Forest-based bio-products: A review of potential pathways for the City of Quesnel

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Executive Summary and Update

The final draft of this report, consisting of Sections 1 through 4, was submitted to the City of Quesnel in March 2020. Much has changed since then, in particular new awareness of the urgency of climate change action within business, finance and government circles. The IEA roadmap[1] is a major driver of this shift.

This rapidly shifting landscape may offer new opportunities for forest communities and industries, including some that were not obvious 15 months ago. This Summary, written in June 2021, outlines Sections 1 through 4, which are unchanged; it also tries to provide a sense of new drivers. A new Section 5, describing next steps, is also reviewed.

Section 2 provides background that remains applicable. Key points are:

- Sustainably-harvested and well-maintained forests will play a key role moving forward. But the chemistry of wood presents challenges, and careful triaging of proposed solutions on the basis of economics is required (Section 2.4).
- Municipal governments may be small players in terms of funds available but are well placed to drive a cluster-based ecosystem that will attract funding and investors (Sections 2.5 and 3.2).
- "You can make anything with lignin, except money". This old joke is true of many wood-based components in a world of cheap oil, or if the product competes with inexpensive petroleum-based platform chemicals such as ethylene or benzene. The concept of volume versus value is outlined in Section 2.7.

Section 3 outlines opportunities for Quesnel, bearing in mind constraints around wood supply and availability of industrial partners able to mobilise significant financial resources. Sections 3.3 to 3.7 outline technology options that were considered ideal for Quesnel at the time of writing. The so-called "elevator pitches" for these five "Best Bets" are repeated verbatim here:

- Redirect existing pulp fibres to new markets: New applications for existing pulp fibres, such as textiles or fibre-reinforced composites, open the door to new markets with minimal impact on mill operations. Some processes may be suitable for co-location and utility sharing with a pulp mill. Section 3.3.
- New uses for kraft mill residual streams: The kraft mill generates a large number of residual and by-product streams which can be recovered and sold. Lignin, methanol, tall oil, turpentine and secondary sludges all have buyers. Section 3.4.
- Novel cellulose fibre streams: Novel fibre streams from cellulose are very high-value products, and two of the leading technologies worldwide are Canadian. Partnerships can open up the opportunity to participate in novel markets. Section 3.5.
- Repurposing existing mill assets: The world is moving to bio-based chemicals, in response to consumer demands. This trend is particularly strong in Europe. Early players who can convert wood to a range of petrochemical substitutes will stake out a space in this growing field. Section 3.6.
- Making better use of mixed feeds: Low-grade residual material with high bark content is best suited for fuels and energy applications which displace fossil-based fuels in mills or in regional district heating systems. Section 3.7.

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[1] International Energy Agency (2021), Net Zero by 2050, IEA, Paris. https://www.iea.org/reports/net-zero-by-2050, viewed 2021-05-20. For a summary review, see https://bio-economy-tbrowne.blogspot.com/2021/06/the-iea-roadmap-to-net-zero-critical.html, viewed 2021-06-12.

The chemistry and economics of these technologies and others are detailed in Section 4. In light of the IEA Roadmap, a range of bio-energy opportunities, also outlined in Section 4, should be added to this list of Best Bets:

- Solid fuels to displace coal in generating stations, in Alberta but especially in newer Asian generating stations;
- Liquid fuels to displace petroleum-based transportation fuels, in particular aviation fuels;
- Gaseous fuels to displace natural gas directly at the point of combustion, or for injection into pipelines.

These pathways require very high carbon pricing through carbon taxes, cap and trade or other policy levers, especially when oil is well below $100/bbl. At the time of writing Sections 3 and 4, it was not clear when or even if these conditions would exist, so fuels were not part of the original list of Best Bets. However, the contributions of biofuels of all types (solid, liquid, gas) are identified as critical by the IEA, driven by carbon pricing approaching $250/t CO_2 by 2050. At these prices, the economics of a lot of technologies suddenly become very interesting.

A recent book by Mark Jaccard points to the fact that politically, carbon taxes are a tough sell. On the basis that the best vaccine is the one in your arm, he makes the point that the best policy is the one that gets implemented. Alternatives to politically risky 'carbon taxes' (which he is careful to call 'carbon pricing') include various regulatory approaches such as the ones used in the past to deal successfully with acid rain or smog in the Los Angeles basin.

The technologies for converting wood to fuels are all well known and operate at the pilot or demonstration stage today; and while the first full-scale plant will undoubtedly encounter many expensive and unexpected challenges, the so-called n^{th} plant is likely to be both technically and economically viable. See in particular Section 4.2. So if the policy landscape provides a strong economic incentive for biofuels, then they should be back on the table.

This report has outlined biorefinery pathways that make technical sense. But industrial implementation requires additional steps. A compelling rationale for pursuing a small number of "Best Bets" needs to be developed in collaboration with industrial partners, the City, other partners such as First Nations, and provincial and federal agencies. These Best Bets need to be identified in a holistic fashion across the entire forest value chain, from harvesting through various solid wood products to the biorefinery and its pulp and paper host. The rapidly shifting climate change environment will shine new light on the challenges facing the region, and may force new ideas to the forefront. Sources include this report, parallel ones on solid wood and wood supply, and information from workshops and other activities undertaken by the City of Quesnel in the course of Future of Forestry Think Tank activities.

Corporate views on innovation and investment are critical. Gaps will need to be identified and missing information filled in, through telephone interviews with industrial leaders at a VP or CEO level, supplemented by additional information searches and personal knowledge provided by consultants in the field.

From this, a list of criteria beyond simple technology needs would be developed and used in a triage process to identify a prioritized list of "Best Bets". The competitive advantage of a Quesnel location, compared to others in BC, in Canada or world-wide, will be critical. Criteria will include, among others, current and future fibre resources, economic and social returns, environmental sustainability, technology maturity and market readiness, and fit with local conditions.

The ultimate objective would be strong interest by an investor in new products to be developed in Quesnel. Section 5.2 covers these next steps in more detail.

1. Project overview

The City of Quesnel has put in place the Future of Forestry Think Tank (FFTT) in order to provide a roadmap to diversify the forest sector in the City, and mitigate or reduce the impact of increased ecological disturbances such as drought, forest fires and insect infestation. As part of this process, the City is undertaking a high-level market analysis and business case development.

Specific questions include the following:

- Who is making wood/paper products that are in demand?
- Where are they being made?
- Is it feasible to make them in Quesnel?
- What are the gaps?

This report was commissioned to summarise opportunities for bio-products from the forest other than the existing traditional pulp or solid wood products. A parallel report addresses solid wood markets; this report is meant to cover the following:

- Introduction and background to biochemicals from wood;
- An overview of the biochemical market i.e. who is producing certain products and what are the range of products available in general;
- The types of innovative products that can be made using the processing Quesnel has available now;
- The opportunities for Quesnel to produce a high-value product (i.e. "the colour of the future" – products such as cellulose nanocrystals);
- Review of biofuels and bioenergy products.

While this report covers a wide range of products from extremely high value products to high-volume but relatively low value energy products, the focus will be on the higher value products.

Of particular interest is the local fibre supply. Most existing industrial facilities within the City process softwood (coniferous) species. Harvesting techniques are moving towards European methods to allow for easier collection of harvesting residues, and to a more managed approach to plantation woods. While these steps will free up additional resources in the form of woody debris, the BC Interior is still facing a reduction in the Annual Allowable Cut (AAC), and these new harvesting techniques may not be in place over the short term. As well, the area is home to an underutilised hardwood (deciduous) resource of uncertain volume, providing added potential material for growth of the industry if sizable volumes are available at reasonable cost.

The City is also aware of the pressing environmental issues of climate change and excess consumption of single use materials. To the greatest extent possible, this report will identify pathways consistent with good stewardship of natural resources and sustainable approaches to product development.

The City is home to West Fraser Forest Products, with multiple facilities in the City or surrounding area: WestPine MDF, Quesnel Sawmill & Planer, Quesnel Plywood, Quesnel River Pulp (QRP), and Cariboo Pulp & Paper (CPP). West Fraser has two additional facilities for plywood and lumber in Williams Lake. The broader area also includes a range of other forestry operations making solid wood products or pellets.

Section 2 describes the concept of the forest biorefinery and outlines some key drivers, constraints and characteristics. Section 3 provides a series of 2-page fact sheets outlining potential opportunities for the City of Quesnel. Section 4 delves into these opportunities and others in considerably more detail.

2. The Forest Biorefinery

2.1. Macro trends

In the last decade there has been a trend to developing wood-based fuels, chemicals and materials, and putting them into products where the incumbent is petroleum-based. The argument is that replacing petroleum is inherently a good thing; and that petroleum refineries get their steam from burning carbon-intensive, petroleum-based residuals, while pulp and paper mills largely get theirs from carbon-neutral, wood-based residuals[2].

This argument is fine as far as it goes, but there is today a large viral interest in reducing or eliminating single use products, fueled by pictures of floating plastic material in the oceans. There is a very real danger that single use products from wood, such as paper straws or shopping bags, will get caught up in this conversation.

The concept of the circular economy is very new in Canada, but it is arguably far more important in EU policy-making circles today than simply promoting bio-based products. In this context, product end-of-life will need to be considered, regardless of where the product came from. For example, there is an easy pathway to ethylene, from sugar cane via ethanol, that is championed by the Brazilian chemical producer Braskem; but in the end it is still ethylene, and if single-use packaging made from it winds up in the ocean, its biomass-based source won't matter. Recyclability, compostability or reusability will be critical to the circular economy; this requires a very long-term chain of custody approach[3] to work properly.

So while the objective of this project, which is identifying new uses of wood consistent with the context of the City of Quesnel and the broader Central Interior, is valid and useful, the broader macro trends towards eliminating single-use products more generally should not be ignored when considering longer term options.

2.2. Introduction and background to the forest biorefinery

The biorefinery writ large makes products from biomass through a series of steps aimed at extracting value from each component of that biomass. This contrasts with the petrochemical refinery, which does the same from petroleum. Specifically, the forest biorefinery is focused on raw materials from the forest, as opposed to agricultural residues, municipal solid waste streams, algae or other marine sources of biomass, etc.

The existing forest industry in Canada is, at heart, a biorefinery: softwood lumber production leads to the generation of chips and bark which are used in turn for pulp and paper, manufactured wood products such as medium density fibreboard, and bio-energy to drive the processes for making these products. Hardwood logs may go directly to pulp and paper, or via various value-added pathways such as hardwood flooring, and may include engineered wood products such as oriented strand board (OSB).

As impacts related to climate change, such as forest fires and insect infestations, affect the composition of Canadian forests, and as world markets for traditional forestry-based products shift, the portfolio of products needed to meet new demands will also shift. Pulp and paper product demand is quickly shifting away from traditional newsprint and office papers; novel building processes require more engineered wood products and less dimensional lumber. The old model of cohabitation between lumber mills and the pulp and paper sector is under threat from both ends.

The forest biorefinery takes advantage of the fact that wood is the original, natural fibre-reinforced composite. Cellulose fibres are long, slender and flexible; when embedded in a matrix of lignin (a type of phenolic resin), the

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[2] Browne, T., "Bans on single-use products: what do they mean for bioproducts?", https://bio-economy-tbrowne.blogspot.com/2019/07/bans-on-single-use-products-what-do.html, viewed 2020-02-07.
[3] Mabee, W., "Guidelines for the circular bioeconomy", BioFor International, Montreal, February 3-6, 2020.

result is a strong, tough and flexible material called wood. Finding new uses for these fibres and associated phenolic resins, as well as the hemicellulose that serves as a binder and coupling agent in trees, is a primary goal of the forest biorefinery. The competition largely comes from petroleum; the disadvantage at this point is that petrochemicals have benefited from an intensive research and development effort over the last 100 years, while R&D into the processes for transforming biomass in general, and wood in particular, have been relatively poorly funded and have only gotten underway in any serious way since the beginning of this century.

The US Department of Energy (DOE) commissioned a landmark study in 2004[4]. Completed by the National Renewable Energy Laboratory (NREL), it compared pathways to chemicals from petroleum and from biomass. Figures 1 and 2, taken from that report, are intended illustrate the complexities of the paths to market.

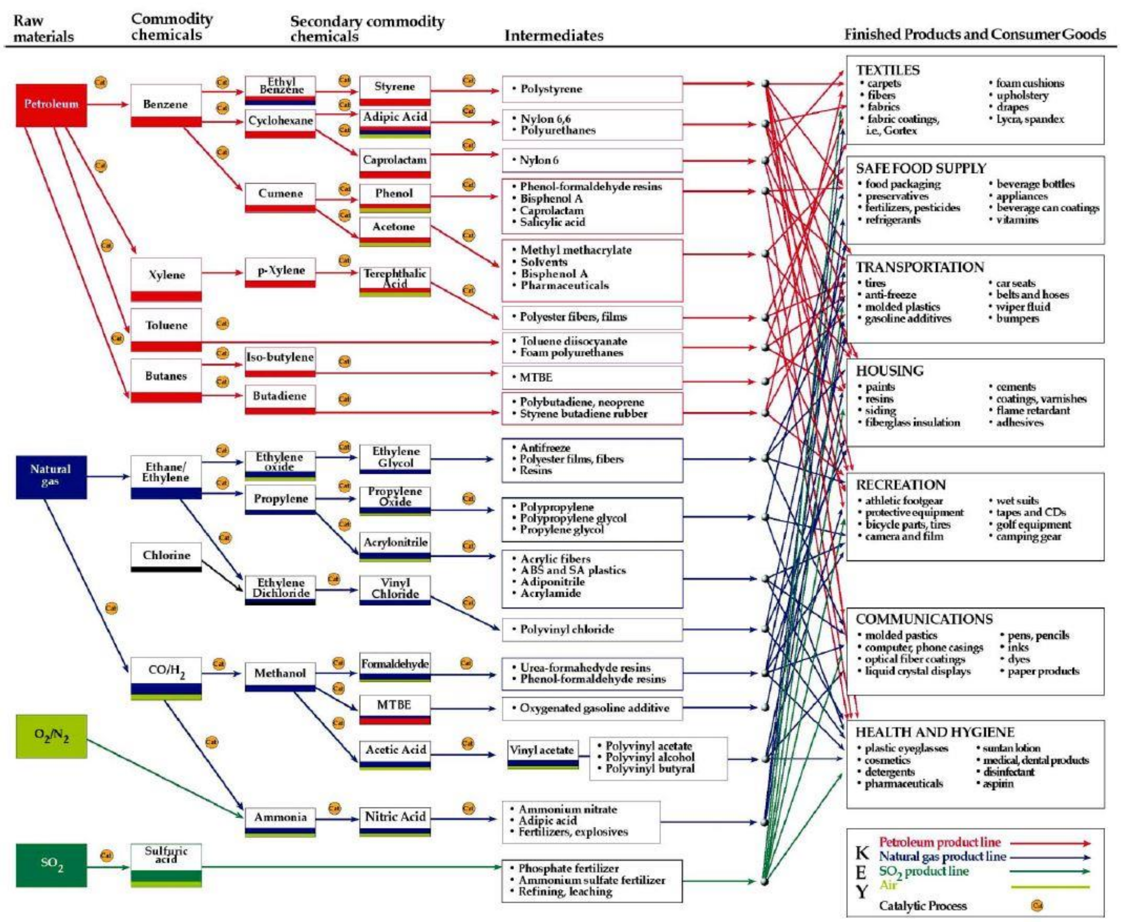

Figure 2 – An Example of a Flow-Chart for Products from Petroleum-based Feedstocks

Figure 1: 2004 DOE/NREL report, Figure 2.

[4] Werpy, T. et al., "Top Value-Added Chemicals from Biomass, Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas", PNNL, August 2004. http://www.nrel.gov/docs/fy04osti/35523.pdf, viewed 2020-01-25.

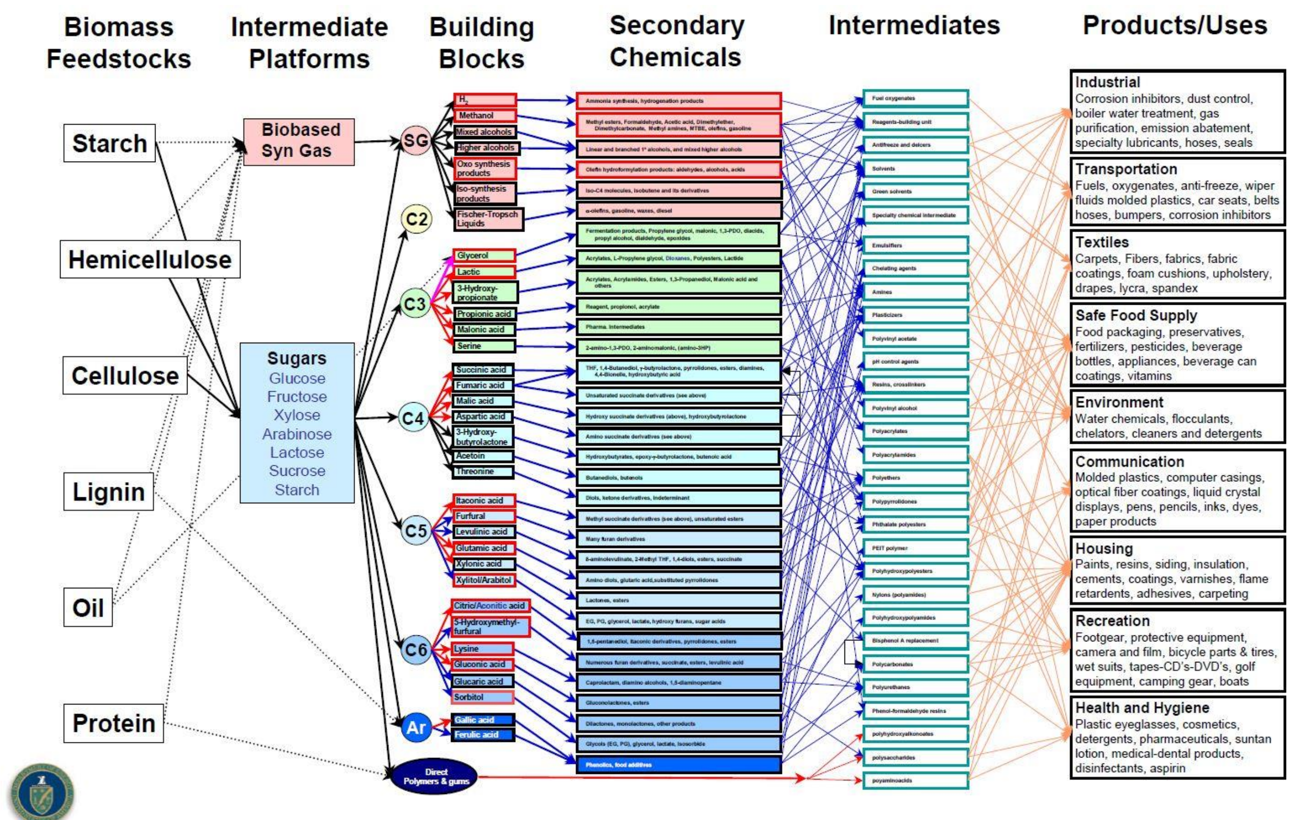

Figure 3 – Analogous Model of a Biobased Product Flow-chart for Biomass Feedstocks

Figure 2: 2004 DOE/NREL report, Figure 3. The complexity of the markets for bio-based products is enormous, leading to a very wide range of opportunities.

