Factors contributing to improved environmental performance in the Finnish kraft pulping industry

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ABSTRACT: This study describes the environmental significance of kraft pulping technology developments in Finnish kraft pulp mills. Data on kraft production technology and process energy were collected directly from seven mills. Results are presented as an average of these data. The study presents the main interactions between technology development and environmental performance, particularly water emissions, air emissions, and energy. Supporting technology (e.g., waste treatment operations) and core technology (e.g., liquor processing) were found to be equally important in reducing the environmental loads from kraft pulp mills. The most important supporting technologies are well-operated activated sludge treatment plants and various purification techniques for air emissions. The most important core technologies include dry debarking, oxygen delignification, improved black liquor concentration, and lime mud drying. Wastewater volume has less effect on releases of chemical oxygen demand (COD) than expected. Energy balances are highly dependent on the age of the mill and on whether the pulping and papermaking operations are integrated. Energy balances are usually unaffected by single technology developments.

Application: Mills can use the Excel-based description tool we developed and their mill-specific data to assess the impact of improvements in core and supporting technology.

Environmental issues are increasingly important to the forest products industry. The requirements of European Union (EU) legislation are growing, as are the environmental concerns of customers, consumers, and investors. It is no longer enough to measure and report releases to the environment; instead there is a need to recognize the environmental effects of different technologies.

We undertook this study to improve the understanding of the industry's environmental performance and to find the interactions between environmental changes and development of kraft pulping technologies. One goal was to understand how core and supporting technologies in kraft pulping have affected environmental releases and energy balances. This knowledge will help companies identify R&D activities and investments that improve environmental performance.

Over time, the industry has steadily improved its operating practices and, as a result, mills have achieved steady incremental improvements in environmental performance and energy balances. This study's primary focus, however, is the role of technology.

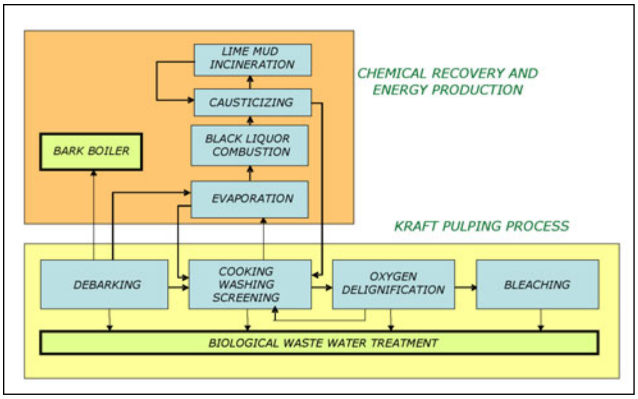
We divided technologies into core and supporting technologies as follows:

- Core technology comprises technological and economic processes in which the forest industry aims to be a pioneer and seeks to develop. A paper machine is one example.
- Supporting technology is what the forest industry applies for its own uses. This technology is often used in other industries but is often tailored to each industry's needs. Wastewater treatment and logistic systems are examples.

Large improvements in environmental performance have been achieved by applying supporting technologies, such as wastewater treatment and fuel switching. We believe, however, that it will become increasingly difficult to reduce environmental impacts by using supporting technologies. Alternatively, environmental improvements can be achieved by improving the industry's core technologies.

STUDY DESIGN

The study includes kraft production technology and the process energy balance (**Fig. 1**). The technology is divided into supporting technology (wastewater treatment plants, bark boiler) and core technology (process technology). The first part of the study consists of specifying the technology development in pulping and recovery technology in Finland and mapping the interactions between the emissions and technology. The second part uses a specific data management tool to describe the trend in technology development and environmental changes. Finally, we look at the energy balance in



1. Study framework divided into stages of pulping process and recovery.

more detail to bring out the benefits of bio-based excess energy production in kraft pulping.

Data are based on questionnaire responses from seven of the 19 kraft pulp mills in Finland. The mills represent various technologies and ages. The long study period, 1984-2003, was set to allow trends to be identified. However, older data were lacking at some mills. In some cases, older data are available from only one or two mills. Although the effects of technology changes were examined mill by mill, we show only average performance levels to protect mill identities. We developed an Excel-based tool to calculate and describe trends in performance and relationships to changes in technology.

