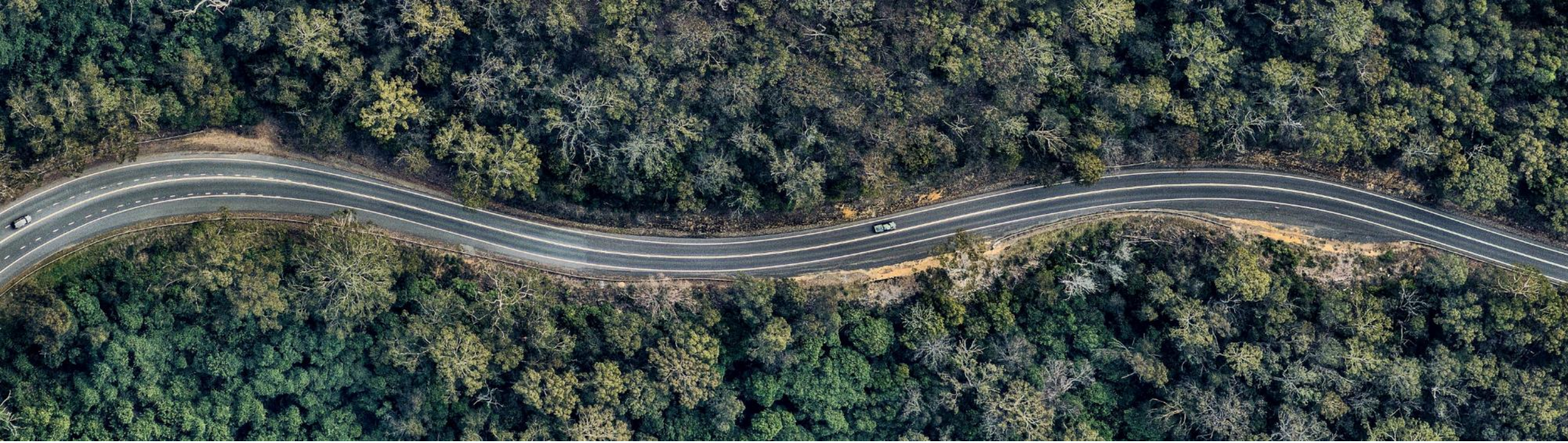

Production of High-Performance Lignin Products in Ontario

A Roadmap to Commercialization

AUGUST 2023

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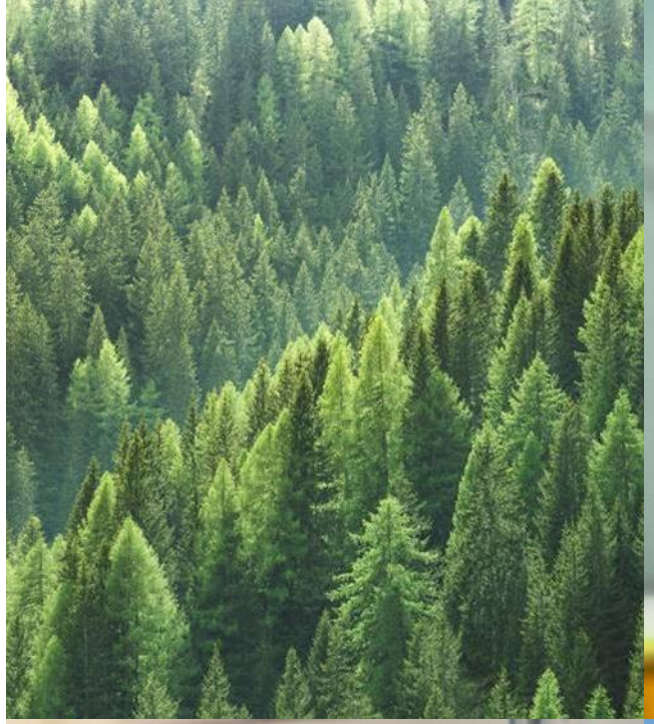
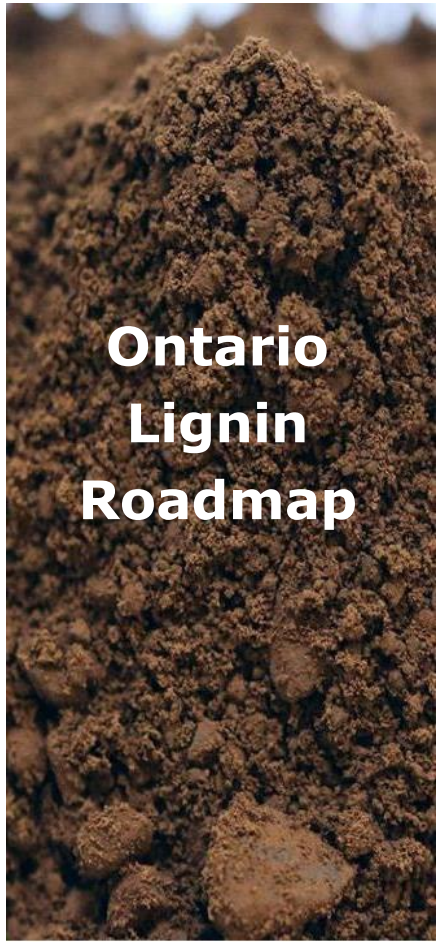


Ontario has a unique opportunity to leverage its natural resources and become a leader in the emerging lignin-based bioeconomy



- Ontario is uniquely positioned to become a leader in sustainability by actively driving the transition towards a net-zero future through the expanded utilization of bio-based products. Although the province is rich in forest-based resources, more than 50 percent of this resource base is underutilized, representing an enormous opportunity cost. However, the province has the potential to leverage its kraft pulp mills and produce lignin, a valuable bio-based co-product of kraft pulping. In doing so, the province will both enhance the resiliency and profitability of its forest products and pulp and paper sectors, while supporting a new bio-based lignin industry
- Additionally, there is a potential to produce so-called biorefinery lignins, made using abundant unmerchantable hardwoods available in Northern Ontario
- Lignin generally has the potential to displace petroleum-based chemicals and materials in a range of products. Global demand for lignin is growing as companies look to substitute petroleum with bio-based products. Recent pulp mill divestitures and closures have constrained lignin supply and as a result supply of lignin is currently unable to keep up with the demand
- An array of commercial products made from lignin are currently available, and numerous innovative applications are on the brink of commercial viability. These include both commodity products as well as high-value specialty products. Ontario boasts markets for many of these products, therefore, in-province production of lignin would be welcomed by these downstream users
- Currently two process technologies for extracting kraft lignin are available. These technologies have been demonstrated in the United States, Finland, and Canada. One of these technologies was developed in Canada and demonstrated in Thunder Bay with the financial support of the Government of Ontario via investments in CRIBE
- AFRY believes that the global markets for lignin are supply-constrained and that new production capacity would be welcomed by downstream buyers
- Governments can play a vital role in accelerating the adoption of bio-based materials made from lignin by implementing a range of policies, incentives, and initiatives. For many applications, additional product development (through RD&D) will be required. Ontario plays a pivotal role in this development journey. Existing resources for R&D support, aligned with industry, can lead to the creation of a strong kraft lignin value chain within Ontario, one that begins with Ontario's underutilized forest resources

Kraft lignin in Ontario could enhance the resilience of the pulp and paper sector, creating new revenue streams from renewable bio-based materials

Ontario's forest products industry is underutilizing its resource potential. The province has the potential to sustainably harvest nearly **27 million cubic meters of wood** from its public forests, yet it only uses forty-four (44) percent of the approved harvest volumes

Ontario produces about **1.3 million tons of chemical pulp per year**. Lignin, a by-product of pulp production is currently used as a fuel, representing its lowest commercial value. A fraction of the lignin can be removed and sold into the fast-growing lignin markets. Lignin extraction capacity in Ontario is estimated at **76,000 mt/a**, which would also allow the potential for **incremental pulp** production of up to **91,000 mt/a**[2]

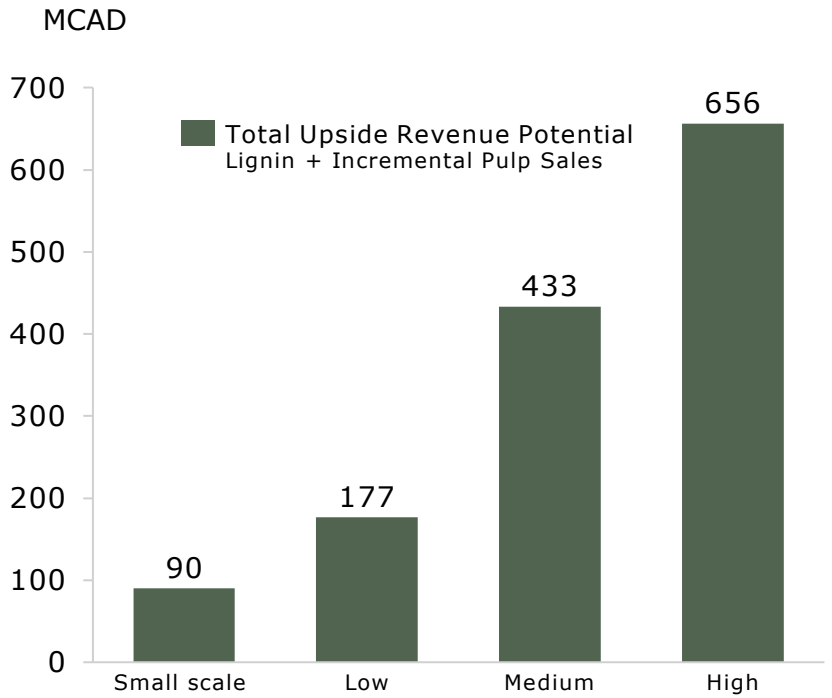
Benefits for the pulp mill

- **+** Potential for increasing pulp production capacity
- **+** Opportunity to generate incremental revenues through the sale of pulp and new lignin-based products
- **+** Easy access to sustainable raw material for high-value added application in an integrated system

Benefits for Ontario

- **+** Lignin as part of a strategy for decarbonization, replacing petroleum-derived products
- **+** Direct and indirect employment opportunities at mill and manufacturing of bioproducts (3-10+ jobs in biomaterials per 1,000 O.D.T/a)[3]
- **+** AFRY estimates a total value creation potential of about CAD 656 million

ONTARIO KRAFT LIGNIN REVENUE GENERATION- BASE CASE[1]



Extraction volume	10 kt	20 kt	50 kt	76 kt
Price Base case	Lignin[4] 790 CAD/ t		Pulp 1,130 CAD/ t	

1. Assumes extraction level of 10 – 25%. Includes upside revenue from both lignin and incremental pulp production 2. Assumes 10% extraction capacity at all four Ontario kraft mills in Ontario
3. Site: gov.bc.ca 4. Lignin as dispersant

Demand for lignin is expected to outpace supply and create opportunities for new Ontario-based production

MARKET FUNDAMENTALS

Demand for lignin is being driven by the need for low-carbon chemicals, fuels, and materials. As a sustainably-derived, renewable carbon-based feedstock, lignin promises to replace fossil-based feedstocks and impart new functionality to materials. The development of lignin applications benefit from regulations that support the use of bio-based feedstocks. However, market penetration is still muted, which is largely due to the lack of reliable supply and slow application development in some areas