2.3. Government policy and the costs associated with transformation

There are significant costs associated with moving a new technology, even one currently at the commercial demonstration stage, to full commercial reality, defined as profitable operation at full capacity for significant periods of time. These costs fall under two headings.

The first challenge is building and trouble-shooting the first, or indeed the second or third commercial installation. Many unexpected challenges will arise as a full-scale plant is built. A recent presentation[5] outlined issues in starting up a cellulosic ethanol plant. Problems included bridging of feedstock in hoppers, plugged lines, deposits, erosion due to sand and silica, unexpected corrosion problems and contamination affecting biological processes, to name a few. None of these challenges had anything to do with the underlying technology, which has been in development since 1983; they had to do with material handling and metallurgy. Government support for first-of-kind plants can reduce if not eliminate the risks at the scale-up and commercial demonstration stages.

The second challenge, which is harder to quantify, is developing a market for products other than fuels. The fuel market is driven by policy initiatives such as renewable fuel standards; if a standard mandates 10% ethanol in gasoline, then there is a market for that amount of ethanol. Note that the first litre of ethanol beyond the mandate does not have a market: When gasoline consumption in the US dropped in 2009, so did the volume of ethanol

[5] Pikor, H., "Scaling up – Iogen's journey bringing cellulosic ethanol to market reality", IFBC/ISLM, Thunder Bay, ON, June 12, 2019.

necessary to meet the mandate. The result was a wave of bankruptcies of corn ethanol plants across the US Mid-West[6]. Government policies are critical for biofuels, but can easily lead to unintended consequences.

Biofuels need to meet a number of well-defined specifications. Developing new markets for higher-value products is far more complex. Product development is slow and expensive and requires substantial back and forth between producer and customer to develop a product which meets the customer's needs at a price that satisfies both parties. The role of government is also critical, but it is much less obvious how policy should be designed to promote bio-products other than fuels.

2.4. Triage tool for estimating economics

A triage tool for ranking projects, which will be used throughout this report, is shown next. This is not meant to provide investment-grade advice, but rather to serve for ranking and comparing paths on an apples-to-apples basis. It has proven useful as a red flag to review assumptions when results seem excessively rosy.

The tool, which is implemented as an Excel spreadsheet, starts with a set of standard inputs which should be used across all technologies being evaluated. The standard input sheet is shown in Figure 3. With an agreed-upon set of standard input costs, technologies can be evaluated with the standard product sheet shown in Figure 4. The objective is not exact numbers but rather comparison and ranking of various options in a what-if scenario.

Change cells in yellow only!					
Standard input data and conversion factors					
Wood, $/odt	$110.00	Caustic, per kg	$0.40	Construction cost multiplier	2.2
LP steam, $/t	$16.10	Sulfuric acid, per kg	$0.15	Total installed cost multiplier	3.2
Enthalpy, GJ/t	2.8	Enzyme, per unit	$0.35	Operating days per year	360
LP steam, $/GJ	$5.75	Acetic acid, per kg	$0.76	Depreciation, years	20
Power, $/kWh	$0.0460	Sodium acetate, per kg	$0.50	Tax rate	30%
Gas, GJ/m^3	0.038	Effluent cost per t sewered	$11.75	Inventory, days	17
Gas, $/m^3	$0.2500			Labour per $ operating costs	$0.09
Gas, $/GJ	$6.58	$US exchange	$0.75	O&M per $ operating costs	$0.15
Petroleum, $/GJ	$16.39	Lignin calorific value, GJ/t	25	Scaleup exponent, n	0.60
Additional input data and conversion factors as needed					
		Consumable 1, per kg	$0.40		
		Consumable 2, per kg	$0.15		
		Consumable 3, per kg	$0.35		
		Consumable 4, per kg	$0.76		
		Consumable 5, per kg	$0.50		
		Consumable 6, per kg	$1.10		

Figure 3: Technology triage tool, standard inputs.

[6] The author recalls being invited to a conference in the late 2000's on the topic of acquiring distressed corn ethanol assets, run by a consortium of bankruptcy trustees.

Change cells in yellow only!			
Project name	Product 1		
Scale, odt/d		500	

Economic Inputs			
Sales	**Yield on wood**	**Sale Price, $/odt**	**Annual sales, $**
Product 1	50%	$300	$27,000,000
Product 2	39%	$750	$52,650,000
Product 3	0%	$0	$0
Sewer losses	11%	**MUST BE POSITIVE**	
Total sales	**$443**	**per odt wood**	**$79,650,000**

Capital	Equipment	Installation	Total
Unit op 1	$12,500,000	$27,500,000	$40,000,000
Unit op 2	$3,650,000	$8,030,000	$11,680,000
Unit op 3	$3,200,000	$7,040,000	$10,240,000
Unit op 4	$12,500,000	$27,500,000	$40,000,000
Unit op 5	$0	$0	$0
Unit op 6	$0	$0	$0
Total capital	**$31,850,000**	**$70,070,000**	**$101,920,000**

Opex	Units per odt wood	Cost per odt wood	Cost per year
Wood, odt	1.02	$112.20	$20,196,000
LP steam, GJ/odt	5.00	$28.75	$5,175,000
Power, kWh/odt	800.00	$36.80	$6,624,000
Gas, GJ/odt	5.00	$28.75	$5,175,000
Input 1	15.00	$6.00	$1,080,000
Input 2	5.00	$0.75	$135,000
Input 3	11.00	$3.83	$689,040
Input 4	0.00	$0.00	$0
Input 5	0.00	$0.00	$0
Input 6	0.00	$0.00	$0
Sewer costs		$1.29	$232,650
Subtotal		**$218**	**$39,306,690**
Labour			$3,537,602
O&M equipment and spares			$5,896,004
Total opex			**$48,740,296**

Economic Outputs	
EBITDA	$30,909,704
Depreciation	$5,096,000
EBIT	$25,813,704
Taxes	$7,744,111
Net income	$18,069,593
Inventory	$3,761,250
Capital employed	$105,681,250
ROCE	**24.43%**
Payback, years	**5.6**
IRR	**17.73%**

Figure 4: Technology triage tool, product evaluation sheet, with economic indicators for a hypothetical Product 1.

Actual costs are typically covered by confidentiality agreements and are frequently not published. Total project value (government plus industrial investment) is often provided on government websites where a project has obtained government funding, but the true additional investment required by industry to get the process operating at capacity, and to get satisfactory products in the hands of customers at prices that are reasonable for both producer and customer, is usually higher, and usually not disclosed. However, where possible, capital and operating costs will be discussed in this report, with the caveat that these are high level estimates and need to be verified through conversations with equipment vendors and engineering firms. While the forest biorefinery remains a viable pathway forward, the challenges should not be underestimated. The rest of this report should be reviewed with this caveat in mind.

2.5. Implementing a local biorefinery eco-system: a guide for policymakers

2.5.1. Canada's Bioeconomy Strategy

Canada's Bioeconomy Strategy[7] is the result of the combined efforts of the Forest Products Association of Canada, Bioindustrial Innovation Canada (BIC), FPInnovations and BioNB. The outcome of an extensive cross-country consultation effort with industry, it has been endorsed by the Council of Forest Ministers. Readers are strongly encouraged to read this report in parallel with the present document. A key component is an account of the development of the Sarnia-Lambton Hybrid Chemical Cluster, and a similar effort in Saskatoon. Several past examples of building biorefinery eco-systems are described next, and more information is available online[8].

2.5.2. Thunder Bay: The Bio-Economy Technology Centre (BETC)

Thunder Bay served as the test bed for the LignoForce system and for continued lignin product and process development, and has become a de facto centre of excellence in the chemistry and use of wood-based lignins from wood. Key success factors included:

- Focus on a relatively narrow pathway, product or set of technologies. The product chosen was lignin;
- Support from a pulp mill (Resolute Forest Products in this case), offering space and utilities on the mill site, as an in-kind contribution, for trialling new technologies in a true industrial setting;
- Technology provider with a promising technology (in this case FPInnovations);
- Financial support from the City, the Province and the Federal government. (The contribution of the City of Thunder Bay was small but was symbolic of the willingness to provide other types of support);
- Proximity to University labs. Shared access to specialised instrumentation, a steady supply of coop and graduate students to work onsite, and close collaboration with professors is critical;
- Other infrastructure is useful: airport, hotels and restaurants, etc. for visitors.

2.5.3. Sarnia-Lambton

The BioDesign Strategy outlines the Sarnia-Lambton Hybrid Chemical Cluster as follows:

> "The Sarnia-Lambton Hybrid Chemical Cluster grew out of efforts by the community to diversify the economic base after a decline in the traditional chemical sector. The not-for-profit organization Bioindustrial Innovation Canada (BIC) was created in 2008 to act as a business and cluster accelerator for the bio-based chemical industry. The formation of BIC initiated the Hybrid Chemical Cluster (HCC) in Sarnia-Lambton. The cluster includes all businesses and organizations involved in the petrochemical, natural gas, and biohybrid chemical industries. Sarnia-Lambton chose to accelerate this industry as Lambton County contains an abundance of

[7] McLaughlin, M., et al., "Canada's Bioeconomy Strategy: Leveraging our Strengths for a Sustainable Future", May 14, 2019. https://www.bincanada.ca/biodesign, visited 2020-02-12.
[8] Budarick, D., "Key Aspects of Developing A Cluster, Case Study of Sarnia-Lambton's Hybrid Chemistry Cluster and Saskatoon's Agriculture Biotechnology Cluster", 2018. The full report is available on request at https://www.bincanada.ca/single-post/2018/01/15/Building-a-Roadmap-for-Cluster-Success, visited 2020-12-13.

> fertile farmland, as well as knowledge and experience in producing both traditional and bio-based chemicals."

A 2nd cluster initiative[9] has just been launched by BIC in partnership with regional economic development support and several municipalities in the Eastern Ontario St. Lawrence Corridor.

2.5.4. Saskatoon

The BioDesign Strategy outlines the Ag-Bio Cluster as follows:

> "Saskatoon's Agriculture Biotechnology Cluster (Ag-Bio Cluster) is one of the country's oldest clusters. The cluster was initially agriculture based but later the aspect of biotechnology emerged with the development of the oilseed crop canola. The Ag-Bio Cluster was conceptualized to accelerate Saskatoon as the hub for agriculture research. Innovation Place was built as a technology incubator to help develop early stage companies by providing facilities for research and development. Biotechnology was further supported by government organizations such as Agriculture and Agri-Food Canada and the National Research Council.
>
> The cluster initiative officially began in 1989 when the not-for-profit organization Ag-West Bio (AWB) was formed. AWB was developed to act as an accelerator for the agriculture biotechnology industry by attracting companies to the area and by providing small investments to help commercialization."

2.5.5. Bioénergie La Tuque: The BELT Project

The City of La Tuque, Québec, like Quesnel, is heavily dependent on the forest sector. BELT[10] is an independent non-profit organisation working to promote biorefinery processes in the city, with a focus on converting available forest residues available annually to biodiesel via pyrolysis[11], a thermochemical pathway described in Section 4.

2.5.6. Nova Scotia Innovation Hub

This organisation[12] serves to create and promote a low-carbon, bioresource-based economy. Partners include federal and provincial government agencies, universities, utilities and forest sector actors.

2.5.7. European clusters

The Swedish town of Örnsköldsvik is home to a cluster[13] centered on the local pulp mill. A broader overview of the Nordic approach may be found here[14]. In Holland and Belgium, the Biorizon[15] cluster is promoting biochemicals.

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[9] https://www.bincanada.ca/single-post/2020/01/22/Bioindustrial-Innovation-Canada-BIC-Continues-to-Support-Canadas-Bioeconomy, viewed 2020-03-09.
[10] Mangin, P.J. et al., "Le projet de bioraffinerie forestière de La Tuque: une première canadienne", 14 September 2016, http://www.ville.latuque.qc.ca/Document/BELT/LT-VISION2023-25-CCIHSM.pdf, visited 2020-02-12.
[11] https://www.remabec.com/fr-ca/energie-verte/pyrobiom-energies/, visited 2020-02-12. Remabec is a Quebec-based harvesting and sawmilling firm.
[12] http://novascotiainnovationhub.com/about/, viewed 2020-03-09.
[13] https://archive.nordregio.se/en/Metameny/Nordregio-News/2014/Bioeconomy-and-Regional-Economic-Development/Case/index.html, viewed 2020-02-17.
[14] Lange, L. et al., "Development of the Nordic Bioeconomy: NCM reporting: Test centers for green energy solutions – Biorefineries and business needs", Nordic Council of Ministers. TemaNord, No. 582, Vol. 2015. https://backend.orbit.dtu.dk/ws/portalfiles/portal/140639248/Development_of_the_Nordic_Bioeconomy_Lange_et_al_2016.pdf, viewed 2020-02-17.
[15] https://www.biorizon.eu/, viewed 2020-02-17.

While not tied to any one geographical area, the cluster addresses a common need and offers incubator space for qualified applicants.

2.5.8. The Sweetwoods model: the importance of partnerships

The Sweetwoods project[16], led by Granuul, an Estonian pellet producer, starts with a conversion process similar to FPInnovations' TMP-Bio process (see Section 4). The other partners are end-users, suppliers or consultants:

- The German firm Tecnaro uses lignin today for a range of niche products;
- French firm Global Bioénergies proposes a sugar to isobutene pathway, via fermentation, which would need to be proven, and claims to have customers for this substitute for petroleum-based isobutene;
- Recticell and Armacell are EU companies making foams and would presumably be interested in lignin;
- Finnish company MetGen is an enzyme provider;
- Spinverse and 2B SRL are EU-based consulting firms;
- Vertech is a French engineering firm.

2.5.9. Opportunities for Quesnel and the broader Central Interior

The Sweetwoods model could easily be applied to Quesnel with different players, e.g. West Fraser (wood supply, infrastructure), a technology provider such as FPInnovations or other, various end-users, and similar list of suppliers (enzymes, equipment suppliers, engineering). This could be repeated for each of several pathways.

Joining in a cluster with other players such as Prince George could allow the City of Quesnel to leverage its capacities and assets. The examples above show how other jurisdictions have faced a sea change in conditions affecting local industry and economic activity, and what steps were taken to address the issues. In all cases a range of funding support was needed, from all levels of government, to allow a small number of dedicated employees to focus various government funding sources on worthy projects, with selection based on an agreed-upon set of criteria. City or County employees can take a leadership role and make a difference. In Thunder Bay, the presence of an arms-length funding organisation supported by the Ontario government (CRIBE) meant that FPInnovations proposals to scale-up the LignoForce and TMP-Bio processes fell on fertile ground.

2.6. The pulp mill as a biorefinery host

The pulp mill, whether based on a kraft or mechanical process, is a likely contender for the role of biorefinery host, because it has the following assets already in place:

- Skilled staff in the areas of wood handling, wood chemistry and large-scale chemical process operations;
- Brownfield industrial site with existing building, operating and environmental permits;
- Fresh water supply;
- Effluent treatment plant;
- Steam and power island;
- Industrial-scale connections to gas and power grids;
- Wood chip and hog fuel receiving and handling systems;
- Other assorted industrial assets.

Other assets in the Quesnel area include forestry operations and feedstock supply, and a large range of supporting players. Sawmills and other solid wood facilities are also potential sites for new processes, but generally do not have all these utilities onsite, or at least not at the same scale. Of course, it is possible that the added load imposed on, for

[16] https://sweetwoods.eu/project/, viewed 2020-02-12.

instance, a pulp mill effluent treatment system by addition of a new bolt-on process may require upgrades to that system, but this will often be cheaper than building an entirely new system.

Within the pulp mill, there are several approaches for implementation of new products. One is to build a new facility onsite, based on shared utilities, but which does not interfere with the pulp mill, or depend on its continued operation. Changes to the use or purpose of the pulp mill do not impact the new facility, except to the extent that shared utilities are affected. The CelluForce plant co-located with the Domtar Windsor mill is an example: it benefits from energy, effluent treatment, staff and security, but has no impact on pulp mill operations. Another option is to use a pulp mill side-stream or by-product which would obviously be impacted if conditions changed within the mill. The lignin plant at the West Fraser mill in Hinton is an example. Finally, there is wholesale repurposing of the pulp mill or portions of it to some new process or product, such that traditional pulp products are no longer produced. Conversion of kraft pulp mills to dissolving pulp, as undertaken by Fortress Global or Aditya Birla, is an example. Each has its own set of risks and benefits.