Finnish pulp mills regularly report several emission parameters to the authorities. The parameters cover a wide range of water and air emissions and solid industrial waste. We focused our study on air and water emissions and energy by using the following parameters:

1. Emissions into water
   - total effluent volume, m^3/air-dried ton (a.d. ton);
   - total phosphorus from the process as g/a.d. ton;
   - total phosphorus to the recipient area as g/a.d. ton;
   - phosphorus concentration as mg/L (in effluent to the recipient area);
   - COD from the process as kg/a.d. ton;
   - COD to the recipient water as kg/a.d. ton;
   - COD reduction as %; and
   - total kraft production as a.d. tons
2. Emissions into air
   - total sulfur (tot-S) as kg/a.d. ton;
   - sulfur dioxide (SO_2) as kg/a.d. ton;
   - total reduced sulfur (TRS) as kg/a.d. ton;
   - fossil carbon dioxide (CO_2) as kg/a.d. ton;
   - nitrogen oxides (NO_x) as kg/a.d. ton; and
   - solid particles (TSP) as kg/a.d. ton
3. Energy balance
   - heat generation: heat generated in the recovery boiler;
   - heat use: heat energy used in the process;
   - excess heat: heat used in the process and heat used for electricity production have been reduced from heat generated in the process;
   - bark heat: heat potential in bark boiler. Dependent on wood species (hardwood bark produces more heat energy) and the amount of chips used;
   - power (electricity) generation: total power produced. Bark boiler included if the allocation to recovery boiler was not possible;
   - power use: electric power used in the mill; and
   - excess power: calculated value, where the power used has been reduced from the power generated

Activated sludge treatment, a supporting technology, was not studied in detail, but improvements to the wastewater treatment plant were factored as a technology change. Nitrogen emissions to water are excluded from the study because the nitrogen level is mainly affected by the requirements of wastewater treatment, a supporting technology. The power (bark) boiler is regarded as supporting technology and technology changes in the bark boiler are excluded. Solid waste was excluded from the study because of a shortage of time and lack of resources.

ENVIRONMENTAL TECHNOLOGY

Kraft pulping process

The kraft pulp production process begins with the wood handling, where the change from wet debarking to dry debarking has helped reduce water discharges. Dry debarking produces bark with a lower water content and leads to a reduced discharge of organic substances in effluent and a better energy balance in the mill. The pulp coming from cooking contains fibers and spent cooking liquor (black liquor). About half the wood dissolves in cooking. Extended cooking and super batch technology are the most important recent developments in core pulping technology from the environmental perspective.

Extended cooking decreases water emissions and the consumption of chemicals in bleaching. Super batch technology has reduced heat consumption. Black liquor is removed from the pulp at the washing stage and returned to the chemical recovery system. Improved washing decreases the consumption of bleaching chemicals and reduces discharges from the bleaching plant. Most technological improvements in washing have a marginal effect on energy consumption. Closed screening has decreased effluent discharge by reducing the total wastewater volume. Most recent technology changes in screening affect pulp quality but changes in energy consumption are minor. After cooking, the delignification can be continued by oxygen delignification. The organic matter that is dissolved during oxygen delignification can be recovered and sent to the chemical recovery system. Oxygen delignification decreases the effluent discharge and consumption of bleaching chemicals, but slightly increases the steam consumption at the mill. Medium-consistency pumps and mixers reduce the need for electricity.

Several technology improvements in pulp bleaching have affected some of the parameters listed earlier. However, the most significant improvements associated with modern bleaching technology have been related to reductions in discharges of chlorinated compounds, a topic our study did not address. The most significant changes have involved lowering incoming kappa number and replacing Cl_2 with ClO_2. Other significant developments have been oxygen bleaching, the optimization of chlorine chemical use (using A-stage for instance), MC-feed and improved mixers, shorter sequences, and replacing conventional filters with the more effective displacement of press washers. Electricity consumption has decreased when shorter sequences have been introduced.

