# A cradle-to-gate life cycle assessment of straw pulp incorporation into telephone directory–grade paper

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## ABSTRACT

*Life cycle assessment methodologies were used to evaluate claims that cereal straw is an environmentally friendlier fiber source for the manufacture of telephone directory–grade paper. The major conclusions are that while less wood is used, the substitution of straw chemical pulp for the mechanical wood component results in increased environmental burdens due to higher energy and raw materials consumption. This is attributed in part to the lack of applicable black liquor recovery systems for straw chemical pulping in North America.*

***Application:***

*This work highlights potential environmental issues associated with alternative feedstocks and processes.*


STUDIES THAT CONSIDER LIFE cycle processes are becoming increasingly important methods of assessing the possible environmental effects of any novel processing. These studies provide valuable data that can be considered in conjunction with other technical and economic feasibility data. In a recently reported pulp and paper example, Bradley (1) used life cycle assessment (LCA) to identify the sources of environmental burdens associated with the production of a weekly European consumer magazine.

Using the terminology of the Society of Environmental Toxicology and Chemistry (SETAC), LCA consists of three phases: goal definition and scoping, inventory analysis, and impact assessment. In an inventory analysis, data are collected, interpreted, and presented as mass flows and environmental loadings. Life cycle study methodologies are continually evolving; this may contribute to both the difficulty and the usefulness of the life cycle process. It should be emphasized that life cycle studies, such as this study, are designed to optimize processes and hence minimize waste rather than to promote specific points of view *(2).*

A recently renewed interest in the use of agricultural residues for pulp and paper manufacture has been motivated by three factors:

- concerns over long-term wood fiber supply requirements as long-term paper product demand is projected to increase
- increasing restrictions on conventional means of agricultural residue disposal (i.e., open-field burning)
- significant environmentalist interest in substituting such fibers for virgin wood fiber.

These factors led to this cradle-to-gate inventory (CGI) study, which considers the relative effects of the substitution of wheat straw chemical pulp, produced in the Canadian prairies, for the British Columbia softwood mechanical pulp component of telephone directory (TD) paper. TD paper is a lightweight, strong, and opaque paper grade that is extremely demanding of quality. In this inventory, technical and economic feasibility data were not considered. We evaluated the sources of environmental burdens associated with the production of 1 metric ton of TD paper in a North American context using specific pulping scenarios. The purpose of this paper is to provide the reader with a snapshot of the results; hence, only raw materials, energy, and water consumption are reported. SETAC guidelines were followed *(3),* and a comprehensive external peer-review process was undertaken in accordance with internationally accepted practices. A copy of the full report is available form Paprican.

## DATA COLLECTION AND QUALITY

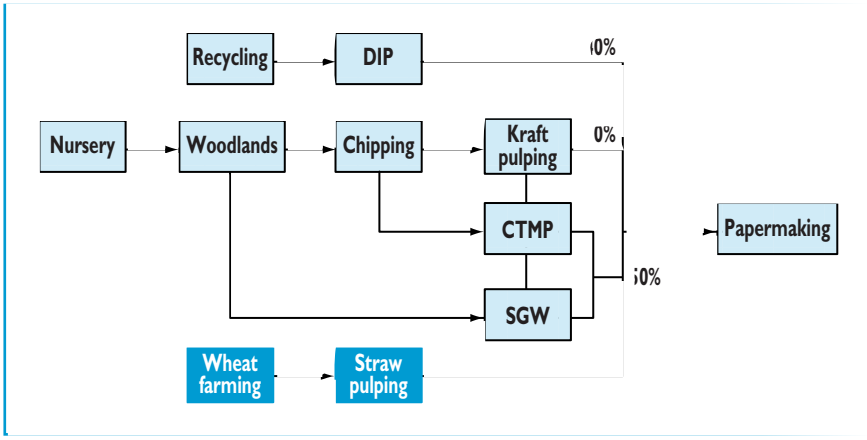
Wood pulping operational data were collected using questionnaires. Additional data obtained were average data on pulp yields from the different pulping methods (Paprican), harvest volume and fuel consumption by the tree harvest method from the Forest Engineering Research Institute of Canada (1996), data on electric power from Energy, Mines and Resources Canada (1994), and energy contents of Canadian fuels from the National Energy Board (1994). When using published data, Canadian data were preferred over U.S. data, which, in turn, were preferred over data from other parts of the world. Data for the straw mill scenario were obtained from either in-house studies or from the open literature.