2.7. Volume versus value

About 70% of a barrel of oil is converted to transportation fuels, but generates only about 43% of the value, Figure 5[17]. Chemicals, plastics and synthetic rubbers consume about 4% of the barrel but generate 42% of the value. (The balance is heating fuels in stationary applications, and products such as lubricants.)

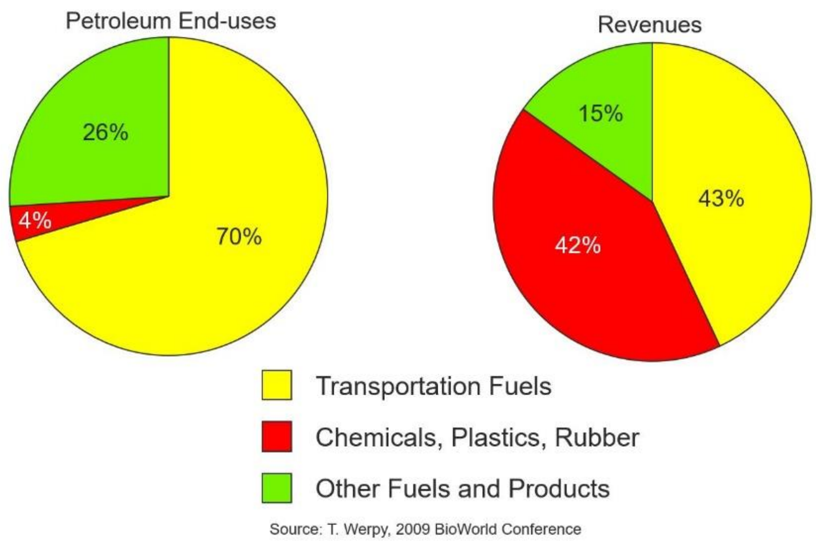
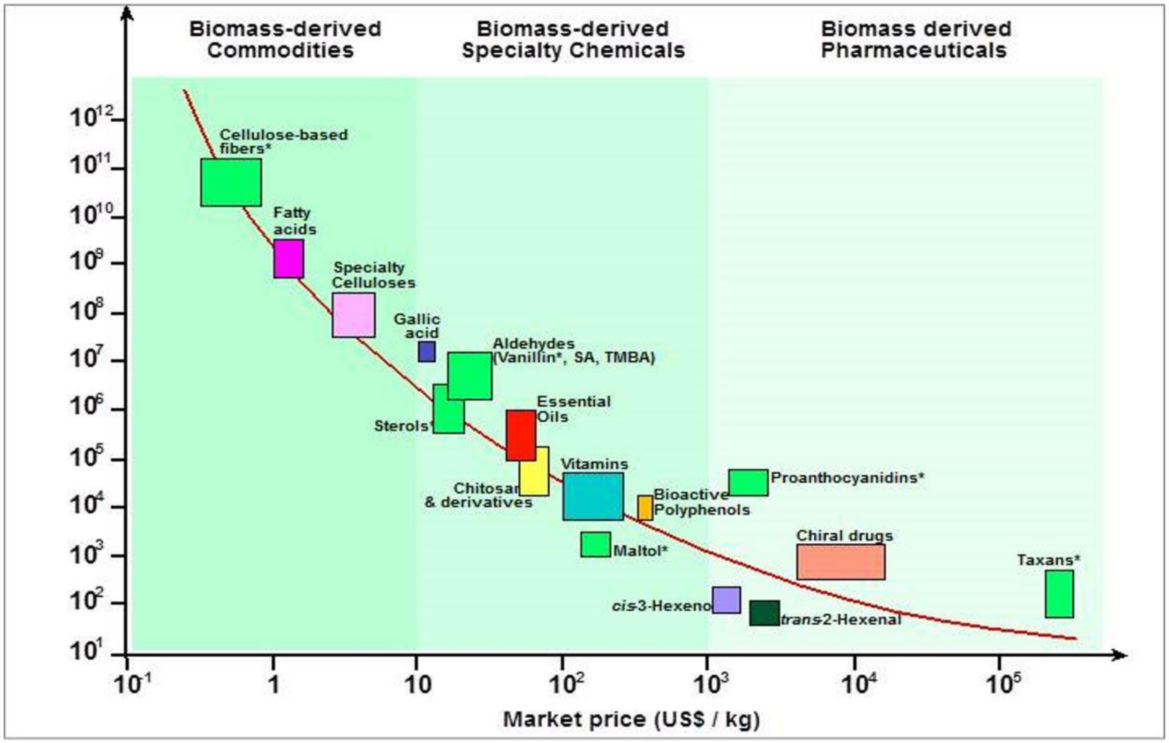


Figure 5: Value versus volume, petrochemical industry. From Werpy, 2009.

Similar charts comparing volume and value have been prepared by Chornet for biomass, Figure 6[18], and NREL for platform chemicals, Figure 7[19]. Both types of product are necessary, especially in the forest biorefinery: given the high cost of recovering biomass, which is thinly spread over large areas of landscape, it is critical to start with

[17] Werpy, T., "New industrial chemicals from agricultural resources", 6th World Congress on Industrial Biotechnology and Bioprocessing, Montreal, July 19-22, 2009.
[18] Chornet, E., "Thermochemical strategies for biofuels, green chemicals, polymeric materials and biofuels", Montreal, November 2005.
[19] Biddy, M.J. et al., "Chemicals from Biomass: A Market Assessment of Bioproducts with Near-Term Potential", National Renewable Energy Laboratory, March 2016. http://www.nrel.gov/docs/fy16osti/65509.pdf, viewed 2020-01-23.

production of high-value, low-volume products; but it is equally critical to do something useful with the residual material left over from initial processing stages.



Source: "Thermochemical Strategies for Biofuels, Green Chemicals, Polymeric Biomaterials and Biofuels", Esteban Chornet, November 2005.

Figure 6: Volume versus value for products from biomass. From Chornet, 2005.

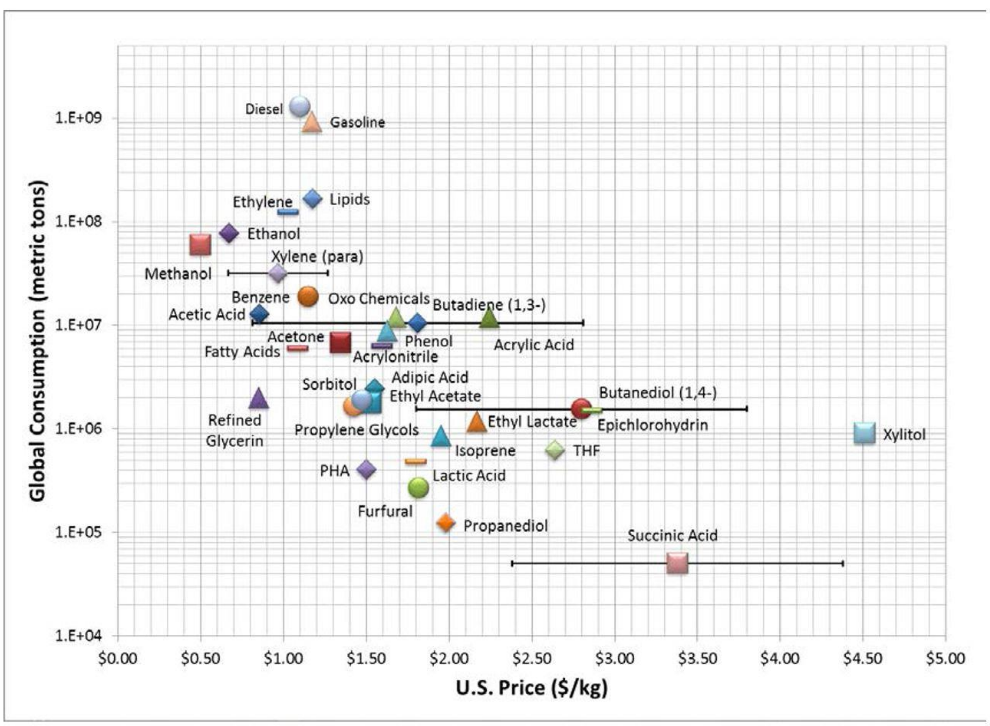


Figure 7: Volume versus value for products from petroleum or biomass. A summary of reported U.S. market price versus annual global volume for selected chemicals. The 3-5-year average price is provided. Error bars are shown for chemicals with large fluctuations in price. NREL, 2016.

Figure 6 shows the world market for conventional pulp and paper products at top left. Specialty celluloses are much more valuable, but market demands for things like dissolving pulp, cellulose nitrates and other specialties means that only a few mills world-wide will do well in each of these areas. A further limitation is that selling specialties requires a large and very highly trained sales force, as each customer will require a small amount of a product specifically tailored to his needs. The forest biorefinery therefore needs to be designed to take into account the commodity focus of the current industry and be consistent with current scales of processing capabilities and feedstock supply.

A critical point from Figures 6 and 7 is that while very high-value markets may be attractive due to high prices, the volumes may be so low that only one forestry installation may be capable of flooding the world market. There may well be a market for taxans (see Figure 6) from wood, at prices of the order of a million dollars per kilogram, but production is likely to be a few tens of kilograms per year, and employment will be limited to a few people. Furthermore, a taxan business will depend on someone else harvesting large amounts of wood and doing something useful with it, with some small level of extractives going to these specialties.

Like Figure 6, Figure 7 shows low value, high volume commodities such as diesel and gasoline at top left. The Ontario firm BioAmber developed a process for converting corn-based sugars to bio-succinic acid (bottom left); the process worked but, typically of start-up companies, the firm went into receivership for reasons unrelated to the technology. The BioAmber plant in Sarnia was purchased by LCY BioSciences and is back in production.

The traditional forest biorefinery follows this outline as shown in Figures 8 and 9[20]. The next step, as demand for traditional pulp and paper products shifts, needs to begin with new products as shown in Figure 10.

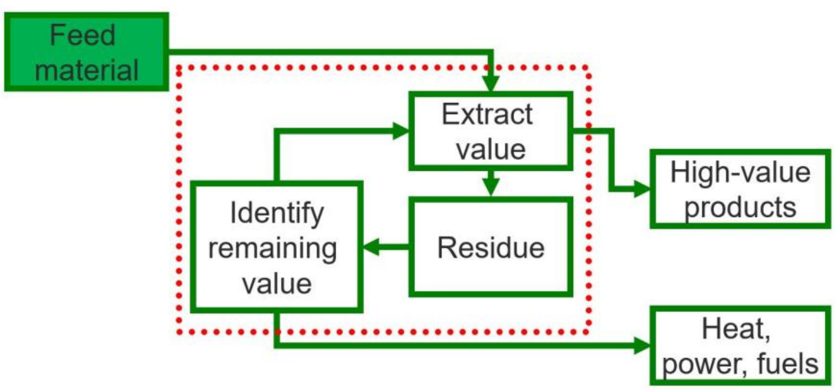


Figure 8: Generalised refinery concept. High value products are extracted from the feed material; residual material is converted to increasingly lower value products. At the end of the process, energy products generate the lowest value. From Browne, 2015.

[20] Browne, T. "Biorefinery development and implementation", course material, Designing the forest biorefinery (Paul Stuart, course leader), Atlanta, October 30 to November 1, 2015.

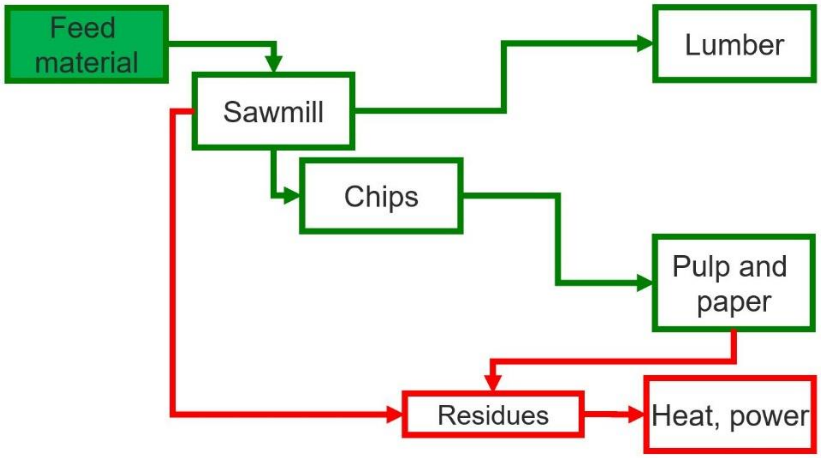


Figure 9: The current "forest biorefinery". Wood is converted to high value uses such as lumber or hardwood flooring and finishing products; chips go to pulp, and bark (along with black liquor from kraft pulping processes) goes to heat and power. From Browne, 2015.

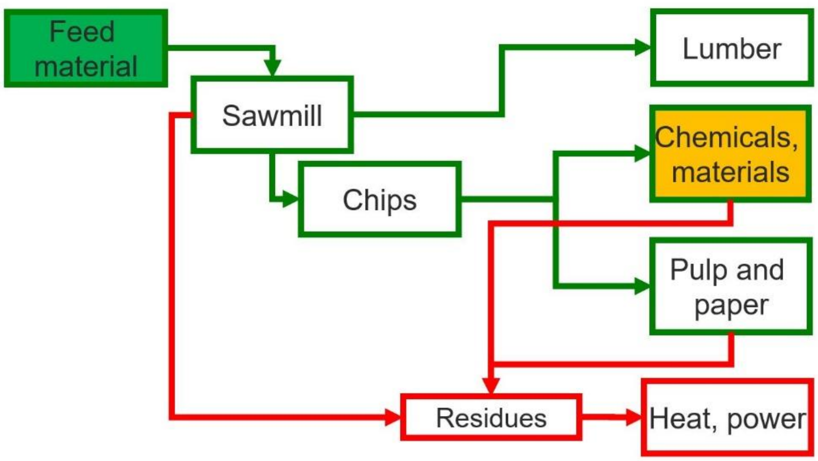


Figure 10: The new forest biorefinery at an early stage. As lumber or pulp and paper demand fluctuates over time, chemicals and materials may take larger portions of the feed. In all cases, residual material is likely to be used onsite for energy to drive processing stages, with excess sold to the grid. From Browne, 2015.

2.8. Feedstock quality

Understanding volume versus value is critical. Feedstock quality is also critical. The most homogeneous feeds, such as well-debarked and washed white wood chips, are easiest to transform and are also the most expensive. Bark and other sawmill residues are of lower quality and more heterogeneous, with forestry residues (roadside slash, forest thinnings and the like) being the lowest quality due to high content of bark, sand, gravel and other contaminants. There are pathways to end products that, for technical reasons, require the best available feedstock; the high cost however can make these approaches prohibitively expensive.

2.9. Carbon impact and other environmental impacts

Carbon accounting includes approaches such as carbon taxes, cap and trade systems, or various other carrots and sticks devised by governments in an effort to reduce GHG emissions. Most biorefinery products will compete with existing petroleum-based products; the economic feasibility of many pathways, especially biofuels or energy, will depend on the price of oil. The old joke about being able to make anything from lignin, except money, is true if oil is

$20/bbl (barrel)[21], which it was in the early days of the AlCell process. Arguably there is a product-dependent minimum price of oil above which biochemicals begin to make sense. Work done by FPInnovations implies that $50/bbl makes lignin-based phenolic glues for plywood competitive with the petroleum-based incumbent on a cost basis (if not on a performance basis).

This report will use the concept of effective oil price, i.e. the price of oil necessary for the product to be competitive. Where that price is significantly higher than the current range of $60 to $70/bbl, policy initiatives will be needed to close the gap.

The carbon impact of a biofuel is much easier to estimate than that of a biochemical, where the immediate use is not combustion. While Life Cycle Assessments (LCA) have their weaknesses, a proper LCA is critical before any pathway can be said, with any degree of certainty, to be less carbon intensive than the incumbent process.

Finally, while wood from Canadian forests is a renewable, sustainably harvested, non-food resource with no land use or food-versus-fuel issues, products made from wood may or may not be compostable, bio-degradable or recyclable. Sugar-based polyethylene will have the same end-of-life issues as petroleum-based polyethylene.

2.10. Markets and economics

Generally speaking, apart from competing with petroleum, the overall economic challenge will be cost of raw materials. In most cases, wood costs will be of the order of half or more the total production costs. No processes convert more than 70% of the energy contained in a dry metric tonne[22] of biomass to a biofuel. This is a yield of about 350 litres per oven dried tonne (l/odt), a very optimistic value. At $100/odt for wood, this is $0.30/l just to cover the cost of wood. Other operating costs (labour, chemicals, energy) will add at least another $0.30/l. The cost of building the plant and generating a profit will likely add at least $0.60/l to the total. Production costs at the plant gate, before fuel taxes or transportation, are going to be at least $1.20/l and will probably be significantly higher. Detailed engineering studies will provide investment-ready numbers, but this is far more challenging than ethanol from corn or, especially, sugar cane, where costs are anecdotally in the $0.40/l range.

Markets for bioproducts are another challenge. Displacing incumbents is challenging if the customer needs to modify his operations to adapt a new product of uncertain performance and market attractiveness. For example, the lignin plants operated by Domtar and Stora Enso are anecdotally operated at capacity only because a significant portion of the lignin produced is burned for heat and power. These facilities have localised reasons for valuing the lignin as a fuel. Another issue affecting all lignin plants is that the production process for phenolic resins for plywood glues must be altered to include lignin, and the resin producer needs to see a good reason to do so. As research continues to improve the quality while reducing the variability and cost of lignin, resin producers should begin to see better reasons to make the switch. This will also be true for succinic acid or any other product. There may be a market, but developing it takes time, money and effort.

