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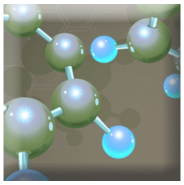

Bio-energy and Bio-chemicals Synthesis Report

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Bio-pathways is a joint project among FPInnovations, FPAC, the CFS, and the provincial governments of BC, Québec and Ontario. The Focus of the project was "How to support the forest sector in choosing the right Transformation Strategies?" It has been a two phase project with this document beginning release under the second phase which had a market focus.

1 Vision

The new Canadian forest sector will profitably transform its renewable, sustainably managed resource into a full suite of valuable products including: high-value chemicals and materials; traditional products such as pulp and paper or construction materials; and energy products such as heat, power and transportation fuels. This resurgent industry will continue to provide jobs to the population in rural and small communities across the country, while helping Canada move to a clean energy supply and reduce its carbon footprint.

1.1 Where are we now?

The Canadian forest sector has access to a large, sustainably managed renewable resource, much of it grown on land unsuitable for agriculture. This resource contributes a range of green products, produced in low-carbon facilities, to the Canadian economy. Traditionally, products from forestry are of three types. Solid wood products include dimensional lumber and a range of panels and composites used in building manufacture. Pulp and paper products include market pulps, newsprint and other mechanical grades, fine papers, tissue and towel grades, and packaging materials. Residues are traditionally used to generate heat and power for use onsite and sale to the grid. However, this model is under stress. Some products, such as newsprint, are facing a structural decline, with a 60% decline in North American newsprint consumption since 1999, while others, such as hardwood kraft pulp, are facing heavy competition from low-cost producers overseas. The highly integrated nature of the industry means that the decline of newsprint can negatively affect sawmills as well, as they no longer have as large a customer base for chips generated as by-products from their operations.

1.2 Where can we go from here?

The Canadian forest sector is in a position to deliver even greater benefits in terms of low-carbon products, whether energy or materials, while improving the industry's bottom line. In order to do so, new product lines need to be identified, to supplement and strengthen the existing sector and to generate new revenue and jobs, and to replace product lines which have seen a decline in demand or are no longer competitive. These products must be based on Canada's advantages, which include large volumes of certified sustainable harvested wood combined with innovative technologies and industrial know-how. For illustrative purposes, the current forest sector model can be contrasted with the petroleum refinery model, Figure 1, where 4% of the feedstock is extracted and converted to high-value products which generate 42% of the benefits. As seen in the second chart, few products in forestry can currently replicate this kind of high-return, low-volume, in spite of the green attributes of the resource, its management and the products generated.

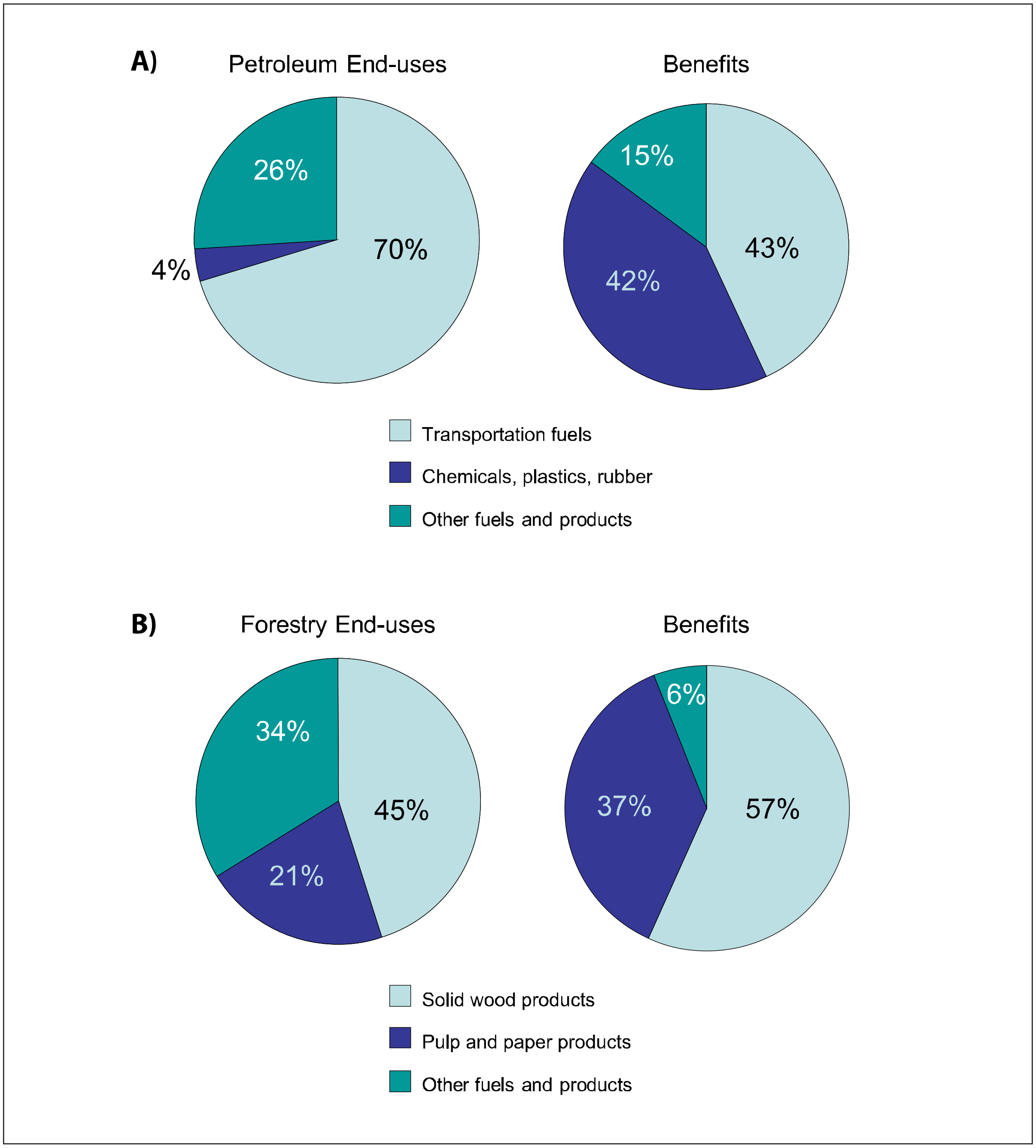


Figure 1. A) Benefits arising from various end-uses of petroleum. Source: T. Werpy, 2009 Bio-World Conference. B) An approximate plot of the same form for the forestry sector.

This report attempts to illustrate some examples of the potential that exists for the forest industry to redesign itself to more closely mimic the economics of the petroleum industry model. There are new businesses, partnerships and products to be developed; some are non-traditional; several will be smaller volume niche markets, or will involve a larger number of smaller customers, than is the case today; most will require more due diligence than has often been done to date. There are many potential opportunities and this report attempts to outline a few of them and highlight some key guiding factors. The steps to a forest industry model that mimics the value-generating capabilities of the petroleum industry can be described as follows:

- Step 1: collect the feedstock
- Step 2: extract products from it generating the highest possible value
- Step 3: repeat Step 2, using any residues as the new feedstock. Repeat until all material has been transformed.

This is illustrated in Figure 2. Products can include traditional and novel ones; the criteria must be to generate the greatest possible value in each step. Generally, heat and power will be a necessary part of the mix, but only after all higher value material has been extracted.

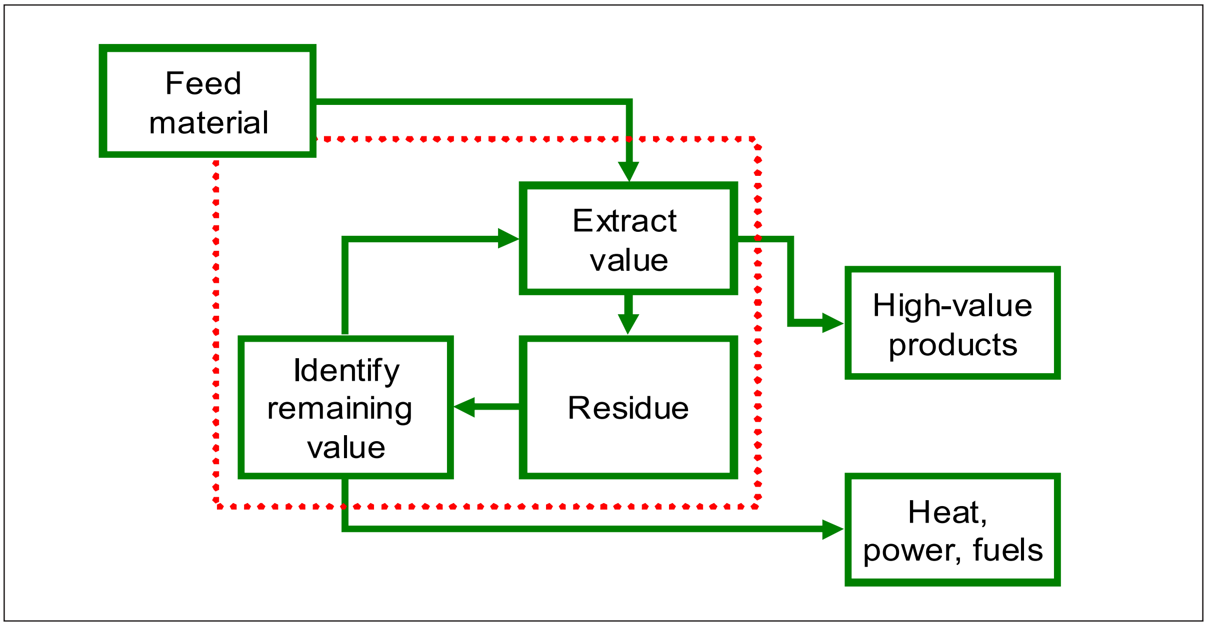


Figure 2. A refinery model based on extracting the largest possible value from a feedstock.

This value-driven, customer-focused approach requires a significant shift in thinking and approach. As new high-value products will need to be defined and developed, so, too, will new industrial partnerships and customer relationships. It is likely that in many cases higher value products will mean smaller markets; Figure 3 illustrates the relationship between market size and value. Cellulose-based fibres enjoy a world market of the order of 10^{11} kg, but typical sales prices are of the order of \$1/kg (\$1000/t). Specialty celluloses, in contrast, represent a market of 10^{8} kg at prices of the order of \$3/kg. For a sector such as forestry, used to delivering 10 million tonnes of NBSK or 10 million tonnes of newsprint, moving up the value curve means dealing with a larger number of smaller customers, each likely to request its own unique set of product performance attributes, or secondary distributors or processors.

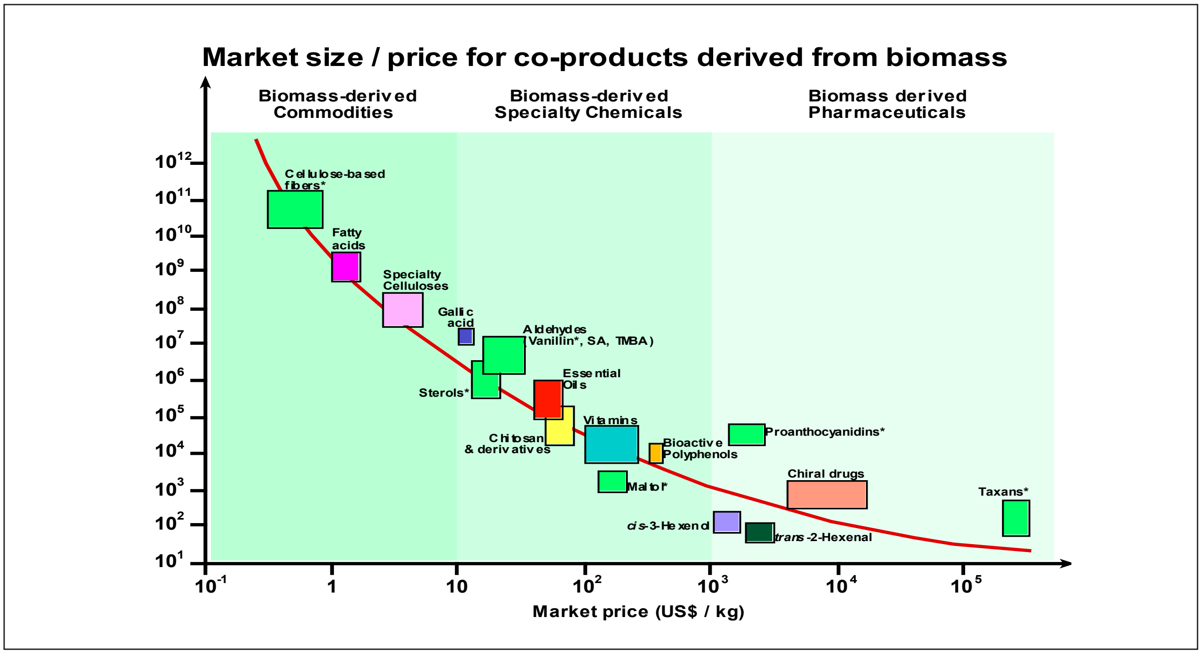


Figure 3. The relationship between annual market size, in kilograms, and price, in $/kg. Source: Esteban Chornet, presented at "Towards a Technology Roadmap for Canadian Forest Biorefineries", Industry Canada Workshops held in Montreal and Edmonton, November 2005.

1.3 How do we get there?

There are two parallel routes to transforming the forest sector—both leading to new, renewable green products. (In fact it is probable that the reality will be a mixture of these two extremes, and that there will be activities that combine pieces of both.) These routes can be characterized as follows:

- a step-wise modification of existing mills and capacities towards a more diversified bio-based business model; and/or
- build green-field mills for bio-production on conventional forest industry sites or as stand-alone mills.

In both cases the most rapid commercialization route possible must be taken. Building pilot demonstration plants at some intermediate stage between the laboratory and full commercialisation reduces technical risk, especially where novel processes or products are involved, but leads to potentially unacceptable delays where competitors may be moving faster. Rapid commercialisation must be the goal, and acceptable risk levels need to be revised in light of the urgency of the situation.

In one route, small-scale modifications to existing mills generate revenue from new products in the short-term and demonstrate new processes leading to these products. This sustains existing jobs and facilities while taking steps to demonstrate the viability of the new forest sector. These will have to be small-scale, partly because the technical risks may not be well known, and partly because some of the markets may be relatively small. The capital costs, in the order of $10M to $50M, are challenging for the existing industry, but not excessively so, especially if risk sharing opportunities are available. However, economies of scale mean that the cost per unit of production will be high, so these plants will have to target high-value products. In turn, current small market sizes for these higher value products impose an upper limit on scale, independently of the need to verify scale-up parameters. If the products are high enough value, price supports are not necessary, but help with the initial capital costs may be needed to offset the capital risk. (It is worth noting that markets for renewable alternatives have the potential to grow faster than their petroleum-based competitors, so first movers have the opportunity to capture market share early.)

This route leads to valuable end-products from a sustainable, renewable resource, and will provide support to existing forestry installations and jobs while displacing fossil fuel-based alternatives. These end-products may do more than replace an existing petroleum-based product, but may bring additional benefits due to unique bio-based properties not achievable with conventional raw materials. This necessarily involves integration with existing sites, including existing or new CHP plants, but the focus is on pre-commercial scale demonstration plants showcasing high-value products, rather than full-scale energy or fuel plants.

