AN ECONOMIC ANALYSIS OF ENERGY, FUELS AND CHEMICALS FROM FOREST BIOMASS

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The forest sector in Canada is rapidly changing, due to shifting markets and increased competition from modern, low-cost mills in tropical countries. The northern hardwood kraft mill, in particular, is endangered. The conversion of these kraft mills to produce energy, fuels and chemicals has been proposed. However, the cost of biomass collection makes large-scale conversion of wood to a single commodity product, such as heat, power or transportation fuels, difficult from an economic perspective.

In the petroleum refinery model, a very small amount of petroleum, perhaps as little as 4%, is converted to chemicals, rubbers and plastics and, according to Werpy,[1] generating as much as 42% of the value obtained. At the same time, some use must be found for the remaining 96% raw material: 70% is converted to liquid transportation fuels and generates another 43% of the value. The final 26% becomes bunker fuels, home heating oils, asphalts, bitumens and other relatively low-value products, generating a final 15% of the value. Clearly, sales of gasoline and Diesel fuel, while not sufficient on their own to ensure profitability, are critical to the profitability of the whole site. Similarly, heat, power or bio-fuels should not be considered as the best use of the entire biomass supply in a biorefinery: there is a need for biomass-generated side-products to generate relatively large revenues from a relatively small stream.

A second issue is one of scale, which derives from the feedstock supply costs. Considering feedstock consumption in terms of the rate at which the energy content is supplied to the plant, even the largest North American pulp mill is small compared to typical petro-chemical refineries or coal-fired generating stations. This is primarily due to increasing feedstock costs as scale increases, which rapidly overshadow the decreasing capital and operating costs. This makes the production of high-value products even more important for the forest biorefinery than the petroleum refinery, as economies of scale will not be available to the same extent for the biorefinery.

This report identifies some lower limits on the necessary revenues per ton of wood supplied, leading to an economically successful biorefinery installation, and compares scales and economics of the forest biorefinery to those of the petroleum refinery. The biorefinery concept, where small volumes of high-value products are produced and the residues are converted to heat, power or fuels, is identified as a necessary economic condition for success, given the costs of large-scale biomass collection.

Keywords: forest biomass, feedstock, biorefinery

INTRODUCTION

The forest sector in Canada is rapidly changing, due to shifting markets and increased competition from modern, low-cost mills in tropical countries. The northern hardwood kraft mill, in particular, is endangered. The conversion of these kraft mills to produce energy, fuels and chemicals has been proposed. However, the cost of biomass collection makes economically difficult large-scale conversion of wood to a single commodity product, such as heat, power or transportation fuels.

This article identifies some lower limits on the necessary revenues per ton of wood supplied, leading to an economically successful biorefinery installation, and compares the scales and economics of the forest biorefinery to those of a petroleum refinery. The biorefinery concept, where small volumes of high-value products are produced and the residues are converted into heat, power or fuels, is identified as a necessary economic condition for success, given the costs of large-scale biomass collection.

Product mix and scale of petro- and bio-refineries

In the petroleum refinery model, as little as 4% of the raw material is converted to chemicals, rubbers and plastics, generating as much as 42% of the value obtained.[1] It is fair to say that there are no small streams in the forest industry generating 40%+ of the revenues. At the same time, some use must be found for the remaining material: 70% of petroleum is converted to liquid transportation fuels, generating another 43% of the value. The final 26% becomes bunker fuels, asphalts and other relatively low-value products, generating a final 15% of the value. Clearly, sales of gasoline and Diesel fuel, while not sufficient on their own to ensure profitability, are critical to the profitability of the whole site. Similarly, heat, power or bio-fuels should not be considered as the best use of the entire biomass supply in a biorefinery: there is a need for side-products to generate relatively large revenues from relatively small streams, while the residues from this healthy primary industry can be converted to commodity chemicals, fuels, heat or power.[2]

A second difference between petroleum and bio-refineries is one of scale, which derives from feedstock supply costs. Considering feedstock consumption in terms of the rate at which the energy content is supplied to the plant, even the largest North American pulp mill is small compared to typical petro-chemical refineries or coal-fired generating stations. Table 1 illustrates this point; an obsolete refinery in Montreal is an order of magnitude larger than Canada's largest pulp mill. As discussed in literature,[2] this is primarily due to increasing feedstock costs as the scale of wood-based refineries increases, which rapidly overshadow the decreasing capital and operating costs. This makes the production of high-value products even more important for the forest bio-refinery, as economies of scale will not be available to the same extent as for the petro-chemical plant.