Overall, it is wise not to under-estimate the challenges in market development, which is a significant hurdle in the development and commercialisation of new products, regardless of raw materials used.

[21] Unless otherwise stated, all oil prices given in this report will be West Texas Intermediate (WTI) prices, given in inflation-corrected 2018 USD/bbl. The WTI price is set at Cushing, Oklahoma, and is a benchmark price commonly used in North America.
[22] Unless otherwise noted, all biomass weights in this report will be given in terms of oven-dry metric tonnes (odt), as this is what the processes described here consume.

2.11. R&D support, technology development and intellectual property

Developing novel bioproducts from bench to pilot scale is expensive and time consuming. Steady and dependable financing over many years is critical to success. The R&D pipeline often starts in university labs; this report will focus on commercially relevant opportunities.

The Finnish forestry giants Stora Enso and UPM maintain large, well-staffed R&D laboratories, and information as to their activities is limited to occasional press releases or carefully controlled conference presentations. In addition, these technologies will have been patented and may not be available for licensing. In Canada, a significant portion of the forest sector supports FPInnovations as the central, shared R&D facility. FPInnovations maintains a research group in the area of bioproducts whose results are available to Members under membership and strategic partnership agreements.

The issues of licensing, intellectual property and patents will need to be addressed on a case by case approach to individual owners of technologies. Some technology owners may not want to license and will need to be convinced to set up in Quesnel. Others may be prepared to license, or may insist on other roles, such as equipment vendor or owner-operator in some form of partnership. Finally, some patents are deployed as a defensive measure to prevent others from entering the space. Interesting technologies may not be available due to reasons that have nothing to do with the suitability or desirability of building in Quesnel.

3. Opportunities for Quesnel

3.1. Critical considerations

All opportunities identified in this section are subject to a range of constraints which have not been explored explicitly or in depth in this study. These are outlined first.

The first one is the issue of the volume and quality of wood available. Wood volumes are under pressure following the Mountain Pine Beetle infestation and two bad forest fire seasons. Furthermore, most processes for chemically or enzymatically separating or modifying cellulose, lignin and hemicellulose will be fairly intolerant of any significant level of bark content. The issue then arises around forest trimmings, thinnings and roadside residues, which are very bulky, and which typically are not economic to haul any distance unless they are ground or chipped in the woods. This leads to a feed material which is heavy in bark and other contaminants such as sand, dirt or gravel, and which becomes less valuable as a result. Opportunities to recover as clean a wood stream as possible need to be seized. On the other hand, existence of a legacy landfill containing bark and wood residues within a very short distance of the various industrial facilities in Quesnel opens up some opportunities, as this resource is likely to be very inexpensive to mine.

All the opportunities listed here depend on being able to build a plant to manufacture a new product. In many cases the technologies exist only at the pilot or demonstration scale; off-the-shelf commercial processes are few and far between. (Technologies still at the bench-scale were not included in this review.) Performing a proper due diligence around technology performance, capital costs and operating costs by interacting directly with technology providers and engineering firms is critical before selecting a path forward.

Freedom to operate is an expression implying the existence, or not, of significant legal barriers to entry to a given market. These barriers are usually related to patent portfolios held by technology developers. In all cases, it is essential to understand the patent landscape, and who controls it; in many cases patent owners are happy to provide a license or to negotiate some form of strategic alliance (possibly up to and including a joint venture) to monetise their patent position. Other technology developers see themselves as owner-operators, or as equipment vendors. Finally, some patents are deliberately defensive in nature, and are intended as a barrier to entry by others. This needs to be determined on a case by case basis.

And finally, new products require new markets. It is at least as difficult to break into a new market as it is to develop a new technology from bench-scale to demonstration scale. Customers need to be convinced they need the product, which must perform better and cost less than the incumbent; so-called "Green Premiums"[23] should be viewed with scepticism until a customer signs a firm purchase agreement including a premium above the price of the equivalent petrochemical.

[23] The so-called "Green Premium" is the additional price the average consumer is prepared to pay for an equivalent product with reduced environmental impact. Most businesses are unwilling, at the planning stage, to bank on a significant potential for higher prices for a 'greener' product, as consumer spending studies show most consumers are unwilling to spend significantly more unless there are other reasons for doing so, such as better performance compared to the incumbent.

The so-called Technology Readiness Level (TRL) is used to identify where a given technology sits on the spectrum from bench-scale to full commercialisation; the Canadian version[24] is used here and is shown in Table 1.

Table 1: Technology Readiness Level (TRL) as defined by Innovation Canada. Levels 7 through 9 represent the pre-commercialization gap for innovations. These are the three levels where innovations are eligible for the Build in Canada Innovation Program.

TRL 1	Basic principles of concept are observed and reported	Scientific research begins to be translated into applied research and development. Activities might include paper studies of a technology's basic properties.
TRL 2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. Activities are limited to analytic studies.
TRL 3	Analytical and experimental critical function and/or proof of concept	Active research and development is initiated. This includes analytical studies and/or laboratory studies. Activities might include components that are not yet integrated or representative.
TRL 4	Component and/or validation in a laboratory environment	Basic technological components are integrated to establish that they will work together. Activities include integration of "ad hoc" hardware in the laboratory.
TRL 5	Component and/or validation in a simulated environment	The basic technological components are integrated for testing in a simulated environment. Activities include laboratory integration of components.
TRL 6	System/subsystem model or prototype demonstration in a simulated environment	A model or prototype that represents a near desired configuration. Activities include testing in a simulated operational environment or laboratory.
TRL 7	Prototype ready for demonstration in an appropriate operational environment	Prototype at planned operational level and is ready for demonstration in an operational environment. Activities include prototype field testing.
TRL 8	Actual technology completed and qualified through tests and demonstrations	Technology has been proven to work in its final form and under expected conditions. Activities include developmental testing and evaluation of whether it will meet operational requirements.
TRL 9	Actual technology proven through successful deployment in an operational setting	Actual application of the technology in its final form and under real-life conditions, such as those encountered in operational tests and evaluations. Activities include using the innovation under operational conditions.

3.2. Support for bioeconomy development in the Central Interior

The City of Quesnel can follow existing pathways to forming a consortium or cluster approach to promoting the forest-based biorefinery in the City and broader Central Interior.

As discussed in Section 2, there are several examples across Canada of municipal or county-level governments that have worked to generate a cluster-type approach to moving the region to new pathways, in light of challenges facing incumbent industrial players. Several of these have been quite successful. The approach requires identifying the larger shifts affecting the region as well as the strengths, and certainly the Future of Forestry Think Tank has made a good start in this respect:

- Impact of the mountain pine beetle and forest fires on wood availability;

[24] https://www.ic.gc.ca/eic/site/080.nsf/eng/00002.html, visited 2020-02-14.

- Impact of the secular decline in demand for certain pulp and paper products;
- Impact of changes in wood construction processes on the dimensional lumber business;
- Strengths begin with the existing forest sector activities, infrastructure, manpower and logistics.

The pathways described in this section all have large uncertainties associated with them, and will require a solid triage process based on due diligence reviews before selecting one or several for further action. These due diligence and triage activities will require the implication of multiple local players, beginning with West Fraser and other industrial actors in the forest sector; all levels of government; First Nations; unions; and other citizens, ENGOs or industrial groups. Outside players will include engineering firms; academic and industrial research centres across Canada and abroad; and advice from representatives from other clusters or regional players such as AgWest Bio, BIC, CRIBE or BELT. Input from equivalent EU organisations is also critical.

A cluster or bioeconomy centre can start out as a virtual centre, with one or two staff coordinating activities across the region from an office at City Hall or elsewhere in Quesnel. The first step, to which this report will hopefully contribute some information, is scoping what that virtual centre should be promoting, and identifying resources to support it. Sarnia-Lambton officials looked around and saw a well-integrated petrochemical complex made up of small branch plants that were at risk of closure by foreign head offices and a corn ethanol plant, all surrounded by some of Eastern Canada's best agricultural land. Paths to biochemicals from agricultural sources, such as the BioAmber one, were obvious ones to support. A key piece is identifying a strong local leader to act as CEO or executive director, with a travel budget for information-gathering and networking purposes. Coordinating and supporting these due diligence activities is an ideal role for such a leader.

Moving up from a virtual centre, industrial space, if available at nominal cost from one of the industrial players in the vicinity, could serve to trial new ideas in an industrial setting, at scales larger than what is possible in university labs. This becomes critical in the scaleup of new technologies: proving something at the gram or kilogram scale is useful, but customers are going to want tonne-scale samples, and engineering firms will want data from pilot plants to assist in designing full-scale plants. As an example, BIC took advantage of the former Dow Chemical research centre, converting it into an incubator space where technology developers could try new technologies in a rent-subsidised pilot plant or incubator context. A cluster or bioeconomy centre can serve to coordinate available funding and space to meet engineering and customer needs before moving to full scale.

Examples exist of university-run incubators, but a strong guiding hand by the centre or an advisory board can be an important success factor; some university incubators have been too focused on university projects to the detriment of novel outside ideas. Nonetheless a strong involvement by community colleges and universities is an important aspect of a successful cluster.

The remainder of Section 3 describes selected options that might provide a decent fit for the Central Interior. See Section 4, Background, for added detail on these and other pathways.

3.3. Pathway 1: Redirect existing pulp fibres to new markets

Elevator pitch: New applications for existing pulp fibres, such as textiles or fibre-reinforced composites, open the door to new markets with minimal impact on mill operations, Table 2. Some processes may be suitable for co-location and utility sharing with a pulp mill.

Outline: Several Canadian pulp and paper companies have used IFIT funding to develop new markets for their pulp fibres, whether kraft or mechanical. One example is as a reinforcing fibre, which brings a premium over the wood flour used in wood-plastic composite decking and similar products. One market that has been well developed, and where agricultural fibres are currently used, is interior door panels for automobiles. These technologies are relatively straightforward but require taking the time and effort to work with potential customers. The automobile manufacturers continue to look for weight savings, and natural fibres impregnated in some form of resin matrix are lighter than incumbent products and work well in areas not immediately visible to the customer. The competition includes agricultural fibres such as hemp.

A more complex pathway is to replace glass fibres in injection molding systems. Pellets of polyethylene or similar materials are available with chopped glass fibres already embedded, and are purchased by injection molders in drums. The automotive applications include areas where greater strength is required, such as glove box doors and other interior components. The Toronto firm Greencore Composites[25] made an early attempt at providing pellets with wood or agricultural fibres instead of glass fibres[26], but was ultimately unsuccessful for reasons that are not clear. Certainly, the hydrophilic nature of cellulose-based fibres needs to be addressed, and a range of approaches have been developed for this purpose. A market review would establish if there is space, and a technology review would address the issue of water retention by wood fibres.

Wood fibres have also been used to make fabrics, commonly by converting dissolving pulp (so-called viscose pulp) to rayon via the carbon disulphide pathway, a process that is not in operation in countries with modern environmental regulations. Researchers at VTT have identified several pathways, and one claims to bypass the need for dissolving pulp: Spinnova. The textile fibre market is large, and cotton is a difficult crop requiring scarce water resources and heavy pesticide application. A process starting with kraft pulp means that the kraft mill can divert production as needed, without the expensive and irreversible conversion of a kraft pulp mill to dissolving pulp. These technologies are in development and may be available for licensing.

New uses for pulp	
EBITDA	$1,055,944
Depreciation	$800,000
EBIT	$255,944
Taxes	$76,783
Net income	$179,161
Inventory	$221,000
Capital employed	$16,221,000
ROCE	**1.58%**
Payback, years	**89.3**
IRR	**1.12%**

Figure 11: Economic analysis for a hypothetical textile plant.

Figure 11 shows a hypothetical plant making 10 t/d of textile fibre using kraft pulp at $750/adt. Viscose staple fibres were trading for 12,500 RMB/t ($CDN 2400/t) in late February 2020[27]. Given a yield on pulp of 65%, $750 worth of pulp makes up to $1560 worth of fibre. With capital costs of $16M, the process is not economic; much lower capital costs, or a higher yield, would improve matters.

[25] http://greencorenfc.com/index.htm, visited 2020-02-15. Most recent update appears to be in 2014.

[26] Pandey, J.K. et al., "Commercial potential and competitiveness of natural fibre composites", Chapter 1 in "Biocomposites: Design and Mechanical Performance" (M. Misra, ed.), Woodhead Publishing, 2015. ISBN 978-1-78242-373-7.

[27] https://www.fibre2fashion.com/market-intelligence/textile-market-watch/viscose-staple-fibre-price-trends-industry-reports/12/, viewed 2020-03-05.

Table 2: Redirect existing pulp fibres to new markets.

Product name	Composites	Textiles
Description	Reinforcing fibres	Textile fibre
Provider(s)	Would have to develop internally	Spinnova
Competition	Domtar, Papiers Masson, others outside forestry industry (agricultural fibres in particular)	Dissolving pulp; bamboo fibre
Type of product	Fibres as reinforcement in composite materials	Substitute for cotton
Market area	Automobile; other industries using Fibre-Reinforced Plastics (FRP); furniture, building products, pre-fabricated housing components, mass transportation, recreational vehicles	Textiles
Market volume	Large	Large
Technology	Pulping, possibly modified	Patented dissolution and spinning process
TRL	6-7	5-7
Integration	Requires conventional pulp fibres; perhaps specific mill operating conditions need to be changed	Requires conventional pulp fibres. Spinnova's process requirements are not known; the process may not need utilities as found at pulp mills.
Feedstock quality	Kraft or Mechanical Pulp	Kraft pulp
Economics	Similar to pulp markets	Compares to cotton
GHG implications	Displaces glass fibres or other low-grade reinforcing fibres; light-weighting	Environmental impact is said to be much lower than cotton or conventional viscose fibre processes
Fit for Quesnel	Excellent	Excellent if the process needs utilities available at the mill
Key challenge	Cellulose fibres tend to absorb water	Novel technology is not commercial yet
Comments	Competition needs to be evaluated carefully, especially agricultural fibres. Suitability of fibres to different applications needs development. Approaches to render fibres hydrophobic will be essential to move to higher value grades. Customer trials would be critical.	The classic process for making clothing from wood pulp, such as bamboo fabrics commonly available, is environmentally very challenging. The Spinnova process is one of 4 developed recently in Finland; and is the only one that does not require dissolving pulp as its feed.

3.4. Pathway 2: New uses for kraft mill residual streams

Elevator pitch: The kraft mill generates a large number of residual and by-product streams which can be recovered and sold, Table 3. Lignin, methanol, tall oil, turpentine and secondary sludges all have buyers.

Outline: Products from kraft mill residual streams can improve mill profitability, by identifying better uses of under-valued streams. The primary economic activity of the mill will, however, remain pulp; these new products will bring in new revenues at the margins, and will only be feasible as long as the pulping process remains unchanged. (Mechanical pulp mills, with much higher yields of pulp on wood, have fewer residual streams and thus fewer opportunities.)

As an example, a hypothetical mill making 1000 t/d of kraft pulp is earning $1M/d if pulp prices are $1000/t. The maximum amount of lignin that can be extracted before recovery boiler operation is impacted is about 150 t/d, with 100 t/d being a safer upper limit. At $1000/t of lignin, added revenues at full capacity are $100K, or an increase in gross revenues for the site of 10%. Actual gains will be less.

On the other hand, these pathways do not generally impede the production of pulp, and provide reasonably inexpensive ways to build an initial bio-products business. Most of these approaches have been used in the forest sector at one time or another, usually as a response to a pressing need such as debottlenecking pulp production, lack of affordable landfill or others. For example, there are several anaerobic digesters operating in Canada[28] on mill effluents, with the biogas generated going to heat and power. This would fit a site with inadequate landfill or effluent treatment capacity and a need for the heat.

As demand for these products increases, other more radical approaches can be considered to meet customer demand.

Figure 12 shows a hypothetical plant making 5 t/d of methanol. Methanex quotes $US 310 per metric tonne as of writing; this analysis uses $CAD 300/t. Hypothetical capital costs of $2M yield a payback period of 11 years. Better numbers for operating costs and capital would serve to identify whether these estimates are accurate, and if payback can be improved. Earnings are low, however, at less than $500,000 per year, and will only contribute a small amount to the mill bottom line.

Methanol	
EBITDA	$377,783
Depreciation	$104,000
EBIT	$273,783
Taxes	$82,135
Net income	$191,648
Inventory	$25,500
Capital employed	$2,105,500
ROCE	**13.00%**
Payback, years	**10.9**
IRR	**9.21%**

Figure 12: Economic analysis for a hypothetical methanol plant making 5 t/d from recovery.

[28] https://millarwestern.com/company/latest-projects/bio-energy-project-whitecourt/, visited 2020-02-17.

Table 3: New uses for kraft mill residual streams.

Product name	**Kraft lignin**	**Methanol**	**Tall oil and turpentine**
Description	Lignin extraction	Methanol	Extractives
Provider(s)	NORAM, Valmet	A.H. Lundberg	Internal
Competition	Domtar, Stora Enso, Suzano	AlPac	Pulp mills running on Southern Pine
Type of product	Lignin to phenolic resins, foams, etc.	Replace fossil-based methanol	Specialty chemicals; biodiesel; oil and gas extraction products
Market area	Biomaterials (Resins, foams, etc.)	Methanol for chemicals or biodiesel	Specialty chemicals; feed to biodiesel
Market volume	Million tonne per year scale; potential production at CPP is well under 100 t/d	Large; potential production at CPP is relatively small at 2-5 t/d	Small (specialties); advice or partnership with specialty chemical firms may be useful. Increase production by adding canola oil. Potential biodiesel use is huge
Technology	Precipitation of lignin from liquor	Purification of kraft mill waste streams	Extraction from soaps etc. in recovery area
TRL	8	8-9	9
Integration	Requires pulp mill operation	Requires pulp mill operation	Requires pulp mill operation
Feedstock quality	Wood chips to black liquor	Wood chips to black liquor	Wood chips to black liquor
Economics	Requires improved lignin quality for $1000/t opportunities	Methanex produces low-cost methanol from natural gas	Specialties from tall oil are valuable. Local biodiesel market?
GHG implications	Depends on market served	Displaces natural gas; used in biodiesel, it improves GHG	Biodiesel displaces petroleum
Fit for Quesnel	Excellent	Review of CPP needed	Depends on fresh wood vs MPB-killed wood
Key challenge	Growing the market at reasonable prices	Residual sulfur levels may be too high for some applications	MPB-killed wood generates very little in the way of extractives.
Comments	Lignin market is still growing slowly. As product quality and consistency improves, market should improve	Local applications where trace sulfur is not an issue would be best. Reduced shipping cost from Port of Vancouver an advantage to a local buyer	Local biodiesel market could be valuable, especially if combined with wood-based methanol instead of the classic natural gas-based methanol commonly used.