In a second route, large green-field biorefineries for production of bio-fuels, bio-energy, bio-chemicals and bio-products are built. In the first route, market size, technical risk and available capital set the constraints for the production of bio-chemicals and bio-products, but in this case the availability of biomass, and the cost of collection over large areas, set the constraints for production together with lack of domestic bio-energy markets and green energy policies.

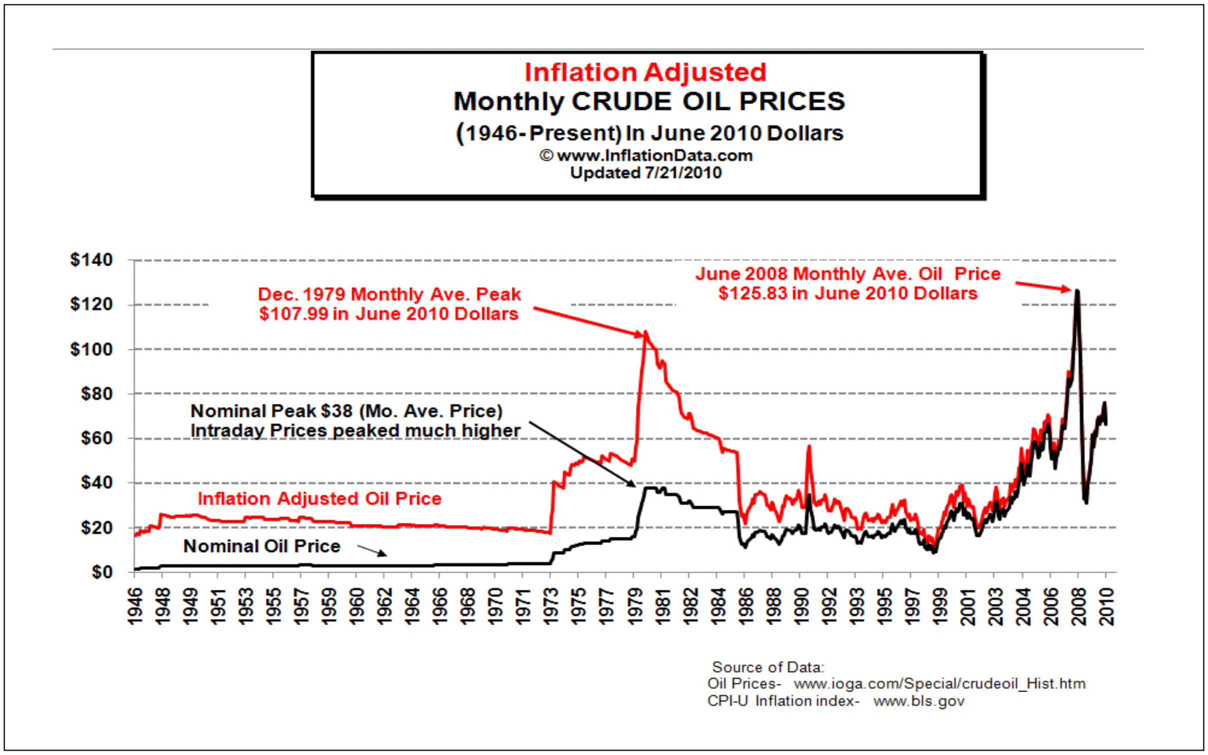
The value of this approach is to quickly supplement significant portions of the Canadian energy sector, whether power generation or transportation fuels from fossil sources, to a greener substitute with resulting reductions in greenhouse gas emissions. Jobs are retained in forestry, and the foundation for more novel high-value products is set.

1.4 What are some key constraints?

1.4.1 Energy pricing in the absence of carbon cost accounting

Energy prices in Canada today remain low, in spite of concerns around carbon emissions. Natural gas is at historical lows of about $4/GJ at the hub, compared with long-term averages of about $6.50/GJ; many forecasters are predicting these low prices will persist for the medium term as shale gas production comes online. Power prices, whether from coal or hydroelectric generating facilities, are in the range $50/MWh to $75/MWh for long-term industrial contracts. It will be seen later that these prices, based on simple economics with no form of carbon accounting, are insufficient to drive wide-ranging adoption of bio-energy or bio-fuels.

Until recent years, with a couple of exceptions due to geo-political events, inflation-corrected oil prices have remained in the $US20/bbl to $US40/bbl range since 1946 (Figure 4). Several analysts believe this is shifting as inexpensive, sweet crude runs out; new production comes largely from high-cost sources, which implies that long-term oil prices, in the absence of unexpected geo-political events or energy policies to address carbon or energy security concerns, are likely to be in the range $US70 to $80/bbl. While this may not be enough incentive for large-scale stand-alone bio-fuel or bio-energy plants, in particular given a Canadian dollar that minimizes the impact of these prices on Canadian industry and consumers, it may make production of bio-materials or bio-chemicals more interesting from a financial perspective.



Source of Data:
Oil Prices- www.ioga.com/Special/crudeoil_Hist.htm
CPI-U Inflation index- www.bls.gov

Figure 4. Inflation adjusted oil prices, in the absence of geo-political events, have remained in the range of $US20 to $US40/bbl from 1946 to about 2004. With the high cost of new oil finds, are we entering a world of $US75/bbl oil?

Section 2 outlines the extent to which forestry might contribute to reduced coal usage in electrical power generation and to reduced petroleum use in transportation fuels, as well as the development of green products and chemicals.

1.4.2 Plant scale is a function of collection costs

Biomass is local; this arises from its bulky, wet and distributed nature. Biomass-based systems will be limited in scale by biomass supply costs, which increase with scale due to the larger distances biomass must be transported. This in turn supports the conclusion that higher value products need to be considered before conversion of residues to energy products can be considered. By comparison, and as a result of higher energy densities by volume, fossil fuel-based installations can benefit to a greater extent from economies of scale than biomass-based facilities. This, in turn, supports the conclusion that higher value products need to be considered before conversion of biomass to energy products can be considered, and that bio-based refineries will need to maintain an even greater focus on higher margin products.

One way of looking at scale is to consider the rate of raw material consumption of a site in terms of its energy content. Dividing the energy content per unit mass, in GJ, by the mass flow rate into the plant in units of mass per second provides a measure of scale in terms of GJ/s, or GW. While this does not take into account the potential value of a feedstock beyond its energy content, it is a useful guide to relative scale.

Table 1 gives a few examples of petroleum- and wood-based plants. For example, comparing the coal consumption at Nanticoke with the annual allowable cut in Ontario, it becomes clear that there is not enough wood to put a significant dent in fossil fuel consumption, although it is possible to displace a portion of it.

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

Plant location/Description	Consumption or product	Capacity, GJ/s (GW)
Shell refinery, Montreal East (to be shut in November 2010)	130,000 bbl/d feed	9 GW oil
Nanticoke, ON	3.5 GW electricity production	11 GW coal
Saudi-Aramco combined 7 refineries	1.5 million bbl/d feed	105 GW oil
US petroleum refining capacity	16 million bbl/d	1100 GW oil
Canada’s largest pulp mills	5,000 t/d wood, 2200 t/d pulp production	1 GW wood feed
Annual allowable cut (Ontario)	13 Mt/y wood	7.8 GW wood feed

With this background in mind, it is possible to start to put some context around the two potential pathways outlined in the previous section. In one scenario, characterized by constrained financial resources, it is unlikely that large-scale projects will go ahead in the short term. A step-wise approach, beginning with small commercial applications attached to existing infrastructure, will serve to prove concepts and develop markets. Given ongoing historically low energy prices, these projects will have to include a high-value, non-energy component. As high-value means low volumes, the fit could be good between the scale of a demonstration plant or smaller mill add-ons and an initial set of customers.In another future scenario, particularly one characterized by some combination of strong and consistent policies around energy and carbon, unexpected geo-political events or concerns around security of supply, the availability of capital for biomass energy projects may increase substantially. It is then possible to think of larger scale energy solutions. Transportation fuels from biomass are probably economic when mill gate prices exceed $1.00 per litre; power production from biomass begins to make sense when power can be sold for $150/MWh or higher. At these prices it begins to make sense to explore energy opportunities and the relevant economies of scale more carefully, as these markets are enormous and the margins slim. However, it is clear that these higher prices will not come about without a consistent policy environment addressing the relative price of low-carbon vs. high-carbon energy sources, and that the appearance of consistency in the policy will be equally important. (Other drivers, such as geo-political events or increased demand in Asia, may inadvertently provide the same incentives.)

Figure 4 illustrates another characteristic of oil prices in the last two decades: increased volatility. Business cases based on average prices are necessary but a business case that takes peaks and troughs into account is better. In the case of price volatility, the best industrial model is one that can (relatively) easily switch outputs (pulp, paper, energy, bio-chemicals, bio-materials) depending on, and to take advantage of, relative market prices and demand.

These constraints on scale arise because the cost of producing transportation fuels from wood is a function of two very different drivers. First, economies of scale imply that both capital and production costs per unit of output will drop as scale increases. On the other hand, feedstock collection costs rise dramatically as scale increases, due to increased transportation distances. As a result, the optimal economic plant size for the production of bio-energy will likely be different from the optimum fossil fuel plant size, particularly given the distributed nature of biomass. Figure 5 shows the costs for a hypothetical gasification and Fischer-Tropsch (FT) BTL synthesis plant, operated on Canadian softwood with a harvesting cycle of 75 years. Minimum production costs of about $0.93/litre occur at a plant size of about 300 million litres, requiring 1.3 Modt/y of wood. This is on the scale of the largest Canadian pulp mill and would likely require similar or even greater access to forest feedstock.

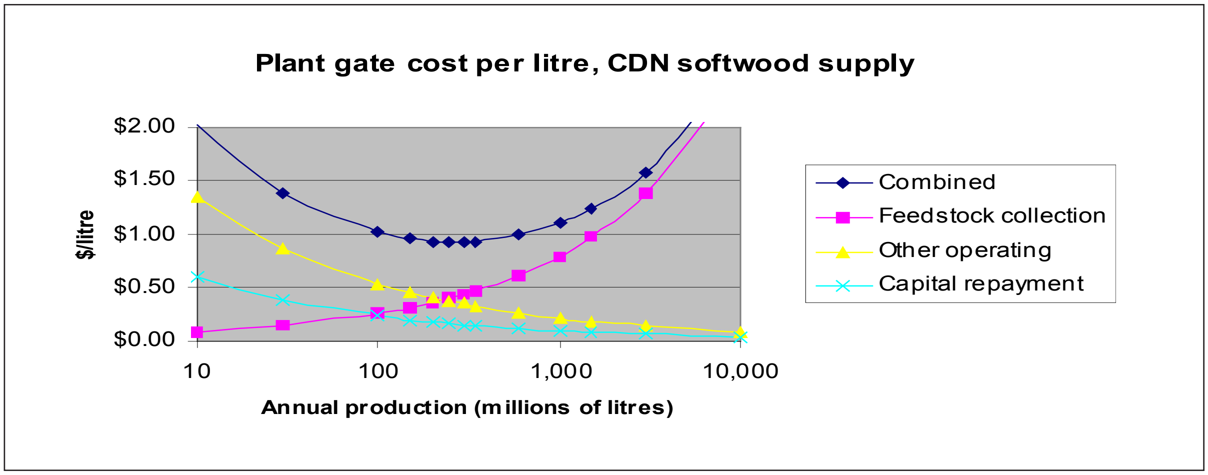


Figure 5. Cost per litre for a synthetic fossil fuel as a function of harvesting, capital and other operating costs. Process: biomass gasification and Fischer-Tropsch synthesis. Capital costs are assumed financed over a 25 year period at 5% interest rate. The minimum plant gate cost of $0.93/litre occurs at a production rate of about 300 million litres, requiring a wood supply of about 1.3 Modt/y. Based on Wright, M. and Brown, R. C., "Establishing the Optimal Sizes of Different Kinds of Biorefineries", *Bio-fuels, Bio-prod. Bio-ref.* 1:191-200 (2007).

The analysis above can be repeated for combined heat and power (CHP), with the following results:

- Heat users in Canadian forestry towns are few and far between. Pulp and paper mills, sawmills, and some institutional users such as hospitals will have year-round needs; other institutional users such as colleges will tend to be seasonal. Compared to compact European towns, for example, residential customers in Canada tend to be very spread out and connection to a new district heating grid may prove to be relatively expensive. So while there may be regions in Canada where the economics of district heating make sense, these will have to be evaluated on a case-by-case basis.
- CHP provides a positive ROCE when the both heat and electricity are put to productive use (for example, when electricity is priced at $130/MWh, steam is valued at $8/GJ and feedstock at $76/t). With the same parameters for power and feedstock, the ROCE is negative when the value of the steam is not captured.
- Integrating CHP with pulp and paper mills or sawmills thus ensures the highest efficiency of the entire system, making best use of existing biomass supply chains by maximizing overall efficiency of heat use, providing greatest employment, and providing a supporting leg for existing industry as it transitions to new products.
- CHP on an existing site also represents the best use of existing energy infrastructure, and represents a stable and secure source of energy. Excess biomass (if any) can be diverted to independent power producers or other stand-alone energy pathways.

1.4.3 Conclusion

Given the impact of scale and collection costs, and the relatively low cost of fossil fuels in the uncertain context around carbon taxes, incentives, price stability and volatility, it seems that there are two possible pathways forward:

- At small scales it is critical to identify and aggressively pursue low-volume, high-value co-products. Residues from these operations can be converted to energy products, which are not likely to be economic in the absence of high-value co-products. (The exception is energy for internal use which represents a stable and predictable supply.) Identifying local users of heat may be a limiting factor on the potential efficiencies. Rapid development of novel, high-value products is feasible and shows promise in improving the economics of existing forestry installations while displacing or supplementing fossil fuel-based products. Government support for capital costs for small demonstration plants in the $10M to $50M range is likely to be important in helping firms absorb these high, up-front capital costs, and to minimize risk for other partners and investors.
- At larger scales, which become possible if relative power and transportation fuel costs increase, it may become reasonable to consider stand-alone energy or fuel systems where scale is only limited by collection costs, not by market size. Here again the low local demand for heat in remote forestry towns is likely to be a limiting factor on efficiencies, although this too may change with the policy environment. The opportunity exists to move to a higher level of bio-fuels usage, which can contribute to reducing Canada's greenhouse gas emissions, particularly in jurisdictions with a higher proportion of fossil fuel-based energy consumption. However, it is clear that high levels of substitution for fossil fuels will require large portions of the annual allowable cut, and possibly significant levels of residuals from forest harvesting. Government policies and support to minimize the gap between production costs of bio-energy and fossil fuel-based energy will likely be important to encourage investment for large-scale production.

2 Specific Case Studies

2.1 Heat and power

Heat and power are traditional energy products derived from biomass and applications range in size from residential use through to large utilities. At an industrial level, biomass is already widely used as a fuel in Canada for this purpose. For example, in 2008, the pulp and paper industry alone produced more than 273,000 TJ of energy in the form of heat and power from non-fossil fuels [2008 FPAC Energy Benchmarking Report Summary]. Biomass comprised most of this fuel in the form of black liquor, bark, sludge and other materials left over from forest manufacturing processes. This represents the largest fraction of biomass-derived energy used in Canada. The energy was used to satisfy internal process needs, but some was also sold as power into the electrical grid.