Chemical and energy recovery

The recovery system at a kraft pulp mill recovers the inorganic pulping chemicals, produces process heat and electrical power, and recovers associated organic by-products, such as tall oil. Modern kraft pulp mills are normally self-sufficient in heat and electrical power. Weak black liquor from washing has an approximate dry solid content of 14%-18%. Before burning, the black liquor is evaporated to gain a dry solid content of between 65% to 78%. Technology changes at the evaporation stage have improved the energy production and reduced SO_2 emissions. The dry solid content of black liquor can be increased to 80% when black liquor heat treatment is used during evaporation.

Improved high dry solids (HDS) combustion in the recovery boiler and more effective flue gas cleaning have significantly decreased SO_2 emissions and increased energy production. At the same time, boiler operation has been improved.

The smelt leaving the recovery boiler is dissolved in the water or in the weak white liquor to produce green liquor. The green liquor is clarified and causticized to convert Na_2CO_3 into NaOH (to make white liquor). $CaCO_3$ (lime mud), which is formed in this stage, is washed and calcined to regenerate the lime. External fuel is needed in the lime kiln, because the lime mud burning is a high-temperature reaction. In this chemical recovery stage, the total reduced sulfur (TRS) has been reduced by development of the odorous gas handling systems.

Activated sludge treatment plant

External wastewater treatment has been used by Finnish pulp and paper mills since the 1970s in the form of mechanical treatment plants and aerated lagoons. Typically, these were relatively inefficient, compared with the modern aerated lagoons operating today at many mills, especially in warmer climates. In 1984, the first activated sludge (AS) treatment plant at a Finnish kraft pulp mill came into operation. Today, AS treatment plants are used at every pulp mill in Finland. AS treatment involves the use of microorganisms that consume dissolved organic material in the water. Nitrogen and phosphorus are required to support the growth of the microorganisms and to ensure efficient treatment. Usually, only nitrogen needs to be added to the effluent because pulp mill wastewater usually contains enough phosphorus. At Finnish kraft mills, biosludge formed in the treatment plant is separated, dried and used as a fuel at the mill power plant or in the bark boiler.

Typical reductions in AS treatment plants are as follows:

- biochemical oxygen demand (BOD) 85%-98%
- COD 40%-70%
- total phosphorus 40%-85%
- total nitrogen 20%-50%
- adsorbable organic halogens (AOX) 40%-65%

RESULTS

Technology and water emission trends

Process changes had complicated effects on COD discharges. Dry debarking and oxygen delignification had the greatest effect in reducing the amount of COD leaving the process. However, the improvement was not seen as clearly or as quickly as expected. It was evident that the conditions at the treatment plant have a greater effect than was assumed. The design and operation of the activated sludge treatment plant play an important role in COD discharges.. Improvements in wastewater treatment caused stepwise reductions in COD discharges, reductions that were very clear in the individual mill results. In addition, oxygen delignification appears to change the nature (structure) of the organic matter in mill effluent and improve the COD removal efficiencies at the treatment plant. Interestingly, COD removal efficiencies were improved but the amount of COD coming from the mill was not decreased. **Figure 2** shows the trend in COD emissions.

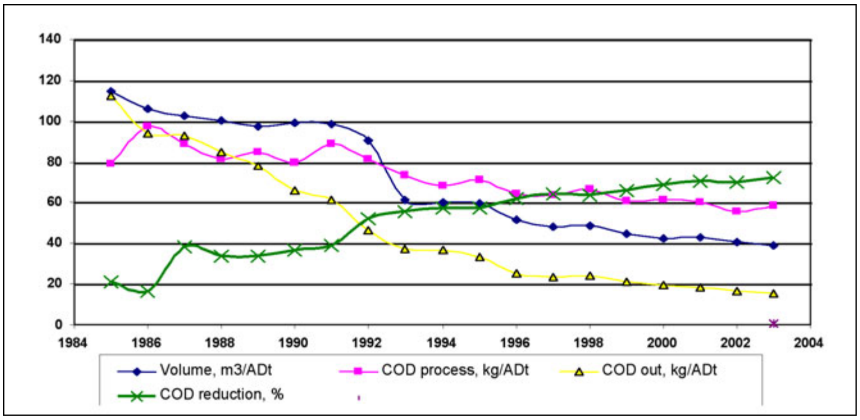
The total wastewater volume appeared to be unrelated to the COD in untreated mill effluent and the COD removal efficiencies at the treatment plant, especially in the individual mill results. The suspended solids loads affected the COD to some extent, but the effects of technology improvements in the process (dry debarking and oxygen delignification) were more obvious.