There are three categories of CGI data. *Primary data* are composed of those inputs that form the functional unit. *Secondary data* are those major inputs that contribute to the outputs arising from production of the functional unit, such as processing chemicals and by-products. *Tertiary data* are considered to be those inputs and outputs that are, by comparison with the primary and

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- The 10% SBK and 40% deinked pulps were supplied by separate coastal British Columbia mills.
- The 50% mechanical pulp component, consisting of 25% SGW pulp and 25% CTMP, is produced by an integrated pulp and paper mill based in coastal British Columbia—which prepared the TD paper.
- Nursery, woodlands, and chipping operations are based in coastal British Columbia.
- Electricity generation fuel mix for British Columbia was used in all phases of the softwood-based directory paper.
- The 50% mechanical pulp (SMP) component is directly sustained with bleached wheat straw chemical pulp (SCP) without consideration of any adverse effects on paper quality.
- Straw pulps will perform as well as softwood pulps under recycling conditions.
- The ODED bleaching sequence was adopted for the straw pulp with expected effluents similar to those of the kraft pulping process using the same bleaching sequence.
- Spent liquors generated during straw pulping could not be processed via conventional recovery methods because of high levels of silica.
- Disposal of spent liquors would involve neutralization followed by aerobic biotreatment with no chemical or energy recovery.
- Wheat farming, straw harvesting, and straw pulping are based in Saskatchewan, although Alberta and Manitoba were included in the sensitivity analyses.
- Straw pulp is transported from the Prairies to the integrated pulp and paper mill located in British Columbia.

***I. Major assumptions of this study***




***1. Flow sheet for softwood (clear)– and straw (shaded)–based telephone directory paper manufacture***

secondary data, unlikely to contribute significantly to the overall environmental burdens. Data quality was evaluated using the 1-to-5 rating system *(4)*. Primary data from the wood-based operations were rated as a 2 or higher. However, straw pulp primary data were typically rated as a 3.

In this study, wood or straw, fiber, pulp, water consumption, and energy are all considered primary data. Although the primary data obtained from direct survey and review literature included high and low ranges, midpoints were used in this study. Sensitive analysis indicated that the range of primary data did not significantly affect the outcome of the study.

## DESCRIPTIONS OF SCENARIOS

The starting point for the study was growing both trees and wheat from seed. In both cases, the life cycle inventory concluded with the production of 1 moisture-free metric ton of TD paper, the functional unit.

TD paper contains 10% softwood bleached kraft (SBK) pulp, 40% deinked paper (DIP), and 50% softwood mechanical pulp (SMP). The SMP component is comprised of equal proportions of chemithermomechanical pulp (CTMP) and stone groundwood (SGW) pulp. The softwood scenario, which is in the current practice, includes all inputs and outputs of these processes. The straw-based scenario used in this study would substitute a wheat straw chemical pulp for the SMP component of the furnish (**Fig. 1**). Other major assumptions are presented in **Table I.**

### *Nursery, woodlands, and chipping operations*

The average age of tree seedlings when shipped for replanting is 35 weeks (Company A, 1996). Seedlings were planted at a density of 1000 per hectare (ha), and the average survival rate was 87% over a 10-year period, beyond which mortality is negligible *(5)*. The average harvest volume is 723 $m^3$/ha, and average hauling distance is 40 km *(6)*. The density of western hemlock wood ranges from 409 to 477 kg/$m^3$ *(7)*. The average of 443 kg/$m^3$ was used for the inventory calculations. Moisture content of green wood was set at 50% *(8)*. The estimated quantity and type of fuel used by different harvesting methods, expressed as a proportion of wood harvested by that method, is based on raw data obtained from Forest Engineering Research Institute of Canada (1996) survey data.