Depending on the rationale for using biomass, the need for feedstock for these purposes can be nearly limitless. For example, to reduce greenhouse gas emissions (principally CO_2) as part of the implementation of the Kyoto Accord in Europe, many large biomass-fired utility boilers have been built or planned to supplement coal-fired units. A few as large as 300 MW_e have been announced, although 50 to 100 MW_e units are more common. The amount of biomass required at the largest scale is immense and these projects are usually coupled with announcements of supply agreements for biomass from many different regions of the world. European utilities are also co-firing wood or wood pellets at up to 20% by mass with coal as a means of reducing greenhouse gas emissions. This is also a large amount of biomass per plant. In both cases, favourable currency exchange rates, along with incentives offered to produce green energy, are such that it has become economic to ship biomass (principally in the form of bulk pellets) to Europe from as far away as northern British Columbia.

2.1.1 Feedstock

In addition to the bark and other manufacturing residues already used in Canada to produce energy, additional forest biomass could be (and is) used to make heat, power and transportation fuels in Canada. Trees from existing harvests, purpose-grown tree crops, roadside residues, thinnings and non-merchantable or low value stands could all be used for this purpose. To put the amount of available forest biomass into perspective, Table 2 estimates the total annual allowable cut (AAC) by province for hardwoods and softwoods and compares it to the harvest volumes taken in 2009. Also included in the table are estimates of roadside residues based on AAC and actual harvest volumes, as well as approximate amounts of residues (bark, sawdust, shavings, etc.) available from manufacturing processes. The definition of AAC varies by province, but is roughly defined as the amount of merchantable timber that can be sustainably harvested on a long-term basis. Current harvest levels are substantially below the AAC in all provinces.

Substantial efforts are now under way in most provinces to quantify the amount of economically available roadside residues and other sources of forest biomass that could be sustainably removed and put to use, but solid numbers are still difficult to obtain (Figure 6). In typical roadside harvesting operations, full trees are skidded to roadside where they are manufactured into merchantable logs. Roadside residues become the non-merchantable parts of the stems which can be economically recovered (e.g., tops, limbs, long butts). This is highly variable, but generally comprise from 15 to 25% of the volume of the merchantable components. Some biomass must be left on site, and an additional component of the total is uneconomic to recover due to its location (e.g., dispersed across the cutover), size, contamination or other non-timber resource constraint. These numbers will vary by province and geography, but provide a reasonable order of magnitude estimate. Estimates of the volume of wood available from non-merchantable and low-value stands are even harder to come by. Internal FPInnovations estimates are that these volumes may not be substantial relative to the AAC – by definition they are either difficult to access, slow to regenerate or low in volume of wood. Thinnings from silviculture and making firebreaks could provide additional amounts of currently underutilized biomass – this is a common practice in Europe.

Table 2. Forest Biomass: Annual Allowable Cut, Harvest Volumes and Residues by Province

	ACC		Roadside Residues based on AAC	Actual Harvest (2009)		Roadside Residues based on harvest	Manufacturing Residues*
	Volume Mm³	Mass Modt	Mass Modt	Volume Mm³	Mass Modt	Mass Modt	Mass Modt
BC	84.3	33.7	6.7	75.4	30.2	6.0	6.5
AB	23.1	9.2	1.8	20.5	8.2	1.6	2.4
SK	7.6	3.0	0.6	2.4	1.0	0.2	0.6
MB	9.6	3.8	0.8	2	0.8	0.2	0.2
ON	32	12.8	2.6	14.7	5.9	1.2	2.6
QC	55	22.0	4.4	29.3	11.7	2.3	6.7
Atlantic	19.5	7.8	1.6	16.7	6.7	1.3	2.2
TOTAL	230	92.0	18.4	112	44.8	9.0	21.2

Notes: *AAC and harvest various provincial sources for 2008 - 2009. Manufacturing residues from D. Bradley, Canada Biomass and Bioenergy Report, 2006
- Mass calculated as 0.4*volume
- Roadside residue calculated as 20% of harvest off cutblock (range 15 to 25%)

Collection and transportation of large amounts of forest biomass from harvest sites to energy plants entails additional cost. Depending on jurisdiction, harvesting methods and equipment may need to be revised to allow forest residues to be consolidated alongside roads during harvesting to minimize the cost of collection. Access to many logging roads is seasonal, and in some cases the terrain and road conditions may not be suitable for chip vans. Densification is necessary – probably at two distinct stages. Initial grinding and size reduction will be required on the logging site to economically bring the biomass to a central processing station. Although biomass can be used locally as boiler or gasifier feedstock in this condition, it would still not be dense enough, nor dry enough, for economical long distance transportation. For this reason, further densifying the biomass to pellets, pucks, bio-oil or other forms will be needed before transporting the biomass to the plant gate. This means that additional handling and processing of the biomass is necessary. In cases where co-firing with coal is contemplated, considerable attention is now being focused on torrefaction, which produces biomass with attributes (energy density, brittleness, water repellency) closer to that of coal. Conversion of the biomass to liquid pyrolysis oil at satellite stations near the harvest sites may also be an option, although as yet unproven.

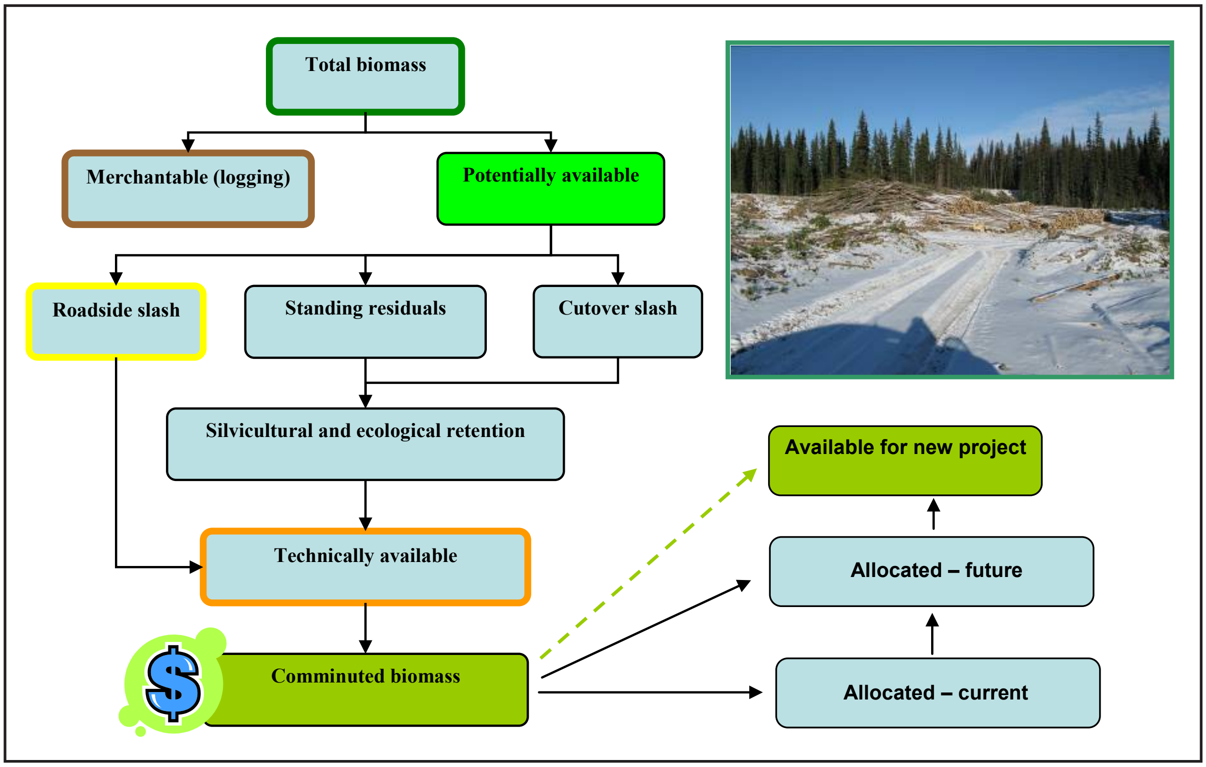


Figure 6. Not all residual biomass on a cut block will be available for use. Some must be left on site for silviculture and ecological retention, more will be too small or scattered for economical collection. Existing contractual arrangements will also reduce biomass availability for projects.

Although energy content is the key metric for selling biomass as a fuel, other qualities, such as ash content, friability and dust generation during handling are also important. In general, white wood pellets are desirable as biomass for fuel because they contain very little ash relative to biomass from annual crops and grasses. Pellets made from recovered forest residues likely possess a similar, but smaller advantage over non-wood sources of biomass. Standards for biomass fuels are being developed in many jurisdictions. ASTM standards are being developed in North America, while European jurisdictions are working under CEN and ISO banners. Individual user and producer groups are also developing standard specifications that apply to their activities. In general, purchasing biomass to the highest quality standards (lowest ash, highest calorific value) will be most critical for low-volume applications such as residential use and small district heat and power systems. For large power applications, biomass cost will almost always trump quality if a choice is available.

Given the size of the potential energy market versus the amount of available woody biomass (including forest residues, merchantable and non-merchantable stands), use of other sources of biomass should be expected. Cereal crops, grasses, agricultural waste, municipal solid waste (MSW) and sorted urban demolition waste are all available to augment the total amount of biomass available for conversion to heat and power. In the US, the ORNL Billion-Ton Study [RD Perlack *et al.*, "Biomass as Feedstock for a Bioenergy and Bioproducts Industry: the Technical Feasibility of a Billion-Ton Annual Supply", ORNL, 2005] estimated the available amount of agricultural biomass (excluding that needed for food) to be greater than 800 million odt, about twice as much as the forest biomass available for conversion to energy products. Use of these non-forest resources can contribute significantly to necessary economies of scale for biomass energy plants when they are available to supplement forest biomass. This synergy may be particularly valuable in provinces with large agricultural landbases.

At least initially, biomass from forest residues may compete directly with agricultural residues and other marginal sources of biomass because large-scale utility operators will source fuels with the lowest cost/GJ where these can be delivered to the power plant gate in bulk. For example, sorted urban waste and MSW often comes with a negative cost to an energy plant because of the offset paid for avoiding tipping fees in landfills. Projects based on such fuels will enjoy competitive advantage over forest biomass-based projects due to much lower feedstock costs. However, MSW and other materials that are currently landfilled will have a negative cost as long as no one wants them. If large-scale demand arises, there will be a price associated with it, the same as with recovered paper. Early adopters will sign long-term contracts and be more profitable than later entrants.

2.1.2 Process design and operating costs

The technology for small-scale CHP and district heating applications is fairly mature and well optimized (at least in Europe), although there will always be new developments in equipment design and technologies. Few projects at this scale produce both heat and power; most often the desire is to provide communal heat for aggregations of houses and commercial/institutional buildings. They are being developed in Canada where the right financial conditions exist, but progress has been inconsistent. Due to their small size, these projects are very sensitive to local differences in capital and operating costs and each project has unique combinations that make it difficult to generalize costs. Competition from conventional energy sources such as natural gas and on-grid electricity is a significant factor and the most compelling arguments come from off-grid communities where the delivered cost of power and fuel are substantially higher than the Canadian norm.

Higher housing density is a key factor, but European successes with small-scale CHP projects also stem from putting in decades of sustained effort to optimize every aspect of the projects, from supportive municipal guidelines and bylaws to highly efficient biomass supply chains, and standard equipment design and installation practices. Over time, similar efficiencies will develop in Canada as experience with these projects is gained. The recent announcement by BC Safety Authority [Catherine Roome, CANBIO 2010, Vancouver, BC] that they will accept some European engineering codes and standards for equipment imported to the province for CHP projects is a unique step forward in this regard, and should help to significantly accelerate the adoption of these technologies.

Typically, the core technology is a small biomass-fired furnace to produce hot water for circulation through buildings, although there are also examples of small gasifiers being used for this purpose in both Europe and North America. In the latter case, systems have been built that couple the gasifier to an electricity-producing genset fired on the syngas. Hot water is produced by heat exchangers for cooling the syngas, and from cooling water circulated around the genset.

Industrial and very large community applications for biomass-based CHP typically fall into the 20 to 100 MW_e range. For these installations, capital and operating costs for conventional technologies are well-known and are dominated, as with most biomass-based systems, by feedstock costs. Most often, the core technology will be a bubbling bed boiler – these are scalable over a wide range of sizes and are quite forgiving in terms of fuel quality and size distribution. Grate boilers and gasifiers have also been built for applications at this scale. A key difference between these and the smaller CHP systems is these are usually steam generators that fall under jurisdictional requirements for pressure vessel operation. Employee skill levels and manning requirements are more stringent—increasing operating costs substantially and making them better suited for co-location with an industrial complex operating on a 24/7 schedule. Finding suitable uses for the heat is also difficult without a large industrial client operating on a year-round basis.

Fast pyrolysis offers another means by which to consolidate the biomass energy into a fuel that can be used as a replacement for fuel oil. One such plant – the first in the world for this purpose – has been announced by Ensyn and Tolko to be built by 2012 at the site of a large sawmill complex in High Level, Alberta. Residues from the sawmill will provide the feedstock, and the oil will be used in part to power several generator sets for production of electricity and providing heat for the complex. At 400 odt/d, the plant is predicted to produce approximately 85 ML pyrolysis oil/year.

Within North America and much of the rest of the world, coal is the most commonly used fuel for large-scale utility boilers producing electricity through steam-driven turbines. These boilers are typically quite large and produce in the order of 400 MW_e or more, typically with several boilers on a single, multi-GW scale site. The Ontario Power Generation complex at Nanticoke is the largest such North American facility with a current combined power production capacity of about 3.5 GW_e. In the absence of green incentives, biomass has not been used at this scale because it is much less energy dense than coal and considerably more expensive to collect. However, European and British proposals for multiple 300 MW_e installations are in place that will require biomass supplied from countries on both sides of the Atlantic and some European utilities now co-fire up to 20% biomass with coal.

2.1.3 Market volumes and revenues

Three scenarios have been examined to look at how much forest biomass might be needed to produce heat and power as a substitute for fossil fuels. These include large-scale substitution of coal, as is currently practiced in Europe, medium-size CHP installations co-located with existing or new value-added processing plants, and small-scale district heating opportunities. Since the conversion of biomass to energy is most economic when the biomass is used locally, it is assumed that the energy products will substitute for consumption within the boundaries of each province.

Following along the path of European utilities, Table 3 shows the use of coal for generation of electricity by Canadian province, and the equivalent amount of wood needed to replace the coal at different levels of substitution. These numbers are large compared to the net annual allowable cut (AAC) for each province shown in Table 2. If biomass replaced 20% of the coal used to produce electricity in Alberta, the largest coal-using province, about 75% of the entire AAC for the province would be consumed for this purpose. In Ontario, it would take nearly 40% of the total AAC to supplant just 20% of the coal with biomass. A similar analysis holds true of the other regions, with the exception of Manitoba – a very small coal user. Note that these numbers depend on harvesting to the AAC; actual harvest rates in several provinces, particularly Ontario, were far below the AAC in 2009 (Table 2).

