is necessary to meet the requirements of the emission reduction scenario under consideration, e.g., the cap-and-trade scenario, UISIS-PNP requires the input of detailed technology costs. Input cost categories for each energy efficiency measure or emission reduction technology include:

- capital and fixed O&M cost
- costs of reagents, water, and electricity
- costs of handling byproducts
- costs associated with the reduction or modification in fuel and/or raw material use.

Emission reduction by the combination of fuel switching and the installation of emission control technology can be analyzed by UISIS-PNP. For example, when the user wants the unit to accomplish high reductions in the levels of SO₂ emissions, the installation of wet FGD may be considered, which would yield up to approximately 95 % reduction. The alternative approach would be for the user to analyze the combination of measures. In this case, the user might select to switch the existing fuel to the fuel with lower sulfur content and install spray drying FGD to accomplish the required level of SO₂ emission reduction. The latter approach would present the benefit of the substantially lower capital cost of spray drying FGD rather than wet FGD, while meeting the required emission reduction level. Output data from UISIS-PNP module are written in appropriate worksheets in an Excel workbook and further linked to various plots to enable visual presentation and analyses of the results. Analyses of the output data from emission reduction technologies are presented for multiple pollutants.

The module can also be used to estimate emissions (e.g. NO_x, PM etc.) reduction by installing of air pollution control equipment from the plant. Bhander and Jozewicz (2017) provide more details.

UISIS-PNP also is capable of analyzing the amount of imports that the U.S. PNP sector might decide to bring into the country. Since imports do not cause emissions in the U.S., they may be used to achieve part of the emission reduction required by the scenario. In parallel, the framework is capable of estimating the capacity of units that may be retiring due to the decrease in revenue.

As shown above, the user has the option of an in-depth analysis of emission reduction scenarios applicable to the PNP sector. The UISIS-PNP modeling framework allows the user to select a number of inputs that affect the scenario under consideration, such as the time

horizon or the extent of emissions reduction. The outputs from UISIS-PNP provide an overview of the impact of a given scenario on the features of the PNP sector such as its revenue, prices of the categories of products, and the amount of imports.

Conclusions

This paper describes the sophisticated yet user-friendly module for the technical and economic analyses of user-defined scenarios in the pulp and paper sector. Industry-specific inputs, market behavior, imports/exports, domestic transportation, and emission control options can be varied, and users can easily incorporate the modifications they wish to assess into the module. UISIS-PNP is a detailed engineering module that was carefully designed to deal with such challenges accurately and effectively. The module provides an innovative comprehensive analysis of the pulp and paper sector in an integrated fashion, and the module was designed based on the understanding that decision makers must balance multiple objectives that vary from one location to another and that often are in conflict with each other. UISIS-PNP is a complex mathematical optimization framework, so its proper use requires quantitative skills, an understanding of economic issues, knowledge concerning environmental issues and pollutant control approaches, and an understanding of the PNP sector.

UISIS-PNP is a decision support tool that was designed specifically to support decisions concerning emission reduction scenarios for the PNP sector with the aim of obtaining an in-depth understanding of potential economic and environmental benefits and issues in that sector. This aim is achieved by the detailed analysis of primary calculations of the overall economic and environmental value for the PNP sector while using data for selected commodities, operations, maintenance, production, and energy consumption. Thus, using the module allows the gradual refinement of the economic and environmental impacts of various emission reduction scenarios on the pulp and paper sector.

The module provides many possibilities and approaches for determining and understanding optimal industrial behavior through aggregated and detailed results that include unit level production, capacity, emissions, energy use, energy intensities, and controls. Analyses and comparisons of emission reduction strategies can be performed using different levels of optimization for the reduction of pollutant emissions. This approach makes it possible to choose the optimal solution regarding the potential impacts of industrial activities on the environment. The module will help private industry optimize production by implementing cost-effective mitigation approaches to comply with environmental regulations. The module will help decision makers understand the environmental and economic impacts of strategies that have been proposed to reduce emissions, thereby ensuring that the future activities of the pulp and paper sector are beneficial to both the environment and society as a whole.

The parameters of the framework include the simulation period, reference year, discount rate, time blocks, commodity characteristics, and the types of emissions, fuels, and plants. The baseline data include the nationwide consumption of pulp and paper, the imports of pulp and paper products, the number of mills, the distances from the mills to demand centers, the production capacity of the pulp and paper industry with associated costs, types of fuels and

their costs. The data also include the characteristics and costs of the mitigation options; energy efficiency measures, and costs; and emission sources and their intensities.