Chipping is considered part of the sawmilling activities. For every metric ton of moisture-free wood, 42% is recovered as lumber, 39% as chips, and 19% as sawdust and shavings (Company B, 1996). Hence,1 moisture-free metric ton of chips is produced from the sawmilling of 2.56 moisture-free metric tons of wood. Accordingly, 39% of the environmental burdens associated with sawmilling are allocated to chipping.

### *Semibleached kraft (SBK) pulping*

Pulp yield from the semibleached kraft process ranged from 40% to 45% and is set at 42% for this study. Specifically, 2.38 metric tons of chips are needed to produce 1 metric ton of semibleached kraft pulp *(9)*. An

ODED bleaching sequence was used (Company B, 1996). Based on a recent design, about 9% of the fresh water intake is assumed to be lost to evaporation and sludge *(10).* The SBK pulp is supplied to the integrated pulp and paper mill in dewatered or dry-lap form to reduce the cost of transport. Moisture content was 20% *(11).*

| Energy source | British Columbia | Alberta | Saskatchewan | Manitoba | Canada |
|---|---|---|---|---|---|
| Hydroelectric | 96.9 | 3.6 | 22.3 | 99.0 | 61.1 |
| Coal | 0 | 87.9 | 72.6 | 0.9 | 18.0 |
| Nuclear | 0 | 0 | 0 | 0 | 16.4 |
| Oil | 0.1 | 0 | 0.1 | 0.1 | 2.8 |
| Natural Gas | 3.0 | 8.4 | 5.0 | 0 | 1.7 |
| Other | 0 | 0 | 0 | 0 | 0.1 |
| **Total** | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |

***II. Electricity generation fuel mixes used in the life cycle inventory, % (24)***

### *Deinked paper (DIP) pulping*

The burdens associated with the collection and transport of old newspapers (ONP) and old magazines (OMG) were assumed to be constant for both the wood and straw pulp scenarios; hence these burdens were not considered in this inventory. The average pulp yield from recycled paper under the operating conditions of the DIP plant is 84% (Company C, 1996) The supply of recycled paper consists of 74% ONP, 15% OMG, 10% flexographics, and 1% used telephone directories. Thirty-five percent of the recycled paper supply comes from British Columbia, 20% from Alberta, 5% from Saskatchewan, 28% from Minneapolis, and 7% from Kansas. All of these are brought in by rail. Deinked pulp is furnished to the paper mill in wet-lap form, i.e., moisture content=50%.

### *Softwood mechanical pulping (SMP)*

Under the baseline conditions, 50% of the paper furnish is made up of mechanical pulp, which is equally divided into 25% SGW and 25% CTMP. Pulp yields from the SGW process range from 93% to 96%; for CTMP, the values range from 90% to 93% *(12).* The midpoints of these ranges were used for inventory purposes. The softwood mechanical pulp is brightened and then supplied to the paper mill at a 20% moisture content.

### *Wheat farming and straw production*

In the Canadian Prairies, 1 ha of farmland produces 7.45 metric tons of grain, straw, chaff, and other biotic residues *(13, 14).* Of this amount, 30%—or 2.2 metric tons—is straw. Stumborg has reported that 0.75–1.5 metric tons of straw must be retained on the soil for erosion control *(14).* Agriculture Canada recommended the higher figure of 1.5 metric tons; hence this figure was used for all calculations *(14).*