Table 3. Substitution of wood for coal in the production of electricity by province. The table shows the percentage of the AAC required to substitute biomass for coal. Any numbers less than 20% might be supplied by roadside residues alone.

Province	Coal for Electricity[4]	Equivalent Wood		% of AAC needed for given level of substitution for coal		
				3% of coal	10% of coal	20% of coal
		Petajoules	Modt			
BC	--	--	--	--	--	--
AB	490	630	35	11	38	75
SK	150	190	11	10	35	70
MB	5.4	6.9	0.4	0.3	1	2
ON	330	430	24	6	19	37
Atlantic	114	146	8.0	3	10	21
Arctic	--	--	--	--	--	--
CANADA	1100	1400	78	3	8	17

[4] Assumptions: Coal to steam efficiency 83%, wood to steam efficiency 65%, heat content of wood 18 GJ/t. Equivalent Wood = [Coal] * [Efficiency of Coal] / [Efficiency of Wood]. Coal consumption for 2004 from Canada's Energy Outlook, an Update.

A large amount of the available timber will continue to be converted into high value products such as pulp, paper and solid wood products, and will not be available for conversion to energy (other than manufacturing residues already used to make heat and power). If all available forest residues (at 20% of AAC) in Canada were devoted to coal substitution, they could barely supply sufficient energy to offset the greenhouse gas emissions of 20% of the coal used to produce electricity. This includes the roadside residues available in BC and Quebec – two provinces that don't produce electricity from coal. At this scale, it would make sense to look for synergies with other forms of biomass such as agricultural waste.

It was clear from the Bio-pathways I study that stand-alone power from forest biomass is rarely economic in the absence of significant financial incentives. In regions where emissions of greenhouse gases are regulated and the adoption of lower carbon options are encouraged, there is a clear and significant market for forest biomass as a substitute for coal, most likely in the form of torrified pellets. The numbers above show that the market is essentially bottomless in this scenario, since the entire AAC plus available forest residues in coal-using provinces like Ontario and Alberta could not fully substitute for the use of coal.

However, even with oil prices substantially above historical norms, the cost of delivering coal or natural gas to the plant gate in North America will almost certainly be substantially lower than providing the equivalent energy content of biomass. Estimates for the cost of procuring biomass from Canadian forest residuals range from $66 to $82/odt ($2.80 to $5.50/GJ). Densifying (pelletizing, torrefaction, fast pyrolysis) costs and delivery to plant gate are additional. Bulk prices for quality white wood pellets landed at Rotterdam have averaged about $199/odt ($9.95/GJ) over the past three years, while bagged residential pellets in the US northeast have averaged about $260 ($13.00/GJ). This contrasts with the delivered cost of thermal coal in Canada at $0.83 to $2.85/GJ [National Energy Board 2009 Reference Case Scenario: Canadian Energy Demand and Supply to 2020; Appendices Table A1.1] and current natural gas prices of about $4 to $5/GJ at the hub. Many large utility boilers are sited adjacent to coal mines, and even enjoy common ownership with the mine. For this reason, it is unlikely that utility owners would ever voluntarily bridge the price gap between biomass and coal, even with sharply higher oil prices. However, political and environmental incentives in North America have some utilities considering the addition of biomass to their fuel mix [EPRI-Vista, BC, OPG announcements]. Substituting residual forest biomass for coal at a 10 to 20% level (similar to current European practice) to reduce greenhouse gas emissions offers a substantial opportunity for the Canadian forest sector.

If stand-alone large-scale power generation from biomass is generally uneconomic without strong environmental incentives, what about cogeneration opportunities? Co-locating a power generation plant with a large 24/7 heat user means the efficiencies are much higher than if the plant is designed for electricity generation alone, even if the power generation potential is reduced by diverting a portion of the heat to other uses. In Canada, the largest biomass-fired plants in this category are generally attached to pulp and paper mills. Most burn bark and other very low-value residues (hogged fuel) that are collected either on-site or from nearby as a consequence of processing logs. Historically, these boilers have been sized and designed to match the heating needs of the mill, but increased focus is being placed on power generation. Significant potential for increased power generation from biomass exists in facilities that have excess steaming capacity as a consequence of modernizing and resizing the pulp/paper operations, or in sawmills that have unallocated processing residues. Recently in Canada, Pulp & Paper Green Transformation Program funding for the pulp and paper industry has been applied for this exact purpose, with many pulp and paper mills committed to installing condensing turbines in the 20 to 50 MW size by 2012. Further gains in biomass power production are still possible from these and similar plants scattered across Canada.

As a consequence of the already installed capital infrastructure, power from these sources of biomass can be produced at a lower cost than building a new power facility. Most of these boilers use hogged fuel and other cheap manufacturing residues and most are operated in conjunction with pulp and paper mills. Some are located next to sawmills and other industrial plants. These boilers support the manufacture of value-added products and the associated highly skilled jobs in each plant. While the financial return for every location will be different, the offset power purchases or added revenue they could obtain from power production would be a step towards turning these facilities into sustainable multi-product bio-refineries and provide financial stability for the operation of the entire plant. Conversely, policies that only incent power production from new independent power producers and force competition for the same existing cheap biomass supplies may have the opposite effect. Operations producing higher value products will be negatively impacted due to rising costs, leading to greater financial instability and the potential loss of employment in the local community.

Location is another consideration for CHP applications, especially on a large scale. The imperatives of the cost of collection of biomass dictate that CHP plants be located as closely as possible to the source of the biomass, as well as the user of the heat. These locations tend to be far from population centres in Canada, and don't always match up with available electrical transmission infrastructure. Significant transmission bottlenecks also exist, for instance between northern and southern Ontario, and along the I-5 corridor in the Pacific Northwest.

At a very small scale are local and community CHP plants that provide district heating to residences, schools and other clusters of small buildings. At these scales, margins are extremely tight, and capital and biomass supply costs significantly affect the economic viability of projects. A critical consideration for the economics of these facilities is the question of how to balance the seasonal heat and power needs. The scale of biomass needed for an individual site is so small that it could be sourced locally in most parts of Canada, even in urban areas where clean, sorted demolition waste can reach significant volumes. Procurement and comminution of biomass at this scale requires some thought, since standard-size grinders and chippers used in the logging industry would be able to produce an entire year's supply of biomass in a matter of days. The most likely location for this type of installation is off-grid communities, where the cost of delivering diesel fuel can be prohibitive and local jobs can be created for wood harvesting, collection and comminution. For example, remote communities in Northern Manitoba were faced with an exceptionally warm spring in 2010, causing ice roads to melt before the usual year's worth of fuel could be delivered by truck. Diesel fuel had to be flown in during the summer and fall of 2010, at great expense. A local supply of biomass combined with a small CHP plant would be worth evaluating, even if most of the heat is vented in the summer.

2.1.4 Return on capital employed

A sample ROCE calculation for industrial scale CHP, based on data used in the Bio-pathways I project is presented in Table 4. The return is positive (17%), because both heat and power are fully utilized. The feed is made up of residues at $76/t, and the power generated is sold for $130/MWh. With power prices of $60/MWh, the ROCE is 4%. As discussed in Section 2.8, this still makes sense where the heat and power are used internally and are generated with a residual stream such as black liquor or bark from operations.

Table 4. ROCE for a 60 MW$_e$ CHP plant operated on residues. From Bio-pathways.

Capex	$225,000,000	
LP steam, 12 GJ/t @$8.00/GJ	$62,400,000	
Steam losses	-$9,360,000	
Electricity, 740 kWh/t @ $0.13/kWh		$54,450,000
Net Sales		$107,490,000
Operating costs		
Wood, 650 kt/y @ $76/t	$42,980,000	
Other	$13,580,000	
Total Cash Operating Cost		$56,560,000
EBITDA		$50,930,000
Depreciation	20 years	$11,250,000
EBIT		$39,680,000
Tax rate	30%	$11,900,000
Net income		$27,780,000
Maintenance	2%	$4,500,000
Accounts receivable DSO	35 days	$10,300,000
Accounts payable DPO	45 days	-$6,970,000
Inventory	17 turns	$3,300,000
Capital employed		$236,160,000
ROCE		17%

2.1.5 Conclusions

In the absence of a 24/7 heat user, low feedstock costs, high feed-in tariffs or both are necessary to make power generation from wood economic. With a large heat user to take waste heat and improve the overall efficiency, the economics improve. Large heat users in the vicinity of biomass supplies are limited to large forestry installations, oil and gas extraction facilities, and a small number of mines and smelters. The existence of sufficient transmission capacity to take the power from remote forestry installations to Canadian or US population centres needs to be considered.

Other heat users near large forestry reserves are hospitals, colleges and municipal infrastructure in the towns that provide services to the industry. Typically, CHP plants designed for these facilities are smaller in scale than the boilers attached to pulp and paper mills. At a very small scale are local and community CHP plants that provide district heating to residences, schools and other clusters of small buildings. At these scales, margins are extremely tight, and capital and biomass supply costs significantly affect the economic viability of projects. Although common in northern Europe, there are very few successful examples of community-based CHP plants in Canada. Low Canadian energy costs are a key factor. At least one off-grid CHP plant is operating in the native community north of Chibougamau, QC.

2.2 Ethanol

Ethanol is readily produced from any sugar- or starch-based feedstock, such as corn or wheat, and current North American production from these sources exceeds 46 BL/y. Most of this production is used as an additive to gasoline, although other markets exist. With more effort, ethanol can also be produced from cellulosic materials like wood, grasses and straw. Other alcohols (methanol and butanol) can also be produced from these feedstocks, and there are significant markets and opportunities for these products as well. Despite the promise, and significant research and development funding provided to cellulosic ethanol producers, almost no ethanol is currently obtained from ligno-cellulosic biomass. An exception is the extraction of ethanol from process filtrates in a Canadian sulphite pulpmill. Although forest biomass is a suitable feedstock for ethanol production, significant technical hurdles exist for routes based on fermentation and there are many competing sources of ligno-cellulosic biomass that may prove easier to convert than woody biomass. There are two major process routes to ethanol; a bio-chemical pathway based on fermentation of sugars and catalytic conversion of syngases produced by biomass gasification. The following case study is largely based on the bio-chemical route.

2.2.1 Feedstock

The main advantage of cellulosic biomass for ethanol production is that it largely originates from non-arable land or from non-food residues. In the case of the bio-chemical route, clean white wood would be the preferred feedstock from forest resources. Principally, this means sawdust and shavings from sawmills, or wood chips from sawmills or whole tree chipping. Some harvest residues and forest thinnings that can be easily debarked might find their way to ethanol production, but the higher lignin content, debris and inherent variability of such material would make these residues less attractive for bio-chemical conversion. The second pathway to ethanol and other alcohols from biomass is via gasification and catalytic conversion of the syngas. This route is essentially agnostic to the source of biomass, and forest-based feedstocks are entirely suited for conversion to these products.

Significant technical hurdles exist for routes based on fermentation and there are many competing sources of ligno-cellulosic biomass that are easier and more convenient to convert than forest biomass. In particular, large quantities of corn stover can be recovered with corn currently used to make ethanol; proximity to existing processing plants clearly gives this agricultural residue an advantage over forest biomass. Effort in the US has been focussed on fast growing crops like switchgrass that can be significantly cheaper to comminute than wood [JY Zhu, TAPPI PEERS Conference, Sugar Platform 101, (2010)].

2.2.2 Products

Different grades of ethanol can be manufactured, depending on the intended market. These include transportation fuels, as a base chemical for the industrial or food industry, or as a feed for the pharmaceutical industry. However, the largest market by far would be for fuel ethanol and this is the market targeted by cellulosic ethanol technology providers. Most cellulosic ethanol technologies, whether through microbial fermentation or gasification, generate by-products that are generally considered to be waste, but may also find markets. These include gypsum, lignin and other organic matter, in addition to the ethanol. Some of the organic material will be combusted to supply internal steam and energy needs. Heat and power are possible by-products from a gasification route.

2.2.3 Process design and operating costs

There are no commercial-size cellulosic ethanol facilities in operation in North America, and consequently, both capital and operating costs remain a subject of speculation. The biological approach to producing cellulosic ethanol is very much similar to starch-based ethanol production, except that the cellulose-containing material has to go through a pre-treatment step prior to enzyme hydrolysis and fermentation, Due to process similarities, it is reasonable to assume that the scale of a commercial cellulosic ethanol plant would be similar to a commercial-size corn ethanol plant. The largest Canadian plant currently produces about 200 ML/y, but several in the US operate at 300 to 400 ML/y [Ethanol Producer Magazine]. Thus, a modern commercial facility producing ethanol through the fermentation of cellulosic materials might be expected to produce between 200 and 400 ML/y. Plants of this size would consume somewhere between 0.75 and 1.5 Modt/y of wood-based biomass. Gasification pathways are still at the pilot stage, but would almost certainly have to be at the same kind of scale to be competitive in a commodity market. Demonstration units proposed by companies like Enerkem and Range Fuels are in the 30 to 40 ML/y range.

2.2.4 Market volumes and revenue

Nationally, the renewable fuels' standard (RFS) requires that 5% of the gasoline sold in Canada be from renewable sources by the end of 2011. Some provincial standards are different – Manitoba has mandated 8.5% renewable content and Saskatchewan has mandated 7.5% renewable content. In principle, this opens a huge market for transportation fuels made from forest biomass. Using ethanol as an example, Table 5 shows the 5-year average of gasoline sales by province, along with the amount of biomass required to meet the RFS standard from different sources. Roadside residuals based on the AAC could supply the entire RFS content in gasoline for each province except Ontario. The story is slightly different when actual 2009 harvest volumes are considered – in that case, the roadside residuals in many provinces would need to be supplemented by other biomass to make up the balance of the renewable content mandated by the RFS.

However, the picture is less rosy when existing production of ethanol from cereal crops is factored into the equation. Current ethanol production from these crops is estimated to be about 1.7 BL across the country, and more production capacity is being considered [Canadian Renewable Fuels Association]. This is nearly all of the mandated renewable content in Canadian gasoline and leaves no room for what is likely to be more expensive competition from forest biomass, especially since the Canadian RFS also allows certain volumes of the renewable fuel content to be imported from other countries. Waste from agricultural crops (stover and straw) are almost certainly going to be considered for conversion to ethanol when these are available in close proximity to existing cereal-based ethanol plants and this material will offer significant competition to forest biomass.