3.5. Pathway 3: Novel cellulose fibre streams

Elevator pitch: Novel fibre streams from cellulose are very high-value products, and two of the leading technologies worldwide are Canadian, Table 4. Partnerships can open up the opportunity to participate in novel markets.

Outline: These products are of higher quality, and therefore more expensive, than conventional pulp fibres. For example, CelluForce NCC is sold in spray-dried form for $50/kg, and is incorporated in composites for inner car door panels, or in oil and gas field fluids. The target markets are small and are ones where the increased performance is worth the increased cost.

A range of novel cellulose products have been developed by FPInnovations in the last decade. Two have been licensed to small firms: CNC has been licensed to CelluForce, which uses the NCC trademark; and nano-fibrillated cellulose (NFC) is produced by Kruger and Resolute Forest Products and marketed in non-traditional markets by Performance Biofilaments. NFC also has applications in traditional pulp and paper products, such as tissue grades, as a reinforcing agent.

CelluForce, originally a joint venture between Domtar and FPInnovations, now includes Schlumberger, Suzano and Investissement Québec as equity partners. The acid hydrolysis process is patented by FPInnovations and licensed to CelluForce. As demand increases to the point of justifying new capacity, a hypothetical installation in Quesnel would require collaboration with CelluForce. (A competing process developed at University of Alberta is in a very early stage of development.) So the process is exciting but may not be a good fit for Quesnel at this time.

Nano-fibrillated cellulose, also patented by FPInnovations, is made in a modified mechanical pulping plant. The initial plant was built by Kruger in Trois-Rivières, Quebec, and produced about 5 t/d. Resolute Forest Products has recently announced a new 21 t/d plant in Kenogami. Both mills were originally newsprint mills, and repurposing an existing refiner was relatively simple in these cases. Technically, this could fit at QRP. Conversations with FPInnovations and Performance Biofilaments (a joint venture between Resolute and Mercer) would be needed to ascertain whether there is an opportunity to participate in the next scale-up, which presumably will arise as production from the new plant in Kenogami is sold out.

Novel fibres	
EBITDA	$1,609,476
Depreciation	$400,000
EBIT	$1,209,476
Taxes	$362,843
Net income	$846,633
Inventory	$170,000
Capital employed	$8,170,000
ROCE	**14.80%**
Payback, years	**9.4**
IRR	**10.58%**

hypothetical novel fibre plant making 20 t/d.

Figure 13 shows a hypothetical high-quality fibre plant making 20 t/d. Sale price is $1000/t, similar to kraft pulp. Revenues at full capacity are thus $3.6M/y. In order for the payback to be under 10 years, capital needs to be under $8M. Wood costs are $100/odt, with a yield on wood of 50%; increasing yield to 90% leads to maximum capital of about $24M for a 10-year payback.

Table 4: Novel cellulose fibre streams.

Product name	**Cellulose nano-crystals**	**Nano-fibrillated cellulose**
Description	CNC	Mechanical pulp fibrils
Provider(s)	CelluForce	FPInnovations patent
Competition	University of Alberta pilot	Current plants operated by Kruger and announced by Resolute
Type of product	Nano-scale cellulose crystals	Fibrillated cellulose
Market area	Specialties	Specialties
Market volume	Small	Small
Technology	CelluForce acid process	FPInnovations modified mechanical pulping process
TRL	8	8
Integration	Shares pulp mill utilities	Requires repurposing at least one refiner (QRP)
Feedstock quality	Kraft pulp	White wood chips
Economics	Expensive process but unique, high-value properties	Less expensive than CNC, broader appeal to a wider market may be possible. Current capacity is about 25 t/d.
GHG implications	Not known	Not known
Fit for Quesnel	Integration with mill utilities would be useful	Excellent opportunity to repurpose portions of QRP, assuming current market conditions for BCTMP warrant this
Key challenge	Market growth is needed to justify added capacity	Performance BioFilaments, a JV between Resolute and Mercer, markets the product. Need and location of eventual new capacity will likely be decided by the JV. Low production rates may be a challenge with existing scale of QRP refiners.
Comments	A long shot. CelluForce is able to expand their existing plant in Windsor, Quebec, as markets demand.	Unique properties due to Western wood may be an advantage. Benefits of HW? Current production is all SW.

3.6. Pathway 4: Repurposing existing mill assets

Elevator pitch: The world is moving to bio-based chemicals, in response to consumer demands. This trend is particularly strong in Europe. Early players who can convert wood to a range of petrochemical substitutes will stake out a space in this growing field, Table 5.

Outline: This opportunity involves repurposing existing pulp mill assets to move to new products. While this is a big step, it may be possible to engineer a demonstration plant in such a way that mill assets can easily swing back to existing products, much as Eastern Canadian kraft pulp mills swing from softwood to hardwood in response to market needs.

The TMP-Bio process is in development by FPInnovations, in partnership with Resolute Forest Products, at the Thunder Bay Bio-Economy Technology Centre operated by FPInnovations. The process begins with a modified BCTMP mill, implying that one of QRPs three lines would be an interesting candidate for conversion. The primary refiner and its associated chip steaming and impregnation stage would have to be fed from a separate hardwood pile, and would have to be able to blow the pulp to a new enzymatic digester and filtration plant. Some changes to refiner operation may also be needed to allow it to run at low energy levels; the scale of the capital requirements, and the challenges involved in swinging back and forth, would need to be addressed in an engineering study.

With these changes in place, a hypothetical, existing 400 t/d line could be diverted for 8 hours to make about 100 t of pulp for enzymatic breakdown. The enzymatic process and other downstream processing take several days to complete, and an additional fermentation stage will add another few days to the elapsed time. This implies an 8-hour diversion of one primary refiner, once a week, would lead to production of about 2500 t/y each of sugars and lignin, at a cost of about 6750 t/y in lost BCTMP production. As customer demand increases, added enzymatic digestion capacity can be built. The challenge becomes deciding to run traditional BCTMP, or the novel process, depending on which is more profitable at any given time.

Economics and availability of the TMP-Bio process for licensing would need to be discussed with FPInnovations. While the author can’t comment on the economics of this process due to continuing non-disclosure agreements, the fact that FPInnovations and Resolute Forest Products have invested in the Thunder Bay pilot plant implies there are reasonable economic reasons for doing so.

Table 5: Repurposing existing mill assets.

Product name	**Sugar and lignins from the TMP-Bio process**
Description	Biochemicals from wood
Provider(s)	FPInnovations (partnership with Valmet); Genomatica or other
Competition	Conventional processes such as steam explosion or acid pre-hydrolysis
Type of product	Biochemicals
Market area	Substitutes for petroleum intermediates
Market volume	Very large
Technology	Separation of lignin and sugar from wood (FPInnovations patents); conversion of sugar to e.g. 1,4-butanediol (Genomatica patents); conversion of lignin to end-uses (in development by FPInnovations)
TRL	5-6
Integration	Requires repurposing at least one refiner and associated chip feed and impregnation systems (QRP), possibly in short campaigns to start (for example 8 hours, once a week) returning the refiner to conventional BCTMP duty as desired. Works best on hardwoods.
Feedstock quality	White wood chips with low bark content; ideally hardwood (mixed HW would likely work, as long as SW content was low)
Economics	Unlike a pulp mill which sells mainly pulp, products from both lignin and sugars must be sold. Given the economics, this is a lignin plant with sugar by-product, unless the sugar is converted onsite to a more valuable end-product.
GHG implications	Depends on use of products. See Section 4.4 and Table 8.
Fit for Quesnel	Excellent opportunity to repurpose portions of QRP, assuming current market conditions for BCTMP warrant this
Key challenges	Sugar stream is mixed xylose plus glucose, not a pure stream; use of lignin fraction to be developed. Decent revenues from both product streams are critical to economics.
Comments	This process has advantages and disadvantages compared to traditional steam explosion or acid processes. In all cases selling both products at a reasonable margin is the key challenge.

3.7. Pathway 5: Making better use of mixed feeds

Elevator pitch: Low-grade residual material with high bark content is best suited for fuels and energy applications which displace fossil-based fuels in mills or in regional district heating systems, Table 6.

Outline: The availability of a large legacy landfill, of the order of 9.1 Mm^3 or about 4.5 Modt, in the vicinity of Quesnel may make this attractive due to low wood delivery costs. A full-scale Renewable Natural Gas (RNG) plant would consume 200 to 300 kodt/y and could thus run for 15 years if fueled with this raw material. However, capital costs for such a plant are enormous[29], and sufficiently high plant gate prices for the gas produced would have to be negotiated with the Province and FortisBC. Smaller uses could also make sense, as shown below.

Table 6: Making better use of mixed feeds.

Product name	Syngas for the lime kiln	Bio-crude	District heating
Description	Displace natural gas in CPP's lime kiln	Bio-Crude for internal use or for sale	
Provider(s)	Nexterra	Ensyn	
Competition	Valmet, Andritz	None at this TRL level	
Type of product	Gasifier for syngas	Pyrolysis plant	
Market area	Internal	Local users of bunker fuel	
Annual wood consumption	50,000 odt/y	36,000 odt/y (Renfrew-scale plant)	
Technology	Fixed-bed gasifier	Pyrolysis plant	
TRL	7	9 (pyrolysis plant); 7 (use as a bunker substitute)	8-9
Integration	Excellent	Excellent	Excellent
Feedstock quality	Bark, sawdust, pins, fines	Bark, sawdust, pins, fines	
Economics	With natural gas well under $5/GJ, support from FortisBC and/or the BC government is critical	Competitiveness with oil at $60/bbl needs to be verified. Need for additional carbon accounting is likely to be high	Nexterra and Ensyn processes can be used to heat local buildings
GHG implications	Eliminates GHG emissions due to fuel in the kiln	Eliminates GHG emissions due to bunker fuel use	Displace fossil -based heating systems.
Fit for Quesnel	Excellent	Excellent	Hospitals have a year-round steam demand
Key challenge	Nexterra gas quality is said to be adequate, but needs to be proven. Valmet and Andritz provide commercial units (TRL 9) but at higher capital costs	Bio-crude is acidic (requiring upgraded storage, piping and fuel nozzles in boilers) and does not mix well with bunker fuels. Concerns exist around water content.	Very low fossil fuel prices and an uncertain carbon pricing environment make this challenging
Comments	Driven by GHG accounting (i.e. effective natural gas price after carbon taxes or other carbon measures)	Key driver would be to consume legacy residue piles	

[29] Gas Technology Institute, "Low-Carbon Renewable Natural Gas (RNG) from Wood Wastes", February 2019. https://www.gti.energy/expanding-production-and-use-of-renewable-natural-gas-rng/, viewed 2020-03-09.

4. Background: detailed product and process descriptions

4.1. Technology providers and business arrangements

The bio-chemicals and bio-fuels field is one where start-up firms proliferate. These technology start-ups generally have as their sole asset a patent portfolio, which prevents others from operating in the same field. Most start off with little or no cash flow from operations. So pathways described below may be technically feasible but may be blocked by owners of patent portfolios. Some owners are prepared to license the right to use a technology or share development costs; others see themselves as equipment vendors or owner-operators. Each approach adds a different level of risk and uncertainty to the analysis as the financial condition of these start-ups can be shaky. Generally, this analysis will focus on providers which already have steady cash flow from operations and are developing novel processes and products out of that cash flow.

4.2. Thermochemical pathways to fuels

The liquid fuels market has the advantage of being large enough to take any volume that could conceivably be produced by the forest sector in Canada[30]. The challenge is one of manufacturing cost (and therefore of effective oil price). The corn ethanol industry in the US has seen ups and downs, in some cases driven by sudden changes in US EPA rules; Canadian producers such as Ensyn have also had to weather shifts in US biofuels policy. The greatest risk to a bio-fuels plant is sudden, unexpected shifts in the policy landscape that render a plant uneconomic overnight due to changes in the effective oil price.

An advantage of thermochemical pathways, such as gasification or pyrolysis, is their relative insensitivity to bark content. Technology providers will tell you that their processes work best on clean white wood chips, but few other technologies will function as well on a heterogeneous stream. This fits the biorefinery model outlined in Section 2: the lowest quality residue needs to go to the lowest quality product, which is usually energy or fuels.

Several technologies are described next and summarised in Table 7.

Chemically, thermochemical pathways are the “big stick” approach, and can handle less homogeneous materials than other processes. In gasification, carbon-containing material is fed into a large reactor, which may be pressurised, where it is subjected to very high temperatures in the absence of oxygen. The result, taken to its extreme, is a highly flammable synthetic gas (syngas) consisting mainly of carbon monoxide and hydrogen. Subsequent processing steps involve reassembling these molecules into something useful, such as methane (renewable natural gas, RNG) or a raw material that can be processed in typical petrochemical plants. The classic process for this second case is Fischer-Tropsch synthesis, named after the German scientists who developed it for use in converting coal to a liquid fuel in the 1920’s. To be economic, these RNG or FT liquids plants need to be large and thus need lots of woody biomass. If making RNG, the process must be next to a pipeline; if making a Fischer-Tropsch synthesis product, proximity to a petrochemical refinery would be very useful.

Ottawa-based company Ensyn provides a bio-crude which is said to be compatible with typical bunker fuels and home heating oils. The process, known as pyrolysis, is a thermo-chemical process that yields a liquid fuel instead of a gas. This is more easily shipped than a gas, which needs to be consumed onsite. The company has reported sales of bio-crude made in their plant in Renfrew, ON, to New England university campuses for central heating plants. Concerns raised included lower heating values compared to petroleum-based fuels, and higher acidity requiring

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[30] Browne, T.C., Singbeil, D. et al, “Bio-energy and bio-chemicals synthesis report”, prepared for the Forest Products Association of Canada and FPInnovations, November 2010. https://www.fpac.ca/wp-content/uploads/publications/Future_of_forestry/Bio_Energy_Final_En.pdf, viewed 2020-01-23.

higher grades of steel in tanks, piping and potentially in burner tips and boilers. One analysis[31] showed that, combining the impact of various renewable fuel credits and other incentives, Ensyn's bio-crude was competing with an effective oil price of about $143/bbl, at a time when West Texas Intermediate was priced at about $30/bbl. In the absence of the various support mechanisms described, the process is not economic. No new plants have been built recently. It is likely that Ensyn would offer to build and operate a plant, selling the product at an agreed price, if customers could be found. Presently Ensyn lists food flavourings, such as Liquid Smoke, on its website. This is obviously a very small market with limited room for new entrants.

The BELT process in La Tuque is a pyrolysis process said to produce a biodiesel from forest harvest residues, but the technology is locked up in non-disclosure agreements and patent licensing deals. It is possible it will be available for licensing at some time in the future.

Vancouver-based Nexterra provides a gasification pathway that converts woody biomass into a so-called syngas (synthetic gas) that can substitute for natural gas in boilers, much as the Ensyn process substitutes for bunker fuels and heating oils. While the gas burns well in a natural gas burner, the heating value is lower, and it is not pipeline-ready due to levels of contaminants. Several commercial installations exist in BC today, operated by Tolko, Kruger and UBC. The units are small, and larger volumes of gas require multiple modular units. Plants are under construction in the UK. Nexterra sells and installs equipment, with the buyer acting as owner and operator. Nexterra also claims to be able to provide syngas of sufficient quality for use in a lime kiln, at a slightly higher capital cost.

Several thermochemical pathways exist for producing fuels or chemicals for sale. These are full-scale gasification plants followed by some sort of synthesis stage, such as Fischer-Tropsch. A critical step is removing trace contaminants from the gas before the synthesis stage; while this is well understood for coal, it is less so for biomass. A leader in the field is Quebec-based company Enerkem, which has developed a gasification process to generate methanol from sorted municipal waste. Their first commercial plant is presently in start-up in Edmonton; the economics are vastly improved due to a negative feedstock price arising from avoided landfill costs. Enerkem has announced a new waste-to-chemicals plant in the Port of Rotterdam, in collaboration with large chemical companies. (Enerkem is focused on the Edmonton and Rotterdam projects and is unlikely to be interested in forestry applications at this time. It is mentioned here to show that the technology can be made to work on very challenging feedstocks.)

The Swedish GoBiGas project aimed to demonstrate renewable natural gas (RNG) from wood waste at a small commercial scale, and was built by the energy utility in Gothenburg, Sweden, with support from the Swedish government. The process, developed by Danish firm Haldor Topsoe and Chalmers University, was a technical success but was shut for economic reasons. Note that Nexterra claims to be able to generate a pipeline-ready natural gas, using their modular system and added gas cleanup equipment, but this has not been proven at demonstration scale.

The classic Fischer-Tropsch process is still in operation worldwide, running on low-grade coal. German and South African firms are leaders in the field. The German firm Thyssen Krupp is working on a pilot plant to run on biomass in partnership with the French oil company Total. As with RNG, scale needs to be very large, and ideally there is a petrochemical refinery next door.