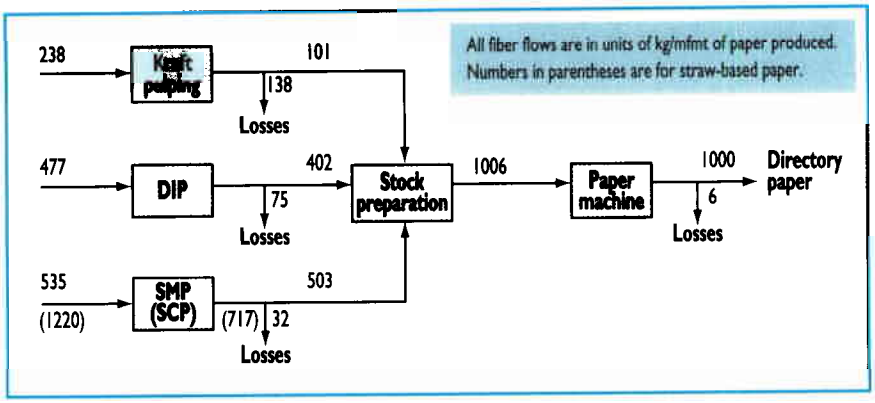
The percentage of dry matter in wheat straw is typically 92.6% *(15);* hence 1 ha of farmland yields 648 kg of dry straw. This accounts for 9% of the total wheat biomass produced on 1 ha of land. Accordingly, 9% of the environmental burdens associated with wheat farming were allocated to straw pulping. Estimates for the various wheat farm operations were based on data published by Boerma *et al. (16)* and Saskatchewan Agriculture and Food *(17).* The average distance for the transport of straw to the mill was set at 50 km *(14).*

### *Straw chemical pulping (SCP)*

Chemical pulping of wheat straw was assumed to be accomplished with a soda-based straw pulping technology using a continuous digester system horizontal tube. The ODED bleaching sequence used for the SBK pulp was also adopted for the straw pulp, and data were obtained from the literature *(18).* In the absence of first-hand data, the reported effluent rates for the kraft mill were applied to straw chemical pulping. Straw losses, energy used, and emissions generated from straw cutting and precleaning in the mill were not taken into account. Steam used in the mill was assumed to be generated with a mixture of coal, oil, and natural gas in the same proportion as their contributions to electricity generation.

Pulp yields from straw range from 40% to 42% *(9, 19)* but have also been reported to be as low as 35%. Regardless, an average pulp yield of 41% was adopted, assuming that any potential Canadian operation will use the best available technology to maximize pulp yield among many other parameters. Straw pulp (at 50% moisture content) was transported from the Prairies to British Columbia by rail.

Chemical recovery from wheat straw pulping remains the greatest technological challenge to acceptance of this raw material as a viable source of fiber. The problems associated with high black liquor viscosity and inorganic contamination remain to be overcome at the mill scale *(9).* Consequently, it was assumed that wheat straw pulping chemicals will not be recycled, nor will the dissolved organic materials be combusted to recover heat. In Canada, black liquor would require an effective means of treatment prior to discharge. Using currently available process technology, it is assumed that the simplest means of disposal would require neutralization, aerobic biotreatment, and aqueous discharge treatment. Neutralizing the spent liquor from straw chemical pulping




*2. Fiber balance for softwood (straw)–based telephone directory paper manufacture. DIP=deinked pulp, SMP=softwood mechanical pulp, SCP=straw chemical pulp.*

| Environmental parameter | Softwood-based | Straw-based |
|---|---|---|
| **Raw materials consumption** | | |
| Total, kg | 1,432 | 2,349 |
| Renewable, kg | 1,250 | 1,934 |
| Wood, kg | 1,250 | 715 |
| Straw, kg | 0 | 1,220 |
| Nonrenewable, kg | 182 | 415 |
| **Energy consumption** | | |
| Total, MJ | 27,672 | 34,626 |
| Renewable, MJ | 21,181 | 12,532 |
| Wood, MJ | 15,653 | 11,201 |
| Hydro, MJ | 5,528 | 1,331 |
| Nonrenewable, MJ | 6,491 | 22,094 |
| Coal, MJ | 0 | 14,716 |
| Oil, MJ | 1,647 | 3,508 |
| Natural gas, MJ | 4,844 | 3,870 |
| **Water use** | | |
| Intake, $m^3$ | 33 | 35 |
| Discharge, $m^3$ | 28 | 29 |

*III. Environmental burdens associated with 1 moisture-free metric ton of telephone directory paper*

### *Papermaking*

The hypothetical paper mill is located in British Columbia. In the case of the softwood-based paper, all pulp inputs come from within the coastal region of British Columbia. For the straw-based paper, straw pulp is brought in from Saskatchewan. Clay filler for the paper is imported from the United States and is brought in by rail. Hog fuel in combustion generates steam for paper drying.