Technology and air emission trends

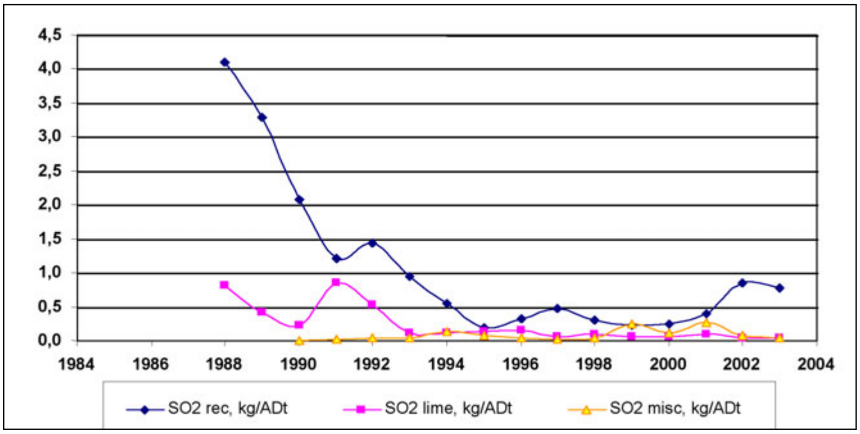
The air emission sources in pulping area were divided into:

(a) black liquor combustion (recovery boiler);
(b) lime mud incineration (lime kiln); and
(c) miscellaneous emission sources. Miscellaneous sources include all other emissions reported together with a separate burner for malodorous gases.

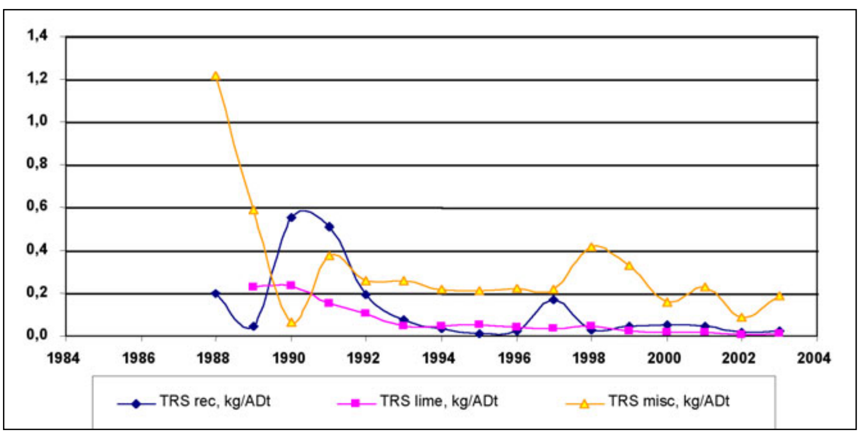
The following technologies to reduce sulfur emissions were in operation or became available over the study period:



2. Trend in chemical oxygen demand and total wastewater volume in 1984–2003. Average data of seven Finnish pulp mills.



3. Trend in sulfur dioxide (SO_2) emissions from the recovery boiler, lime kiln, and from miscellaneous sources in 1984–2003. Average data from seven Finnish pulp mills. (Best available technology [BAT] emission level 0.2–0.4 kg S/a.d. ton for bleached pulp, which means 0.4– 0.8 kg SO_2 /a.d. ton).