The required effective price of oil for biofuels from wood can be high. In 2008, the Swedish forestry company Stora Enso, in collaboration with the Finnish oil company Neste, announced a demonstration-scale plant to convert bark

[31] Roberts, D., "Access to capital and how to finance a forest sector transformation: Setting the scene", BioFor International, Montreal, February 2-5, 2016.

and sawdust from a sawmill to a refinery-grade Fischer-Tropsch oil at their sawmill and pulp mill plant in Varkaus, Finland. The technology was developed by the Finnish government research institute VTT, analogous to Canada's National Research Council, and was built by a reputable equipment vendor. Technically the project was said to be a success; but by 2015 it had been mothballed for economic reasons. The partners stated that the inability to come to an agreement with the Finnish government over 20-year price support for biodiesel was to blame, but it is also possible that failure to obtain a large EU grant for building of a full-scale plant contributed to the closure. Either way, the need for ongoing government support is obvious.

Table 7: Thermochemical pathways to fuels and energy. See Table 1 for a definition of Technology Readiness Level (TRL).

Product name	**Bio-Crude**	**Biogas for heat**	**RNG**	**FT liquids**
Provider(s)	Ensyn	Nexterra	Haldor Topsoe, GTI	Thyssen Krupp
Type of product	Heating oil	Gas for heating	Pipeline-ready renewable natural gas	Synthesis liquid for petrochemical refining
Market area	Institutional heating plants	Institutional or industrial heating plants	Fuels	Fuels
Market volume	Large	Large	Large	Large
Technology	Pyrolysis	Gasification	Gasification and synthesis	Gasification and synthesis
TRL	8-9	9	6-7 on biomass, 9 on coal	6-7 on biomass, 9 on coal
Integration	Brownfield	Brownfield	Brownfield	Brownfield
Feedstock quality	Clean bark or forest residues, or better	Clean bark or forest residues, or better	Clean bark or forest residues, or better	Clean bark or forest residues, or better
Economics	Depends on carbon accounting	Depends on carbon accounting	Depends on carbon accounting and wood prices	Depends on carbon accounting and wood prices
Fit for Quesnel	Depends on cost of biomass and local use for the fuel	Depends on cost of biomass and local use for the fuel	Depends on wood supply (large) and pipeline proximity	Depends on wood supply (large) and proximity to a refinery
Challenges	Quality of the oil (high acidity, water content, does not mix with bunker)	Gas quality	Economics require very large plants, in turn requiring very large raw material volumes	
Comments	Can be located next to the wood supply; fuel shipped via tanker	Needs to be next to the end-user as the fuel cannot be shipped	Fortis BC needs to be involved	Better suited to the Husky refinery in PG?

The Finnish forestry company UPM makes a biodiesel, called BioVerno[32], using a proprietary process. The process is said to be hydrotreatment of tall oil, a by-product from kraft pulp mills, although the volumes produced imply supplies of tall oil exceeding the amount available in Finland. Other sources of biomass, such as canola or palm oil, are likely being used. The product was developed at UPM's research centre in Kaukas and is produced within the adjoining mill in Lappeenranta, Finland. Capital costs of this approach are likely significantly lower than for a large-scale Fischer-Tropsch plant.

While this analysis appears negative, it should not be rejected out of hand. The combination of new approaches, such as the Nexterra approach to a cleaner syngas which is said to be cheaper, with the availability of forest residual material, should be looked at. In particular a legacy landfill pile may be a suitable feed for one of these processes. FPInnovations is well placed to evaluate volumes of residues available at a range of prices corresponding to different haul distances from Quesnel (for example $30/odt, $60/odt and $90/odt), and an initial review should be conducted to decide if more in-depth analysis is warranted. But this does not change the fact that some form of consistent and fixed carbon accounting will be needed to increase the effective oil price against which these technologies will be competing, and this over a 20-year investment horizon.

Other processes such as hydrothermal cracking (HTC) have been proposed, for instance by Vancouver company G4, or Canfor's project with Licella[33], but these are still at very small scale and will not ready for commercial application for several years. The production of fuel-grade ethanol from wood will be described in the section on enzymatic sugar production.

4.3. Other energy products (hog fuel, pellets, char, heat, power)

Pulp mill energy systems may be re-arranged to upgrade heat to a level sufficient for heating of municipal or public buildings, if not residential districts[34]. District heating opportunities exist where there are large heat sinks, such as hospitals, colleges and municipal buildings; pulp mill waste heat or bark-fired systems such as the Nexterra gasifier or Ensyn pyrolizer can provide heat as needed. While there are exceptions, the Nordic approach to district heating for residential use does not generally work in a Canadian context, for reasons which are outside the scope of this report.

Mill waste heat can also be used for other low-grade heat applications such as greenhouses[35]. Heat from pulp mills or biomass energy systems was proposed for fish farming at one time for a coastal Swedish mill, although it is not clear that the farm is running today due to environmental concerns[36].

The economics of power generation from biomass, in the absence of a host for the waste heat, is well understood and is dependent on BC Hydro contract offers.

Hog fuel, pellets and char are known technologies and won't be described in any further detail here.

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[32] https://www.upmbiofuels.com/traffic-fuels/upm-bioverno-diesel-for-fuels/, viewed 2020-01-26.
[33] https://www.licella.com.au/pulp-paper/, viewed 2020-03-09.
[34] Marinova, M., et al., "Economic assessment of rural district heating by bio-steam supplied by a paper mill in Canada ", Bulletin of Science, Technology & Society, 28(2), p.159-173, 2008. doi:10.1177/0270467607313953. https://publications.polymtl.ca/2297/1/2008_Marinova_Economic_assessment_rural_district_heating.pdf, viewed 2020-02-10.
[35] https://blog.resolutefp.com/2017/09/resolutes-newest-product-offering-cucumbers/, viewed 2020-02-10.
[36] https://www.fishfarmingexpert.com/article/swedish-court-halts-three-fish-farms/, viewed 2020-02-07.

4.4. Chemicals from sugar platforms

The US Department of Energy (DOE) has commissioned several reports identifying sugar-based pathways to intermediate chemicals currently produced by petroleum refineries. The first report, mentioned earlier in this report and produced by NREL in 2004[37], was exhaustive; the second NREL review in 2016[38] did not uncover any new pathways. (See Figure 7 above for a summary of the 2016 report). A parallel EU project came up with a similar list in 2015[39], and furthermore summarised published estimates of GHG reductions compared to the petroleum-based alternative. The conclusions of the two later reports need to be considered in light of oil prices, which at the time of writing were beginning to drop from the $100/bbl level, but the main conclusions stand.

4.4.1. Overview of sugar-based pathways in the EU

There are two considerations here:

First, the potential for sugar-based products to supplant petroleum-based products is potentially enormous, and the European chemical industry has identified this pathway as a critical one. Large investments in R&D and demonstration plants are being made by the EU, the chemical industry, and government agencies active in the Antwerp-Rotterdam-Amsterdam (ARA) port area.

Second, the source of the sugars is an issue. If anything, world sugar prices, which are dominated by Brazilian sugar cane producers, are lower than oil prices. (They are also much more variable, as a bad crop can have a huge impact). Alternatives include sugar beet, which is grown in Europe and is also cheap and easily converted to a very pure sugar stream; in North America corn is less readily converted to sugar and is therefore more expensive. Wood and other so-called cellulosic materials such as corn stover, wheat straw and other agricultural residues are very recalcitrant, with low yields and lower purity levels. These are therefore quite expensive. Any wood to sugar pathway needs to take the reality of Brazilian sugar cane into account.

In this context, the author visited various installations in and around the Port of Rotterdam in 2016.

The Port of Rotterdam is big[40]: at 450 Mt/y of cargo, it is Europe's biggest and 6 times the size of the Port of Vancouver. It was only recently surpassed by Singapore and Shanghai as the world's largest port. Including the ports of Amsterdam and Antwerp, total capacity of this well-integrated complex is well over 750 Mt/y. Rotterdam is also a large petrochemical complex, including 5 oil refineries, 6 refinery terminals, 5 bio-fuel plants, 11 independent tank terminals for oil products, and 7 power plants (of which 3 are designed to run on coal and pellets), all linked by 1500 km of pipelines. At that time there was one biomass-fired CHP plant, making 21 MW of electricity and 80 t/h of steam.

This is important because a biorefinery can be located in one of two places: Next to the biomass supply (for instance, Quesnel), or next to the end-user (for instance, Rotterdam's extended petrochemical park). With a large and stable

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[37] Werpy, T. et al., "Top Value-Added Chemicals from Biomass, Volume I: Results of Screening for Potential Candidates from Sugars and Synthesis Gas", PNNL, August 2004. http://www.nrel.gov/docs/fy04osti/35523.pdf, viewed 2020-01-25.

[38] Biddy, M.J., Scarlata, C. and Kinchin, C., "Chemicals from Biomass: A market assessment of bioproducts with near-term potential", NREL/TP-5100-65509, March 2016. http://www.nrel.gov/docs/fy16osti/65509.pdf, viewed 2020-01-25.

[39] E4tech, RE-CORD and WUR (2015) "From the Sugar Platform to biofuels and biochemicals". Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791, version 2.1, April 2015. https://ec.europa.eu/energy/sites/ener/files/documents/EC%20Sugar%20Platform%20final%20report.pdf, viewed 2020-01-25.

[40] https://www.portofrotterdam.com/en, viewed 2020-01-26.

supply of wood pellets available to it, Rotterdam is well placed to compete, even if the ten-year cost of pellets has ranged from €115/odt to €185/odt[41].

The Dutch and Flemish governments have made strong policy commitments to a greener, 'circular' economy. There is a new realization that biofuels will arise as by-products from bio-chemicals production, and not the reverse. There is a strong political desire to see a bio-chemical industry arise in the chemical park in the Port of Rotterdam. Biomass availability is limited locally, and is likely to consist mainly of wood pellets imported from the Baltics, Russia, Brazil, the US South-East, and Canada for use in coal-fired power plants. Flows of pellets through the Port of Rotterdam are about 9 Mt/y today[42]. Note the Port also mentions wood chip imports on its web page[43], although this is probably limited to Baltic states. This should be a particular concern for Canadian governments: we can convert our wood supply to bio-chemicals at home; or we can make pellets for the EU to do so in Rotterdam.

In particular, the wood to sugar pathway, leading on to organic acids such as succinic acid, lactic acid, 1,4-butanediol, FDCA (furan dicarboxylic acid) and others as identified by NREL and EU reports cited above, has been identified by EU players as critical[44].

The food-versus-fuel debate is part of this preference for wood, but the main reasons for this push have to do with consumer demand for green products, which is much stronger in the EU than in North America. The consumer is pressuring large brand owners, such as Coca-Cola, Nestle, IKEA or Lego, for 'green' alternatives; these in turn are pressuring chemical suppliers such as BASF and others who otherwise would have little or no incentive to move in this direction. The so-called Coke "plant bottle", made partly with a sugar-based bio-chemical from Avantium, is an example. The NaturALL Bottle Alliance, regrouping Sarnia-based Origin Chemicals and brand owners such as Pepsico, Danone and Nestlé, is a competitor to the Avantium process used by Coca-Cola.

Separately, the Dutch are planning to shut their coal-fired power plants, and limit wood pellets to combined heat and power applications. Large power generators such as RWE now find themselves (presumably) with large long-term commitments to buy pellets which they may not need.

Dutch and Flemish industry players who are driving the agenda may be well-versed in the petrochemical world, but they do not understand lignin, although they do recognize the value of bio-aromatics from lignin, and that these new uses for lignin will be critical if the path to sugars is to be profitable. They are spending large sums in Dutch and Flemish R&D facilities[45] to quickly get up to speed on lignin properties and transformation processes, as well as looking to buy knowledge from research institutes such as VTT, RISE and FPInnovations. Essentially the traditional forest R&D community, led by VTT, RISE and FPInnovations, are providing R&D on a "push" model, trying to identify pathways that fit nicely into their current forestry constituencies; the Dutch and Flemish R&D community, led by VITO (Belgium) and TNO (Holland) are working on a "pull" model driven by demand from the chemical industry in response to consumer demands. This explains the large differences in funding availability.

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[41] Fritsche, U.R. et al., "Margin potential for a long- term sustainable wood pellet supply chain", IEA Bioenergy Task 40, 05/2019. http://task40.ieabioenergy.com/wp-content/uploads/2019/05/Fritsche-et-al-2019-IEA-Bio-T40-Margin-Pellet-Study.pdf, viewed 2020-02-11.
[42] https://www.pellet.org/wpac-news/pellet-hub, viewed 2020-02-11.
[43] https://www.portofrotterdam.com/en/doing-business/logistics/cargo/dry-bulk/biomass-handling-storage-and-distribution, viewed 2020-02-11.
[44] Zoetemeyer, R., "Redefinery: A large scale Biorefinery Cluster Initiative, the conversion of lignocellulose into chemical building blocks", BioFor 2016, Montreal, Canada, February 2, 2016.
[45] https://www.biorizon.eu/, visited 2020-01-29.

At one time there was an EU objective to build a 1 Mt/y plant making sugars and lignin[46], probably via steam explosion, by 2019, and multiple plants shortly thereafter; but this was overly optimistic, and the objective has been quietly dropped from recent press releases. More recent news releases describe pilot work to generate samples for testing[47]. The key players[48] driving this very aggressive agenda are:

- The Port of Rotterdam, which has created a new 80-hectare site on reclaimed land to host bio-chemicals producers;
- Power producer RWE, who would look after pellet supply and logistics;
- Various bio-chemical producers, currently using sugars from sugar beet or sugar cane, who would take five and six carbon sugars from wood and convert them to various intermediate chemicals;
- A range of world-class petrochemical firms who would convert these intermediates to products the brand owners can use in packaging and other applications;
- Coal-fired power producers, who would initially burn lignin for fuel as uses are developed.

The consortium managing this project is well aware that earning significant value from lignin is critical to the sugar pathway and is supporting an aggressive R&D program to develop new lignin-based products. Budgets were €3.7B in combined industrial and EU funds period 2014-2020. Renewed funding is being sought under the Horizon Europe program for a further 7-year program.

4.4.2. Pathways from sugar to chemical intermediates

The 2015 EU report is outlined in Table 8. A highlight is bio-based 1,4 butanediol (BDO), which is a drop-in replacement for petroleum-based BDO with market size of 2.5 Mt/y. The EU report identifies low productivity and poor tolerance of the micro-organisms to the BDO as it is generated and suggests micro-organism strain development should be an area of focus. The TRL of 7 reflects this challenge, but the report is now over 5 years old, and micro-organism development is proceeding very quickly. Recent market analyses point to slow growth in production of bio-based BDO[49] as well as current overcapacity in the petrochemical-based BDO due to rapidly growing Chinese capacity; at the same time progress is being made on conversion pathways from sugar[50]. As with any pathway, proper due diligence is necessary to ensure the technology and market are both positive. Genomatica has licensed their sugar-to-BDO technology to Novamont[51], who operate a 30,000 t/y plant in Italy, and would likely be willing to license to anyone else who felt there was a market opening for a new player.

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[46] See for example this 2014 press release: http://news.bio-based.eu/biorizon-well-way-development-biobased-aromatics/, viewed 2020-01-28.
[47] Recent lignin pilot work is described here: https://www.biorizon.eu/news/event-report-biorizon-forging-ahead-with-bio-aromatics-upscaling, viewed 2020-01-28.
[48] http://www.biorizon.eu/biorizon/, accessed 2020-01-26. Members are listed here: https://www.biorizon.eu/community/members/
[49] https://ihsmarkit.com/products/butanediol-chemical-economics-handbook.html, viewed 2020-01-26.
[50] https://onlinelibrary.wiley.com/doi/abs/10.1002/bbb.2016, viewed 2020-01-26.
[51] http://biomassmagazine.com/articles/13742/novamont-opens-plant-for-production-of-biobased-1-4-butanediol, viewed 2020-01-26.

Table 8: Key sugar-based products, based on Tables 1, 4 and 5, EU report [2015]. Greenhouse gas savings relative to petroleum incumbents were culled from an extensive literature survey and thus reflect a range of studies. Note that some companies listed, such as BioAmber, have been taken over or have gone out of business.

Data current as of 2015					Bio-product market				Total bio + fossil market			
Product	**Major actors**	**Key markets and value proposition**	**Cost relative to fossil-based alternative**	**GHG saved relative to fossil alternative**	**Price $/t**	**Volume, t/y**	**Sales, $M/y**	**% of total market**	**Price, $/t**	**Volume, kt/y**	**Sales, $M/y**	**TRL**
Acrylic acid	BASF-Cargill-Novozymes; OPXBio-Dow	Drop-in for a common intermediate	20% to 48% better when commercial	>70%	$2,688	300	$0.90	0.01%	$2,469	5,210	$12,863	5
Adipic acid	Biochemtex DSM; Rennovia; Verdezyne	Drop-in for Nylon 6,6 and polyurethane	Competitive	70% to 90%	$2,150	1	$0.002	0.00%	$1,850 to $2,300	3,019	$5,600 to $6,900	5
1.4 butanediol (BDO)	Genomatica; others	Drop-in for fossil based BDO	15% to 30% better; competitive at $45/bbl	70% to 117%	$3,000	3,000	$9	0.10%	$1,850 to $2,300	2,500	$4,500 to $8,000	7
Succinic acid	Reverdia; Succinity; BioAmber; Myriant	Substitute for a range of polymers	Equal	75% to 100%	$2,940	38,000	$111	49%	$2,500	76	$191	8
Furan dicarboxylic acid (FDCA)	Avantium; Corbion; others	PEF a substitute for PET (e.g. Coke Plant Bottle)	Possibly high	45% to 68%	High	45	$10	100%	High	0.045	$10M	5
Lactic acid	NatureWorks; Corbion; others	Substitute for packaging, insulation, etc.	TBD	30% to 70%	$1,450	472,000	$684	100%	$1,450	472	$684	8

Other chemicals in the list are also drop-ins; lactic acid is commercial and is sold into a range of mature markets such as biodegradable cutlery and other products. However, entering this market requires competing with NatureWorks and Corbion, two large and well-entrenched players. A pitch to Corbion or NatureWorks to build a plant in Quesnel would be challenging, time consuming and risks being unsuccessful unless site-specific advantages to them can be identified. On the other hand, the expected growth in demand for substitutes for single-use plastics could drive this market very quickly, opening up opportunities for a nimble player.