FORESTRY OPERATIONS: HIGH VALUE PRODUCTS AT BIOREFINERY SCALE

A hardwood biorefinery model

The concept of biorefinery revolves around separating the incoming feed into its constituent components, and extracting the best value from each one, rather than converting the entire supply to commodity chemicals, heat or power.

The largest Canadian hardwood pulp mills consume around 4500 to 5000 t/d, or about 1.7 Mt/y, of fast-growing aspen or poplar breeds. However, these mills are supplied by plantations. The mills supplied by natural forests face higher feedstock costs and are typically smaller. The analysis that follows focuses on modifying an existing 850 t/d hardwood kraft mill, consuming about 715 kT (420 MW_{th}) of dry wood per year.

It is further assumed that the feed consists of white wood in the form of hardwood chips. Table 2 describes the assumptions made regarding costs and revenues.

Pathways from hemicellulose

Hemicellulose can be extracted through a range of methods.[3] A potential product from hardwood hemicellulose is furfural, a precursor for several polymers.[4] With a wood supply of 2041 t/d, it should be possible to extract 51 t/d of furfural or other sugar-based chemicals worth $21 M/y at $1200/t. This pathway is illustrated in Figure 1, which shows the estimated costs and revenues of operating such a plant. Additional sugar streams from this process could be fermented to ethanol, or sent to recovery, as assumed here.

Another option is to ferment all hemicellulose to ethanol. Converting 200 t/d of hemicellulose to ethanol would yield 26.5 ML/y, worth $17 M/y at $0.65/L. The revenues per ton of sugar consumed, at $246/t, are low; there would have to be additional benefits, such as increased pulp production, due to debottlenecking of the recovery boiler, to make this economically sensible.

Pathways from lignin

The availability of lignin depends on which portion of it must be burned to drive the recovery reactions. In this case, 51 t/d of lignin could be removed by precipitation and reused elsewhere. (It is worth noting that not all hardwood mills will be able to extract this mass of lignin without running into problems in the recovery boiler). The process has been developed and demonstrated.[5]

The potential uses of lignin include substitution for phenols in phenol formaldehyde resins.[6] Baker[7] has stated that the lignin for carbon fibre will have to be under $650/t for making the carbon fibre prices attractive in mainstream automotive applications. In both cases, the potential revenues can be conservatively estimated at $750/t of lignin at the plant gate, or $13.4 M/y. This is also illustrated in Figure 1, where lignin extraction is presumed to be limited by the minimum energy content necessary to maintain operation of the recovery boiler.

Table 1
Rate of raw material consumption of various plants in terms of energy content per sec (1 GJ/s = 1 GW)
Petroleum 6 GJ/bbl; condensing power from coal assumed at 35% efficiency; wood 18 GJ/t

Plant location, description	Consumption or product	Feed rate, GW
Montreal Shell refinery, shut Nov. 2010	130000 bbl/d	9 GW oil
Nanticoke coal-fired power	3.5 GW power production	11 GW coal
7 Saudi-Aramco refineries	1.5 million bbl/d	105 GW oil
US petroleum refining capacity	16 million bbl/d	1100 GW oil
Canada’s largest pulp mills	5000 t/d wood	1 GW wood

Table 2
Assumptions and data ($ CDN)

Delivered wood, odt/y	714286
Purchase prices	
Wood, $/odt	100.00
Bark, $/odt	50.00
Natural gas, $/GJ	6.50
Elect. input, $/kwh	0.05
Sale prices	
Lignin, $/odt FOB mill	750.00
Ethanol, $/L	0.65
Heat (LPS), $/GJ	8.00
Elect. output, $/kwh	0.13
Heat (district), $/GJ	0.00
Furfural, $/t	1200
NBSK pulp, $/t	750
Dissolving pulp, $/t	1100
Yields	
Kraft pulp yield, %	42
Dissolving pulp yield, %	37
LP steam, CHP, GJ/t	12
Power generation, CHP, kWh/t	740
Wood heat value, GJ/t	18
Wood to steam efficiency, %	65
Gas to steam efficiency, %	85

Pathways from cellulose

The cellulose portion of the feed, if sold as market kraft pulp, generates $225 M/y. However, competition with the Brazilian mills makes this pathway difficult. Other pathways for a hardwood mill include dissolving pulp for rayon or viscose, specialty cellulose products, such as cellulose acetate, or new products, such as micro- or nano-crystalline cellulose. All lead to lower yields, all promise higher returns, but most are currently small markets compared to hardwood kraft pulp.