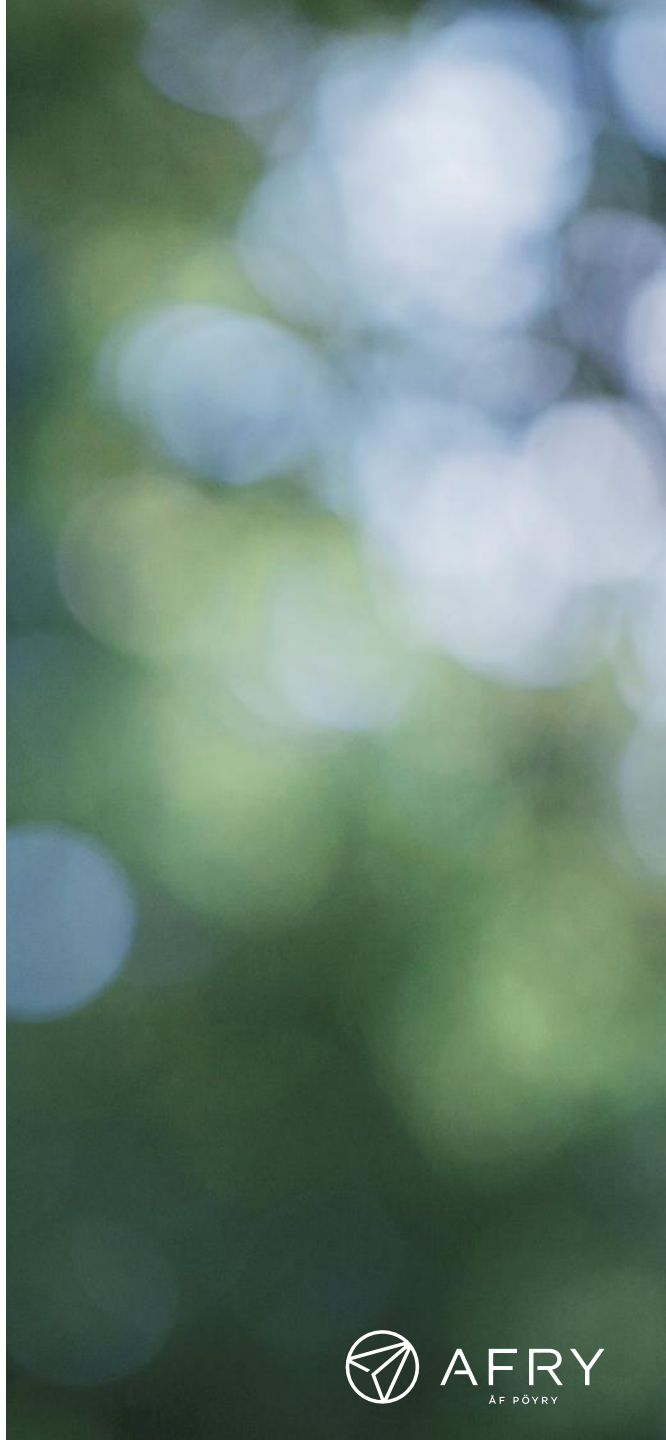
LIGNIN PRODUCTION

Current global supply for kraft lignin is estimated at 50 kt[1], the majority of lignin is being used in Europe as lime kiln fuel to substitute for high-cost natural gas. Current commercial demand comes from promising applications, e.g. phenolic resins and dispersants. Current capacity has been negatively impacted by **recent mill closure announcements,** which **were due not due to lignin markets or technologies but to the lack of wood supply, pulp mill closures, and change of ownership**. Biorefinery lignin capacity based on woody feedstocks is estimated at about 15 kt, with applications focusing on value-added applications

POTENTIAL OFF-TAKERS

Future demand will depend on application-specific technology development, where the role of lignin producers will be critical. Kraft lignin clients, with the most potential, are companies with previous experience in lignin as a raw material, strong RD&D resources, and a high target for sustainability. In North America, kraft lignin supply is constrained by long-term off-take agreements, which limits lignin availability for developers of lignin-based products. **The recent mill closure announcement will tighten the supply and open opportunities for negotiation**

1. Recent mill closure announcement and change of lignin supply happened during the preparation time of this report.



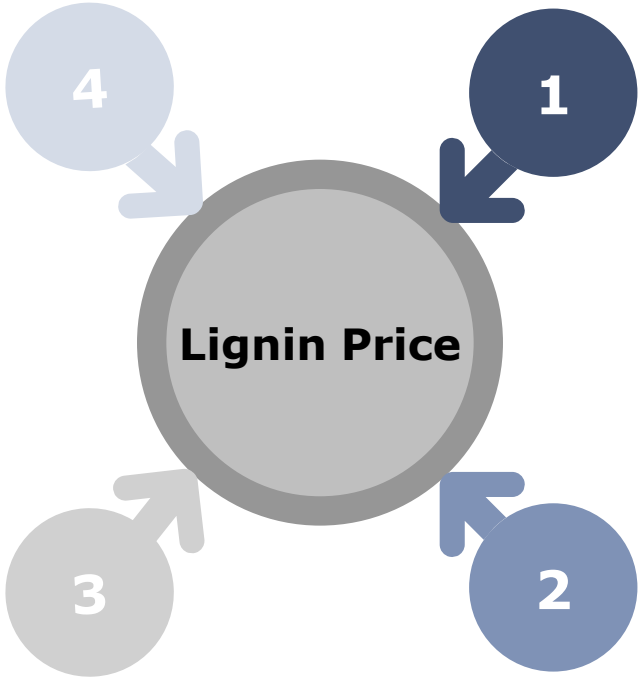
Lignin price is driven by supply and demand dynamics, offered properties and paying capability of the off-takers

Supply Development

The short supply of lignin to the open market inhibits commercial-scale product development. More supply and assurance could open opportunities to develop more commercial products

Paying Capabilities

Different end-use will have different paying capabilities depending on their end products' price dynamics and intermediate products if any



Technology and Quality

Lignin has some valorization limitations

New technologies to enable lignin isolation with more reactive structures will be a gate to bigger opportunities in exploring end-uses

The price of lignin is subject to vary depending on its properties

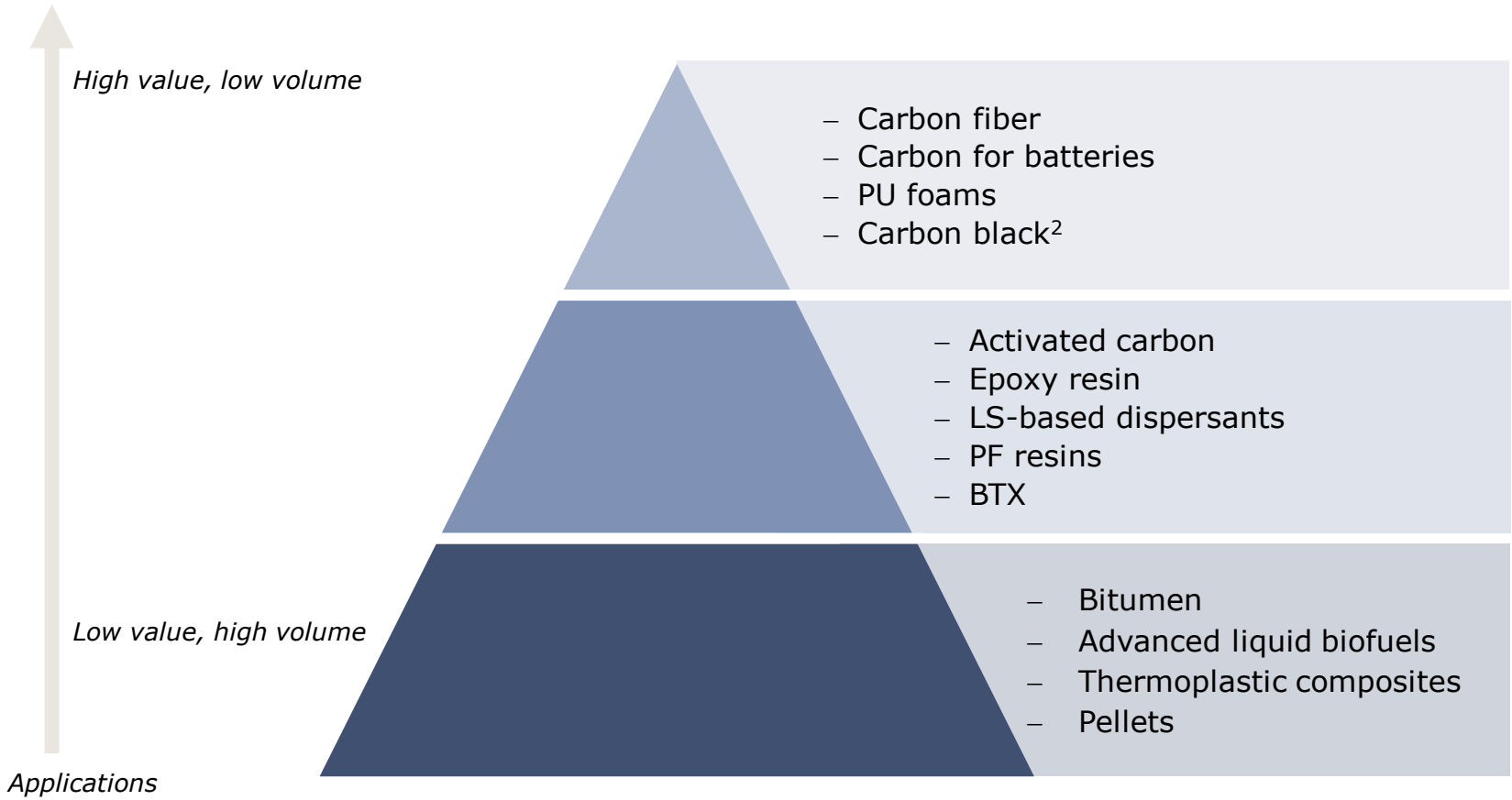
Sustainability

Substitution product price will directly affect the lignin price

Corporate sustainability and hunt for sustainable material could be a positive driver toward lignin usage and setting up premium price for lignin as an emerging renewable feedstock

Premium lignin products bring high pricing but small market off-take by volume, while low value products often represent large volume markets

- There is a large number of potential applications for lignin, with very different market volumes, and product value[1]
- Premium markets have very high value end products, such as different technical carbons and PU foams, but they represent a small market off-take potential by volume
- Products with medium value but larger market volume include epoxy resins, lignosulphonate dispersants and PF resins
- End use markets with lowest value typically represent the largest market potential by volume; these include bitumen, and thermoplastic composites

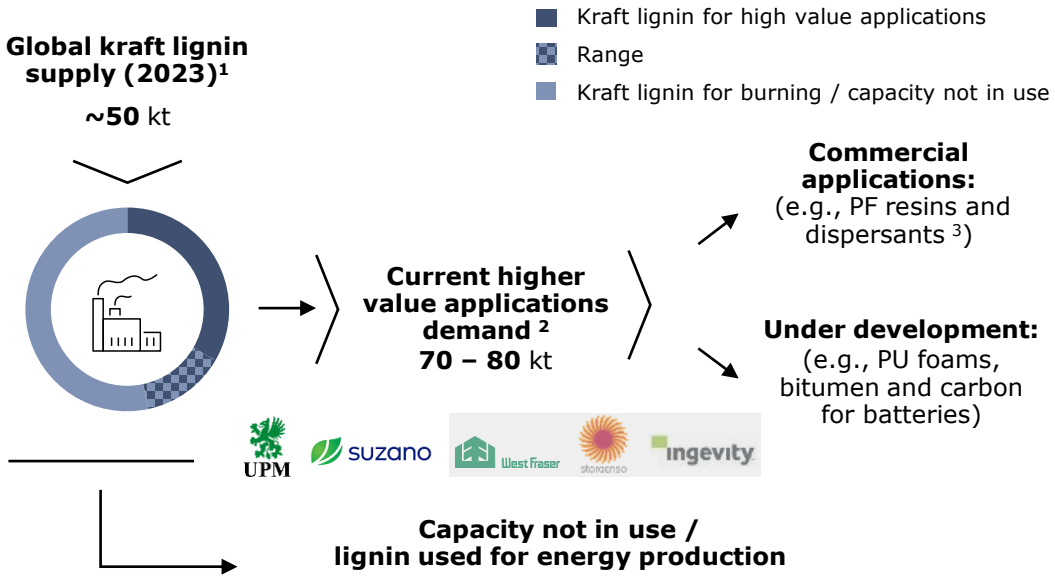


1. For market volumes, the theoretical maximum market size for lignin, with product-specific lignin replacement ratio is taken as a reference. Value refers to the value of the product that lignin would be substituting. 2. Carbon black is an exception as a high-value and high-volume product. (UPM's target application for hydrolysis lignin)

KL producers use their lignin internally, as there are few commercial off-takers. Currently, global supply and demand are in balance