Table 5: Percent of AAC and 2009 Harvest Volumes Needed to Satisfy RFS for gasoline (based on bio-chemical ethanol)

Province (%RFS)	Gasoline Sales 5-yr avg (ML)	RFS (ML)	Forest biomass needed (Modt)	% AAC	% roadside residues based on AAC	% 2009 Harvest	% 2009 Roadside Residues
BC (5%)	4,603	230	0.82	2	12	3	14
AB (5%)	5,606	280	1.00	11	54	12	61
SK (7.5%)	2,096	157	0.56	18	92	58	292
MB (8.5%)	1,482	126	0.45	12	59	56	281
ON (5%)	15,903	795	2.84	22	111	48	241
QC	8,704	435	1.55	7	35	13	66
Atlantic	3,152	158	0.56	7	36	8	42
Arctic	65	3	0.01				
Canada (5%)	41,611	2,081	7.43	8	40	17	83

Notes: Assumes ethanol yield of: 280 L/odt

Renewable fuels' standards in the United States are written somewhat differently, with some mandated production targets set for starch and cellulosic-based ethanol. By 2022, their RFS II calls for 36 billion gallons of renewable fuel to be blended into transportation fuel, with different targets apportioned to gasoline, diesel fuel and specific products like cellulosic ethanol. US production of ethanol from cereal crops is restricted to a maximum of about 15 billion gal/y (~60 BL), and various incentives and funding mechanisms have been put in place to encourage large-scale development of cellulosic-based product. One roadblock to using more ethanol in the US is the "blend-wall" – gasoline in the US is currently restricted to a maximum content of 10% ethanol, and this has been met entirely by starch-based ethanol. Considerable lobbying is under way to allow this number to rise to 20% to make room for cellulosic ethanol. These activities may eventually translate to demand for higher renewable content in Canadian gasoline as well, but likely won't result in significant export opportunities for Canadian companies, due to the level of incentives offered to US producers and the existence of some tariff barriers aimed at cheaper ethanol produced from sugarcane in countries like Brazil.

2.2.5 Return on capital employed

The analysis that follows assumes a fermentation plant with a capacity of 200 million litres, requiring an investment of $315M. Feedstock would amount to 714,000 odt/y; average cost is assumed to be $100/t. Total annual operating cost would be in the vicinity of $150M. Assuming a plant gate sale price of $0.65/L of ethanol, total ethanol sales would be $130M. The ROCE in this case is negative (-20%), with an EBITDA of -$63M/y. Considerable uncertainly rests with these numbers, particularly with respect to the assumed operating and capital costs. Capital estimates as low as $169M have been published for similar sized plants based on corn stover and switchgrass as feedstock, with cash operating costs of about $70M [Ag Marketing Research Center, Oklahoma State University]. The latter is based on unrealistic (for regional white wood prices in Bio-pathways) feedstock costs of about $50/odt and the change in capital alone does little to affect the negative ROCE.

According to some technology providers, lignin production could be up to 400 kg/odt of wood supplied, although this is likely to be optimistic. The most likely use for the lignin is as fuel for the plant. However, assuming the needed power can be purchased at $0.06/kWh and that 180,000 tonnes can be diverted for an annual higher value market for lignin at a plant gate sale price of $750/t (see Section 2.5), the corresponding EBITDA would be positive due to new revenue of $135M. The ROCE is now 21%, illustrating the critical role that high-value co-products will play in the economics of any wood to biofuel plant. The base case (ethanol only) is illustrated in Table 6.

Table 6. ROCE of a fermentation cellulosic ethanol plant. From Bio-pathways.

Capex		$315,000,000	
Sales			
	Ethanol, 200 ML @$0.65/L	$130,000,000	
Net Sales			$130,000,000
Operating costs			
	Wood, 714 kt/y @ $100/t	$71,400,000	
	Other	$60,000,000	
	Total Cash Operating Cost		$177,000,000
EBITDA			-$47,000,000
Depreciation		20 years	$15,750,000
EBIT			-$63,000,000
Tax rate		30%	$0
Net income			-$63,000,000
Maintenance		2%	$10,710,000
Accounts receivable DSO		35 days	$12,500,000
Accounts payable DPO		45 days	-$21,800,000
Inventory		17 turns	$10,500,000
Capital employed			$322,400,000
ROCE			-20%

2.2.6 Conclusion

The case for ethanol from wood is difficult to make. Yields may not be as high as shown, as many of these numbers have been demonstrated only at the bench scale or are theoretical calculations based on total sugar or carbon content. And while it may be technically possible to run a gasification plant on bark, cheap bark requires a healthy primary industry to generate bark at that price. It is thus not likely that we will be able to provide the entire country with renewable fuel from wood without the wood cost being that required for whole logs or chips. So the ROCEs given here may be taken as optimistic, and the economics generally negative.

Improving the economics would require finding valuable uses for the lignin produced. On a relatively small scale, for instance in the case of a number of 400 ML/y plants, this means finding uses for 400,000 t/y of lignin per plant. Options exist to burn this amount, or convert it to value-added products. However, Section 2.5 demonstrates that markets of this volume do not exist today and the best use of this volume of lignin would be as a fuel for stationary combustion in CHP plants, at a value substantially less than $750/t. (At 28 GJ/t of lignin and $6/GJ for delivered natural gas, the energy content of a tonne of lignin is worth $168.)

2.3 Synthetic Hydrocarbons

Synthetic hydrocarbons can be derived from a number of thermal conversion processes such as coal liquefaction, fast pyrolysis or via gasification/catalytic conversion technologies like the Fischer-Tropsch (FT) process. It is diesel fuel made from this latter process that will be the major focus of this case study. Other products that can be made via thermal treatment/catalytic conversion of biomass include methane, methanol, ethanol and dimethyl ether (DME).

Bio-diesel in North America is currently being produced mainly through the trans-esterification of animal fats, soy oil, canola and restaurant fats. The gasification and FT process to produce bio-diesel is entirely distinct from the trans-esterification process and can be fed with a wide range of carbonaceous materials. Strictly speaking, the product is not a bio-diesel, but a true synthetic diesel as the chemical composition of the product is a mix of hydrocarbon chains indistinguishable from petroleum-based diesel.

2.3.1 Feedstock

Since the FT process requires a gasifier to convert the feedstock into syngas, it can accept a wide variety of marginal biomass as a fuel. This is also largely true of other thermal conversion processes. Some attention needs to be paid to feedstock cleanliness, as the downstream catalysts employed to convert the syngas to liquids can be poisoned by common contaminants like chlorine and sulphur. For the FT process in particular, the major constraint will be scale of the plant. Due to the high capital costs of a FT plant, it needs to be built to a very large scale and the footprint of the plant in terms of feedstock harvesting may be such that it would need to compete for more expensive forms of fibre than forest residues. In the case of FT plants, it would definitely be advantageous to locate the plant in regions where other types of biomass, like agricultural waste, were also readily available. Otherwise, feedstock-related issues are the same as for heat and power, and readers are referred to section 1.2.2.

2.3.2 Products

By using different catalysts and manipulating the C:H ratio of the syngas, a variety of synthetic hydrocarbons can be produced via the Fisher-Tropsch catalytic conversion process [Fischer-Tropsch Technology, Steynberg and Dry, 2004]. Depending on the reactor, FT fluids can include straight run diesel components, waxes, naphtha and olefins. The waxes, naphtha and olefins are further refined into a wide variety of valuable end-products. The refining technology is similar to that used for petroleum-based crude oil with allowances for the specific components of the FT fluids. Unlike ethanol or bio-diesel from lipids, syn-diesel can be blended with fossil-fuel diesel at any point in the existing supply chain and transported to other provinces or the US In the absence of tariff barriers, the US market represents an excellent export market opportunity due to US Energy Independence and Security Act of 2007 (EISA) requirements.

In common with other gasification processes, the FT process generates waste heat as a by-product of cooling the syngas from the gasifier. The FT catalysis reactions are also strongly exothermic and additional heat is produced during the conversion to FT liquids. Based on balances provided by Steynberg and Dry for coal to FT fluids technology, surplus electricity of between 2.4 and 2.9 MWh/t primary FT fluids might be produced from a gasification/FT process plant. This option is seldom discussed in reviews of processes designed to convert biomass to FT fluids, but offers an opportunity that should be explored further.

Using different catalytic technology, the Swedish firm Chemrec is proposing the production of methanol and DME synthesized from syngas. DME is a gas at room temperature, with properties similar to propane. It turns liquid with mild pressurization, and can serve as a fuel for vehicles where the refuelling infrastructure exists, and where modified vehicles are available. As with natural gas or hydrogen, extensive use of DME in transportation is unlikely unless the infrastructure is built; a fungible fuel such as a synthetic diesel will gain widespread use faster.

Fast pyrolysis also affords the means to convert biomass into liquid transportation fuels. Envergent, a joint venture of Ensyn and UOP-Honeywell was formed to develop the technology necessary to modify raw pyrolysis oil and make it suitable for direct injection into a gasoline refinery as a crude oil substitute; much like FT fluids.

2.3.3 Process design and operating costs

Gasification of coal and natural gas, followed by conversion to FT fluids is well established technology. Operating and capital costs are both high. Typically, these plants are located at the site of stranded assets that cannot readily be taken to market in their existing form, although Eastman operates some large coal to FT fluids' reactors in the US as part of a large chemical processing complex. No commercial biomass-based FT conversion facilities are currently in operation, although Choren has built a 15 ML demonstration plant in Freiberg, Germany that began operation in 2008. A consortium including Neste Oil and Stora Enso has built a pilot facility adjacent to the Stora Enso pulp mill in Varkaus, Finland

DME and methanol are both produced from catalytic conversion of syngas, but not via the FT process. Selectivity and process costs are said to be cheaper, but there are no operating commercial plants from which to draw experience. The Chemrec technology involves pressurized gasification of black liquor from pulp mills to produce the syngas, but there is no reason that conventional gasification of biomass could not also make a suitable syngas for conversion to DME or methanol.

2.3.4 Market volumes and revenue

The North American targets for the use of renewable fuel are ambitious. The US EISA requires the use of 36 billion gallons of renewable bio-fuels by 2022, of which 21 billion gallons must come from non-corn or starch feedstocks. More than 1 billion gallons of bio-diesel must be included in this mix by 2010, and in increasing amounts in subsequent years. In Canada, the RFS calls for renewable content of diesel fuel to be at least 2% by the end of 2011. A large market opportunity therefore lies in the production of FT diesel and other fungible fuels from biomass.

In 2009, net sales of low-sulfur diesel fuel in Canada amounted to 23 BL and total diesel sales came to more than 26 ML [Statistics Canada]. As shown in Table 7, use of harvest residuals could satisfy the entire renewable diesel content in the Canadian RFS. In fact, nearly all of the total diesel fuel consumption in Canada could be filled from forest biomass, although it would take most of the AAC.

Table 7. Percent of AAC and 2009 Harvest Volumes Needed to Satisfy RFS for Diesel fuel (based on FT Diesel)

	Diesel Sales 5-yr Avg, ML	RFS (2%) on 5-yr Avg, ML	odt needed	% AAC	% potential forest residuals	% 2009 Harvest	% 2009 Harvest Residuals
BC	3,382	68	287,787	1	4	1	5
AB	6,407	128	545,285	6	30	7	33
SK	2,061	41	175,418	6	29	18	91
MB	1,072	21	91,222	2	12	11	57
ON	6,929	139	589,717	5	23	10	50
QC	4,422	88	376,322	2	9	3	16
Atlantic	2,333	47	198,587	3	13	3	15
Arctic	327	7	27,843				
Canada	26,933	539	2,292,180	2	12	5	26

Notes: Assumes FT Diesel yield of: 235 L/odt

2.3.5 Return on capital employed

A 180 ML/y plant would require an investment of $403M and 670,000 odt/y of wood (Table 8). As with coal-based FT, small fractions of the primary FT fluids can also be converted to other high-value products and these may significantly increase revenue. Revenue would be $148M/y from FT diesel and $19M/y in naphtha and other value-added products for a total of $167M/y. Annual operating costs, other than wood, are estimated at $64M. The original Bio-pathways model for a medium-sized FT plant had a slightly negative ROCE, but with the value-added products, the ROCE improves to 3.9%. More intriguingly, adding electricity sales converts an EBITDA of $18M to a gain of $62M, This gives a ROCE of 15%, which again illustrates the importance of co-products. There is considerable uncertainty in the estimates for capital and operating costs for a medium-scale FT fluids plant, since no real operating experience has been gained to date. Biomass pricing for this scenario has been assumed to be for roadside residue, but the plant size is such that sufficient roadside residue is unlikely to be available within a reasonable transportation distance. Paying pulpwood prices for the biomass would reduce the ROCE considerably.

2.3.6 Conclusion

As with ethanol, the economics of fuel from gasification and FT processes are dependent on very narrow margins and large volumes. The yields, operating costs and capital costs still need to be evaluated in pilot and demonstration scale units, and could easily be less favourable than the numbers used here. The cost of biomass remains a huge component of estimated operating costs; using low-cost residues may not be possible, given that the medium-size FT plant is roughly equivalent to a medium-sized NSBK mill. Using low-cost residuals also implies the existence of a healthy, high-value industry to generate those residues from wood which will cost, in the case of conventional feedstocks such as northern softwood species, at least $100/odt delivered. Conversion of all available forestry resources is sufficient to replace all diesel use in Canada, but leaves none of the resource available for other users.

Table 8. ROCE of a FT diesel plant (original Bio-pathways assessment did not include revenues for naphtha and other value-added products; ROCE was -1%).

Capex	$403,000,000	
Sales		
Syn-Diesel, 180 ML @$0.80/L	$148,000,000	
Naphtha, 0.195 L/L syn diesel and $0.55/L	19,300,000	
Net Sales		$166,900,000
Operating costs		
Wood, 670 kt/y @ $76/t	$58,200,000	
Other	$72,260,000	
Total Cash Operating Cost		$130,500,000
EBITDA		$36,400,000
Depreciation	20 years	$20,160,000
EBIT		$16,270,000
Tax rate	30%	$4,800,000
Net income		$11,400,000
Maintenance	2%	$8,000,000
Accounts receivable DSO	35 days	$14,000,000
Accounts payable DPO	45 days	-$16,000,000
Inventory	17 turns	$7,700,000
Capital employed		$417,000,000
ROCE		3.9%

2.4 Energy products: Conclusion

Energy products from wood in Canada must inevitably face the high cost of wood collection and delivery. As scale increases, operating and capital cost per unit of output decline, but feedstock costs climb rapidly. The optimum scale is arguably in the 1 GW range for most scenarios, compared with coal-fired generating stations or petroleum refineries where a 10 GW plant is typical. (A 1 GW wood-supplied plant consumes about 1.7 Modt/y.) Several approaches may serve to improve the economics of stand-alone energy plants (whether they generate heat and power, or transportation fuels).

Use of residues or other low-cost feed is the first area to be explored. Forestry residues are of two types; those left in the forest, which are likely to be as expensive to collect as merchantable timber, and those remaining after primary transformation. This second type of residue may be less expensive, depending on what commercial arrangements can be made with the facility generating them, but only when the primary transformation step has earned a large revenue stream to compensate. Also, the volume will be relatively small, so that wholesale replacement of existing energy systems based only on low-cost residues is unlikely.

Other residues, such as agricultural residues, dedicated plantation crops, fast growing woody biomass or the renewable portion of municipal waste streams should be looked at on a case-by-case basis. As with forestry, such biomass is local (and may be seasonal); delivery logistics and distances are critical parts of this new supply chain, and are outside the scope of this document.

Given the impact of scale and collection costs, and the relatively low cost of fossil fuels in the uncertain context around carbon taxes or incentives, it seems that there are two possible pathways forward:

- At small scales it is critical to identify and aggressively pursue low-volume, high-value co-products. Residues from these operations can be converted to energy products, which are not likely to be economic in the absence of high-value co-products. (The exception is energy for internal use which represents a stable and predictable supply.) Identifying local users of heat may be a limiting factor on the potential efficiencies.
- At larger scales, which become possible if relative power and transportation fuel costs increase, it may become reasonable to consider stand-alone energy or fuel systems where scale is only limited by collection costs, not by market size. Here again the low local demand for heat in remote forestry towns is likely to be a limiting factor on efficiencies. The opportunity exists to move to a higher level of bio-fuels usage, which can contribute to reducing Canada's greenhouse gas emissions, particularly in jurisdictions with a higher proportion of fossil-based energy consumption. However, it is clear that high levels of substitution for fossil fuels will require large portions of the annual allowable cut, and possibly significant levels of forest residue harvesting. Government policies and support to minimize the gap between production costs of bio-energy and fossil fuel-based energy will be necessary to encourage investment for large-scale production.