The dissolving pulp market today totals about 4.5 Mt/y, and is growing rapidly due to a combination of increasing Asian demand for textiles and poor cotton harvests; the addition of other 265 kt/y is not likely to seriously destabilize the market. Figure 2 suggests that the kraft mill is converted to dissolving pulp, using the existing wood supply at a yield of 37%.

Use of residues

The best first use of residues is in a power or recovery boiler, to generate heat and power for internal use. If there is enough energy available for plant needs, then the heat and power may be sold to the neighbouring industries or to the grid. Alternatively, the excess residue can be directed to pyrolysis or gasification processes, generating liquid or gaseous fuels for burning in the lime kiln, or for the synthesis of bio-fuels and chemicals.

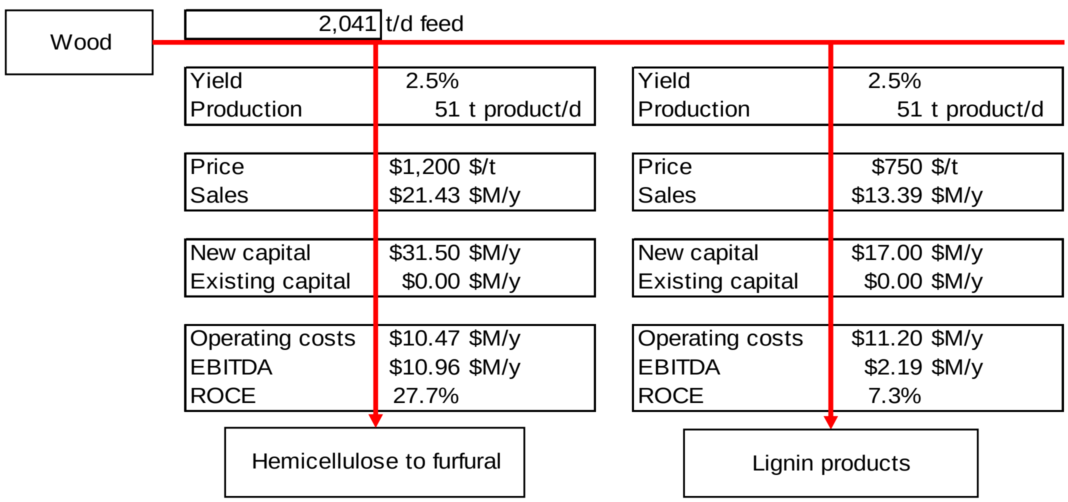

Figure 1: Extraction and conversion of sugars prior to pulping, and extraction of lignin from black liquor

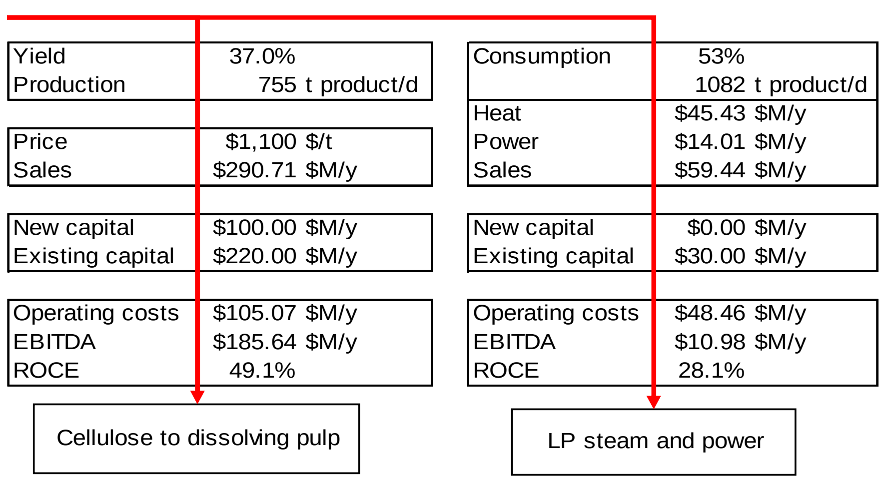

Figure 2: Cellulose to dissolving pulp and black liquor solids to recovery. The balance of 5% is sewered

A modern bleached kraft mill generates enough heat and power to be able to operate, on the average, at a small level of power sales to the grid[8] and no purchased fossil fuel, except for the lime kiln. This modern mill requires 18.8 GJ/t steam and 638 kWh/t of power. Most of the steam (15.8 GJ/t) and all power are supplied by the recovery boiler, with an additional 3 GJ of steam per ton of pulp generated from bark. In this example, the recovery boiler avoids costs of $45 M purchased fuel and $14 M purchased power. The energy value of the recovery island (other than chemical recovery) is thus $59 M/y, as illustrated in Figure 2, where the production of heat (12 GJ/t of solids consumed) and power (740 kWh/t solids) corresponds to a cogeneration plant equivalent to the average of condensing and backpressure power in Canada today.