### *Energy*

Canadian data on electricity generation and energy contents of fuel were used in this CGI. **Table II** shows the electricity generation fuel mixes in the provinces of British Columbia, Alberta, Saskatchewan, and Manitoba—and Canada as a whole. *(20)*.

### *Excluded operations*

The endpoint of this life cycle inventory of telephone directory paper is papermaking. Therefore, directory printing, distribution, use, collection, and waste management activities were not considered. However, inasmuch as deinked pulp is part of the paper furnish, the process of recycling was automatically taken into account. The underlying assumption is that, given the lack of straw-related recycling data, wheat straw is assumed to perform as well as wood when recycled.

## RESULTS AND DISCUSSION

A summary of the life cycle inventory under the baseline conditions is shown in **Table III**. The environmental burdens reported are those associated with the manufacture of 1 moisture-free metric ton of telephone directory paper made with 10% kraft pulp, 40% DIP, and 50% of either softwood mechanical pulp or straw chemical pulp. Note that the values individually identified with kraft, DIP, and papermaking are the same for both softwood-based and straw-based paper, because both paper furnishes are assumed to have equal kraft pulp and DIP contents and that both use the same papermaking process (data not shown).

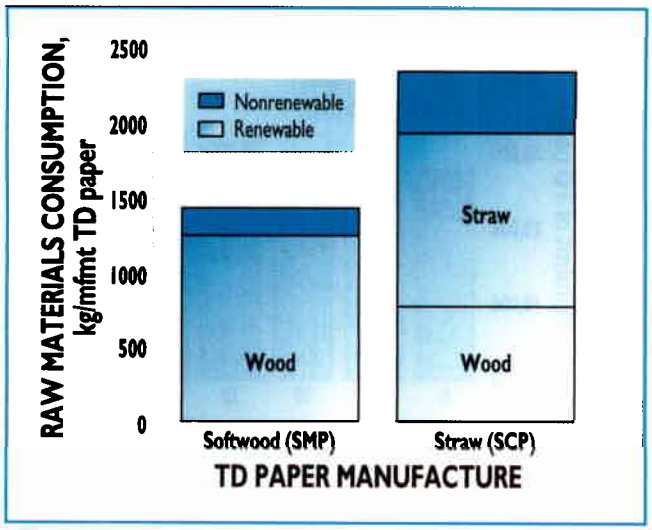
### *Raw materials consumption*

Process fiber for both scenarios was balanced, as shown in **Fig. 2**. Total raw material consumption for the wood-based scenario was 1432 kg/moisture-free metric ton, while that of the straw based scenario was 2348 kg/moisture-free metric ton (Table III). In both cases, over 80% of the raw materials used originated from renewable sources, specifically wood and straw biomass. The straw-based TD paper consumes approximately twice the amount of nonrenewable materials than the softwood-based TD paper (**Fig. 3**). Differences arise because of the need to replenish pulping chemicals and to neutralize and treat spent liquor generated during straw pulping. Other inefficiencies during straw pulping also contribute to this disparity.

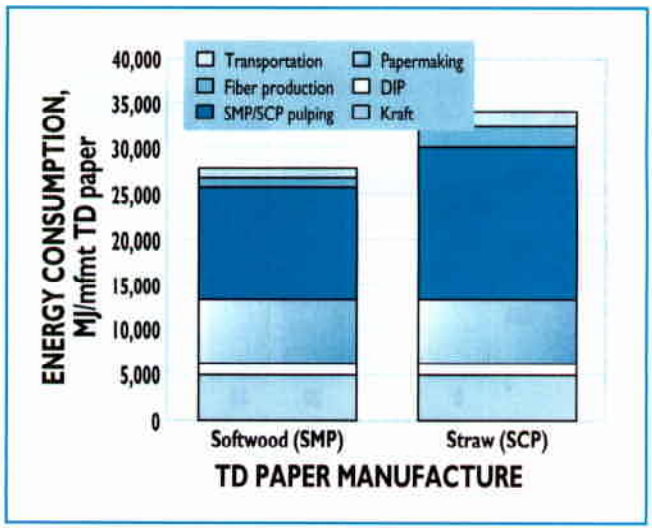
### *Energy consumption*

The breakdown of the energy consumption into the different stages of manufacture is presented in **Fig. 4**. The production of softwood mechanical pulp is very energy intensive.