4.4.3. Enzymatic sugar production from wood

The products described in the preceding section require a sugar stream as feed. Cellulose is essentially a polymer of glucose, a so-called 6-carbon sugar. Glucose is easily fermented to ethanol or to a wide range of other products. The objective of enzymatically converting wood-based cellulose to glucose has been addressed by large R&D efforts over the last two decades, not least by researchers led by Jack Saddler at the UBC Faculty of Forestry.

The first step in any enzymatic process is the initial pre-treatment stage, which opens up the cellulose structure for access by enzymes, and perhaps to remove lignin and hemicellulose. Classic approaches include acid pre-hydrolysis and steam explosion. Both are acid-based approaches, which has its own set of issues: acidic conditions tend to inhibit enzymatic treatment and damage sugars, but the equipment is inexpensive. Both are easily available from existing vendors.

Once an open cellulose structure has been obtained, with or without lignin removal, the next step is conversion to glucose monomers. There are several major challenges:

- As a defense against rot, which arose through natural selection, cellulose is naturally resistant to enzymatic breakdown;
- Wood also contains lignin, which further impedes typical enzymes in their work to break down cellulose; the ideal starting point is therefore cellulose from which the lignin has been removed in some type of pulping process, further increasing costs;
- Hemicellulose can be broken down into sugars as well, but typically generates 5-carbon sugars such as xylose. Buyers of sugars will prefer glucose or xylose, but mixed streams will have to be sold at a discount;
- Given the presence of lignin and hemicellulose, and given the recalcitrance of cellulose, the yields of sugar per tonne of wood are low, and there will remain a lignin-rich residue (a so-called lignin-carbohydrate complex, or LCC) from which significant value needs to be extracted in order to make the process economic;
- Enzymes have traditionally been difficult to engineer to be more aggressive towards cellulose.

Given all of this, it will be obvious that wood is not the best candidate for enzymatic processes. Nonetheless, work continues in the area due to interest in the high-value products that can be made from a sustainably harvested, non-food, renewable resource with no land-use change issues. Currently the two major enzyme producers offer products that are reasonably effective from a yield standpoint, but that are still not economic unless the lignin co-product can generate a significant revenue stream. The Finnish company MetGen is using advanced methods for trialling large numbers of novel, genetically modified enzymes at a very quick pace to accelerate the development of enzymes that can potentially break down cellulose as well as lignin. So too is NREL Berkeley, with robotic systems capable of producing 250,000 new enzymes per year. Progress may turn out to be rapid.

The final issue is use of the lignin-rich residue. This is addressed in the section on lignin below.

4.4.4. Sugar production via the TMP-Bio process

The TMP-Bio process, developed by FPInnovations and currently in development at the FPInnovations pilot plant hosted by Resolute Forest Products in Thunder Bay, Ontario, provides a novel alkaline pre-treatment pathway to wood-based sugars[52]. Alkaline conditions avoid the issues around inhibition that can be problematic with acid processes. The process is basically a simplified version of the chemi-mechanical pulping process such as the one operated at QRP, followed by an enzymatic process to degrade cellulose. For a variety of technical reasons, the process was initially developed to run on hardwood, which can be somewhat easier to convert than softwood, at the cost of increased levels of 5-carbon sugars in the end-product. (There are markets for 5-carbon sugars, but less so for mixed sugar streams; and the technologies for separating 5 and 6 carbon sugars are expensive and of limited effectiveness.)

The process is inexpensive to implement, especially if existing refiners can be repurposed; the output consists of a mixed five- and six-carbon sugar stream and a lignin-rich residue. Economics developed by FPInnovations show that typical market prices for a mixed sugar stream are too low on their own to make the process economic; revenue from the lignin-rich residue must be significantly higher than from the sugar stream. Essentially this becomes a lignin plant with a sugar by-product, not the reverse, unless sugar is converted to a value-added product onsite. Further information on the current state of the technology, and its availability for licensing, may be obtained from FPInnovations.

The competition includes a range of steam explosion and acid hydrolysis pathways. The Sweetwoods process uses a screw feeder instead of the refiner proposed by TMP-Bio for destructuring biomass, and uses acid instead of alkali. Screws have a habit of plugging, while refiners are well known and already installed; alkaline conditions minimise the impact on downstream enzymatic and fermentation processes. A proper due diligence process will be necessary to identify the most appropriate technology.

4.4.5. Potential for chemicals from sugar platforms in a Central BC context

Given the existence of the QRP mechanical pulping mill in Quesnel, and given the potential for consuming underutilised aspen and birch, the main option would start with implementation of a process such as TMP-Bio process at QRP. Both mixed sugar and lignin fractions would need to be sold.

Conversion of the sugar product to some form of end-product is necessary to minimise shipping costs: the sugar stream will be an 8% to 15% slurry in water and will be very expensive to ship any distance, or to dewater to minimise shipping costs. It therefore makes more sense to convert to value-added products, typically through fermentation processes, before dewatering and shipping. The succinic acid plant in Sarnia ships succinic acid in a granular powder form, and some similar form of product will be needed. This also helps overall site profitability.

It is worth noting that the workforce for these types of plants is likely to be highly specialised and not currently available in the Central Interior. There will be a need for training, to move existing employees to the new plant or train new ones.

The most likely product candidates for early acceptance are those which are drop-in, chemically identical duplicates of existing petrochemical products, as this will reduce the risk to the customer and bring the focus to cost competitiveness with the incumbent. BDO is an obvious choice. A paper prepared by this author for FPInnovations in 2016 outlines some other options. As West Fraser is a member of FPInnovations, their staff will be aware of the latest R&D developments in this area and will be best placed to identify any investment

[52] Disclaimer: The author of this report contributed to the TMP-Bio patent but will earn no financial gain if it succeeds.

opportunities. Conversations with former BioAmber staff, or with Bioindustrial Innovation Canada in Sarnia, may clarify challenges to be overcome, as BioAmber was considering moving from succinic acid to BDO at the time of the bankruptcy. Other companies include Genomatica who are open to licensing their technologies.

4.5. Chemicals from lignin

4.5.1. Lignin overview

Lignin is a short word that covers a wide variety of materials, with a wide range of properties. The first indicator of lignin properties is the source: hardwood, softwood and agricultural lignins are made up of three distinct monomers that can't always be interchanged in a given end-use. (This report will focus on hardwood and softwood only). The second indicator, which has a bigger impact on potential end-uses than the source, is the unique set of processing steps taken to separate lignin from wood. The scientific literature is full of descriptions of lignin obtained from sulfite, soda or Organosolv pulping processes; these will not be discussed here since the use of the cellulose fraction is problematic, and it is unlikely that anyone will build a new pulp mill using any of these processes in the near term.

Staff at FPInnovations are building a series of pathways from kraft lignin to products and the necessary processing steps to get there. The main beneficiary of this work at this time is West Fraser, and they will have the most up to date information. A summary follows; this report will focus on kraft lignins, and lignin from the TMP-Bio process.

The main attraction of lignin is that it is a so-called aromatic molecule. The petroleum refinery makes six basic molecules which underpin almost the entire range of petrochemicals. Three are so-called aliphatic molecules: straight-chain molecules, meaning the carbon atoms are linked in a daisy chain: ethylene (2 carbon atoms), propylene (3 carbons) and a couple of different 4 carbon molecules starting with butylene. With some exceptions, sugar-based molecules will largely be straight-chain molecules. The other three molecules, benzene, toluene and the xylene isomers, are called aromatics; the six carbon atoms in these molecules are arranged in a hexagon. Aromatics, which account for 40% of petrochemicals, serve as the basis for a range of engineered plastics with properties that cannot be obtained with the straight-chain molecules or their derivatives. And since lignin is the only natural aromatic molecule, it becomes obvious that products requiring the functionality of aromatics, such as phenolic resins, are the place to start when trying to market lignin.

That being said, prices of the basic aromatic molecules are generally too low for lignin to compete on a cost basis. One recent presentation[53] implied that there is a "green premium" to be had for a bio-based para-xylene, but this would have to be demonstrated through firm purchase orders. It is likely important to convert lignin to an intermediate chemical, where the added processing moves the end-product to a more valuable, if smaller volume market. An example is the recent development of a BPA-like bio-substitute developed by a PH.D. student at KU Leuven[54], which appears to have the properties required to make poly-carbonate substitutes without the hormone problems associated with BPA (bisphenol A). The resin pathways described below also work in this context.

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[53] Galowitz, S., "Origin Materials: wood to specialty chemicals", BioFor International, Montreal, February 3-6, 2020.
[54] Koelewijn, S.-F., "Safety by natural design: benign bisphenols from biomass", Ph. D. Thesis, K.U. Leuven, 2019. https://www.kuleuven.be/doctoraatsverdediging/fiches/3E13/3E130554.htm, viewed 2020-02-07.

A range of reports have tried to provide lignin roadmaps similar to the DOE and EU reports on sugar pathways. A leading researcher in the area of lignin properties has published a recent overview of lessons learned[55]. NREL continues to work in this area, supported by DOE[56]. A book on the topic was published by NREL staff in 2018[57]. A very recent report summarises the latest understanding of lignin properties and markets[58].

4.5.2. Kraft lignins

As the operator of Canada's only kraft lignin plant, and operator of the world's first LignoForce process, West Fraser staff will be very familiar with the two major different approaches to operating the plant, and the suite of end-products that can be made with each type of softwood lignin produced. The first "launch market" defined for softwood kraft lignin by West Fraser and FPInnovations was as a substitute for plywood resins, which are phenolic in nature. Subsequent pathways include resins for medium-density fibreboard (MDF)[59]. This was partly for historical reasons: the first lignin plant was built and operated by the Howard Smith Pulp mill in Cornwall, Ontario in the early 1950's. The purpose was to offload the recovery boiler to make more pulp; the lignin was used as a glue in the Arborite process for kitchen countertops. At the time, the price of petroleum-based glues was still very high, so this process made economic as well as technical sense. By the mid-1960's, the plant in Cornwall had a new, larger recovery boiler; and the price of petroleum-based resins had dropped to levels comparable to today's prices. The lignin plant was shut, and Arborite switched to petroleum-based resins. So using lignin as a glue in a panel is not a new idea; the issue is the R&D gap with petroleum-based phenolic resins.

FPInnovations assembled data on oil prices and historical petroleum-based resin prices, showing that lignin is competitive in this market on a cost basis when oil exceeds $40 to $50/bbl. Technically, initial lab work showed plywood performance was not affected until the lignin substitution rate exceeded 50%, but process operations issues in the plywood mill limited initial substitution rates to a range of 10% to 20%. As petroleum resins benefit from 70 years of research, and lignin only a decade, this is good progress and it is expected that better results have been or will soon be obtained.

The same is likely true of other applications. For example, the Quebec-based company Enerlab has a process for incorporating kraft lignin into polyurethane products, and is aggressively working with lignin producers to design lignin products that will fill their need. However, Enerlab is a small player in this field, and it will be important to get the attention of larger players to increase volumes. Furthermore, obtaining the regulatory approvals needed for properties such as fire retardancy is time-consuming and expensive. The Ontario form Woodbridge Foams, which makes polyurethane foams for use in automotive seat cushions and body panels, is aware of the potential. In this context Natural Resources Canada has announced funding for two new pathways from biomass to foams[60].

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[55] Glasser, W., "About making lignin great again—some lessons from the past", Front. Chem., 29 August 2019. https://doi.org/10.3389/fchem.2019.00565, https://www.frontiersin.org/articles/10.3389/fchem.2019.00565/full, viewed 2020-01-28.

[56] Beckham, G.T., "Lignin Utilisation", Technology Session Review Area Lignin, NREL, March 6th, 2019. https://www.energy.gov/sites/prod/files/2019/04/f61/Lignin%20Utilization_NL0025416_0.pdf, viewed 2020-01-28.

[57] Beckham, G.T. (ed.), "Lignin Valorization: Emerging Approaches", Royal Society of Chemistry, 2018. https://doi.org/10.1039/9781788010351; https://pubs.rsc.org/en/content/ebook/978-1-78262-554-4, visited 2020-01-28.

[58] Dessbesell, L. et al., "Global lignin supply overview and kraft lignin potential as an alternative for petroleum-based polymers", Renewable and Sustainable Energy Reviews, Volume 123, May 2020, 109768.

[59] Paleologou, M., "Kraft lignin: A new bioproduct platform", BioFor International, Montreal, February 3-6, 2020.

[60] https://www.canada.ca/en/natural-resources-canada/news/2020/02/canadian-innovation-leads-to-greener-insulation-products.html, viewed 2020-02-07.

Funded by IFIT, Domtar's Espanola mill has developed a process for compounded and modified lignin pellets for use in adhesives, thermoplastic composites and foams[61]. Other similar projects are underway, with more or less fanfare.

It is to be expected that West Fraser is working on these and other pathways, in collaboration with FPInnovations. The market is growing slowly, but it is growing; and the pull from European chemical firms, as described in the section around the Port of Rotterdam above, may lead to increased demand in the future, especially if the necessary sugar plants are slow to start up.

The LignoForce system was designed by FPInnovations and licensed to the Vancouver firm NORAM, and is operated by West Fraser at their mill in Hinton, Alberta. The competing LignoBoost system is offered by Valmet, and is in operation at mills run by Domtar (Plymouth, North Carolina) and Stora Enso (Sunila, Finland). The Sunila mill is said to be working on using lignin in novel battery electrodes, which takes advantage of the high carbon content in lignin.

Finally, the Brazilian firm Suzano is operating a lignin plant of its own design; information on performance is not readily available. The LignoForce system is more flexible, and has significantly reduced safety risks due to the patented process to convert reduced sulfur compounds to sulfur dioxide very early in the process. In the context of Quesnel, the obvious path forward is to build a second softwood lignin plant at CPP; the choice of vendor would be made by West Fraser. A process integration study would be needed to verify the suitability of CPP as a host[62].

Table 9 summarises some of the lignin pathways in place or in development.

Table 9: Summary of some lignin pathways currently underway.

Lignin product	**Description**	**Current players**	**Current status**
Energy	Burn lignin in a power boiler to reduce load on the recovery boiler and increase pulp production	Domtar Plymouth	Active
Energy	Burn lignin in the lime kiln to reduce fossil use and GHG emissions	Stora Enso Sunila	Active
Plywood glues	Partial substitution of phenol-formaldehyde glues	WF Hinton; Suzano?	Active
MDF glues	Partial substitution of pMDI glues	WF Hinton	Development
Lignin-based plastic pellets	Substitute for plastic pellets used in injection molding	Domtar Plymouth and Espanola	Active
Isocyanate	Replace the isocyanate component of poly-urethane foams	Enerlab	Active
Urethane	Replace the urethane portion of poly-urethane foams	Woodbridge?	Development
Thermo-acoustic foam	Substitute at least 60% with lignin	Mecanum Inc.	Research

[61] https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/37569.pdf, viewed 2020-02-11.
[62] Bakhtiari, B., "Techno-economic perspective for integrated biorefineries: impacts of mill bottlenecks and system boundaries", BioFor International, Montreal, February 3-6, 2020.

4.5.3. Lignin from the TMP-Bio process

The lignin-rich residue from the TMP-Bio process is a completely different product from kraft lignin, since it contains as much as 35% unconverted cellulose fragments and short sugar polymers. As a result, it may not compete with the niche markets for which softwood kraft lignin, at 99% purity, is so well suited. While this author was involved in the early development of the TMP-Bio process, including the identification of potential end-uses and customers, most of that information is still confidential and restricted to FPInnovations members. Nonetheless researchers and company executives[63] have publicly discussed applications in animal feed, biocides, plant growth regulators, pest repellants, flocculants and dispersants. While this is a fairly standard list of things that can be made from lignin and while it is unlikely that the research efforts are addressing all of these simultaneously, it is likely that at least some of these hold enough promise to be worth looking at. In the Quesnel context, the obvious pathway is installation at QRP of a hardwood TMP-Bio process, with sugar stream used as described above, and the hardwood lignin stream used in products as identified by FPInnovations and West Fraser.

4.5.4. Lignin from classic enzymatic processes

The lignin-rich stream generated in an enzymatic process preceded by an acid hydrolysis or steam-explosion pre-treatment stage will be similar to the TMP-Bio lignin stream. It will consist of lignin and residual sugar polymers, cellulose fragments, and possibly the remnants of the enzymatic proteins. Currently this material, where generated in corn ethanol plants, is burned.

4.6. Other pathways using kraft mill by-products

These pathways, like lignin from black liquor, all take advantage of pulp mill streams that currently go to recovery or the sewer. The volumes will be low, markets will be small local opportunities, and the processes will depend on the continued operation of the pulp mill.

Methanol, also known as wood alcohol, can be extracted from the recovery cycle and purified. A process designed by A.H. Lundberg, and improved by FPInnovations, has been in operation in an Alberta mill for several years now. The scale if applied to CPP would likely be of the order of 2 to 5 tonnes per day. Methanol is typically made from methane (natural gas) by Methanex and shipped from their stranded gas assets around the world, so the biggest advantage would be for a local user of methanol who could save on shipping costs from the Port of Vancouver. The 'green' attribute would be a bonus. Typical local uses of methanol may include windshield washer antifreeze, or as one of the components in the production of biodiesel from canola or other oil crops.