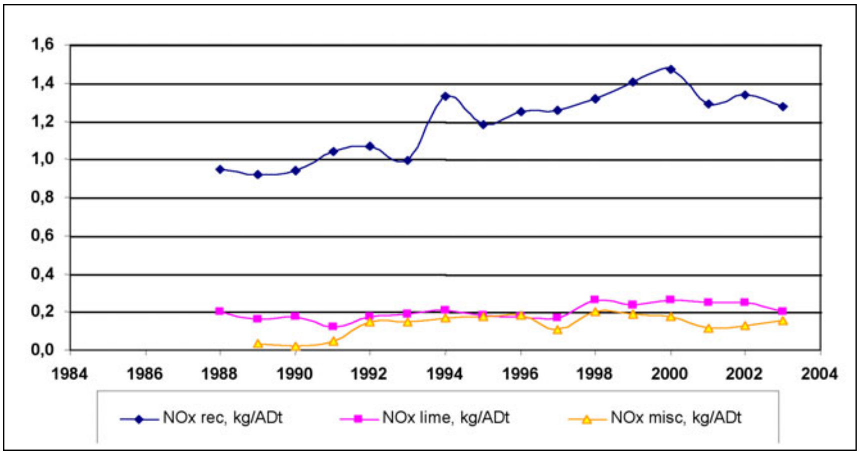


4. Trend in reduced sulfur (TRS) emissions from the recovery boiler, lime kiln, and from miscellaneous sources in 1984–2003. Average data from seven Finnish pulp mills. (Best available technology [BAT] emission level 0.1– 0.2 kg S/a.d. ton for bleached pulp, which means 0.2 – 0.4 kg TRS /a.d. ton).

- high dry solids combustion in recovery boiler (HDS);
- controlled combustion conditions;
- noncondensable gases incineration (NCGinc), LVHC (low volume high concentration), HVLC (high volume low concentration) techniques for collecting and combusting odorous gases;
- scrubbers on the recovery boiler and lime kiln;
- lime mud drying (LMD); and
- improved process control

A decreasing trend in sulfur dioxide (SO_2) and total reduced sulfur (TRS) emissions can be seen in **Fig. 3** and **Fig. 4**. Figure 3 shows that SO_2 emissions from the recovery boiler have been reduced efficiently due to the increased solids content of black liquor and high dry solids combustion technology (HDS). HDS has decreased SO_2 emissions at several mills. In general, if the solids content of black liquor is at least 70%, then the sulfur emissions from the recovery boiler will be below levels of environmental significance. An increased temperature in the furnace leads to increased sodium in the gas phase, which reacts with sulfur and thus reduces the total sulfur and SO_2 emissions by forming Na_2SO_4 (sodium sulfate), which is recovered in the electrostatic precipitators. On the other hand, HDS increases the sulfur content in the process vent gases. In the Finnish pulp mills, the strong malodorous gases (LVHC) and weak malodorous gases collection (HVLC) are combusted. LVHC technology has been in use since the 1980s and HVLC since the 1990s. The term noncondensable gas incineration (NCGinc) is a general term that covers LVHC and HVLC.

Figure 4 shows the trend in TRS. Different mills measure or estimate TRS emissions differently, accounting for some of the variability. Improved technologies for managing odorous gases (NCGinc, LVHC, and HVLC collection) and lime kiln scrubbers have reduced TRS emissions. TRS decreases if the lime mud is dried before being fed into the



5. Trend in nitrogen oxides (NOx) emissions from the recovery boiler, lime kiln and from miscellaneous sources in 1988–2003. Average data from seven Finnish pulp mills. (Best available technology [BAT] emission level ($NO+NO_2$ as NO_2) 1.0–1.5 kg/a.d. ton for bleached pulp).

lime kiln, an effect that was especially evident in the individual mill data. The most important source of TRS is miscellaneous sources, where the estimation of emissions is most uncertain. However, TRS emissions have been trending downward from all sources.

The results from individual mills illustrate that scrubbers (recovery boiler and lime kiln) and high dry solids combustion are the most important technologies for reducing SO_2 emissions to very low levels (i.e., close to zero). Improvements in the NCG incineration, lime kiln scrubber, and lime mud drying have had the biggest effect in reducing TRS emissions. Although emission reductions were drastic in most cases, it does not mean that the situation remained static. The emissions might increase temporarily because of changes in raw materials or production or startups of modernized processes.

The control or reduction of the NOx emissions at kraft pulp mills has usually been focused on the recovery boilers. Approximately 20%-30% of the nitrogen that comes to the process in wood is converted to NOx in the recovery boiler. Furthermore, the recovery boiler is the major source of NOx emissions in the whole pulping process. NOx emissions can be affected by combustion conditions (e.g., temperature, load, air distributions and black liquor droplet size).