The total energy consumption associated with 1 moisture-free metric ton of softwood-based telephone directory paper is 27,672 MJ, of which 77% is from renewable and 23% from nonrenewable resources. The corresponding estimate for straw-based telephone direc-




*3. Renewable and nonrenewable raw material consumption for softwood- and straw-based telephone directory paper manufacture*




*4. Energy consumption for softwood- and straw-based telephone directory paper manufacture by processing stage*

tory paper is 34,626 MJ, broken down into 36% and 64% from renewable and nonrenewable sources, respectively. Total energy consumption of the straw-based paper is higher than that of the softwood-based paper. The nonrenewable energy used by the straw-based paper is also higher than that of the softwood-based paper, but this is largely due to the high energy input associated with the use of coal, which is the main source of electricity in Saskatchewan.

Differences in the proportions of renewable energy used in the two scenarios are attributed to differences in pulp yield and to the combustion of hog fuel for power generation in the softwood scenario. Chemical and heat recovery from wheat straw pulping black liquors could improve the renewable energy balance of such a process, and this further highlights the need to develop an efficient black liquor desilication system.

Fiber production energy burdens are also higher for the straw scenario, indicating the energy-intensive nature of agriculture compared to forestry (Fig. 4). There is no difference between the kraft, DIP, and papermaking components for each scenario. Transportation is higher for straw pulping but is a minor component of both scenarios. Most of this burden (95%) is attributed to straw pulp transport from the Prairies to the British Columbia coast.

### *Water consumption*

The water balance for the manufacture of 1 moisture-free metric ton of both softwood-based and straw-based telephone directory paper is shown in Table III. Water consumption was similar for both scenarios. Softwood-based directory paper uses water at a rate of 33 $m^3$/moisture-free metric ton, of which 28 $m^3$/moisture-free metric ton is discharged. Straw-based directory paper uses slightly more water at a rate of 35 $m^3$/moisture-free metric ton. The greater water consumption reflects the additional water required to bleach straw chemical pulp *(18)*. The discharge is about 29 $m^3$/moisture-free metric ton, of which 14.3 $m^3$/moisture-free metric ton is spent liquor. Most of the environmental burdens associated with effluent treatment are associated with this liquor.

Fresh water supplies to the various pulp and paper mills constitute the bulk of the water intake, although water contributions from wood [50% moisture content (MC)], straw (7.4% MC), recycled paper (6% MC), and chemicals *(10)* were also taken into account. The total water discharge comprises the volume of wastewater discharged, losses to evaporation and sludge, and the 7.5% moisture content in the finished paper product.