Summary of Supply and Demand

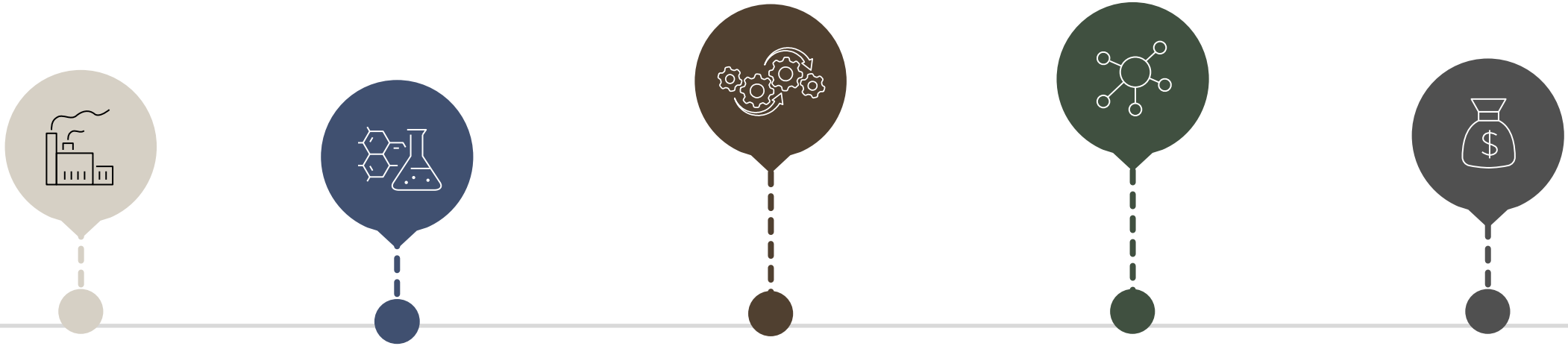
- Generated as a by-product from kraft pulping, the majority of the kraft lignin supply is burned as fuel at pulp mills. However, a significant part of the lignin could be recovered without disruptions in the pulp mill energy or chemical balance and sold as a co-product. Lignin recovery **reduces the load on the pulp mill recovery boiler** and serves to **debottleneck** the production process
- There is a potential to increase lignin extraction capacity globally and especially in Canada, but this depends on the **addressable market**
- Current estimated addressable market size for lignin-based phenolic resins for adhesive applications in North America is 60 kt/a
- Growth in the construction industry in Canada and especially in Ontario is expected to propel the demand for wood adhesives
- Sulfonated kraft lignin dispersant market is ~ 170 kt in NA. With the loss in lignosulfonate supply, the demand for sulfonated kraft lignin could increase
- Kraft lignin market demand mainly depends on **legislation**, **price reduction, brand owners' sustainability targets,** and **lignosulfonate supply gap**
- Not all kraft lignins are the same. Kraft lignin properties and application potential depend on the wood species, the extraction process, and, for some markets, subsequent modification steps
- Recent mill closure announcements had a major effect on the global lignin supply landscape from **150 kt in 2022** to ~ **50 kt in 2023**



Main kraft lignin producers[1]	End use application developer
Stora Enso[1]	In-house development
Ingevity[1]	In-house development
West Fraser[1]	In-house development
Domtar	UPM
Suzano	In-house development

1. 2023 kraft lignin supply at 50 kt due to mill closure announcement (KL global capacity was 150 kt in 2022) 2. Commercial mainly PF resin and dispersant 3. Modification is required

Successful kraft lignin market entry requires not only motivated off-takers, but also partnerships with technology suppliers and application developers



Kraft lignin extraction

Looking into the right pulp mill with debottlenecking targets

Application development

Kraft lignin is attracting increasing interest in the R&D sector, and many **specialized companies, universities, and research centers** in Canada are actively working on that

Lignin modification

Most kraft lignin suppliers modify lignin, predominantly by sulfonation. Deodorization might also be required for some applications but further modification (e.g., quality improvements) can also be done by the end-user

Product distribution

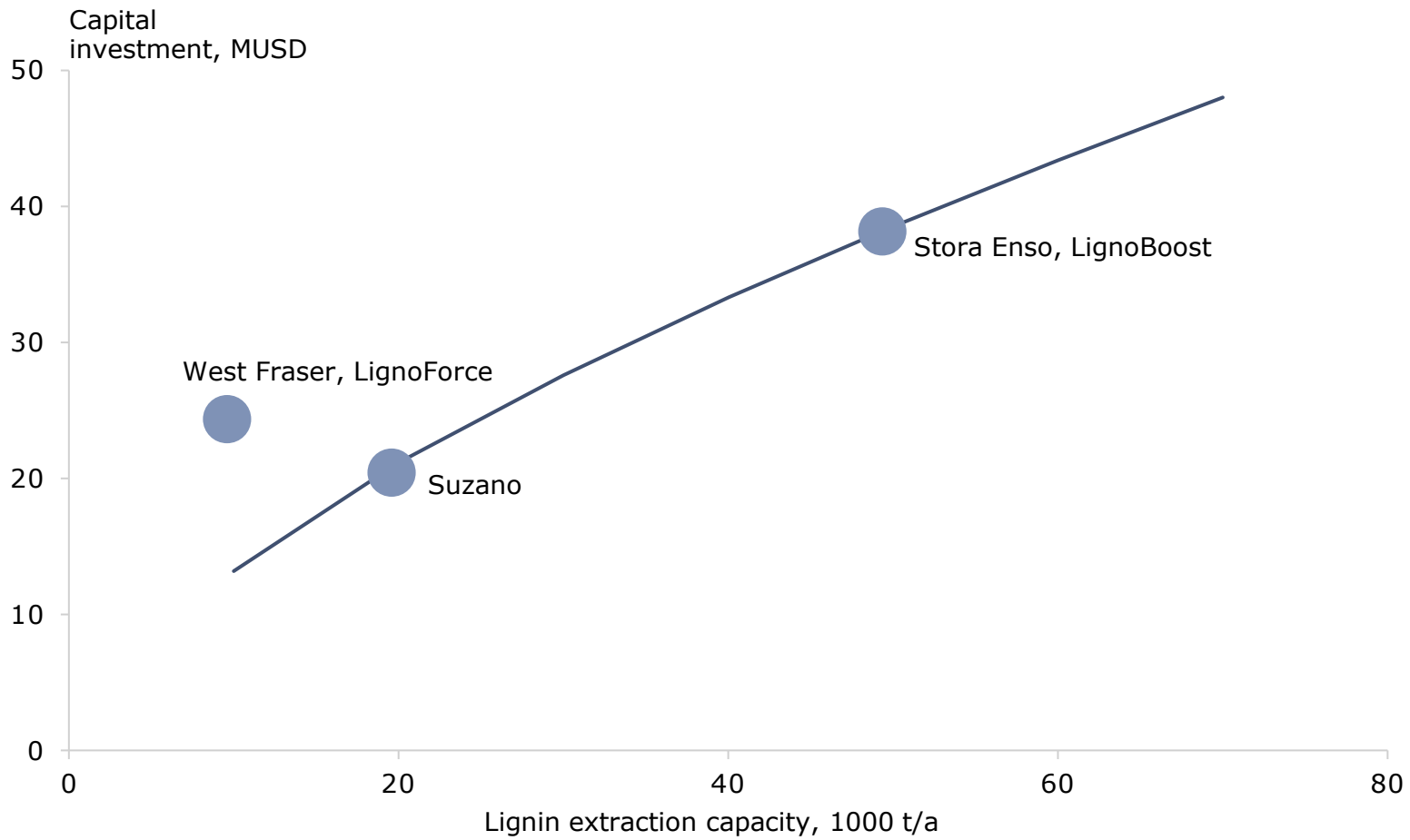
Integrated off-taker

Kraft lignin for PF resins is today mostly through direct sales from producer to end-use client

Kraft lignin off-taker

Most potential kraft lignin clients are companies with previous experience of lignin as raw material, good R&D resources and high sustainability targets

Investment costs for kraft lignin separation estimated to be 20 – 45 MUSD. Capital costs depend on the plant size and are highly mill specific



- CAPEX curve is drawn based on Stora Enso's Sunila investment (50 kt/a, ~39 MUSD) and Suzano's 20 MUSD investment (20 kt/a) announcement in 2015
- However, West Fraser's LignoForce process (10 kt/a) resulted in a higher total investment than the 20 kt Suzano facility
- The differences in total CAPEX mainly result from additional rebuilds and adaptations at the site, and these are always mill specific
- For an **Ontario mill** with **50 kt/a** extraction volume, **total investment** is around **45 MUSD**, and with 20 kt/a, it is estimated at 20 MUSD[1]
- KL can be granulated to produce pellets, which compared to dry powder, are easier and faster to package. Stora Enso invested 17 MUSD in granulation and packaging plant[2]
- The estimated **OPEX requirements** for **NA mills** is **~220 – 320 USD/t**[3]

1. Based on public announcements, AFRY estimates and NORAM installation costs estimates, 50 kt/a plant with H2S04 and granulation smaller scale will push fixed operational costs up
2. Stora Enso announcement
3. does not include the product drying, granulation and packaging cost Granulation can be done in wet or dry form; however dry granulation requires high temperatures

Scenarios for supply-demand balance outlook for kraft lignin supports the need for new entrant in the market even in the low case scenario

SUPPLY scenarios Kraft lignin supply development follows market demand and maturity – in low and medium scenarios, pulp mills still burn part of lignin as lime kiln fuel, but in the high scenario investments are driven by high-value, end-product markets

DEMAND scenarios Demand growth is based on kraft lignin substitution potential in different end use sectors, rather than on the growth rate of the substituting products. A majority of demand comes from applications that are closest to commercial scale, and some demand is also expected from a few other promising applications, e.g. PU foams and carbon for batteries[1]

LOW

- Global kraft lignin market is still immature, as only limited success has been reached in product R&D, and technical complications continue to limit the lignin extraction volumes
- Ontario mill is the only new supplier that has entered the market, and global demand has slightly grown from the current 80 kt/a
- Geographical market focus is strongly on Europe and North America, as other regions follow less ambitious sustainability targets

MEDIUM

- Kraft lignin market has clearly moved forward from today, and some new products have entered the market
- Development has attracted a handful of new suppliers, but many investments are driven by debottlenecking purposes, and a large share of lignin is still burned as lime kiln fuel
- Despite growing interest in lignin, development success has been limited, time to market periods are long, and many suppliers still struggle to find off-takers for their kraft lignin

HIGH

- With sufficient effort on new product development, kraft lignin has finally established a strong global position as a high-value bioproduct raw material
- Both global supply and demand have more than doubled from current supply
- Many technical challenges have been solved, and lignin is a well-functioning and wanted raw material for PF resins, dispersants, and PU foams
- UPM has been successful in lignin-based product development in Carbon black, and Stora Enso develops the lignin-based anode material: both add to the global demand significantly

1. PF resins and dispersants Currently, Kraft lignin supply capacity is ~50 kt/a globally.

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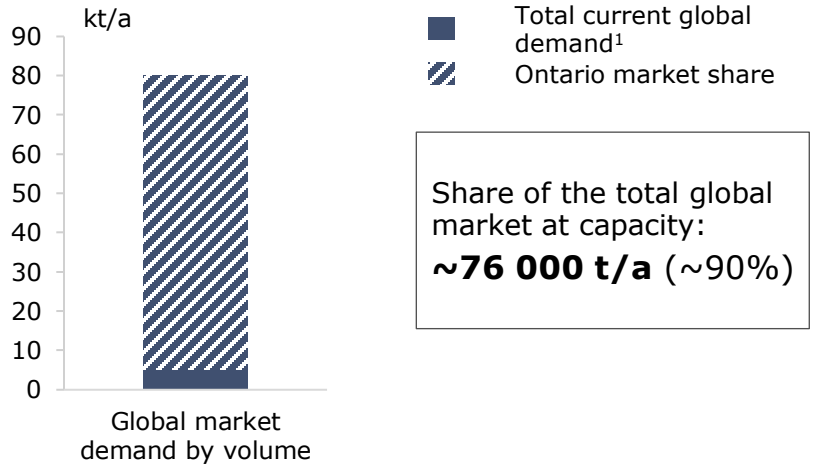
Recommended extraction capacity for Ontario is 10-50 kt/a, depending on global application development

ONTARIO SHARE OF GLOBAL KRAFT LIGNIN MARKET DEMAND



Share of the total global market at capacity:
~76 000 t/a (~90%)

Recommended capacity

	CAPEX (MCAD)[2]	OPEX (CAD/t)[2]	Revenue[3] (MCAD)
10 kt/a	20-25	450-500	90
50 kt/a	55-60	350-450	433

- Given available Ontario's chemical pulp production of 1.3 Mt, the total estimated lignin extraction capacity would be ~ 76 kt/ a (~90% share of the total current global KL market)
- Despite the high potential volume of softwood lignin extraction, accessible and suitable market volume depends on application developments beyond PF and dispersants and higher lignin price
- There is potential for cost saving in drying and granulation with further integrated concepts such as OSB production at the site
- Mill-specific info e.g., extraction capacity and recovery limitation should be considered
- Based on demand estimates, the capacity recommendation for the lignin extraction system is 10- 50 kt/a, depending on risk appetite, and the willingness of mills to burn part of extracted lignin as lime kiln fuel
- If Ontario wishes to pursue lignin extraction with larger capacity, it should be prepared to burn a large share of lignin as fuel, or not to run the system at full capacity
- **Besides lignin extraction capabilities, lignin modification and application development partners need to be identified. This is a critical component of success!**

1. Demand based on commercial applications PF and dispersant, additional demand is possible from new-off takers 2. Based on CAPEX estimation on p. 13, 1 CAD= 0.75 USD 3. Revenue from lignin and additional pulp based on the price of lignin 790 CAD/t and Pulp at 1130 CAD/t

Extraction capacity must be aligned with mill needs and end-use markets

INVESTMENT DECISION → **PARTNERSHIP DEVELOPMENT** → **APPLICATION TARGETED KRAFT LIGNIN SALES**

Option 1: Low risk

Small scale commercial

To reduce investment risk:

Mill should select plant size to optimize pulp production by off-loading recovery boiler

Ontario mill could extract small scale samples up to **10 kt** for client testing to verify lignin quality and potential off-takers interest

Option 2: High risk

Commercial scale

Based on demand estimates, capacity recommendation for lignin extraction system is no more than **50 kt/a**

End product R&D **should be started with pilot samples** in 2024-2025 to achieve larger off-take by 2030

Screening and selection of technology providers will be critical to project success

ANDRITZ

NORAM

Valmet

Establish a dedicated in-house kraft lignin **sales team**

Build relationships with potential **off-takers** for application testing and **R&D**

Be prepared to showcase **lignin suitability and performance in selected applications**

AFRY recommends;
PF resins, dispersants, Bitumen
PU foams and Li-ion Batteries

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Biorefineries intend to valorize all biomass fractions; while lignin recovery depends on the process, it is targeted to be high purity

- The number of biorefineries with strong aim to utilize all fractions of woody biomass is increasing.[1]
- Biomass pre-treatment methods are varied and include:
  - Acid hydrolysis (Avantium)
  - Ionic liquids (Lixea)
  - Organic solvents (Bio-Sep)
  - Extrusion combined with enzymatic hydrolysis (Sweetwoods and **UPM**)

Current global production capacity: **10-15** Kt/a*

*The capacity could be as high as 80 kt with the addition of Fibenol, Bio-Sep and UPM volumes. However, the capacity increase will be consumed by the producers internal target applications and unavailable to the open market.