Depending on the external fuel, part of the NOx emissions come from the lime kiln. The amount of thermal NOx (NOx formed from nitrogen in air) from the lime kiln can be reduced by controlling the combustion temperature. Proper handling of all noncondensable gases (NCGs) and causticization vent gases is important in controlling the NH_3 (ammonia) balance in the mill. Low-NOx burners are also used to reduce NOx emissions.

Figure 5 shows that the average NOx emissions from the recovery boiler increased from 0.9 to 1.3 kg/a.d. ton from 1988–2003. However, the increasing trend was not seen at every mill and emissions in different years vary at an individual mill (e.g., renovating the recovery boiler increased NOx emissions). No technology has clearly reduced NOx emissions from the recovery boiler. NOx from lime kilns has remained at the same level, approximately 0.2 kg/a.d. ton, and there is a slight increase in miscellaneous NOx emissions as well. NOx monitoring has been based on analytical measurements in Finland since 1990. Differences between the mills in both monitoring and reporting of NOx emissions may have affected the emission trend.

Trend in energy (heat and electricity) balance

The modern kraft pulping process can produce excess heat and electricity. At mills where pulping and papermaking are integrated, some heat and electricity are used in the paper mill. In an integrated mill, the whole potential of backpressure power can be exploited due to the steam requirements of the paper mill. A nonintegrated pulp mill can sell the excess energy as condensing electricity to the grid. Development of excess energy production is of special interest because of the potential to produce energy from renewable resources (bark and black liquor).

The trends in mill energy balances were followed to find out if the energy balances had improved due to technology changes in the process. When we looked at the average energy data from the mills, it seemed that there were no specific changes in the heat balance during the last 20 years. Heat generated, heat used and the amount of excess heat (as GJ/a.d. ton) had remained constant. The trend in heat generation decreased slightly and heat production from bark increased over time. This was due to dry debarking and an increase in bark dry substance.

Both electricity generation and electricity demand have increased by approximately 10% since 1985. Improvements in extended cooking, the on-site manufacturing of bleaching chemicals, oxygen delignification, and handling of malodorous gases increased use of electricity. The specific approaches to producing electricity are highly mill-specific and it was difficult to make comparisons between the mills. Electrical power can be produced directly from the steam in the recovery boiler or from an integrated steam system that serves the recovery boiler and bark boilers.

Data from individual mills included in this study suggest that where energy-intensive technology was adopted, improvements elsewhere compensated for the mill energy balance. The mill's age had the biggest effect on the energy balance, although the beneficial effects of integrating the pulping and papermaking processes were also significant. In addition, changes in the production volume and the nature of the raw material (hardwood or softwood) affected the energy balance.

To find out how new technology has affected the energy balance trend, we chose the "best technology" (i.e., the most modern) mill of each decade and studied the development of heat and electricity consumption and production, excess energy production, and energy production from the bark boiler. The period of study is 1970–2000 and the analysis is based on real data. **Table I** shows the results.

We also made a hypothetical calculation to describe the effects of black liquor gasification coming into use in 2040. We made a simple calculation by converting all steam from gasification directly to electric power. The gasification calculations assumed that

(a) no excess heat is produced;
(b) no energy efficiency improvements or changes in energy consumption occur; and
(c) no external fuel will be used in the lime kiln in 2040.

The last column in Table I expresses the situation in 2000 when the heat is used for drying (market pulp is produced). Note that drying has been excluded from other cases.

The results show that heat generation (energy from black liquor combustion) has constantly increased at the best mills of the period. Heat consumption (i.e., heat use) has been reduced by approximately 25%. An exception is dried pulp. The production of excess heat, which has been expressed as heat balance, was negative in the 1970s. Therefore, external energy (heat and power) had to be purchased to fulfill the energy balance. A heat balance was achieved in the 1980s and there has been excess heat since. Use of electrical power has decreased by approximately 20%. The production of excess power was negative in the 1970s and started to increase in 1990. Black liquor gasification would increase heat generation and excess power significantly.