Summary

Of the 2041 t/d of wood supplied, 51 t are converted to furfural, 755 t to dissolving pulp, 51 t to lignin products, and 1082 t are burned to generate heat and power. The remaining 102 t/d are sewered where it could be converted to methane in an anaerobic digester.

The recovery island generates $11 M/y worth of excess power, but does not provide sufficient heat to meet all needs. If natural gas is the incremental fuel, purchases of about $13 M/y are necessary to make up the deficit. Modifications to the cogeneration system to provide more steam (at a cost in power generation) may solve this; alternatively, a bark boiler will generate the excess steam, as well as the additional power for the grid. While it is likely that the reduced bleaching load, when compared to a market kraft pulp mill, will lead to reduced steam demand, this will likely be offset by distillation costs for the sugar stream.

Table 3 shows the revenues for both various streams and the mill as a whole. The capital costs are illustrative only, including both the costs of the converting mill and a value for the existing capital stock. The overall return on capital employed (ROCE) is a healthy 44%, with the dissolving pulp plant supplying most of the earnings. Net sales (excluding the benefit due to energy production in the recovery area) are of $326 M, or $455 per ton of wood consumed.

The baseline kraft mill makes 857 t/d of hardwood kraft pulp, corresponding to earnings of $225 M at $750/t; the benefit per ton of wood consumed is of $315/t. If the mill continues to make conventional kraft pulp, but adds chemical extraction from sugars or lignin, the added revenues contribute to the overall economic health of the site.

Table 3
Breakdown of costs and revenues for a dissolving kraft pulp mill making chemicals from hemicellulose and lignin as by-products

Detailed economics, dissolving pulp biorefinery ($M except prices per ton)					
Base case	Furfural (tons)	Lignin (tons)	Dissolving pulp (tons)	CHP	Overall
Capital costs					
New capital spending	$31.50	$17.00	$100.00		
Existing capital stock			$220.00	$30.00	$398.50
Total capital employed	$33.51	$17.90	$343.10	$33.18	$432.09
Production (tons/y)	17857	17857	264286		
Price per ton	$1200.00	$750.00	$1100.00		
Net sales	$21.43	$13.39	$290.71	$59.44	$384.97
Operating costs	$10.47	$11.20	$105.07	$48.46	$175.20
EBITDA	$10.96	$2.19	$185.64	$10.98	$209.77
ROCE	27.69%	7.25%	49.11%	28.09%	43.55%

Other options for the use of the 714286 tons of wood consumed include the production of ethanol, Fischer-Tropsch liquids or power for the grid. In the absence of carbon accounting, the revenues per ton of wood consumed are significantly lower for these cases. For fuels with a yield of 300 L per ton and a price of $0.75/L at the plant gate, the revenues are of $225/t; in the case of condensing power, 1450 kWh/t and $100/MWh generate only $145/t. As plant size grows to achieve better economies of scale, neither fuels nor power can provide the revenue needed to offset the increasing feedstock collection distances and the associated transportation costs that come with the scale.

The opportunities are thus to generate new value from novel products, to improve energy efficiency and heat integration, to identify low-cost fuels for added heat and power, and to reduce the volumes of wood flowing to lower value products. The next step in the process of designing the biorefinery will be to repeat the very high-level order-of-magnitude analysis here presented, with better estimates of capital and operating costs, process integration issues, markets and revenues.

CONCLUSIONS

The existing Canadian hardwood kraft pulp mill is an endangered species. The competition with modern mills running on eucalyptus in warm climates has proven very difficult for all, with several mills having been forced to shut their doors. The conversion of these hardwood mills to commodity chemicals or fuels, however, is likely to bring in less revenue per ton of wood consumed than the pre-existing kraft mill. The biorefinery concept, where wood is disassembled into its constituent parts and maximum value is obtained from each component, will prove more resilient, offering the potential for revenues at least as high as the kraft mill it replaces.

Short- to medium-term options involve making better use of the existing capital infrastructure, by adding chemical extraction stages to an existing kraft mill. This is a stop-gap measure; in the example given here, pulp continues to provide the largest revenue stream. As experience is gained in chemical extraction technologies and markets, new brownfield plants focused on other high-value products will be built.

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