RECENT ACTIVITY

Sweetwoods' BBI JU project[2] (21 MEUR investment) in Estonia delivered the first lignin samples in 2021

UPM's Leuna facility in Germany (750 MEUR investment) converts hardwood to lignin and sugars (~220 kt) with start-up Q3-Q4 2023

TARGET APPLICATIONS


Adhesive


Animal feed


Asphalt


Fertilizers


Plastic & Rubber


Thermoplastics

- While many biorefinery concepts target lignin as a co-product, all regard sugar fractions as their main product. Many use fractionated lignin as a fuel to meet the energy requirements of the biorefinery.
- Most commercial and R&D projects are carried out by European companies and the projects are mainly supported by funding provided by the European Union.
- There are currently no identified potential biorefinery lignin suppliers in North America.
- In the past, CRIBE has supported TMP-Bio pilot plant, an alkaline biorefinery process using thermo - mechanical process to convert 100 t/a of biomass to lignin and sugars.

1. Requires a target application for all biomass fractions both lignin and sugars. Compare to traditional wood processing industries where <50% of the wood is transformed into valuable products
2. The Bio-Based Industries Joint Undertaking, which includes Fibenol and Sweetwater Energy

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Biorefinery lignin extraction requires a sugar platform roadmap

- Projects aiming to produce lignin as the main product are few. With the share of ~70 % carbohydrate in wood the successful extraction of **biorefinery lignin** requires a **sugar platform**
- Unlike kraft lignin, the production of biorefinery lignin in Ontario would require either investment in a greenfield facility or the repurposing of a pulp mill or similar production facility. This biorefinery would be the first of its type in North America
- In Europe, however, biorefineries can be found in Germany, Estonia, and Scotland. The feedstock of choice is both agricultural and wood residues.
- For example, **UPM** has invested over **750 MEUR** to build a 15-hectare biorefinery site with a **220 kt** production volume:
  - Sugars (65–70% of wood) are converted to Bio-Monoethylene Glycol (BioMEG), Bio-Monopropylene Glycol (BioMPG) and industrial sugars. MEG is used for the production of textiles, plastics, PET, packaging, and industrial coolants while MPG is used in composites, pharma, or cosmetics products
  - Lignin fraction (20-35 % of wood) in the form of functional filler (~70 kt) for rubber and tire application
  - Feedstock being Beechwood and residues from sawmills, start of production in 2021 and ramp up by 2024
- With a more systematic approach to enzyme solution, Fibenol is now starting up its first lignocellulosic biorefinery in Estonia. The combination of Sunburst™ pre-treatment technology and tailored enzymatic cocktails from Novozymes provides more than 90% conversion of birch wood processing residues into high-quality cellulosic sugars and co-products, including high-purity lignin LIGNOVA™

With the 250,000 cubic meters (0.24 million green tonnes) of hardwood that can be easily available from a short distance of a mill in Ontario a biorefinery concept is only viable if the sugar platform and end-use markets are fully understood.

Significant demand for sugar platform products, especially for advanced ethanol, but further technology and process development are needed

ADVANCED ETHANOL

Demand for cellulosic biofuels is expected to increase significantly. Besides sulphite mills, 2G ethanol plants are yet to be commercialized. Industrial wood residues are preferred feedstocks

GLYCOLS (MEG, MPG)

These drop-in chemicals can be made from woody feedstock but at higher costs. Significant market changes are expected in the near future as UPM, with first-mover advantage, enters the market with hardwood-based MEG and MPG

PARAXYLENE

Paraxylene used in PET and polyester production could have market potential and US-driven development is preparing for commercialization

FURFURAL

Contrary to commercial furfural production from agroresidues, Sappi extracts C5 sugars from its pulp mill hydrolysates. Other wood-based processes need further development

FDCA

There is a sugar pathway to produce 2,5-furandicarboxylic acid (FDCA) to replace petroleum-based plastic bottles

BUTANOL

Recent efforts to bring biobutanol to market for chemical applications and as a transport fuel have brought the product to light, but commercial viability of biobutanol remains unclear

An Ontario specific market study is required

Currently outside the scope of this report

The role of government

- Align Provincial and Federal Government program funding mechanisms to de-risk biorefinery investment by the private sector
- Invest in infrastructure projects that support biorefinery operations

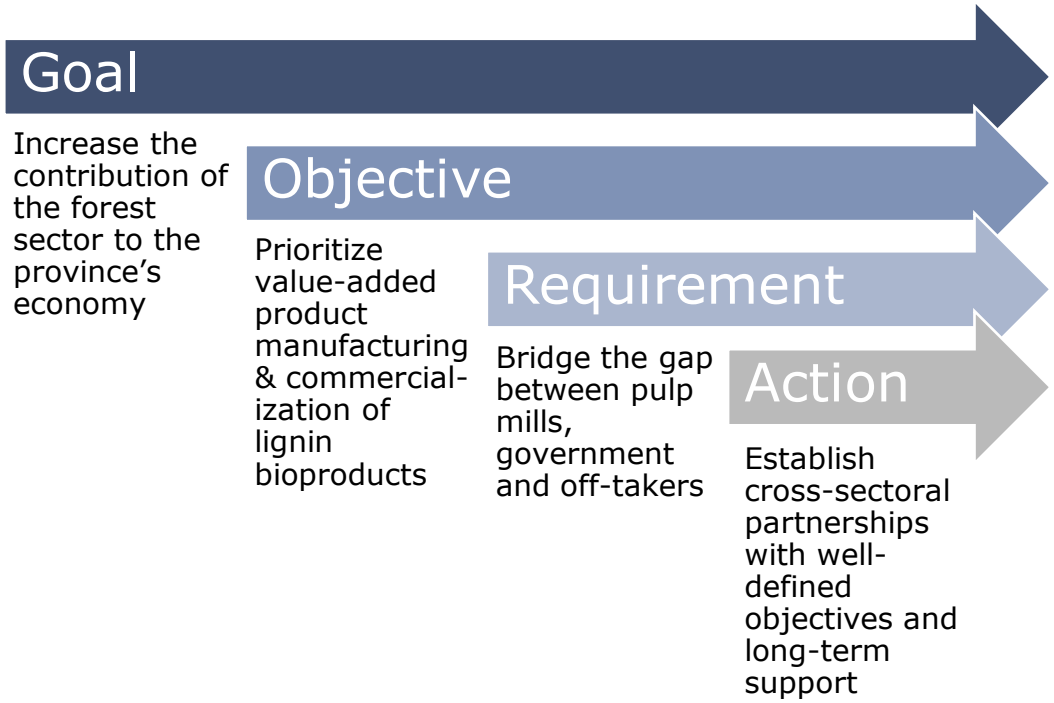
- Consider new policies to encourage the use of bio-materials through, for example, public procurement
- Use subsidies and production tax credits to off-set the cost of manufacturing

- Show strong support through direct participation
- Promote R&D funding, research and industry partnerships, and international cooperation
- Continue to support and invest in established research and innovation clusters and networks

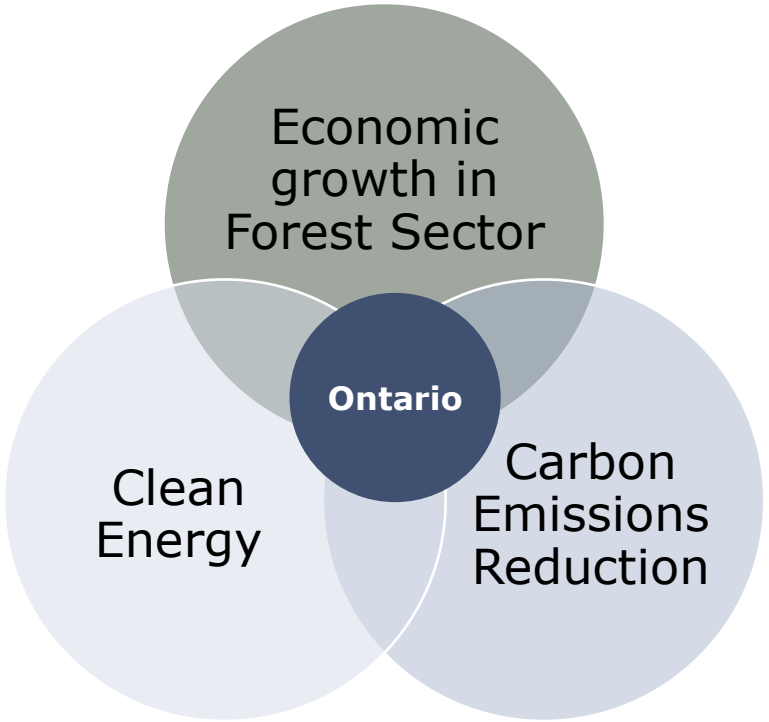
Governments can play a vital role in accelerating the adoption of bio-based materials made from lignin by implementing a range of policies, incentives, and initiatives.

As a key industrial engine of Canada, Ontario is well positioned to contribute to advance a lignin-based bioeconomy

LIGNIN DEVELOPMENTS REQUIRED COMMITMENT



BIO-BASED LIGNIN DEVELOPMENT SUPPORTS MULTIPLE PROVISIONAL STRATEGIES



A lignin roadmap in Ontario and commercial success requires …

5. Demonstration

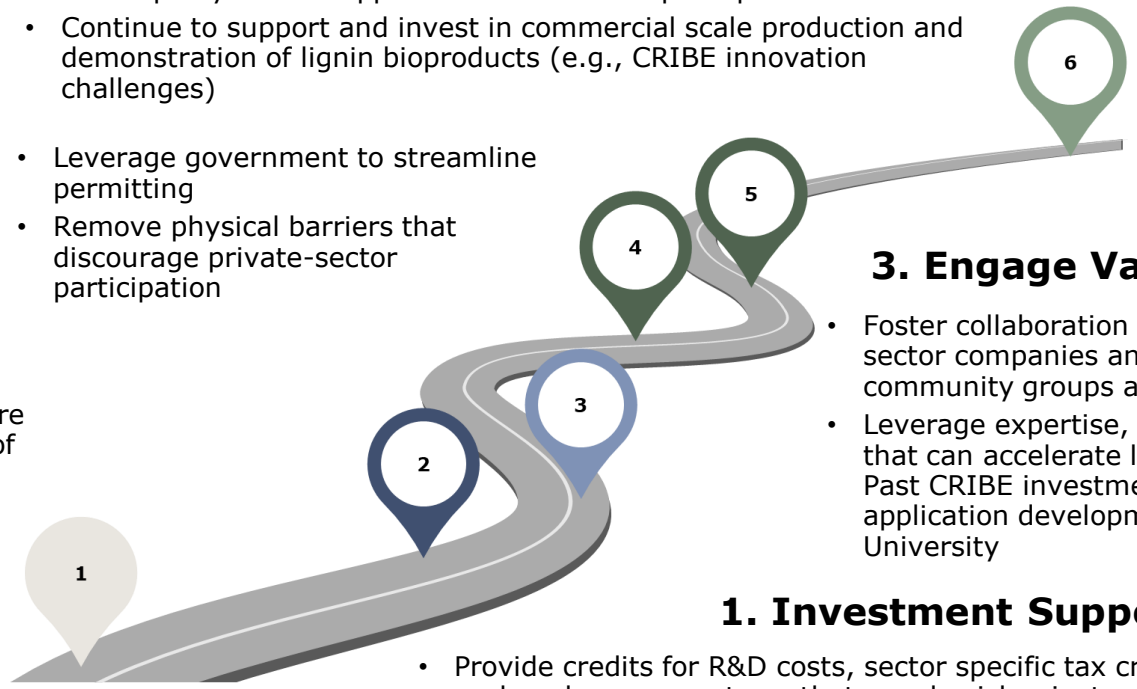
- Demonstrate commercial-scale production of lignin bioproducts
- Develop key market applications that can expand product demand
- Continue to support and invest in commercial scale production and demonstration of lignin bioproducts (e.g., CRIBE innovation challenges)