	1970 GJ/a.d. ton	1980 GJ/a.d. ton	1990 GJ/a.d. ton	2000 GJ/a.d. ton	2040 GJ/a.d. ton	2000 dried GJ/a.d. ton
Energy from black liquor	12.00	15.00	17.00	18.00	20.00	18.00
Process heat use	13.5	12	11	10	10	13.5
Process power use	2.97	2.63	2.66	2.27	2.27	2.77
Heat balance	-3.72	0.22	2.59	4.13	2.00	0.00
Power balance	-0.95	-0.11	0.58	1.33	3.85	0.83
Bark, sold	2.00	2.50	3.50	4.00	4.00	4.00

I. Trend in energy consumption and production in kraft pulping as GJ/a.d. ton between 1970–2000. Calculations based on the best Finnish kraft pulp mill technology of a certain time period. The example from 2040 expresses a hypothethical calculation for the situation if black liquor gasification technology were in use. Heat is used for pulp drying in the last case (2000 dried).

The kraft pulping process has high energy efficiency and the amount of excess energy (heat and electricity) has improved continuously over time. These best mill results are different from the average mill results because of the age distribution of the mills and the varying technology available. The data, therefore, represent a technology level that is better than the average mill data.

CONCLUSIONS

The effects of technology on environmental performance and energy balances were studied by identifying step-by-step changes in emissions and energy balances and correlating the information with mill-specific technology improvements. Supporting technologies, such as wastewater and emissions treatment technologies, were found to play a more important role in managing water and air emissions than was assumed. Important supporting technologies include well-operated activated sludge treatment plants, various purification techniques for air emissions, and the bark boiler (in terms of its impact on the energy balance). Dry debarking and oxygen delignification are examples of core technologies that have reduced COD emissions. Reductions in wastewater volume had less effect on COD than was expected. Core technology plays an important role in the reduction of sulfur emissions. SO_2 and TRS emissions were reduced by increasing the solids content of black liquor and by lime mud drying technologies. Most NOx emissions come from the recovery boiler. Average NOx emissions from the recovery boiler appear to be increasing but no technology was identified that clearly affects recovery boiler NOx. The amount of thermal NOx (i.e., formed from atmospheric nitrogen) from the lime kiln can be reduced by controlling the combustion temperature. The data on NOx emissions may have been affected by use of different monitoring and reporting methods.

In considering the best technology for reducing emissions, it is important to examine potential impacts on emissions elsewhere in the mill and impacts on other types of emissions. Narrowly focused efforts may decrease emissions in one process stage or in one parameter, but lead to increased emissions in another. SO_2 and NOx emissions, in particular, have such interactions.

No specific technology was found to affect the trend in the energy balances at the average mill level. However, the energy balance clearly improved over time at mills equipped with the most modern technology available at any given time. At these best technology mills, the heat generation (energy from black liquor combustion) has constantly increased over time as the heat consumption has been reduced by approximately 25%. Finnish kraft pulp mills have been self-sufficient in heat production since the 1980s and have been producing excess heat since then. The use of electrical power has decreased by approximately 20% at the mills in question and the production of excess power has increased continuously since the 1990s.

The kraft pulping process and the practice of integrating pulping with papermaking are good examples of efficient renewable energy production and use. In discussing the potential for biobased energy production, the pulp mills' role should be emphasized. Production of bioenergy from black liquor is the forest industry's core technology and its financial and environmental significance are growing as energy and environmental costs increase.

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Editor's note: The literature noted here primarily serves as general background information, according to the author. Most data was gathered from mills by questionnaire. Therefore, the author opted not to directly cite references throughout the text, as it was not possible to do so accurately.

INSIGHTS FROM THE AUTHOR

This study is part of a broader study overview of the impact of the forest industry's technology over the entire value chain. We needed to know the environmental role of kraft pulp mills.

The biggest challenge was in collecting data directly from the mills, as well as understanding different energy concepts and separating the effects from different technologies. It was surprising to learn that activated sludge treatment plants still have a major role in water emissions.

Mills can use the Excel-based description tool we developed and their mill-specific data to assess the impact of technology. Our next step is to advance the use and benefits of biobased excess energy from the kraft pulping process.

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