2.5 Lignin-based products

2.5.1 Feedstock

Lignin will be a by-product of many of the processes described so far. Cellulosic ethanol production based on fermentation pathways will generate a lignin stream, and if ethanol from this process ever becomes a large-scale commercial reality, there will be huge quantities of lignin to dispose of. As well, existing chemical pulping processes remove lignin to liberate the cellulose for sale. At this point, most lignin is burned to generate heat and power; additionally, in chemical pulp mills, the heat liberated serves to drive chemical reactions that recover fresh cooking liquors from spent liquors. This use extends well beyond simply generating energy, and is a critical part of the process of separating cellulose from lignin. That being said, the calorific value of the so-called black liquor, containing lignin and spent cooking liquors, often exceeds the calorific value required to drive this recovery reaction by a substantial margin, so that a portion of the lignin can safely be removed without impacting the ability of the mill to recover cooking liquors. This is particularly true of softwood pulping processes; hardwood pulping generates less lignin and the liquor thus has a lower calorific value. (Other mill impacts of lignin extraction are not insignificant and need to be addressed on a case-by-case basis.)

Lignin is a complex, aromatic polymer. Its basic structure is relatively similar across northern softwood species; hardwood lignin and agricultural lignin are each somewhat different from softwood lignin. The building block of softwood lignin is primarily coniferyl alcohol whereas hardwood lignin is composed of equal proportions of coniferyl and synapyl alcohols. The additional methoxy groups on the aromatic rings of synapyl alcohols prevent the formation of certain linkages (e.g., 5-5 or dibenzodioxocin linkages) which results in hardwood lignins being more linear (less branched) in structure compared to softwood lignins. Beyond the species-dependency, the properties of lignin will depend to a very large degree on the process used to produce it. This in turn depends on the purpose of the process and, ultimately, on the proposed end-use of the cellulose and lignin streams. A wide range of properties are potentially available and are being mapped as a function of extraction process, added transformation steps and desired end-use. Lignin properties, characterization and end-use remain active research fields, and much remains to be learned.

2.5.2 Products

2.5.2.1 Substitute for carbon black

Carbon black is currently used as an additive in almost all rubber products, most importantly rubber tires for trucks and cars. Carbon black provides the wear and abrasion resistance and tensile strength of the tire. Carbon black is produced from the incomplete combustion of heavy aromatic hydrocarbons. Lignin has been tried in tires in the past as a partial substitute for carbon black. In North America there are only 6 manufactures of carbon black, as shown in Figure 7.

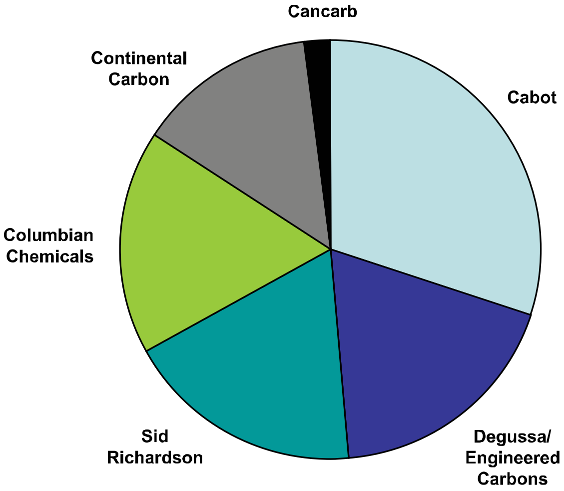


Figure 7. North American Carbon Black Capacity by Company, 2006. Source: Freedonia 2007.

Tires account for nearly 70% of all carbon black demand. The recession of 2008/9 significantly reduced tire demand and thus carbon black demand. As the economy recovers, demand for carbon black is expected to return to 2006/7 levels. As the carbon black industry is very concentrated it is difficult to determine transaction prices, although Columbian Chemical publishes their list prices monthly as shown in Table 9.

While published list prices are in the $2,200/t to $3,200/t range, representatives of one major tire manufacturer, which benefits from large purchasing leverage, have revealed verbally that transaction prices of US$1200/t are common for certain grades while a small rubber compounder revealed prices of the order of $2200/t. It is possible that the difference reflects volume discounts available to the tire manufacturer. Further market research is needed to confirm carbon black transaction prices. If transaction prices of $1200/t are common, production costs could be $1000/t or less, and the forest sector may need to be prepared to undersell a competitor with production costs in this range.

Table 9. Rubber carbon black list prices, Columbian Chemicals, January 2009, US$ FOB plant.

Grade	US$/metric tonne
N-121	$3262
N-326	$2310
N-550	$2288
N-650	$2239
N-762	$2206

Clearly a robust market strategy for building a substitute for carbon black will be needed. More information will be needed about the ability of carbon black producers to lower prices, and other tactics they may be able to employ in the face of a new competitor.

Technical challenges also remain. Initial results with rubber compounders are promising, and the potential for a profitable business in the $750 to $1000/t range is encouraging. The tire market, at just over 1Mt/y, could easily take all the lignin from all recovery-limited kraft pulp mills in North America, although this application is more demanding than non-tire uses; rubber users who do not face regulatory issues around tire safety may be able to move more quickly in generating demand although at a smaller scale.

2.5.2.2 Substitute for phenol formaldehyde resins

The phenolic nature of lignin has led to its use as a resin for gluing wood-based laminates, such as kitchen countertops and other decorative applications. This process was in place from the 1940's until at least the 1970's in one Canadian mill, but was discontinued as petroleum-based resins became more affordable. These petroleum-based phenol-formaldehyde resins, and more recently isocyanate resins, have replaced lignin in this application and have benefitted from several decades of continuous product improvement. Current research has shown that lignin should be able to replace as much as 50% of the phenol in phenol-formaldehyde resins in the manufacture of plywood, and perhaps 30% in other types of composite wood panels with no major changes in strength properties; further process and product improvement should improve these figures further. In the light of decisions in several US states to limit or ban the use of formaldehyde in resins for home building, this is potentially an interesting market.

As well, less formaldehyde is needed in the resin when lignin replaces the phenol component, thus providing an added savings. Lower use of formaldehyde in the manufacture of PF resins might also provide additional advantages in relation to reduced formaldehyde emissions at PF resin plants, wood product plants and in the market place. Table 10 shows the reduction in formaldehyde consumption in phenol formaldehyde resin manufacture at various levels of phenol substitution by lignin.

Table 10. Lignin substitution rates and corresponding formaldehyde reduction in panels.

Substitution of phenol by lignin	Reduction of formaldehyde consumption
0%	0%
25%	8.3%
40%	14.5%

Replacing 40% of the phenol with lignin reduces the formaldehyde requirement by 14.5%. In the recent past phenol prices have been between US$1,000 and $1,200 per tonne. Formaldehyde prices have been between US$500 and $700 per tonne. By replacing the phenol and saving up to 14.5% of the formaldehyde, lignin could offer considerable value in this segment.

Phenol formaldehyde resins are primarily used in structural engineered wood products such as plywood, oriented strandboard (OSB), laminated veneer lumber (LVL) and Glulam beams. They are also used in general bonding adhesives and molding compounds. Demand for phenol formaldehyde resins by segment is shown in Table 11.

Phenol formaldehyde adhesives are typically 50% solids content, and of the solids, 50% is phenol. Thus the total phenol volume consumed in the wood panel phenol formaldehyde adhesive market is between 325,000 and 350,000 tonnes. If lignin replaces 30% of the phenol this would equate to between 97,500 and 105,000 tonnes of lignin per year. There are also opportunities to replace resins in other applications, such as foundry resins, adhesives in fibreglass insulation material, binders for the stabilization of soil during oil drilling and as a binder in brake pads and other automotive products. Improved thermal stability, anti-oxidant properties, insulation properties and/or shelf life are among the advantages that might be available.

Table 11. North American phenolic resin markets (tonnes). Source: Freedonia 2002.

	1992	1996	2001	2006	2011
Wood panels	959,545	1,149,091	1,236,636	1,302,273	1,409,091
General bonding	379,091	481,818	565,909	590,909	640,909
Molding compound & other	100,455	109,091	116,818	129,545	145,455
Total	1,439,091	1,740,000	1,921,364	2,022,727	2,195,455

2.5.2.3 Lignin as a feed to carbon fibre production processes

Patents exist pointing to the potential to convert lignin into a feedstock for carbon fibres as a replacement for polyacrilonitrile. Carbon fibre demand is limited by high prices. Automakers would gladly use more if the price were lower, and lignin has the potential to do this while still providing new revenue streams for the forestry sector. However, while resin applications are likely to be marketable in 1 to 2 years, substantial lignin use in the manufacture of carbon fibre may be 5 to 10 years off.

Carbon fibre is used in aerospace and automotive applications where its low weight is a critical characteristic. Production rates are low as costs are high; the market demand for a lower cost material is large. Wide deployment of a natural substitute for polyacrylonitrile in this application would both reduce the carbon footprint of the production process and improve the fuel economy of the vehicles in which it is used.

According to researchers funded by the US Department of Energy, annual production of carbon fibre today is of the order of 50,000 tonnes, at a typical production cost of about $9.50/lb. Of this, the cost of the raw material, polyacrylonitrile, represents about $5.00/lb ($11,000/t).

Among the larger users, Boeing will require 35 tonnes for each 787 Dreamliner, and Airbus will require similar amounts for each A380. Automotive manufacturers currently use small amounts in very high-end automobiles but would use much more in lower-cost vehicles if prices were competitive with aluminum. This threshold has been identified as $4 to $5/lb, meaning the raw material would need to be below $2.00/lb. Given the expected yield of carbon fibre from lignin, this represents lignin prices below $1.00/lb, or $2200/t. At these prices, volumes would be significantly higher than today's production costs permit; 50 kg/vehicle in 500,000 luxury vehicles means 25,000 t/y additional production, while 25 kg/vehicle in 6 million economy vehicles means 150,000 t/y. (Annual global automobile production is 64 million units, and the average conventional fibre-reinforced composite content is about 10 kg/vehicle.)

2.5.3 Process design and operating costs

In the kraft mill, lignin extraction processes require a reaction vessel and a filter of some type. Typical quoted capital costs for a 50 t/d lignin plant range from $15M to $25M, depending on mill configuration; prior to installation, time must also be spent modeling the mill to identify other process-related issues and mill impacts arising from the removal of lignin. Operating costs have been estimated at $200 to $250 per tonne of lignin, mainly due to chemical consumption; it is likely that process integration activities once the first pilot mill becomes operational will reduce this number.

In mills where the recovery boiler limits the total amount of wood that can be processed, there will be additional potential to generate added pulp production by unloading the recovery boiler. By processing more wood, more lignin is generated and this can only be handled if some is diverted from the recovery boiler. The economic benefits can then be larger if there are no added production bottlenecks immediately behind the recovery boiler, and if the mill is in a position to sell the added pulp. Theoretically, each tonne of lignin removed leads to an additional tonne of pulp production, but this will be site-specific.

2.5.4 Market volumes and revenue

Market volumes are likely to be less important than feedstock volumes. The typical 1000 t/d Canadian softwood kraft pulp mill can theoretically remove 150 t/d of lignin before the calorific value of the black liquor drops too far to drive the chemical recovery reaction, but a more realistic upper limit is likely to be 50 to 100 t/d before other production bottlenecks arise, or chemical imbalances in the mill require large purchases of make-up caustic or acid. With total Canadian softwood pulp production of about 10 million tonnes, total annual available lignin might not be much higher than 500,000 tonnes. Hardwood mills generate less excess lignin and their suitability for lignin extraction would need to be evaluated on a case-by-case basis. The availability of lignin from potential agricultural-based ethanol plants is unknown and is beyond the scope of this report.

At a calorific value of 28 GJ/t, lignin contains most of the energy content of wood. However, at $6/GJ for natural gas at the mill gate, the heat value is only $168/t, well below the operating costs to extract this lignin. (Comparing with oil at $75/bbl, the calorific value of lignin is higher at $350/t.)

Phenol today sell for $0.55/lb, or about $1200/t. Sales of lignin-based resins at $750/t would cover operating costs and split the remaining difference between lignin producer and resin manufacturer. This figure also corresponds roughly with estimates of necessary lignin prices for widespread adoption of carbon fibre in the automotive industry. Added revenue for a 1000 t/d kraft mill selling 50 t/d of lignin-based products at an average of $750/t would be $13M/y. Added pulp production of 50 t/d, assuming that the recovery boiler is a production bottleneck and that no other bottlenecks exist to prevent this added production, would generate added revenue of $12M/y at historical kraft pulp prices of about $650/t. Assuming the net benefit to the mill is a more conservative $100/t of additional pulp production, the net revenue due to pulp production are $1.7M/y.

2.5.5 Return on capital employed

Analysis of one Canadian softwood kraft mill showed that extracting 50 t/d of lignin would provide an additional 50 t/d of pulp production through debottlenecking of the recovery boiler. The revenue stream in this case (which is likely to be repeated in the majority of Canadian pulp mills) thus consists of added pulp sales as well as lignin sales. These assumptions haven't been modeled in Bio-pathways, but Table 12 shows just the economic analysis associated with the add-on lignin plant. Lignin sales were assumed to be $750/t and operating costs were estimated to be $250/t lignin produced. Under these conditions, the corresponding ROCE is 44%.

Table 12. Preliminary financial analysis of an add-on 50 t/d lignin plant to an existing kraft mill. Not included in Bio-pathways I; assumes $250/t operating costs.

ROCE, add-on lignin plant		
Capex	$20,000,000	
Sales		
Lignin, 50 t/d at an avg $750/t	$13,310,000	
Pulp, 50 t/d at $100/t marginal	$1,750,000	
Net Sales		$15,060,000
Operating costs		
Total Cash Operating Cost	$4,440,000	$4,440,000
EBITDA		$10,620,000
Depreciation	20 years	$1,000,000
EBIT		$9,620,000
Tax rate	30%	$2,890,000
Net income		$6,730,000
Maintenance	2%	$400,000
Accounts receivable DSO	35 days	$1,400,000
Accounts payable DPO	45 days	-$550,000
Inventory	17 turns	$270,000
Capital employed		$21,550,000
ROCE		44%

At least initially, the market for lignin at $750/t may not exist, and in the early years lignin sales are likely to be dominated by fuel substitution. The ongoing historically low prices for natural gas in

North America make this a losing proposition, as the value of lignin on a straight energy substitution basis is $168/t, less than the estimated production costs of $250/t. It is likely that the first plant will experience slow growth in value-added markets as customers are developed, while subsequent plants will benefit from ground-breaking market development and will have access to value-added markets from startup. For this reason, government support for a portion of the capital costs of the first plant would be helpful in reducing the risk.