Tall oil can be converted into a range of specialty products. Companies such as Arizona Chemicals (now Kraton Corporation[64]) buy tall oil and convert it to a range of high-value, low-volume specialties. Another option is to convert it to biodiesel. Work by FPInnovations many years ago estimated that biodiesel production from tall oil would be limited to about 3 litres per tonne of pulp production; the only Canadian location where this made sense was if the three Prince George mills combined their tall oil and sold the resulting fuel to the Husky refinery. Bearing in mind that this so-called fatty acid methyl ester (FAME) biodiesel cannot be used in cold weather above about 2% substitution rates, there could be a small market in the BC forest sector for a locally-made biodiesel, especially if combined with local methanol extraction. Currently tall oil is burned, whether in recovery or in lime kilns, if not sold to one of the specialty companies. This pathway makes sense only if CPP is consuming fresh

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[63] Tremblay, R., "Resolute Forest Products' vision for the future of the forest products sector", BioFor International, Montreal, February 3-6, 2020.

[64] https://www.kraton.com/, visited 2020-01-28.

wood, as beetle-killed wood will be very low in extractives. Addition of canola oil or residues will increase tall oil production by decreasing solubility of soaps in black liquor, making them easier to recover.

Turpentine can be extracted from softwood pulping processes. The amount of turpentine available will depend on the wood species, with southern pine being particularly rich in these extractives. The potential volumes would have to be estimated for CPP and QRP, but are likely to be low, especially if the mills are still consuming dead beetle-killed wood.

Pulp mill secondary sludges, which are incinerated or landfilled today, can be a source of so-called PHAs and PHBs, which can be converted to bio-degradable plastics. Bosk Bioplastics claims[65] to have sold out their 50 kT/y plant last year. The process of getting to market involved two critical steps. The first was developing the full process from PHA to a pellet that would allow injection molders to switch from polyethylene with no changes to their process; the second required getting brand owners such as cosmetics packaging manufacturers to decide they want the product enough to lean on their suppliers. The first step was driven by the second. The dependence on cosmetics packaging implies the process is not cost-effective for conventional packaging; extraction of PHAs is costly due to the low concentrations in pulp mill sludges.

4.7. Fibres, textile fibres, micro-fibrils and nano-crystalline cellulose

So far, this report has focused on using lignin as a chemical, and breaking down cellulose to a sugar which can also be used as a platform for chemicals. But cellulose fibres are Mother Nature's "carbon fibre" and can be used in a wide range of applications.

4.7.1. Novel uses of conventional pulp fibres

Conventional kraft and mechanical fibres are being developed for a range of applications, such as blown insulation. Figure 14 shows a cellulose-based acoustic insulation product being blown into the ceiling of the author's residence during renovations in the winter of 2017-18.

More interesting applications involve modifying the cellulose fibre, leading to increased cost but also increased performance. IFIT funding has supported Domtar Dryden in offering a so-called "modified softwood pulp fiber for high-performance composites"[66]. Papiers Masson, also funded by IFIT, is working on a modified TMP fibre for composites[67] such as interior car door panels. Capacity is given as up to 40 tonnes per day of densified wood fibre. While wood flour is commonly used as a low-cost filler in these types of composite, the emphasis on fibres for auto parts implies that they contribute some level of strength to the final product.

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[65] Boudreault, P., "Lessons to be learned from a bioproduct marketing approach in the plastics industry", BioFor International, Montreal, February 3-6, 2020.
[66] https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/37608.pdf, viewed 2020-02-11.
[67] https://cfs.nrcan.gc.ca/pubwarehouse/pdfs/38433.pdf, viewed 2020-02-11.

Figure 14: Commercial cellulose-based insulation material.

4.7.2. Cellulose nano-crystals

Cellulose nano-crystals (CNC), formerly known as nano-crystalline cellulose (NCC), was developed at McGill University and scaled up by FPInnovations. (The term NCC is a CelluForce trademark). The patented process was licensed to CelluForce[68], originally a joint venture between FPInnovations and Domtar; oil industry company Schlumberger, Suzano and Investissement Québec later took equity positions. Installation of a new CNC plant would be done in partnership with CelluForce as demand increases and drives new commercial units. The product portfolio is confidential, but the Schlumberger application is known to involve use as a viscosity modifier in completion fluids for oil and gas wells. The CelluForce website lists a variety of other products across a range of industries.

The University of Alberta and the Alberta Innovates research institute (now InnoTech Alberta[69]) have developed a parallel process, covered by another set of patents, which is being trialled by one of the Alberta pulp and paper mills; the availability of this technology for licensing would need to be verified. The performance of this product is not well known publicly, and the production capacity is significantly smaller than the CelluForce plant in Windsor, Quebec; scale-up beyond pilot operation still needs to be done.

68 https://www.celluforce.com/, visited 2020-01-28.
69 https://innotechalberta.ca/research-facilities/cellulose-nanocrystals-cnc-pilot-plant/, visited 2020-01-28.

4.7.3. Cellulose filaments

There is a bewildering array of cellulose filament products being offered which range in price and performance from the basic kraft fibre to the very high-tech, but very expensive CNC nano-crystalline fibre. One example is the nano-fibrillated cellulose (NFC) process, also developed by FPInnovations and in operation at Kruger and (most recently) announced by Resolute[70] mills in Quebec; this product is marketed through an arrangement with Vancouver-based Performance Biofilaments[71], a joint venture between Resolute Forest Products and Mercer International. The recent announcement of the new plant operated by Resolute implies that markets are growing. It is believed that other mills are producing NFC, but are doing so without press or fanfare, and are incorporating the material internally in their process. There are applications in the paper making process for NFC to enhance performance properties of paper (for example tissue strength). The process is a modified mechanical pulping process, hence the interest from Eastern Canadian newsprint producers. The availability of a license to implement this technology at QRP would need to be verified, and market projections verified with Performance BioFilaments.

The Finnish forestry company UPM once had a cellulose filament process, but these efforts may have been redirected into other avenues such as a cellulose-reinforced product for use in 3D printing[72]. While this technology is unlikely to be available for licensing to Canadian companies, it is an example of the large range of R&D activities in this field.

4.7.4. Textile fibres

Several processes have been developed recently in Finland to convert cellulose to a textile fibre for use in clothing. To understand the benefits, it is worth reviewing the competition.

Current processes for making rayon from wood fibre start with a dissolving pulp mill. The Indian conglomerate Aditya Birla (AV Group) operates such mills in New Brunswick, Ontario and Sweden, and ships the pulp to India to be converted to rayon. That rayon process involves carbon disulphide and is very challenging from an environmental perspective. The process is common in India and China, but there are no rayon plants using the carbon disulphide process in the Western world. (There are many companies offering clothing made from bamboo, with the unstated implication that this is "greener" than the equivalent petroleum-based process for making rayon, but this ignores the issues around the carbon disulphide process required to convert the bamboo into rayon.) A less toxic process has been developed by the Austrian firm Lenzing and is available for licensing. Both approaches require that the pulp mill be dedicated to the production of a viscose fibre. In the context of Quesnel, these traditional approaches would require spending of the order of $100M to convert the CPP mill, permanently, from kraft to dissolving pulp, at which point the mill is "all in" and cannot easily go back to making conventional kraft pulp. Given the swings in the dissolving pulp industry[73], this is a risky move.

Within this context, at least four separate processes have been developed in Finland to make textile fibres without the environmental impact of the carbon disulphide process.

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[70] https://resolutefp.mediaroom.com/2020-01-15-Resolute-invests-38-million-in-its-Kenogami-mill-in-Quebec, visited 2020-01-28.
[71] http://www.performancebiofilaments.com/EN/products, visited 2020-01-28.
[72] https://www.upm.com/about-us/for-media/releases/2019/04/upm-and-carbodeon-developing-cellulose-and-nanodiamond-materials-for-3d-printing/, visited 2020-01-28.
[73] See for example https://www.newswire.ca/news-releases/fortress-global-enterprises-announces-unsuccessful-completion-of-strategic-initiative-892578894.html, visited 2020-01-28.

The Infinited Fibre Company (IFC)[74] has licensed a process technology developed by VTT. It is likely that new licenses could be obtained from VTT; the Finnish energy company Fortum has invested in IFC[75]. This process, however, requires dissolving pulp as the feed material, in turn requiring conversion of an existing kraft mill, such as CPP, to this new product stream. This is a large commitment in terms of cash and in terms of committing to a new market which has significant variability in pricing. (The process is also claimed to run on recovered cotton clothing.)

Spinnova's process, also spun off from VTT, is said to make a textile fibre directly from kraft pulp through a mechanical process. The pulp mill is thus free to continue selling pulp into existing markets, diverting fibre to textiles as markets demand, but with no alterations to existing pulping processes. This process would benefit from co-location with a pulp mill, but likely does not depend on it; indeed, cellulose fibre could be purchased on the open market from suppliers such as kraft mills, cotton recyclers, etc. Spinnova's process, also developed at VTT and presently at the pilot stage, spins micro or nano-scale cellulose fibres into a filament, possibly with some form of binder to keep it all together[76]. Spinnova's business model is also open to licensing.

The Finnish pulp producer Metsä Fibre has developed its own process in-house. Involving ionic liquids and based on technology from Aalto University (formerly Helsinki University of Technology), it requires market kraft pulp as its feed, and is being trialled at their new pulp mill in Äänekoski, Finland[77]. At this time, Metsä is not considering licensing this technology, but company officials contacted by the author have said "never say never". Note that ionic liquids can be expensive and recovering them for reuse challenging.

A fourth process developed recently by VTT, BioCelSol, was described recently, but this also appears to require dissolving pulp[78] as a feed. The pre-treatment process is enzymatic. This is still at the laboratory scale.

At least the first three processes listed have been permitted under Finnish environmental rules and should therefore be suitable for use in Canada. Estimates of market volumes have not been provided publicly but are potentially large. Costs are not known and are being kept confidential. IFC and Spinnova, however, would welcome enquiries.

[74] https://infinitedfiber.com/, visited 2020-01-28.
[75] https://www.fortum.com/media/2019/04/fortum-complements-its-value-chain-biorefining-investing-infinited-fiber-company, viewed 2020-01-28.
[76] https://spinnova.com/, viewed 2020-01-28.
[77] https://www.metsafibre.com/en/about-us/Production-units/Bioproduct-mill/Pages/Bioproducts.aspx, viewed 2020-01-27.
[78] Hörhammer, H., "Alkaline oxidation method for producing dissolving pulp for textile fibres", BioFor International, Montreal, February 3-6, 2020.

4.8. Technology summary in a BC Central Interior context

Table 10 summarises the largest potential opportunities other than fuels.

Table 10: Summary of bio-chemical processes in a Central Interior context. Other opportunities are listed in Section 3.

Product name	TMP-Bio process		Kraft lignin	Cellulose fibre products
Provider(s)	FPInnovations + Genomatica		NORAM or Valmet	Spinnova
Type of product	Sugar stream to BDO	Lignin stream to?	Lignin to resins	Textiles
Market area	Bioplastics	Biomaterials	Biomaterials	Textiles or composites
Market volume	Up to 2.5 Mt/y	?	Plywood resins are ~1 Mt/y	Potentially large
Technology	Enzymatic conversion of cellulose to sugars, then fermentation to BDO. To be verified on a mixed sugar stream	Separation from sugar stream by centrifuge or filtration	Lignin precipitation from softwood kraft black liquor	Fibrillation; acid treatment of kraft fibres, fibre spinning, etc.
TRL	6-7	6	8	5-7
Integration	Best suited to repurposed or new TMP line at QRP		Excellent fit with CPP; depends on the kraft mill operating	Standalone but could benefit from integration with CPP
Feedstock quality	Hardwood chips		Softwood chips	Kraft pulp
Economics	Competes with cheap Brazilian sugar	Needs \$1000/t market opportunities	Needs \$1000/t market opportunities	Growing markets will drive new plants
Fit for Quesnel	Excellent		Excellent	TBD
Comments	Still in development. Pilot plant work ongoing in Thunder Bay		Market growth will dictate when this is implemented	Licensing and patent issues make this a potentially complex space

5. Conclusions and next steps

5.1. Conclusions

The BC Central Interior has a range of opportunities to make better use of the forest resource available in the area. While existing players, such as Canfor, Tolko and West Fraser, continue to generate good economic value from traditional products such as lumber, pulp and paper, the world will be looking for new carbon-neutral products if climate change is to be addressed by 2050.

Quesnel is characterised by established production sites, with industrial operating permits, wood handling and supply systems and logistics, energy generating islands, effluent treatment systems, and (most importantly) trained staff able to maintain and operate these utility systems. All of this supports a range of core production facilities.

Quesnel also must deal with a forest resource that has been impacted by climate change: insect infestations and forest fires are not likely to go away.

Sections 1 through 4 of this report outline a series of technology pathways to novel value-added products that make sense in a world where climate change action is slow or non-existent, and where the effective price of oil remains low. The Executive Summary outlines new opportunities that make sense if an aggressive approach to limiting global warming, such as the one proposed by the IEA, is widely implemented. The IEA predicts oil prices will drop as oil demand drops to essentially zero by 2050; this has the perverse effect of making bioenergy projects largely uneconomic and is offset by calls for carbon pricing schemes in the order of \$250/t CO_2 by 2050. This makes most biomass to fuels processes economic.

The following technologies are reasonably mature and lead to products with reasonable value propositions:

- Redirect existing pulp fibres to new markets: New applications for existing pulp fibres, such as textiles or fibre-reinforced composites, open the door to new markets with minimal impact on mill operations. Some processes may be suitable for co-location and utility sharing with a pulp mill. Section 3.3.
- New uses for kraft mill residual streams: The kraft mill generates a large number of residual and by-product streams which can be recovered and sold. Lignin, methanol, tall oil, turpentine and secondary sludges all have buyers. Section 3.4.
- Novel cellulose fibre streams: Novel fibre streams from cellulose are very high-value products, and two of the leading technologies worldwide are Canadian. Partnerships can open up the opportunity to participate in novel markets. Section 3.5.
- Repurposing existing mill assets: The world is moving to bio-based chemicals, in response to consumer demands. This trend is particularly strong in Europe. Early players who can convert wood to a range of petrochemical substitutes will stake out a space in this growing field. Section 3.6.
- Making better use of mixed feeds: Low-grade residual material with high bark content is best suited for fuels and energy applications which displace fossil-based fuels in mills or in regional district heating systems. Section 3.7.

The chemistry and economics of these technologies are further expanded and detailed in Section 4. In light of the IEA Roadmap, a range of energy opportunities, also outlined in Section 4, should be added to the list:

- Solid fuels to displace coal in generating stations;
- Liquid fuels to displace petroleum-based transportation fuels, in particular aviation fuels;
- Gaseous fuels to displace natural gas directly at the point of combustion, or for injection into pipelines.

5.2. Next steps

For this report to lead anywhere, the next step is to develop a compelling rationale for pursuing a small number of potential projects (so-called "Best Bets") in collaboration with one or more industrial partners, the City, other partners such as First Nations, and relevant provincial and federal financing agencies. While this report focused on uses of chips and bark in a pulp and paper context, the next step needs to be a holistic review of opportunities across the entire forest value chain, from harvesting through various solid wood products to pulp and paper, and as such should begin with a full review of all background documents. The rapidly shifting climate change engagement by governments and industries will shine new light on the process, and may force new ideas to the forefront. Sources include this report, parallel ones on solid wood and wood supply, and information from workshops and other activities undertaken by the City of Quesnel in the course of Future of Forestry Think Tank activities.

Identifying Best Bets and the appropriate Industrial Champions will be critical. Steps that could lead to this outcome are listed next.

Gaps need to be identified and missing information filled in. This will require telephone interviews with industrial leaders at a VP or CEO level, ideally undertaken by someone with C-suite executive experience, supplemented by additional information searches and personal knowledge provided by consultants in the field. In particular, understanding corporate views on innovation and investment are critical; this requires high-level discussions.

From this, a list of criteria beyond simple technology needs will be developed and used in a triage process to identify a prioritized list of "Best Bets" taken from the larger list of opportunities identified. The competitive advantage of a Quesnel location, compared to others in BC, in Canada or world-wide, will be a critical point. Criteria will include, among others, current and future fibre resources, maximum economic and social returns, environmental sustainability, technology maturity and market readiness, and fit with local conditions. The analysis will include a SWOT analysis (Strengths, Weaknesses, Opportunities and Threats) in a so-called NABC structure (Needs, Approach, Benefits, Competition).

Investors and Champions will be motivated to invest and move forward towards industrial reality by sufficiently compelling value propositions for 2 to 3 Best Bets. A roadmap to industrial reality will cover the following topics:

- Identify Quesnel advantages in light of new climate change momentum;
- Identify two or three Best Bets that take advantage of those competitive advantages;
- Outline of the markets for the products deriving from these technologies;
- Identification of industrial Champions for the Best Bets;
- Identification of investors, partners and others willing to contribute to success.

About the Author

Tom Browne holds a bachelor`s degree in mechanical engineering and a doctorate in chemical engineering, both from McGill University. He joined FPInnovations in 1994 to work on energy use in pulp and paper processes. During this period, he edited a monograph entitled “Energy Cost Reduction in the Pulp and Paper Industry”. He was promoted to Research Manager, Mechanical Pulping, in 2001. As Research Manager for Biorefinery and Bioenergy from 2006 to his retirement in 2016, he managed a research team developing and commercializing novel biorefinery processes for the pulp and paper industry. Among other successful commercialization exercises, his team developed, patented and licensed out the LignoForce™ system for removing lignin from kraft black liquor, and supported its move to full commercial implementation. He has published a number of papers on the techno-economic conditions necessary for the success of the forest biorefinery, including key contributions to the Future Bio-Pathways Study conducted by FPInnovations in association with the Forest Products Association of Canada and the Canadian Forest Service (a branch of Natural Resources Canada).