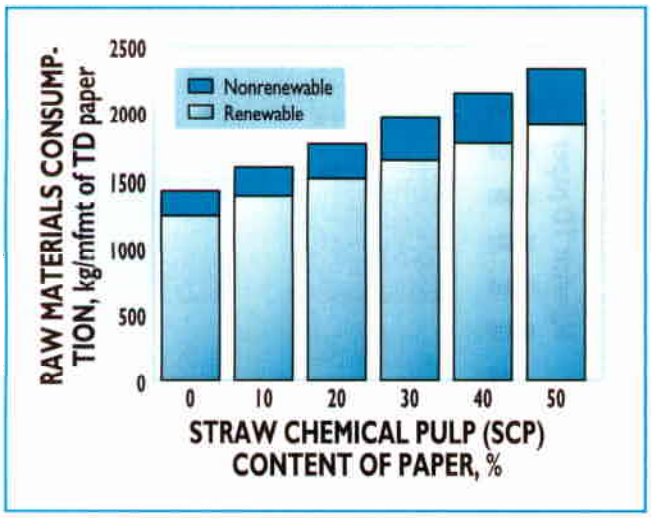
## SENSITIVITY ANALYSES

### *Effect of straw pulp substitution*

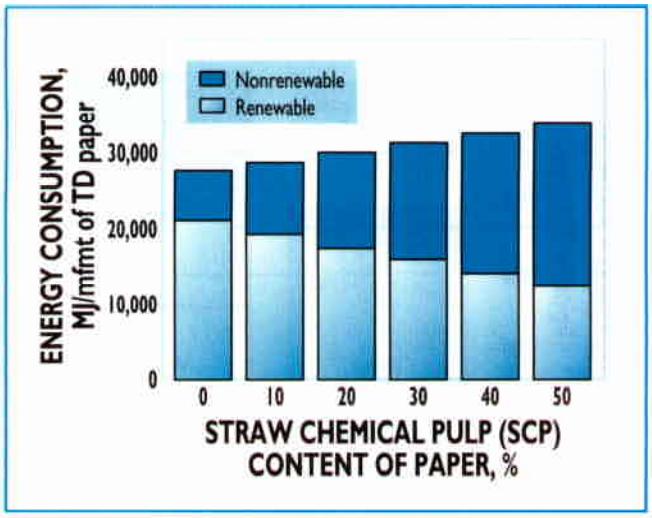
A series of sensitivity analyses examined different combinations of softwood and straw pulps comprising the 50% mechanical pulp component of the paper furnish. The other 50% of the paper furnish remained unchanged. The effects of straw substitution on raw materials use and consumption are illustrated in **Figs. 5 and 6**, respectively, and show that increasing the percentage of straw pulp in the TD paper furnish would increase:

- total, renewable, and nonrenewable raw materials consumption (Fig. 5)
- total and nonrenewable energy consumption (Fig. 6).

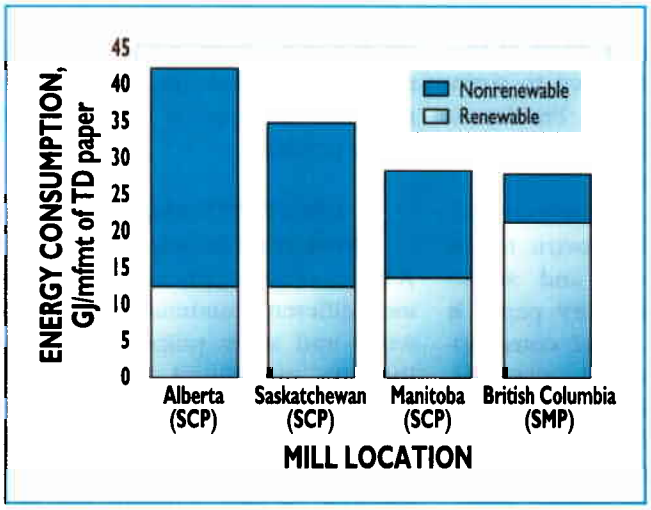
These results indicate that the straw-based paper would require more nonrenewable raw materials and would produce more concentrated effluents (but not necessarily greater volumes) than its softwood-based counterpart. This arises from the direct substitution of high-yield softwood mechanical pulp for a low-




*5. Raw materials consumption for TD paper manufacturing at different straw pulp substitution levels*




*6. Energy consumption for TD paper manufacturing at different straw pulp substitution levels*




*7. Energy consumption for TD paper manufacturing at different straw pulp mill locations*

yield straw chemical pulp. The disadvantages of straw-based paper production remain the lack of appropriate technologies for desilication, process chemicals recovery, and heat recovery. Using these scenarios, the results indicate that the manufacture of softwood-based telephone directory paper entails less environmental burdens than the manufacture of straw-based telephone directory paper.

### *Effect of straw pulp mill location*

The effects of locating straw-pulping facilities in Alberta and Manitoba were evaluated in the second set of sensitivity analyses. Placing the straw pulp mill in Saskatchewan, Alberta, or Manitoba would have significant effects on the energy consumption (**Fig. 7**) due to the different mixes of fuel used to generate electricity in the three Prairie provinces (Table II). The effect of transporting the straw pulp to the coastal British Columbia paper mill on energy consumption is minor. The increase in total energy consumption obtained by locating the mill in Alberta, which produces 73% of its electricity from coal, would be due to nonrenewable energy consumption.