2.5.6 Conclusion

Lignin extraction and reuse has been, and can easily once again become a valuable method of generating added revenue in the context of a functioning softwood kraft pulp mill. Old product lines need to be revived, and new ones devised, but the capital and operating costs do not appear excessive given likely revenue. The economics are much improved where the mill can take advantage of potential added pulp production, and where the lignin can be directed to value-added markets – replacing natural gas at current North American prices is not economically sensible except as a stop-gap measure. Table 13 illustrates the total potential market volumes.

Table 13. Potential market volumes for a range of lignin products.

	Current market size, Mt	Potential revenue to the forestry sector, $/t	Total market volume at 10% penetration, kt	Revenue at 10% penetration, $M
Carbon black	1.4	$1000	140	$140
PF resins	2.2	$750	220	$165
Carbon fibre	0.1	$1500	10	$15

2.6 Sugar-based platforms

2.6.1 Feedstock

Apart from sugars generated from cellulose as described above, sugars can be extracted from the third component of wood, which is hemicellulose. Generally in papermaking applications, hemicellulose is welcome as a glue helping to bind fibres together and make a stronger sheet. Hemicellulose can be removed prior to pulping, but the cellulose stream that arises is generally of poor quality and does not make a reasonably strong sheet of paper. Hemicellulose extraction therefore makes sense where the cellulose and lignin streams are not destined for papermaking applications, and in fact is necessary in the production of viscose-grade or dissolving pulps where cellulose content levels of 96%+ are necessary.

In the production of dissolving grades of pulp using a kraft pulping process, hemicellulose extraction processes are usually installed prior to pulping. The resulting stream will in all cases be a fairly dilute mix of sugars of various kinds, as well as chemicals such as acetic acid or furfural. The chemistry can be fine tuned to shift the chemical content of the material removed, for instance to produce more furfural and less sugars, or to shift the balance between monomeric and oligomeric sugars, but in all cases the stream remains a dilute mixture. Separations and dewatering technologies will therefore be necessary to generate relatively pure streams.

2.6.2 Products

Fermentation to ethanol is a potential pathway, especially if the hemicellulose is from a softwood supply and is rich in six-carbon sugars such as glucose. (Fermentation to ethanol still doesn't work very well with the pentose sugars removed from hardwoods.) However, the volumes will be relatively small, and the capital cost per litre for the fermentation plant and distillation equipment will be high. While it is possible to produce industrial grades of ethanol at a higher selling price than fuel-grade ethanol, these markets are relatively small and are dominated, in North America, by a small number of existing players. In the case of low volumes, or in the case of hardwood supplies, it is better to look for chemical pathways unless there are other reasons for making ethanol.

A dozen such sugar-based platforms were analyzed in detail by the US Department of Energy in 2004, and each has its pros and cons. There is no space here to revisit each of these, but xylitol, furfural, levulinic acid, succinic acid, glycerol and butanol are among the products that are proposed from hemicellulose. In particular, butanol is a fermentation product that may be more valuable than ethanol, and where the biology is more tolerant of 5-carbon sugars; this pathway needs better evaluation. As with other pathways, it is important to ensure that the revenue and margins per tonne of product reflect the cost of the biomass.

2.6.3 Process design and operating costs

A common process for removing hemicellulose from chips is the Lenzing VISCBC process, which is designed primarily to produce a viscose grade of pulp. Operating costs for this modified kraft pulping process are expected to be similar to the equivalent kraft process, with the understanding that the yield loss arising from hemicellulose extraction means fewer tonnes of production; costs per tonne may thus be 10% to 15% higher. Capital costs to convert an existing kraft mill will be very site specific, but figures in the $75M to $120M range to convert a 700 t/d kraft mill to a 600 t/d viscose mill can be expected based on recent conversions. Further capital costs will be required to extract, separate and purify saleable chemicals from the sugar stream.

Keeping the hemicellulose stream out of the recovery boiler will also lead to added pulp production in cases where the recovery boiler is a bottleneck to production. This is especially true of hemicellulose as this is the wood component with the lowest calorific value; the cost to concentrate the stream and burn it is barely offset by added steam generation. At the time of writing, added pulp production in a viscose-grade mill is far more valuable than in a conventional kraft mill, due to much higher prices; the economics will be driven by this added revenue stream.

2.6.4 Market volumes and revenue

Market volumes will be limited by availability of the material. The small number of viscose-grade pulp mills, which is driven by the small (but growing) world market for the cellulose stream, implies that total sugar availability will be low. In a typical conversion of a kraft mill producing 750 t/d of market pulp, the typical viscose-grade pulp production rate is closer to 600 t/d. This implies that the total availability of hemicellulose-based sugars is likely in the order of 42,000 t/y per mill. With only a few such mills in Canada, annual availability of sugar streams is unlikely to exceed 100,000 t. Furthermore, this stream contains a range of chemicals, all in relatively small quantities. The cost of extracting and purifying these streams means that relatively high-value markets will need to be identified. Papermaking and dissolving sulphite mills are another potential source of sugars. Because in such mills the pulping process is acidic, the sugars are not degraded to saccharinic acids as is the case at kraft pulp mills. As a result, the residual pulping liquor (called red liquor) at sulfite mills is rich in sugars. Four such mills exist in Canada from which another 100,000 t/y of sugars could be available.

World-wide, the production of dissolving pulp is in the order of 4 million tonnes. A large portion of this is from sulfite mills, where the hemicellulose in the red liquor can easily be fermented. Total availability of sugar streams from kraft dissolving pulp mills world-wide is thus in the order of 300,000 t/y.

Other potential sources of hemicellulose include fermentation-based ethanol plants with pre-hydrolysis extraction stages. This implies that the ethanol production costs are reasonable and that the ethanol plant is profitable on its own, since the sugar stream extracted in the pre-hydrolysis stage will be relatively small.

2.6.4.1 Furfural

Furfural is an example of a product that can be extracted from hardwood hemicellulose streams. The primary source of furfural today is a wide range of agricultural residues.

Currently priced at $1500 to $1800/t in North America, most production is Chinese and cash costs of production, including transportation to a West Coast port, are said to be in the order of $700 to $800/t. It will be necessary to be able to sustain sales prices below this level for extended periods to remain competitive. World furfural volumes were 365,000 t/y in 2007, of which 272,000 was Chinese; there are no North American producers today, most having been driven out of business by aggressive Chinese pricing tactics.

The furfural yield from hardwood hemicellulose streams is likely to be low. A 600 t/d viscose mill can produce up to 14,000 t/y of furfural. Total Canadian production potential is thus no more than 35,000 t or 10% of the world market. Value of this market, at $1800/t, is $63M; at a more realistic $900/t it is $31M spread over a small number of mills. The implication is that, while valuable, this will remain a side-product, with viscose pulp representing approximately $630M/y in revenue for the same mills. (The added benefit of increased production in the case of a mill where production is limited by the recovery boiler would be in addition to this calculation, and would be site-specific.)

North American demand has been steady at about 20,000 t/y since 2004, although it has been as high as 45,000 t/y in the past. The decline is due to a drop in North American demand for several products made from furfural, such as tetra-hydro-furan and furfuryl alcohol. (Demand for these has grown in Asia as manufacturing processes using these feedstocks have shifted there.) However, the demand for furfural as a feedstock to make furfuryl alcohol in foundry resins and other applications remains steady at about 13,000 t/y, and North American producers would appreciate a more stable pricing and supply arrangement than is currently available from the more volatile Chinese supply. (It is also possible that some foundry resin manufacturers are buying furfuryl alcohol directly from other sources, thus increasing the potential size of this market.) A typical viscose-grade mill modeled on the Lenzing VISCBC process could supply most of this market. However, there exist a number of known pathways to products such as nylon which are not presently exploited, possibly due to concerns around Chinese pricing; at least one large chemical company expects to need significant amounts of furfural in the medium-term.

Lenzing Pulp makes 4000 t/y of furfural from beech sulphite condensate in Lenzing, Austria. This is almost half of EU production; the remainder comes from almond shells in a Spanish plant. Most Asian production is used internally and costs are low; Chinese producers face anti-dumping tariffs in the EU and US. There is no realistic export market at this time, given the small potential volumes and potential size of the North American market.

Chinese producers remain the primary competitors, with Lenzing holding a large portion of the EU supply. Discussions with producers of foundry resins have revealed that the volatile supply and pricing characteristics of the Chinese supply are frustrating, and that a more stable arrangement with a North American producer could be interesting. Pricing will likely remain an issue. It is possible that increased demand for xylose, which is among the precursors to furfural, will limit furfural production in China, thus driving prices up.

Furfural is one of a series of potential products from hemicellulose streams from viscose plants. While potential volumes are small, so is North American demand. The product is an example of a value-added side stream which will benefit one or two mills, and it is not likely that large numbers of mills will develop this product; the purpose of the analysis presented here is to illustrate one of a large number of smaller niche markets that hold the potential to support the forest sector as it moves to a refinery-based model. Each mill that moves in this direction will need to identify a range of smaller niche products, and not all can engage in the same market.

2.6.5 Return on capital employed

The following economic analysis is hypothetical, and meant to be representative of any number of small add-on processing facilities making specialty chemicals. Assuming that an existing viscose-grade pulp mill produces 600 t/d of dissolving pulp and 120 t/d of sugars which are presently sent to evaporation and recovery for burning, and assuming that 40 t/d of a chemical such as furfural could be extracted from the sugar stream, annual revenue from chemicals at $1200/t is $17M. (Fermenting the same stream will generate 5 million litres of ethanol per year, or $3.25M/y at $0.65/L.) This amount of revenue may be overly optimistic, given likely long-term market prices for furfural. Assuming further that the mill is a converted kraft mill, and that the pulping equipment is capable of operating at a daily rate of 650 t/d of pulp production, another 50 t/d of viscose-grade pulp may also be produced. Viscose-grade pulp prices have recently reached highs of $1600/t. Mill operating costs are likely to be similar to a conventional kraft mill, so where a kraft mill can obtain a net benefit of $100/t on sales of $650/t, implying operating costs of $550/t, it is reasonable to expect that the net benefit of a new tonne of viscose-grade pulp production will be, conservatively, at least $500/t. The added pulp production thus brings in $8.75M for total benefits of $26.25M/y.

Operating costs will be dominated by energy required for concentration of the sugar-rich stream and distillation of the furfural stream from 6% to 99%+ furfural. This is a function of the content and concentration of the sugar stream, and the desired end-product; rough estimates lead to a total operating cost of about $7.1M/y. Net benefits are thus $19.2M/y.

Capital costs will include separations' and distillation equipment. Modifications to the pulp mill will be required if the mill uses the conventional Lenzing VISCBC pre-hydrolysis process, where the sugar stream is neutralized using white and black liquor, as this damages the sugar stream. Costs will thus be mill-specific. As an example, modifications to a Lenzing process in Canada have been estimated at $10M to $12M, while the necessary separations' and distillation plant for generating furfural have been estimated at $15M to $25M. Using the mid-point, a 14,000 t/y furfural plant would cost in the order of $31.5M. In this example, ROCE is 51% (see Table 14). Assuming a more reasonable $750/t for furfural generates a ROCE of about 32%.

2.6.6 Conclusion

Pathways from hemicellulose streams to novel chemicals need to be developed, as these can easily present a bottleneck in recovery boilers in viscose-grade pulp mills. The small volumes available mean that it should be possible to identify niche markets with reasonably high prices. Different mills may have to identify different pathways for their streams, due to the small volumes of some of the markets; this is at least partly offset by the low volumes available from Canadian mills. Extraction, separation and purification steps remain R&D challenges. The economics of these pathways are not as well defined as for lignin, where extensive engineering and marketing studies have identified capital and operating costs, as well as probable sales prices, to a much narrower tolerance, but preliminary estimates show that reasonable paybacks may be expected for an add-on to an existing viscose-grade pulp mill. As in the case of lignin extraction, government support for capital investments will significantly reduce the risk involved and thus promote more rapid implementation.

Table 14. Hypothetical financial analysis (not in Bio-pathways) of an add-on furfural plant to an existing hemicellulose pre-extraction stage in a dissolving pulp mill. Extraction of 1 tonne of hemicellulose is assumed to yield 1.25 additional tonnes of pulp production.

ROCE, add-on furfural plant		
Capex	$31,500,000	
Sales		
Lignin	$0	
Hemicellulose to furfural (40t/d)	$17,000,000	
Ethanol	$0	
Pulp, 50 t/d at $500/t marginal	$8,750,000	
Net Sales		$25,790,000
Operating costs		
Total Cash Operating Cost		$7,100,000
EBITDA		$18,690,000
Depreciation	20 years	$1,580,000
EBIT		$17,110,000
Tax rate	30%	$5,140,000
Net income		$11,970,000
Maintenance	2%	$630,000
Accounts receivable DSO	35 days	$2,470,000
Accounts payable DPO	45 days	-$880,000
Inventory	17 turns	$420,000
Capital employed		$34,150,000
ROCE		35%

2.7 Fibre-based products

Fibre-reinforced composites are a key component of a large range of products. The fibres are often made of glass, and this represents an opportunity to identify potential uses of wood fibre as a substitute. (Portions of this section were contributed by Yawer Khan of the Forest Products Association of Canada.)

2.7.1 Feedstock

Canadian softwood forests generate some of the best fibre in the world. Light, strong, flexible and renewable, it has a host of useful properties. There are a range of applications other than paper or construction materials where the advantages of a northern softwood fibre could be valuable:

- As a replacement for glass or other fibres in fibre-reinforced composites. The automotive industry, in particular, is very interested in this approach, since the replacement fibre would be renewable, recyclable and possibly lighter. (Other benefits remain to be proven at the R&D stage.) There are two major pathways:
  - loose fibrous material fed to various injection molding equipment with plastic pellets;
  - fibrous mats, resembling paper, serving in fibreglass sheet applications.
- As a replacement for insulating panels in building envelopes. This is addressed in the synthesis report on building materials.

The ability of the pulp and paper and fibreboard sectors to tailor fibre properties to end-user needs is very valuable. From coarse, porous, bulky sheets resembling a crude newsprint sheet (and possibly made using idled newsprint assets) to fine, strong kraft fibres and everything in between, a serious evaluation of potential products and pathways needs to be undertaken.

One major concern will be the chemical compatibility between fibre and various polymeric matrices. This is an area of active research.

2.7.2 Market volumes and revenue

Some of these markets will be small. For instance, Magna International, a Canadian automobile parts manufacturer, already makes a load floor for the rear of mini-vans and SUVs which incorporates recycled cardboard in a honeycomb composite structure. The outer layers are currently fibreglass with a polyurethane matrix. If each panel is about 1 m^2, the fibreglass mat has a basis weight of 300 g/m^2, and each panel requires two such mats (one for each side), each vehicle will require 600 grams of fibre for this application. Multiplied by Magna's estimate of 6 million minivans produced annually in North America, this is only 3600 t/y demand. However, there are many more applications for fibreglass mats; another manufacturer makes headliners and consumes another few thousand tonnes per year. Interior door panels in a typical automobile weigh 3 kg; at 4 panels per vehicle and 6 million vehicles, and with a 10% substitution by wood fibres, the total annual wood fibre demand for this application might be another 7,500 tonnes.