6. Proliferation

- Increased demand for lignin-based products stimulates new investment in capacity in mills throughout Ontario

4. Accelerate Development

- Leverage government to streamline permitting
- Remove physical barriers that discourage private-sector participation



3. Engage Value Chain Participants

- Foster collaboration with government agencies, private sector companies and research institutions, as well as community groups and First Nations leaders
- Leverage expertise, resources, and market reach in Ontario that can accelerate lignin development and deployment. Past CRIBE investments resulted in lignin research and application developments at BETC lab and Lakehead University

2. Support Primary Markets

- Promote primary industries to ensure a consistent and long-term supply of woody residues.
- Develop efficient supply chains that minimize production costs and enhance overall competitiveness.
- Implement forest management policies that support optimal utilization of resources while preserving long-term sustainability.
- Support programs like Nexfor to promote collaboration

1. Investment Support

- Provide credits for R&D costs, sector specific tax credits, and other incentives, such as loan guarantees, that can de-risk private sector investment
- Use green goods and services procurement practices to promote lignin-based products
- Past investments by CRIBE have resulted in the development of a bio-refining regional innovation cluster in Thunder Bay that includes FPInnovations, Lakehead University

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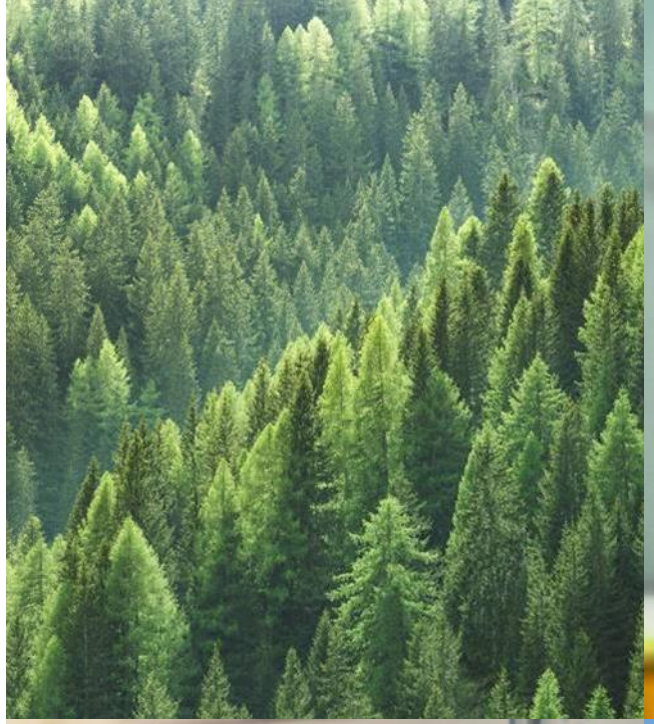
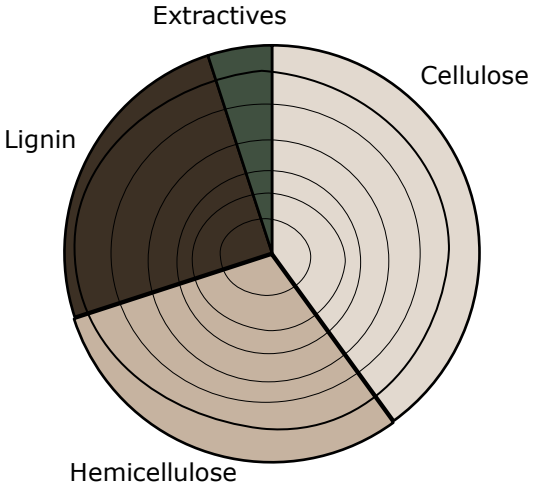


Biorefining companies must utilize all components of biomass to achieve economical competitive platforms

- Woody lignocellulosic biomass has a complex polymer structure composed of cellulose, hemicellulose and lignin constituents and extractives
- Depending on the source of feedstock the components distribution could be different
- The exact lignin structure depends on the feedstock, with softwood, hardwood and other vegetation having different lignin contents and characteristics. Furthermore, the lignin fractionation process significantly affects the properties of the lignin produced. The majority of the technical lignin is produced from chemical pulping processes, namely kraft and sulphite pulping

CHEMICAL COMPOSITION[1] BASED ON WOOD TYPE (%)

Wood type	Cellulose	Hemicellulose	Lignin	Extractives
SW	37–43	20–30	25–33	2–5
HW	39-45	17-35	20-25	2-4



1: as weight percentages of dry wood l SW: softwood, HW: hardwood

Technical lignins possess significant variation in regard to product purity, functionalities, and chemical characteristics

	Origin	Main attributes	Lignin properties
Kraft lignin	Kraft pulp mills	– Kraft lignin can be extracted as a by-product – Mainly used for PF[1] resin production in small scales	– High purity – Contains sulfur – Soluble at alkaline pH in water, Lignin A and B from Lignoforce process have different solubility in water[2]
Hydrolysis lignin	Cellulosic ethanol refinery	– By-product from cellulosic ethanol production – Several different biomass pre-treatment methods employed	– Low purity – Sulphur free – Polysaccharide and protein impurities – Limited solubility in organic solvents, insoluble in water
Lignosulphonates[1]	Sulphite pulp mills	– Makes up majority of commercial lignin market – Utilised mainly as a dispersant in various applications	– Low purity – Sulphonated and water soluble
Soda lignin	Soda pulp mills	– Typically, at non-wood pulp mills – Only few developers globally	– Moderate purity – Sulfur free – High silica content – Soluble in organic solvents, insoluble in water
Organosolv lignin	Organosolv pulp mills	– Fractionates biomass into relatively pure cellulose, hemicellulose, lignin fractions – Only few developers globally	– High purity – Sulfur free – Soluble in organic solvents, insoluble in water
Biorefinery lignin	Biorefinery lignin	– Lignocellulosic biomass fractionation strategies to valorize lignin – Several different biomass fractionation methods – Only few developers globally	– Lignin properties and functionalities dependent on the process – High purity lignin

1. Lignosulphonate supply decreases due to the sulphite pulp mills closures 2. Lignin B being more soluble in water

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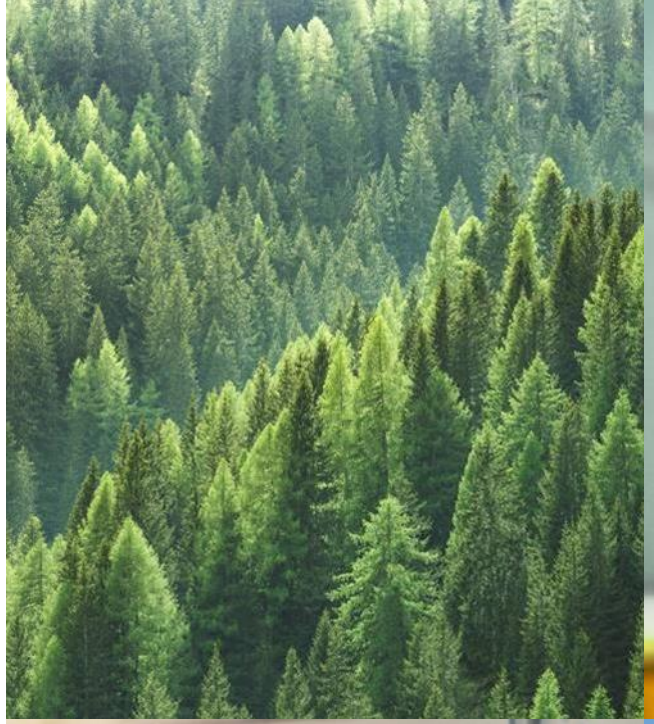

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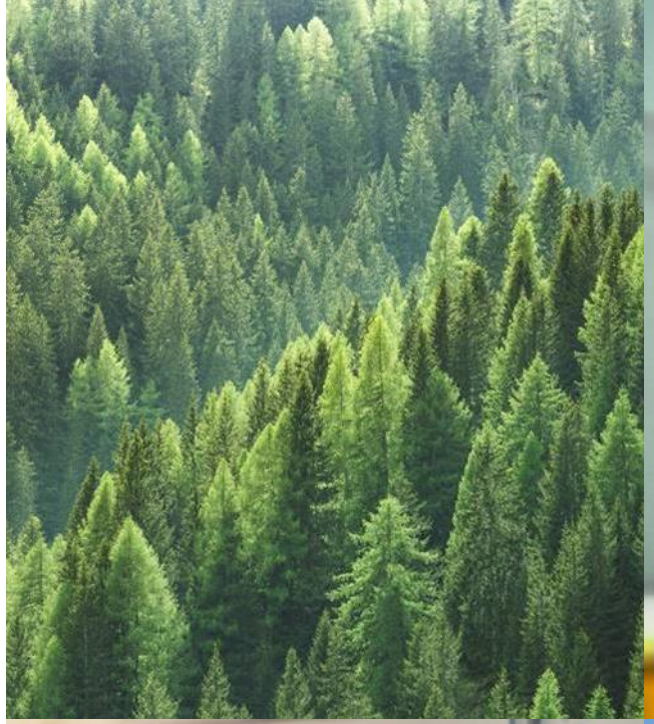

Kraft lignin is mainly used for energy generation, but holds potential for higher value applications

- Kraft lignin is obtained from black liquor in kraft pulping, and its recovery can offer several benefits for the pulp mill operations
- Its **properties** and **application potential** depend both on the **wood species** and the **extraction process**
- Currently, kraft lignin is mainly burned to provide energy for the pulp mill, kraft lignin business is most attractive for pulp mills that could benefit from recovery boiler debottlenecking
- Market is driven by a technology push rather than market pull. However, the use of lignin is supported by the general concern for the environment and the demand for sustainable solutions

Consideration in kraft lignin market

- ✚ Substantial R&D work is performed by kraft lignin suppliers, who utilize large part of their lignin internally
- ✚ Market entry of novel biochemicals, such as lignin-based products, requires significant effort and high investments in application and supply chain development

Development challenges

- ▭ Despite significant development activity, Product performance liability and risk mitigation require government support and a bio-premium

  Regulatory landscape should provide strong support to advanced feedstocks and bio-based products
- ▭ Some kraft lignin characteristics, such as its color, smell and its reactivity, limit its usage in certain applications

There are two main kraft lignin separation technologies - The kraft process is best at harnessing the cellulose fibers

	LignoBoost	LignoForce
Description	Separation by 2-steps lignin extraction via CO_2 acidification and precipitation, and further acid conditioning to achieve desired purity	Improvement of LignoBoost by addition of oxidation stage before CO_2 acidification to increase precipitation and filtration rates
Product	Kraft lignin	Kraft lignin A and B
Status	Commercial	Commercial
Disadvantages	- Requires extensive filtering process - Mill's sulfur balance changes and requires make-up chemicals	- Colloidal lignin has disadvantages in some end-use applications
Tech. Supplier	Valmet	Noram
Example mill	Domtar's Plymouth Stora Enso's Sunila	West Fraser's Hinton