Relocating the straw pulp mill from Saskatchewan to Manitoba, which produces 99% of its electricity from hydroelectric sources, would decrease total energy consumption to the levels of the British Columbia–based wood scenario. However, energy supplied from nonrenewable sources would still be higher with the straw-based scenario than with that of the wood-based. Again, this is due to the lack of chemical and energy recovery for the straw chemical pulping scenario.

## FUTURE OPPORTUNITIES

Pure cereal straw pulps are reported to exhibit lower drainage rates and a weak wet-web strength compared to wood. In addition, the shrinkage rate in the dryer section is higher for straw pulps *(21)*. Therefore, the issue of machine runnability and the effect on paper quality must be investigated thoroughly for various types of straw pulps (SAICA, Alcell®, Universal, and potassium pulping processes) in different combinations with other paper furnish components. This will affect the environmental burdens associated with paper production incorporating straw pulp. Also, whether these pulps can meet the very demanding specifications of a TD paper is as yet uncertain.

For example, a semichemical or chemimechanical straw pulp may produce a higher-yield pulp with a lower pulping chemical demand. However, this pulp would require extensive brightening, suitable drainage, and other characteristics that may be difficult to achieve. Several processes exist that are either single facilities making products other then directory paper or that have been tested at the pilot or laboratory scale. For compara-

tive purposes, an inventory approach to evaluate their environmental burdens would be very valuable.

Studies on Canadian straws have shown the ash content to average about 8%, of which 60% is silica *(22)*. In the straw pulping scenario, the silica content of the straw would be too high to make chemical recovery feasible; hence a treatment-and-discharge scenario was used. This presents a significant environmental burden, which further highlights the need for the development of appropriate chemical recovery; this is preferable to disposal from both environmental and economic perspectives. Several innovative technologies that have attempted to deal with this issue include:

- the Austrian Energy and Environmental black liquor desilication process, which has shown promise at the pilot scale
- the Thessalian Paper Industry mill at Larissa in Greece, which was undertaking full chemical recovery by including an additional evaporator set with dumping of a portion of its lime mud (this mill is no longer in operation)
- the NACO mill in Foggia, Italy, which is able to desilicate the green liquor because the oxygen-based pulping process mitigates any black liquor viscosity problems, although significant volumes of contaminated lime are dumped.

Adopting the chemical recovery system used at the Thessalian or the NACO facilities would significantly alter the environmental burdens assigned to the straw pulp mill in this CGI, although careful consideration would have to be given to the significant volumes of lime that would require disposal.

This CGI has assumed that a straw mill would draw its power from the logical grid as mandated by local regulatory restrictions in many Canadian provinces. However, the authors also recognize that different strategies for minimizing energy consumption are also available. In light of the significance of the energy consumption on the environmental burdens associated with wheat straw pulping, alternative energy generation technologies, such as a natural gas-fired turbine with waste heat recovery, could provide the required steam and power for a pulp mill. This scenario could reduce the environmental burdens associated with the purchase of grid power generated by coal-fired thermal power plants.

A recent LCA undertaken by STFI *(23)*, which described the pulping of reed canary grass in different scenarios, reached similar conclusions with respect to energy and raw material consumption.

## CONCLUSIONS

The main conclusions with regard to the substitution of SMP by SCP in the production of TD paper are as follows:

- Using the best available mill-scale technology for the production of straw chemical pulp generates greater environmental burdens than those of the current softwood residues-based mechanical pulp production process.
- The major environmental burdens associated with the production of straw chemical pulp are the nonrenewable energy and raw materials consumption.
- These results further highlight the importance of the development and mill-scale implementation of a straw black liquor chemical and heat recovery process.

Many other possibilities, as yet unproven, could be investigated with respect to improving the environmental burdens associated with the production of wheat straw pulp for paper products. However, the lack of commercial straw pulp production experience within the very strict North American environmental guidelines has precluded their use in this study. In addition, advances in wood pulping technology may also alter the environmental burdens of the wood-based scenarios. Other factors, such as economics, fiber supply, logistics, and pulp quality, also require consideration in a North American context before the feasibility of straw pulping can be proven. **TJ**

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