The module presents an opportunity for users to understand the optimal behavior of the pulp and paper sector on a regional or national basis. Analysis of emission reduction strategies can be performed and compared using different levels of optimization of the reduction of pollutants. Strategies may be simulated over long- and short-time horizons, such as a pollutant reduction strategy that occurs over a decade or a criteria pollutant strategy based on one year.

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References

- AF&PA. [Last accessed on July, 09, 2016] 2014 American Forest & Paper Association (AF&PA) Sustainability Report - Better Practices Better Planet 2020. 2014. Available at: <http://www.afandpa.org/docs/default-source/one-pagers/-2014-sustainability-report.pdf>
- Benway, SJ. [Last accessed on Nov, 17, 2016] Industry Surveys - Paper & Forest Products, Standard & Poor's. 2013. Available at: <https://securingalpha.files.wordpress.com/2014/01/paper-forest-products.pdf>
- Bhander, GS. Universal Industrial Sectors Integrated Solutions Model for the Pulp and Paper Manufacturing Industry – Universal ISIS-PNP. U.S. Environmental Protection Agency; Cincinnati, OH: 2015. EPA/600/R-14/322
- Bhander GS, Jozewicz W. Analysis of emission reduction strategies for power boilers in the US pulp and paper industry, Energy and Emission Control Technologies. Davepress. 2017; 5:27–37.
- EIA. [Last Accessed Dec. 17, 2014] Unless otherwise noted, all factors are, from the Energy Information Administration. 2014. <https://www.eia.gov/renewable/data.php#solar>
- EIA. [Last Accessed June, 6, 2016] U.S. Energy Information Administration. State Energy Data System. Wood and Biomass Waste Price and Expenditure Estimates. 2015. Available at: http://www.eia.gov/state/seds/sep_fuel/html/pdf/fuel_pr_ww.pdf
- EPA. U.S. Environmental Protection Agency. Nitrogen Oxides (NO_x), Why and How They Are Controlled, Publication No. EPA/456/F-99-006R. 1999.
- EPA. U.S. Environmental Protection Agency. EPA Air Pollution Control Cost Manual, Sixth Edition. Section 6: Particulate Matter Controls, Chapter 3: Electrostatic Precipitators. Publication No. EPA/452/B-02-001. 2002.
- EPA. U.S. Environmental Protection Agency. AP-42. Fifth Edition. Volume I: Stationary Point and Area Sources, Chapter 1: External Combustion Sources, Section 1.6: Wood Residue Combustion in Boilers. 2003.
- EPA. [Last Assessed Aug. 07, 2017] U.S. Environmental Protection Agency. Technical Support Document for the Pulp and Paper Sector: Proposed Rule for Mandatory Reporting of Greenhouse Gases. 2009. Available at: <https://www.epa.gov/sites/production/files/2015-06/documents/ghg-mrr-finalpreamble.pdf>