ADDITIONAL TECHNOLOGIES

- Until 2013, Ingevity, as part of MeadWestvaco (WestRock), was the sole commercial kraft lignin producer. The company developed its own kraft process to isolate unsulfonated lignin followed by sulfonation and molecular reactions which allows to obtain different lignin products
- After 10 years of lignin R&D, Suzano entered the kraft lignin business with 20Kt of hardwood lignin extraction capacity. Suzano lignin brand is called Ecolig; it is produced in Limeira, Sao Paulo, Brazil, and is a co-product of their pulp production. The company has its own process to obtain Ecolig, which boasts high antioxidant potential, adsorption of UV radiation, and binding properties to the final product
- FPInnovations' Thunder Bay demonstration plant with LignoForce technology is sized to produce up to 50 O.D. kg/day of lignin and operates on a semi-continuous basis. It offers the flexibility to test black liquors from external mills to produce kraft lignin in the base form as well as lignin in the acid form
- LignoBoost XS is the traditional lignin extraction process developed by Valmet but can be easily transported and installed at the mill site. In 2022, Mercer Rosenthal announced a pilot-scale (350 tonnes/a) LignoBoost XS delivery to their lignin R&D Center in Thuringia, Germany
- **Andritz's LignaRec™ lignin recovery concept applies similar process principles as Valmet's LignoBoost process**

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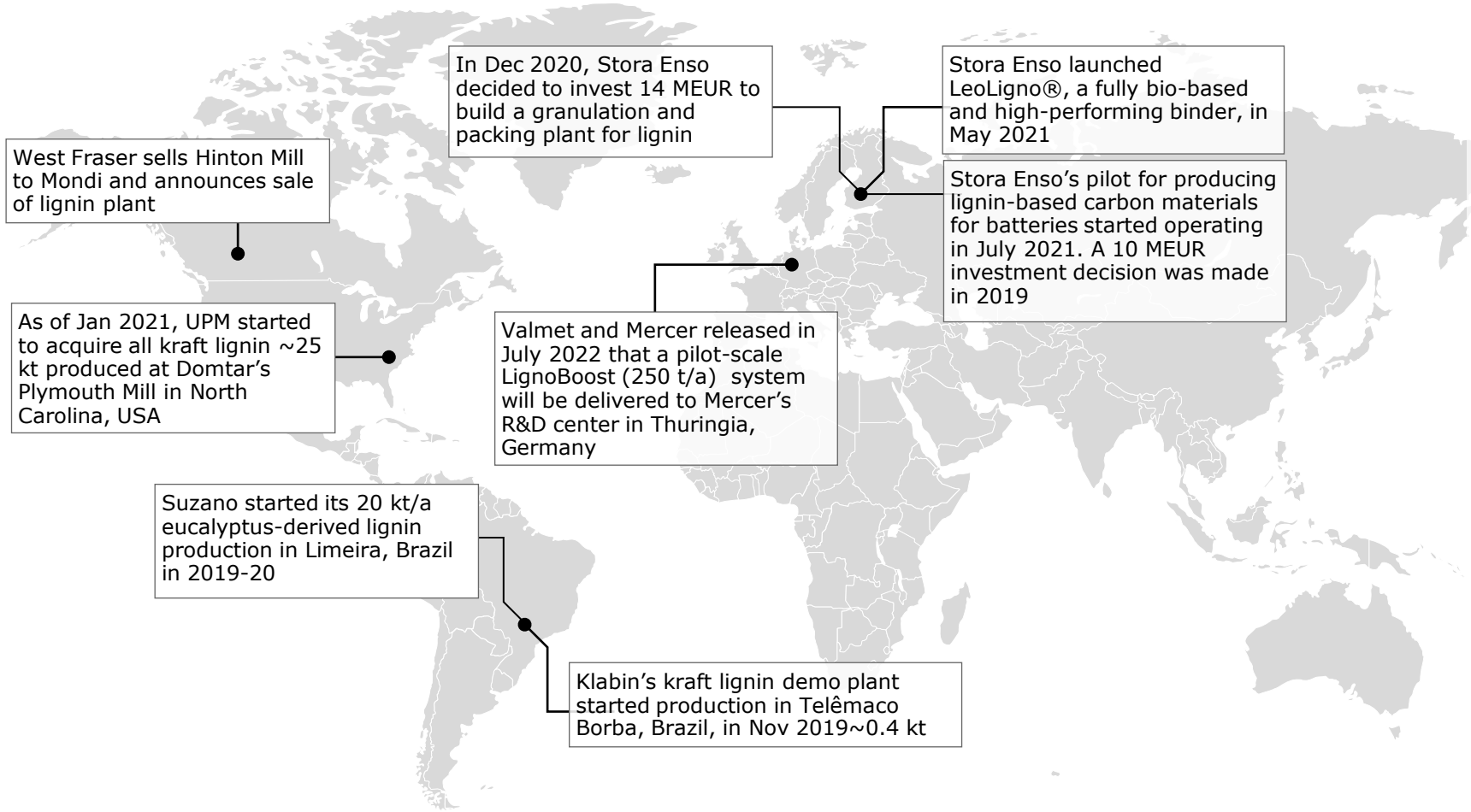
Current commercial kraft lignin supply capacity is about 50 Kt/a globally; more recent updates involve lignin's downstream applications



- There have been no recent announcements on commercial-scale kraft lignin extraction investments
  - In pilot scale, Valmet is to deliver a LignoBoost XS system for Mercer in Germany
- Many recent updates are focused on downstream applications of lignin
  - Stora Enso has been very active in its lignin-related R&D, focusing on binders and carbon materials for batteries. However, Stora Enso has recently announced the closure of the Sunila mill as part of cost-saving measures[2]
  - UPM's agreement with Domtar allows them to expand their existing lignin-based products business
  - Metsä will start a demonstration plant at Äänekoski mill in cooperation with ANDRITZ with a capacity of 2 t/ day LigniOx

1. RISE in Northern Europe is also extracting lignin for High value ends use applications. 2. The closure is a result of wood raw material shortage due to the Ukraine war and the lower price of pulp with new market entrants in Europe. The company's CFO assures that the lignode project will continue but not necessarily at Sunila, maybe at a pilot plant or Skutskär Mill in eastern Sweden

Kraft lignin can be utilized in various products – species and extraction process play a major role in suitability of lignin for a target application

FUELS AND ENERGY

Advanced Liquid biofuels: Lignin is a potential feedstock for biofuel production. Conversion routes include gasification and pyrolysis to green gasoline and diesel

Pellets: Pelletized lignin can be an alternative biofuel for heat and power plants

BINDERS, ADHESIVES & COATINGS

PF resins: The phenolic structure of lignin allows lignin derivatives to be used as a phenol replacement in phenol-formaldehyde resins. PF resins[1] are widely used as wood adhesives

Epoxy resins: Epoxy resins contains two components, epoxies and hardeners. Lignin can be used to replace the hardener e.g., Bisphenol A (BPA). Epoxy resins are used as coatings, adhesives and in composites

Bitumen: Lignin is similar to aromatic fractions of bitumen and offers adhesive and UV stability properties. Bitumen is used as binder to hold asphalt together

DISPERSANTS

Dispersants: Chemically modified kraft lignin[1] can be used as a dispersing agent, complexing agent, flocculent or thickener

Dispersants are extensively used in paints, coatings, oil, gas as well as construction industries

TECHNICAL CARBONS

Activated carbon: Through thermal processing, lignin can be converted into activated carbon. Activated carbons can be utilized in various air and water filters to remove impurities

Carbon black: Lignin can be used as CB replacement. Carbon black is commonly used in car tires

Carbon for batteries: Lignin-based graphite can be used in battery applications for electric vehicles and energy storage

Carbon fiber: Lignin can be used as precursors for carbon fibers by blending it with PAN. CF are used to give structural support in composite materials

BIOPLASTICS

Thermoplastic composites: Lignin can be used to replace inert fillers used in thermoplastics such as carbonate. Lignin-thermoplastic composites has been used in commodity goods such as speakers, toys and design objects

PU foams: Lignin can be used as a substitute for fossil polymer precursors in polyurethane production, polyols. Lignin's rigid structure makes it more suitable for rigid PU foam applications such as insulation, construction and automotive parts

CHEMICALS

Platform chemicals: Lignin is a potential feedstock for aromatic platform chemicals, BTX (benzene, toluene, xylene) and phenol. Lignin can be converted into monomeric biochemicals through various routes

1. Kraft lignin needs to go under sulphonation or oxidation reactions to become water soluble

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Lignin needs an additional modification step in the majority of the applications, making the commercialization of the product challenging

													
Application	PF resin	Dispersants	Bitumen	Carbon for batteries	Thermoplastic composites	PU foam	Advanced liquid biofuels	Carbon black	Carbon fiber	BTX	Industrial pellets	Epoxy resin	Activated carbon
Competition	Low	High	High	High	Very high	Very high	High	High	High	High	Very high	High	Very high
Sustainability demand	High	Low	Medium	Medium	High	Medium	Very high	Medium	Medium	High	Very low	Low	Very low
TRL	8	9	7	5	6	6	6	7[1]	5	4	7	4	7

> *Policies and regulations by governments could be the main driver in using lignin as a non-halogenated material in flame retardants*
>
> *Lancotek Products , AFRY Interview*

> *Developers have to be clever about lignin extraction routes, techno economic numbers, site specific analysis, carbon credit incentives and government support are required to justify any major investments*
>
> *West Fraser, AFRY Interview*

> *Lignin and Biocarbon-based polyols can be incorporated in PU foams to lower the CO2 Footprint and improve flammability however even ppm levels of sulfur will be problematic for consumers.*
>
> *Automotive and packaging foam manufacturer, AFRY Interview*

> *In ten years, lignin-based phenolic resins will be the new normal on a global level.*
>
> *Christian Hübsch, Director in Lignin business, UPM Biochemicals*

> *Over the past few years high quality kraft lignin has become popular in the dispersant industry.*
>
> *Kraft lignin market expert, AFRY Interview*

1. UPM lignin functional filler

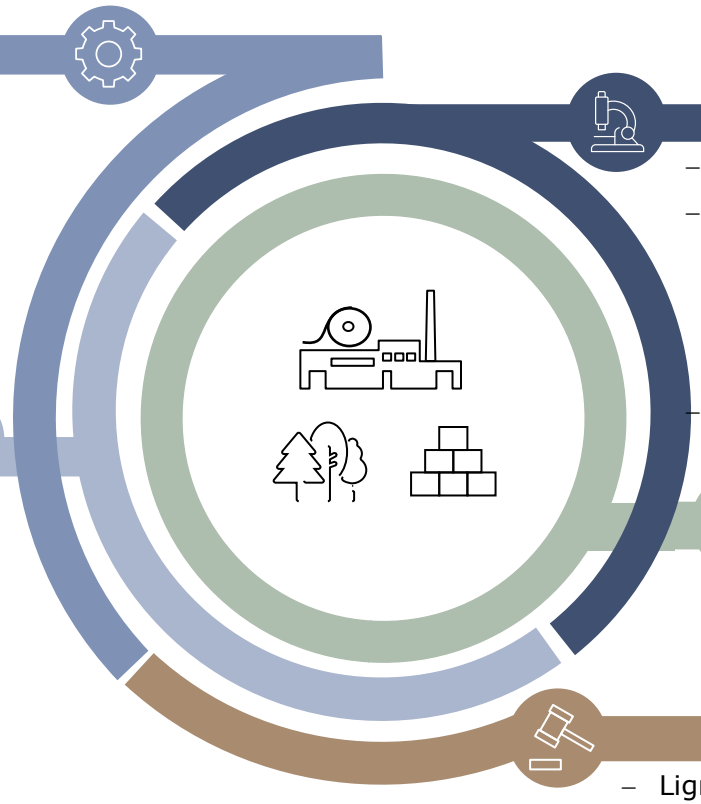
Debottlenecking is a key driver for KL extraction. Market demand mainly depends on legislation, price, and brand owners' sustainability targets

DEBOTTLENECKING

- Process debottlenecking is viewed as a more likely strategic driver for global kraft lignin supply increase, than development of lignin-based high-value applications
- Mapping of pulp mills with high interest and/or need for debottlenecking is extremely difficult, due to the limited public information

LEGISLATION AND PRODUCT STANDARDS

- Regional adhesives markets are controlled by product standards, which in the future can define e.g., maximum carbon footprint or minimum bio-based share for resins
- sustainability standards for PF resins need to be introduced
- Flame retardancy regulations in the bedding, furniture, insulation, and automotive sector often conflict with the push to reduce volatile organic compounds (VOCs) that come with many flame-retardant additives. Lignin-based PU foams could reduce the need for these compounds



PRICE REDUCTION

- Price is mainly driven by the end-use
- Foam is a commodity-driven market, which is highly price competitive. The cost of foam production is largely dependent on the cost of the raw materials used; Recently, shortages of key petrochemical-based commodity chemicals in these foams have driven the costs upwards
- Undesired properties linked to KL-based PU foams may also limit market uptake, even if price is competitive

BRAND OWNER SUSTAINABILITY DEMAND

- Large brand owners often apply their own sustainability targets, not defined by regional standards or legislation, which can speed up lignin market development