Potential markets exist for a forestry manufacturer willing to pursue a larger number of smaller customers than is the case today. The fibreglass market is a growing one where demand typically exceeds supply. A CAGR of 6.3%, leading to a market of US$8.4B by 2015 is expected. The current market for reinforcement applications is 4 to 5 Mt/y worldwide today, with the US market at 1.1 Mt for textile glass.

The four largest producers control 52% of the market, with Owens-Corning and PPG controlling 26%. China Fiber Glass represents 12% of world production; the volumes produced in Asia are expected to increase substantially in the near future, although Chinese producers are increasingly the target of EU anti-dumping tariffs. While only one Chinese firm appears in the top 4, Chinese production was 37% of world capacity in 2007. Automotive parts' suppliers have verbally expressed concerns around volatility of Chinese pricing, and the reduction in North American production capability, and (as with furfural) a stable North American supply might be interesting.

Worldwide, growth is expected to be high in the glass wool insulation market, while textile fibreglass demand may be limited by competition from natural fibres. In the US, textile glass is expected to grow to 1.3 Mt by 2013. Applications include reinforced plastics where improved strength and other properties will be required to move into more demanding applications. Quoted list prices are typically in the order of $0.90/lb, or $2000/t. However, the Chinese industry exported 790 kt of fibreglass in 2006, and the emergence of anti-dumping tariffs in EU jurisdictions implies that Chinese producers may be able to drop their transaction prices substantially before losing money.

Among the existing producers of composites reinforced with natural fibres is Greencore, a spin-off from University of Toronto research activities. Greencore produces pellets containing wood fibres and resin for use in interior panels for automobiles and other products. The company is currently moving to demonstration scale following initial development of their proprietary technology at the University of Toronto.

2.7.3 Return on capital employed

With a US market for textile glass of 1.3 Mt in 2013, a 10% penetration represents a relatively small tonnage compared to typical Canadian pulp and paper mills. Additional markets in the glass wool insulation market would increase this to about 3 Mt. Two potential scenarios exist for moving into this market, depending on the results of ongoing R&D work.

If fibre can be produced using existing pulp mill lines with little or no modification, small runs can be produced in a number of mills without impacting the ability of the plant to revert to conventional paper-making grades the rest of the year. The market would allow for several mills to supply a range of relatively small customers at very low capital cost. The principal capital expense would in this case be some form of flash dryer or other drying process, and (possibly) equipment to produce fibre in a form suitable for use in injection or extrusion processes.

If the ideal fibre characteristics require substantial modifications to existing pulp mill equipment, the equipment can then be used only for composite markets and will no longer be suitable for paper making grades of pulp. In this case, there is in all probability room for only a few such conversions in Canada before production reaches 10% of US demand, or 300 kt.

Table 15. Hypothetical financial analysis of a conversion from TMP to composite grades of fibre (not in Bio-pathways). Annual production is 70,000 tonnes, corresponding to a small- to mid-size TMP line. Capital costs are for illustrative purposes only; identifying the necessary changes to existing capital stock has not been done largely because the product development work is under way.

ROCE, TMP conversion to 70 kt/y fibre-to-composite plant		
Capex	$100,000,000	
Sales		
Fibreglass substitute @ $1000/t	$70,000,000	
Net Sales		$70,000,000
Operating costs		
Wood	$7,368,421	
labour (fixed + var)	$4,970,000	
Power	$3,500,000	
Heat	$1,470,000	
Other	$3,000,000	
Total Cash Operating Cost		$20,308,421
EBITDA		$49,691,579
Depreciation	20 years	$5,000,000
EBIT		$44,691,579
Tax rate	30%	$13,407,474
Net income		$31,284,105
Maintenance	2%	$2,000,000
Accounts receivable DSO	35 days	$6,712,329
Accounts payable DPO	45 days	-$2,503,778
Inventory	17 turns	$1,194,613
Capital employed		$107,403,164
ROCE		41.61%

This case is illustrated in Table 15, with highly hypothetical estimates for capital conversion costs to an existing, fully depreciated mill. Here an existing 200 t/d TMP plant is converted to produce 70,000 t/y of fibreglass substitute, which sells for $1000/t at the plant gate. Wood is assumed to cost $100/t, with a 95% yield to useable fibre. Power in the TMP plant is assumed to be 800 kWh/t, implying only the primary refiner is required; total power required is 1000 kWh/t at $0.05/kWh. Heat for drying is assumed to require 3.5 GJ/t, supplied by natural gas in a flash dryer at $6/GJ. (It is possible that some of this drying energy may be provided by waste refiner heat.) Labour and other costs are assumed equal to energy costs, a good approximation in existing TMP plants where wood, labour and energy costs are relatively similar in scale. The big unknown is capital cost; assuming a very high capital cost of $100M, ROCE is still a respectable 42%, and lower capex requirements will only improve this figure. Proper due diligence, following appropriate product development at the R&D scale in partnership with end-users is warranted.

2.7.4 Conclusion

The market for fibreglass is small compared to potential volumes available from Canadian pulp mill assets, and the number of wood fibre suppliers to a natural fibre composite market will be small if conventional pulping lines in the order of 200 t/d are converted. However, the revenue can be interesting and the capital required may be low; proper due diligence is required to evaluate and guide the ongoing R&D and product development activities. Collaboration with companies such as Greencore may be an interesting approach; partnership with end-users to properly define the required properties will be critical.

2.8 The forest biorefinery

It is so far clear that with wood delivery costs at $100/t, a range of stand-alone energy products is not economically viable unless effective oil or power prices are significantly higher, or if low-cost residues can be identified. In the first case, it is uncertain whether effective oil prices can be driven high enough to incent bio-fuels or bio-energy projects without contributing to a recession; in the second, ‘low-cost’ residues will be those generated onsite from other production processes making higher value products. These residues are not truly low-cost, as it still costs $100/t to collect and deliver them regardless of end-use, but by their availability, their poor suitability to higher-value products, and the necessity of doing something with them, they represent an opportunity to enhance the overall value of the plant. Essentially, ‘low-cost’ residues imply the existence of a high-value economically viable product line.

Current examples include diverting sawdust and bark from a sawmill to a pellet, gasification or pyrolysis plant, or generating industrial-grade ethanol from spent sulfite cooking liquors. Both are examples of the biorefinery, which is defined as an integrated site or group of sites, making a range of products from a bio-feedstock: the primary process extracts very high-value products, the secondary one a lower value product from the residues arising from the primary step, and so on until the final residue is converted to energy. The current forestry model is such a biorefinery, where the highest value products are construction materials; residues in the form of chips are converted to pulp and paper products; and residues in the form of spent cooking liquors, sawdust or bark, are converted to heat and power. Table 16 illustrates the conversion of an existing kraft mill to higher value products, in line with this structured approach to value creation.

Table 16 illustrates where the wood goes in a kraft mill, and what the revenue is for each of the streams. (The benefit due to organics to recovery is the heat and power which would otherwise have to be generated through purchased fossil fuels or from the grid.) Table 16 also illustrates a potential kraft mill biorefinery, where 2.5% of the wood is removed as a hemicellulose stream and converted to furfural, the remainder of the hemicellulose is converted to ethanol, 5% is removed and converted to lignin-based products, and 40.5% goes to the recovery system. (The remaining 5% is sewered and generates no value, as in the first case.) While the value of heat and power generated drops from $68 to $52, the revenue from new products increases to the extent that added revenue of $33 is generated for each tonne of wood consumed.

Table 16. Benefit per tonne of wood consumed

Kraft mill		Mass flow	Revenue/t	Benefit
Kraft pulp		42.0%	$750.00	$315
Organics to recovery		53.0%		
	Heat		$91.76	$49
	Power		$36.00	$19
Flow to sewer		5.0%	$0	$0
Total benefit per tonne of wood		**100.0%**		$383

Kraft mill biorefinery		Mass flow	Revenue/t	Benefit
Kraft pulp		42.0%	$750.00	$315
Furfural from hemicellulose		2.5%	$1,200.00	$30
Lignin to resins		5%	$750.00	$19
Ethanol		0.0%	$182	$0
Organics to recovery		40.5%		
	Heat		$91.76	$37
	Power		$36.00	$15
Flow to sewer		12.5%	$0	$0
Total benefit per tonne of wood		**100.0%**		$415
Added benefit				$33

Dissolving pulp biorefinery		Mass flow	Revenue/t	Benefit
Dissolving pulp		37.0%	$1,100.00	$407
Furfural from hemicellulose		2.5%	$1,200.00	$30
Lignin to resins		2.5%	$750.00	$19
Organics to recovery		45.5%		
	Heat		$91.76	$42
	Power		$36.00	$16
Flow to sewer		12.5%	$0	$0
Total benefit per tonne of wood		**100.0%**		$514
Added benefit				$131

The benefits of converting to dissolving pulp are also clear. The value of avoided energy purchases climbs to $58 as more solids are diverted to the recovery boiler, and the total benefit compared to the kraft mill case increases by $131 per tonne of wood consumed.

Table 16 also illustrates the revenue accruing from a tonne of wood consumed. While this does not include the added capital and operating costs of the biorefinery, it provides a good first approximation: if a process earns less per tonne of feed than the current mill, overall economics are likely to be poor. They will certainly be poor if the revenue is less than the cost of providing the raw feedstock.

A more detailed analysis has been completed to show the economics of such a biorefinery, in particular the return on capital employed (ROCE). Results are shown in Table 17, where the costs and benefits of each component are evaluated individually and then as an integrated whole.

Table 17. Hypothetical economics of a dissolving pulp biorefinery ($M except prices per tonne or per litre). Not in Bio-pathways.

Base case	Furfural	Lignin	Dissolving pulp	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	$33.14	$431.92
Production (tonnes, litres)	17,857	17,857	264,286		
Price per tonne, per litre	$1,200.00	$750.00	$1,100.00		
Net sales	$21.43	$13.39	$290.71	$59.06	$384.59
Operating costs	$10.47	$11.20	$105.07	$48.46	$177.35
EBITDA	$10.96	$2.19	$185.64	$10.60	$207.24
ROCE	27.69%	7.25%	49.11%	26.99%	42.98%

Pessimistic version	Furfural	Lignin	Dissolving pulp	CHP	Overall
Capital costs					
New capital spending	$37.80	$20.40	$120.00		
Existing capital stock			$264.00	$36.00	$478.20
Total capital employed	$39.42	$21.00	$400.81	$38.13	$504.47
Net sales	$17.14	$10.71	$232.57	$47.25	$307.67
Operating costs	$12.12	$12.99	$122.39	$48.46	$198.48
EBITDA	$5.03	-$2.27	$110.18	-$1.21	$109.19
ROCE	8%	-16%	22%	-8%	17%

The assumptions are the same in Tables 16 and 17. Total capital employed includes maintenance capital, inventory and accounts receivable and payable calculated using standard factors. In the base case, the overall ROCE is 43%. The pessimistic version still shows an overall ROCE of 17%. The assumption in this case is that all expenses are increased by 20%, and all revenue decreased by 20%, when compared to the base case. Furfural and pulp show a positive ROCE, and the benefits of the other streams need to be evaluated on the basis that keeping them out of the recovery boiler is likely to allow higher pulp production – redirecting 35,700 t/y of lignin to recovery instead of novel products, for instance, may reduce pulp production by up to 35,700 tonnes. The resulting loss in pulp sales of $43M/y will influence the overall profitability of the mill; this and other impacts need to be looked at on a mill-by-mill basis.

2.9 Chemicals: conclusions

Opportunities exist to move the forest sector to a range of novel value-added products. These are likely to be smaller volume markets than the traditional, multi-million tonne per year markets that pulp and paper or solid wood providers are used to, and will therefore require a new focus on market development, new product development, customer segmentation and delivery of a larger number of smaller orders than might be the case today.

While the markets are likely to be small, they are also likely to be profitable, especially where the refinery concept is adopted.

3 Conclusion

The vision stated at the beginning of this report is simple: The new Canadian forest sector will profitably transform its renewable, sustainably-managed resource into a full suite of valuable products including: novel, high-value chemicals and materials; traditional products such as pulp and paper or construction materials; and energy products such as heat, power and transportation fuels. This resurgent industry will continue to provide jobs to the population in rural and small communities across the country, while helping Canada move to a clean energy supply and reduce its carbon footprint.

The Canadian forest sector has access to a **large, sustainably managed, renewable resource** which contributes a range of green products, produced in low-carbon facilities, to the Canadian economy. However, this model is under stress as some products face structural decline while others face stiff competition from low-cost producers. The highly-integrated nature of the industry means that the decline of one sector hurts the others. New or revitalized industry segments are needed to fill these gaps in the traditional supply chain.

The Canadian forest sector is in a position to deliver even greater benefits in terms of **low-carbon products**, whether energy or materials, while improving its bottom line. In order to do so, new product lines need to be identified, to supplement and strengthen the existing sector and to generate new revenue and jobs. These products must be based on Canada's advantages, which include large volumes of certified sustainable wood harvests combined with innovative technologies and industrial know-how, along with advantages that bio-based materials have over their petroleum-based analogues. The petroleum refinery model, where 4% of the feedstock is extracted and converted to high-value products generating 42% of the benefits, should be a model for this new forest sector.

There are **new businesses, partnerships and products** to be developed: some are non-traditional; several will be represented by smaller volume niche markets, or will involve a larger number of smaller customers, than is the case today; most require more due diligence than has been done to date. The steps to a forest industry model that mimics the value-generating capabilities of the petroleum industry can be described as follows:

- Step 1: collect the feedstock
- Step 2: extract products from it generating the highest possible value
- Step 3: repeat Step 2, using any residues as the new feedstock. Repeat until all material has been transformed.

Products can include traditional and novel ones; the criteria must be to generate the greatest possible value in each step, and to commercialise the novel products and integration opportunities as quickly as possible. Generally, heat and power will be a necessary part of the mix, but only after all higher value material has been extracted. This value-driven, customer-focused approach requires a significant shift in thinking and approach. As new high-value products will need to be defined and developed, so too will new industrial partnerships and customer relationships.

There are two parallel routes to transforming the forest sector. Both lead to new, renewable, green products. (In fact it is probable that the reality will be a mixture of these two extremes, and that there will be activities that combine pieces of both.) These routes can be characterized as follows:

- a step-wise modification of existing mills and capacities towards a more diversified bio-based business model; and/or
- build green-field mills for bio-production on conventional forest industry sites or as stand-alone mills.

In one route, small-scale modifications to existing mills generate revenue from new high-value products in the short-term and demonstrate new processes leading to these products. Small market size for some products, potential for high technical risk and lack of available capital set the constraints. This approach sustains existing jobs and facilities while taking steps to demonstrate the viability of the new forest sector. This necessarily involves integration with existing sites, including existing or new CHP plants, but the focus is on pre-commercial scale demonstration plants showcasing high-value products, rather than full-scale energy or fuel plants.

In a second route, large green-field biorefineries for production of bio-fuels, bio-energy, bio-chemicals and bio-products are built. The availability of biomass, the cost of collecting it over large areas, and a lack of domestic bio-energy markets and green energy policies set the constraints.

In either case the quickest path to commercialization must be taken, as high-value, low-volume markets by definition may not have room for a lot of players. Given the urgency of the situation facing the forest sector, acceptable risk levels need to be revised if emerging markets are not to be taken by competitors.

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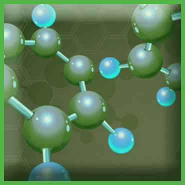

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