- EPA. U.S. Environmental Protection Agency, Available and emerging technologies for reducing greenhouse gas emissions from the pulp and paper sector. Office of Air and Radiation, Environmental Protection Agency; 2010a.
- EPA. U.S. Environmental Protection Agency. AP-42, Fifth Edition. Volume I: Stationary Point and Area Sources, Chapter 1: External Combustion Sources, Section 1.3: Fuel Oil Combustion. 2010b. May 2010 (corrected)
- EPA. [Last accessed on July, 09, 2016] U.S. Environmental Protection Agency. Memorandum from J. Bradfield and K. Spence, to Project Files. 2012. Available at: https://www.epa.gov/sites/production/files/2015-06/documents/tech_review_memo_subpart_s.pdf
- EPA. U.S. Environmental Protection Agency, Alternative Control Techniques: NO_x Emissions from ICI Boilers. Office of Air and Radiation, Office of Air Quality Planning and Standards RTP 27711; 2012a.
- EPA. [Last Assessed Aug. 07, 2017] U. S. Environmental Protection Agency. Industrial/Commercial/Institutional Boilers and Process Heaters Database. 2012b. Database available at: <https://www.epa.gov/stationary-sources-air-pollution/industrial-commercial-and-institutional-boilers-and-process-heaters>
- EPA. Universal Industrial Sectors Integrated Solutions Model for the Portland Cement Manufacturing Industry, November 2013, Version 3.0. U.S. Environmental Protection Agency; Research Triangle Park, NC 27711: 2013. EPA/600/R-14/089
- EPA. [Last Accessed July. 10, 2017] U.S. Environmental Protection Agency. What Is Emissions Trading?. 2017. Available at: <https://www.epa.gov/emissions-trading-resources/what-emissions-trading>
- ERG. [Last Accessed July. 10, 2017] Eastern Research Group, Inc. Methodology for Estimating Cost and Emissions Impacts for Industrial, Commercial, Institutional Boilers and Process Heaters National Emission Standards for Hazardous Air Pollutants, Appendix B-1b: Emission Reduction Existing Boiler Final. Memorandum to J. Eddinger. U.S. Environmental Protection Agency, OAQPS (C439-01). 2002. Available at: <https://yosemite1.epa.gov/ee/epa/ria/nsf/vwTD/F08671A7E50CB61E85256C9F005247BF>
- GHGRP. [Last Accessed Aug. 07, 2017] Greenhouse Gases Reporting Program. U.S. Environmental Protection Agency. Greenhouse Gas Reporting Program data publication page. 2017. Available at: <https://www.epa.gov/ghgreporting/ghgrp-pulp-and-paper>
- Holloway, T., Hanks, K. [Last Accessed Aug. 7, 2017] Costs/Impacts of the Subpart MM Residual Risk and Technology Review, EPA Contract No. EP-D-11-084; Work Assignment No. 4-05. Memorandum to K. Spence and B. Schrock, U.S. 2016. Available at: https://www.epa.gov/sites/production/files/2016-12/documents/153_impacts_memo_revised.pdf
- NCASI. National Council for Air and Stream Improvement (NCASI). Pulp and Paper Mill Emissions of SO₂, NO_x, and Particulate Matter in 2010. Special Report No. 12-03. 2012.
- RISI Inc.. North American Graphic Pulp & Paper Capacity, Pulp & Paper Historical, Paper Packaging, World Market Pulp & Paper Capacity, Tissues Capacity, Mills Assets data Report, 2011: Resource Information Systems Database (Purchased by ORD/NRMRL/APPCD). 2011.
- RTI. Research Triangle Institute International (RTI), Draft memorandum from Katie Hanks and Tom Holloway to Beth Palma. 2009.
- SFIF. Swedish Forest Industries Federation, Forest Industry Statistics Swedish Forest Industries Federation. Stockholm, Sweden: 2017. Available at: <http://www.forestindustries.se/forest-industry/statistics/international/>
- Srivastava, R., Vijay, S., Torres, E. Reduction of Multi-Pollutant Emissions from Industrial Sectors: The U.S. Cement Industry-A Case Study, Chapter 8 in 'Global Climate Change-The Technology Challenge'. Princiotta, FT., editor. Springer; New York: 2011. p. 256-298.
- Smook, GA. Handbook for Pulp and Paper Technologists. 3. Angus Wilde Publications Inc.; Vancouver, B.C.: 2002.
- Timber Outlook. Recycling and Long-Range Timber Outlook, background Research Report 1993, RPA Assessment Update USDA Forest Service, Table: 54, 62–64. 1993.

Fig 1.
Management of input and output data.

Fig 2.
General structure of UISIS-PNP module (Bhander 2015).

Fig 3.

The effect of 50 % coal use reduction on emissions of NO_x, SO₂, PM, and GHG emissions.

Table 1

Nationwide GHG Emissions from the Pulp and Paper Manufacturing Industry in the U.S. (EPA 2010a).

Emission Source	Million metric tons of CO₂e/year
Direct emissions associated with fuel combustion (excluding biomass CO ₂)	57.7
Wastewater treatment plant CH ₄ 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 ₂ from biomass fuel combustion (biogenic)	113
Total emissions	173.69

Note: Indirect GHG emissions associated with off-site generation of steam and electricity that are purchased by or transferred to the mill are not included.

Table 2Applicability of NO_x Control Technologies (EPA 1999; EPA 2010a).

Boiler Type	Wood/Hog Fuel (% NO _x Reduction)	Coal (% NO _x Reduction)	Natural Gas (% NO _x Reduction)	Residual Oil (% NO _x Reduction)
LNB	No	Yes (50) ^b	Yes (50)	Yes (50)
ULNB	No	No	Yes (75)	No
OFA	Yes (25)	Yes (25)	No	Yes (25)
SNCR	Yes (50)	Yes (50)	No ^c	Yes (25)
SCR	Yes (75) ^a	Yes (90)	Yes (90) ^d	Yes (90)
RSCR	Yes (75)	Yes (75)	Yes (75) ^d	Yes (75)
LoTO _x ^e	Yes (90)	Yes (90)	Yes (90)	Yes (90)

Note: LNB=low NO_x burner, ULNB=ultra-low NO_x burner, OFA=overfire air, SNCR=selective non-catalytic reduction, SCR= selective catalytic reduction, RSCR= regenerative selective catalytic reduction, LoTO_x=process name

^a tail-end configuration,

^b pulverized coal only,

^c retrofit possible; not on new units,

^d new units possible; not on retrofits,

^e requires downstream wet scrubber.