SUPPLY GAP LEFT BY LIGNOSULPHONATES

- Lignosulfonates production volume is expected to decrease towards 2030, as some old sulfite pulp mills will be closed. The resulting supply gap could be filled with kraft lignin dispersants. There are fossil-based competing products that can serve as lignosulphonate replacements, and the possibility for new bio-based competitors should not be excluded

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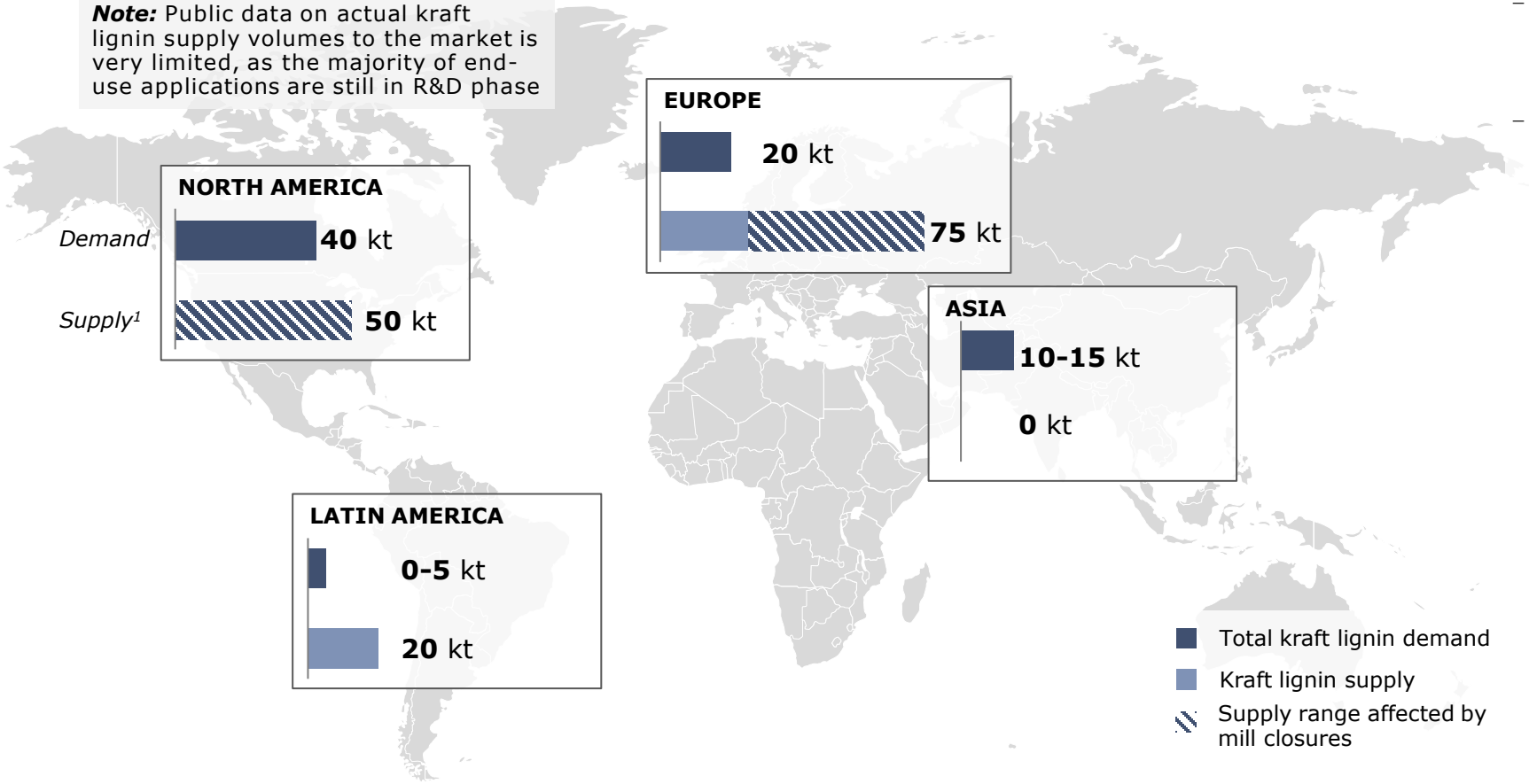
Global kraft lignin demand is mostly driven by regional legislation and product standards, public sector policies, and brand owner sustainability demand

Note: Public data on actual kraft lignin supply volumes to the market is very limited, as the majority of end-use applications are still in R&D phase



- Global kraft lignin extraction capacity is 50 kt. Estimated current demand is based on the commercialized application of lignin-based PF resin and dispersant[2]
- Main players in the kraft lignin landscape can be excluded from potential suppliers for any new interest in the lignin market as they all have dedicated application development strategies for lignin
  - Stora Enso is focused on application development for its own kraft lignin. Sunila mill closure announcement might have a downside effect on lignin developments[3]
  - Ingevity focuses on dispersants application, the announcement of North Charleston closure might affect the Ingevity lignin supply in future
  - Domtar now sells all of its production to UPM (Europe supply)
  - West Fraser Hinton mill has recently been sold to Mondi group, and lignin production will cease.
  - Suzano focuses its lignin supply on to own technology and application development

1. the Domtar ~25 kt volume to UPM applied to Europe Supply. Ingevity and West Fraser as suppliers in North America might face difficulties in near future due to mill closures.
2. with NA players being West Fraser and Ingevity 3. Sunila mill closure could affect the supply.

Kraft lignin value has the potential to increase in 2030, if energy storage applications are successful

VIEW TO CURRENT KRAFT LIGNIN PRICING

- Global kraft lignin supply capacity is 50 kt/a
- Most of the KL capacity is either not utilized and/or KL is extracted and burned in lime kilns – only a small share is converted into high-value products
  - Therefore, from a mill-operations point of view, the value of KL is as an alternative fuel for the lime kiln to replace, e.g. natural gas, petroleum coke, wood residues such as bark and sawdust, or bio-oil
- However, for KL sold on the market, the value is based on the estimated lignin price, when lignin is substituted the fossil alternative in the different products
- Kraft lignin value stream has increased over the past ten years as KL-based PF resins have started to enter the market
- Currently, phenolic resins and dispersants are the main commercial end-use applications for market KL, but in the future AFRY expects demand for anode material to become increasingly high this links to R&D success in material development by companies like Stora Enso.

MARKET LIGNIN VALUE BY END-USE

- As alternative fuel in the lime kilns and power boilers – **low case**
  - In the energy value calculation, the alternative energy value per tonne of kraft lignin burned as natural gas fuel replacement in lime kilns is estimated at 112 CAD. When applied regional average natural gas price of 4.78 CAD/GJ (Alberta 2022)[1], and lignin energy value of 23.5 GJ/t[2]
    - The use of lignin as fuel requires a high gas price to be justified. In Nordic countries with the price of natural gas ~ 19.5 CAD/ GJ, the lignin value as fuel in the lime kiln will be ~ 500 CAD / t
    - A collapse in natural gas prices in Canada will result in gaining a lower value when burning lignin as fuel in lime kilns
    - All kraft lignin separated from BL but not sold in the market is assumed to be burned in lime kilns
- As phenol replacement in phenolic resin and dispersant – **Base case**
  - The current value for kraft lignin estimated based on dispersant application and phenol replacement in phenolic resin and has ranged from 790 – 1300 CAD/t[3]
  - Sulphonated kraft lignin price depends on several factors, such as its level of chemical modification, and end-use application.[4]
- As graphite replacement in lithium-ion batteries anode – **High case**
  - if realized will increase the lignin value significantly

1. Alberta Energy 2. Literature 3. assuming sulfonated kraft lignin has higher price than lignosulfonate cost saving potential has taken into account 4. Lowest value applications include dust control, while highest valued are oil drilling muds and other dispersant applications such as oil recovery and lead batteries.

Suitability of unmodified kraft lignin for a target application is limited, modification processes are often required to reach a certain level of quality

Application	Product that KL would substitute	Suitability of unmodified kraft lignin	Cost of kraft lignin processing to produce the substitute[3]	Competitiveness	*Kraft lignin modification*[1]
PF resins for wood adhesives	Phenol	Suitable at low substituition rate, softwood lignin more reactive than hardwood	Low	Competitive, close to commercial adoption	*Chemical modification to increase lignin reactivity towards formaldehyde*[1]
Lignin-based dispersants	Ligno-sulfonates	Not suitable	Low	Competitive, commercially done in North America	*Sulfonation or oxidation (i.e., Lignoforce) to make kraft lignin water soluble*
Bitumen	Bitumen	Suitable below 30% replacement	No additional cost	Demand for bio-based asphalt in Canada allows kraft lignin to be competitive if bio-premiums are available[2]	*None up to 25% (Deodorization might be needed, depending on the case)*
PU foam	Polyol	Not suitable at high substituution rate	Low-to- medium	Lignin-polyol has the potential to be lower in cost than other conventional polyols, contingent on the level of lignin functionalization required	*Deodorization and more modifications to introduce more polyols*
Carbon for batteries	Graphite	Suitable at low ash content[2] but further carbonization is required	-	Technology is too immature to estimate competitiveness	*Purification and removal of ash, Carbonization followed by graphitization*

1. Mainly Softwood kraft lignin is required, modification at higher substitution rate 2. Some European countries e.g. the Netherlands give bio-premium to lignin-based asphalt to support the development of this application 3. impurity levels threshold for each application needs to be verified with the application developers

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Most potential kraft lignin clients are companies with previous experience in lignin as raw material, good R&D resources and high sustainability targets

POTENTIAL OFF-TAKERS FOR KRAFT LIGNIN IN DIFFERENT END USE APPLICATIONS INCLUDE:

PF resins

- Integrated forestry companies that have in-house plywood production, and previous experience with lignin product development
- Certain PF resin producers in North America, who have current or past activity with lignin-based PF resins

Bitumen

- Potential off-takers in construction and paving in Ontario. Promising trials in Thunder Bay by Lakehead University in partnership with Pioneer Construction and FP Innovations with 5% replacement of bitumen

Dispersant

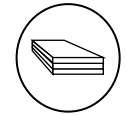
- With decline in the supply of lignosulfonate from sulfite mills there is interest from large multinational enterprises who have previously applied lignosulfonates in their products, R&D resources for product development, ambitious sustainability targets and production sites in North America

PU foam

- Foam converters that are backward integrated to blending, as these have extensive in-house chemistry expertise and testing capabilities that would enable development and partnership opportunities
  - Companies with ambitious sustainability targets, previous experience in bio-based feedstocks and those that have production sites. One company in Canada called Enerlab, QC is using lignin in PU foam at low substitution rates

Batteries

- With Ontario being a hub for clean energy, the automotive industry, and EVs the demand for sustainable batteries can be significant but subject to success in R&D and commercialization

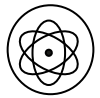


PLYWOOD PRODUCERS

PF RESIN PRODUCERS

MULTINATIONAL CHEMICAL COMPANIES WITH GOOD RESOURCES

PAVEMENT AND ROAD CONSTRUCTION

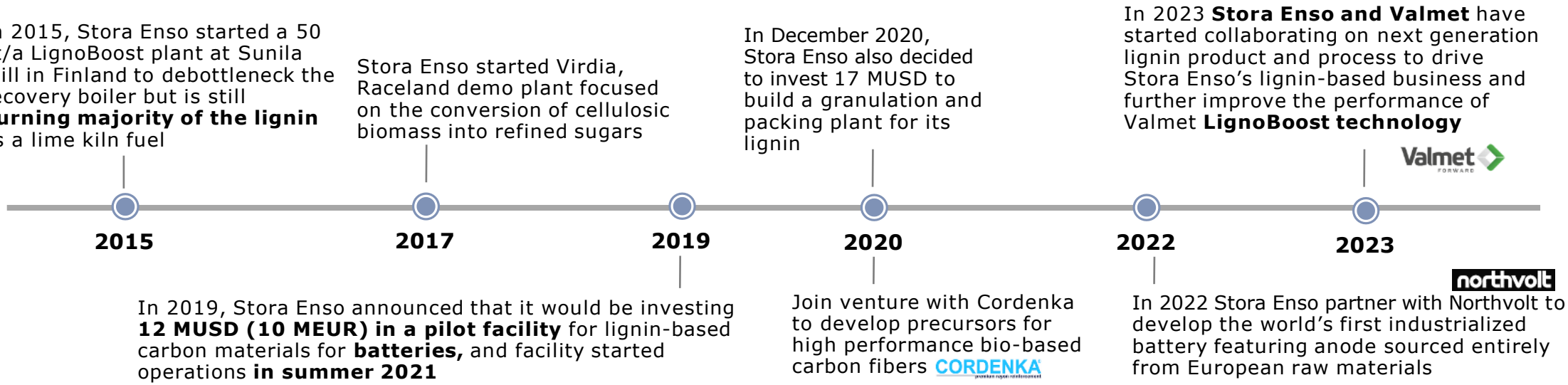


FOAM PRODUCERS WITH BLENDING EXPERTISE

BATTERY AND CAR MANUFACTURER

Although Stora Enso actively conducts R&D work on higher value end products, most lignin is still burned in the lime kiln

STORA ENSO DEVELOPMENT TIMELINE



STORA ENSO BUSINESS DEVELOPMENT

- Stora Enso takes a **R&D perspective** on bioproduct development, focusing on attracting people with high R&D competence
  - Development expenses are accounted as part of R&D expenses
  - The company has made **investments in emerging technologies**, with lesser focus on market demand

- Stora Enso has a dedicated biomaterial division in their company structure, which indicates a strong interest in bioproducts:
  - The division's offerings consist of kraft pulps, fluff pulp, dissolving pulp, and other pulp mill-derived bioproducts such as lignin, tall oil, and turpentine
  - **Currently, with the Sunila mill closure announcement the lignin supply and development might be affected**

West Fraser applies recovered kraft lignin in phenolic resins for their technical wood products – 10,000 t/a plant started operations in 2016

- West Fraser started kraft lignin production at its pulp mill site in southwestern Canada in 2016
  - Product is branded as Amallin™
  - The company has a lignin extraction capacity of 10 kt/a
- Primary strategic initiative for lignin extraction was to develop a bio-based alternative for petroleum-derived resins, utilized in adhesives in the company's various technical wood products. Extraction is performed via the proprietary LignoForce™ process, jointly developed by FPInnovations and NORAM Engineering with support from the Government of Ontario through CRIBE. **The future of the lignin plant is unknown following the sale of the mill to Mondi Group**

POTENTIAL END USE APPLICATIONS FOR AMALLIN™

Adhesives	Polyurethane foams
Composites	Carbon fibers
Surfactants	Dispersants

PRODUCT PROPERTIES

- Compared to fossil-based chemicals, West Fraser highlights Amallin™'s traceability, low cost, and savings in CO_2 emissions in downstream processes
- Its high-quality properties include
  - Low odor, ash and sulfur content
  - High carbon content
  - No heavy metals

MANUFACTURING PROCESS

LignoForce™

- LignoForce™ system recovers high-purity lignin from kraft pulp
  - As with LignoBoost®, installing LignoForce can increase pulp production volume at the mill by reducing load on recovery boilers
- As a unique feature of the technology, black liquor is oxidized with oxygen, prior to the lignin acidification with CO_2

Photo source: FPInnovations and Enerlab websites, AFRY photo bank.

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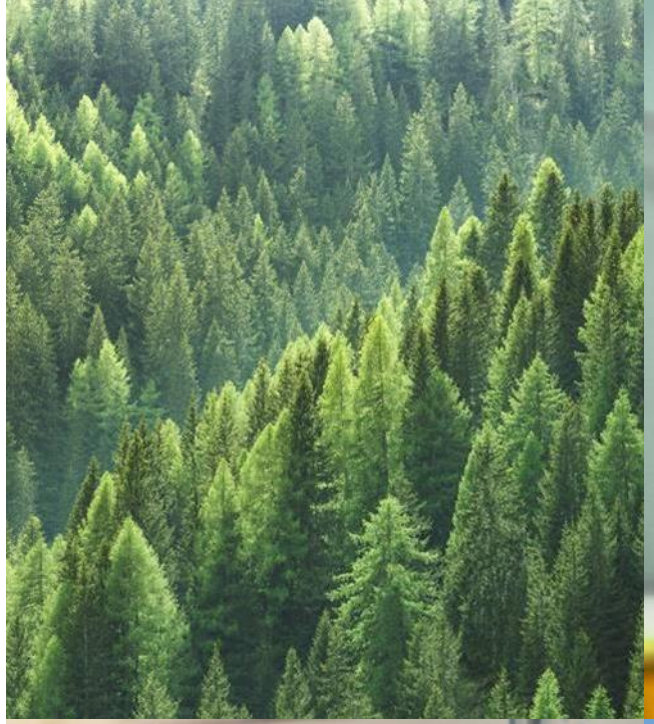


Biorefinery lignin comes from aiming for value-added applications by producers

- Main sources of biorefinery lignin are processes aiming to fractionate and valorize all fractions of biomass i.e., cellulose, hemicellulose, and lignin
  - Developers such as Avantium, Sweetwater Energy, Bio-Sep, and UPM are focusing on this route
- Biorefinery lignin can come from "lignin-first" biorefineries where biomass is fractionated while keeping the native structure of lignin intact
  - Developers such as Bloom Biorenewables is focusing on this route
- These biorefining concepts based on the fractionation of biomass can utilize a variety of technologies; acid hydrolysis, ionic liquids, enzymatic hydrolysis

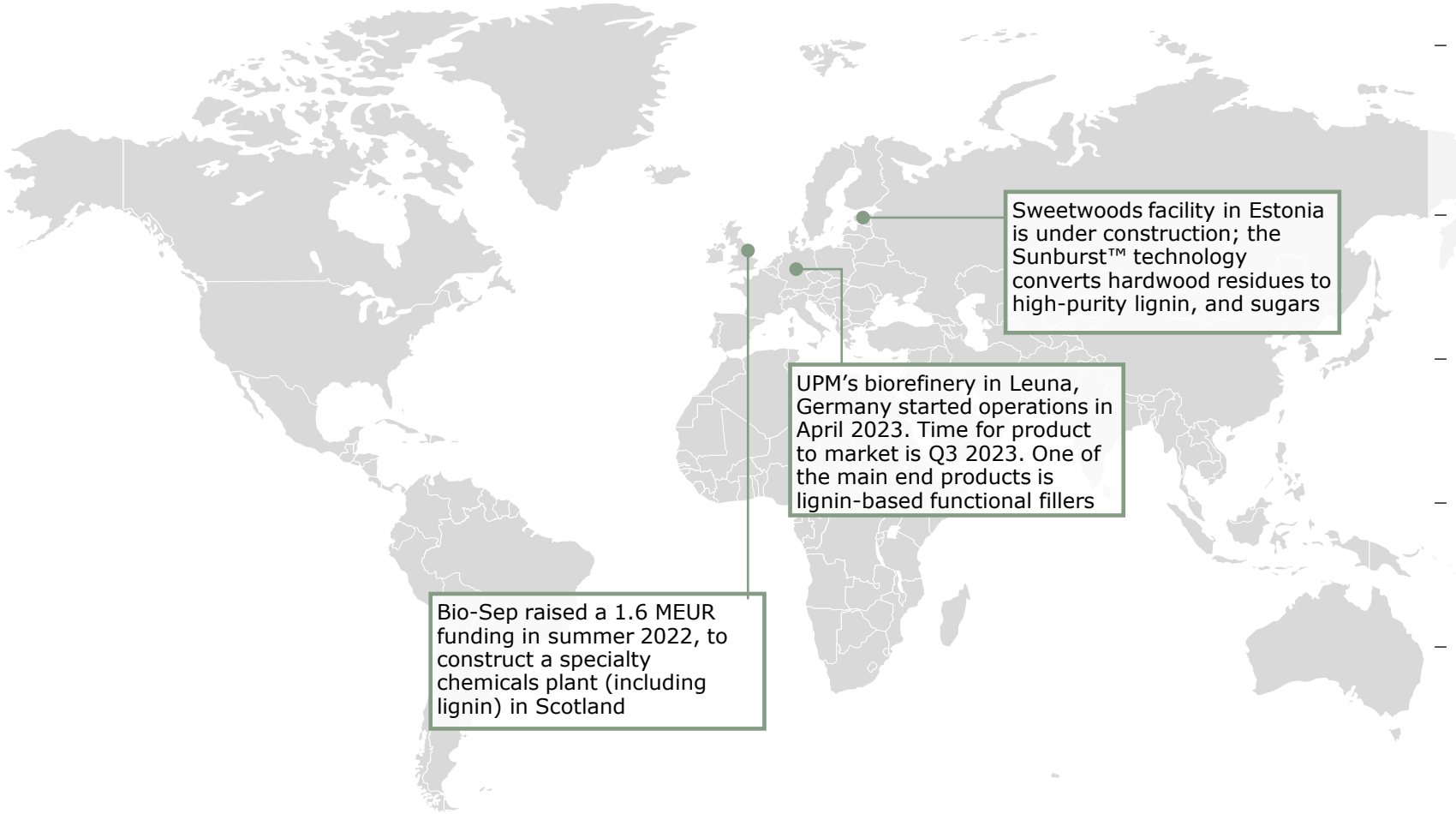
Market drivers for biorefinery lignin

- ✚ High purity, allowing lignin utilization in various high value products
- ✚ Sulfur free, or minimal sulfur content of the product
- ✚ Environmental megatrends, which promote minimizing the waste generation of industrial processes
- ✚ Non-food feedstocks as sources of sugar for bio-based plastics and chemicals

Development challenges

- ▭ Most of the projects are only emerging, and reaching constant, industrial scale production will take time
- ▭ Different process concepts can yield lignin with diverse chemical characteristics

Projects aiming to produce lignin as the main product are few, aiming at kt production scale and are in Europe; including UPM, Bio-Sep and Sweetwoods



- UPM's wood-based chemicals facility in Leuna, Germany with glycols as the main product and lignin functional fillers is expected to come online in late 2023; the lignin product will be replacing carbon black in various rubber applications
- Within Sweetwoods Project, Sweetwater Energy pretreatment technology platform is established and operated by Fibenol, with the flagship plant fully functional in 2023
- Bio-Sep raised 1.6 MEUR funding in summer 2022 and aims to start construction of its first commercial-scale plant (13 Kt/a of wood raw material) in Scotland in 2023
- Lixea currently has a small pilot in Sweden, developing a pretreatment technology for lignocellulosic biomass, based on ionic liquids, and aims to build a demo plant of 30 kt/a in the future
- **There are currently no identified potential biorefinery lignin suppliers in North America, as all the projects that are planning facilities at kt scale are in Europe**

1. In addition, companies such as Lignopure, Lignorganic, CH Bioforce, Vertoro, MetGen and LXP group develop lignin extraction technologies, high-quality lignin-based applications and/or produce of sulfur-free lignin

UPM is expected to utilize majority of the lignin from new Leuna facility internally, while Avantium has their main focus on other products than lignin

	UPM	Sweetwater/Fibenol	Avantium
Description	UPM uses enzymatic hydrolysis to treat wood biomass and produce Bio-MEG and Bio-MPG from the sugars and renewable functional fillers from the lignin. The pre-treatment technology is not disclosed.	Sweetwoods uses Sweetwater's Sunburst pre-processing technology, where wood chips enter a giant twin-screw extruder that deconstructs them into a mixture of wood sugars and lignin, called the whole slurry. The process combines steam, pressure and acids in a 20-second reaction. During the process, the material undergoes through an enzymatic process before is release in two main streams as lignin and sugars	Avantium's technology, DAWN®, enables the conversion from agricultural and forestry residues to high value chemicals and materials
Products	Biorefinery lignin, bio-glycols and industrial sugars	Biorefinery lignin and sugars	Industrial sugars and lignin
Feedstock	Hardwood Biomass, Beech	Hardwood Biomass, Birch, Residues are collected from plywood and sawmills, as well as saw log harvesting operations	Agricultural and forestry residues
Advantages	Combination of wood processing and petrochemical processes Alternatives to fossil materials	The process can convert more than 90% of woody biomass into high-value products with minimal environmental impact The fractionation process is efficient and fast, taking only 20 seconds to turn wood chips into wood slurry	Additional higher value applications development for lignin
Capacity	220 kt /a of biochemical Lignin-based functional fillers volume is estimated at 70 kt/a	8 kt/a of different lignin grades and 10 kt/a cellulosic wood sugar	Theoretical maximum ~5 t/a of lignin (20 t/a of wood chips)
Target lignin application	Renewable functional fillers (RFF) for rubber and thermoplastic applications, e.g., car tires and other automotive components, hoses and seals	Lignova crude for phenolic resin and thermoset materials Lignova pure for polyurethane and carbon fiber and PF resin	Bitumen replacement for asphalt
Example mill	Leuna, Germany (2023)	Demo plant at Estonia (100% production in 2027)	Pilot bio-refinery in Delfzijl, Netherlands

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Europe is currently the key region in biorefinery lignin activity

	Bio-Sep	Bloom Biorenewables	KU Leuven
Description	Sonichem process uses ultrasound to break the chemical bonds in the feedstock to liberate the cellulose, sugars and lignin fractions. The fractionated mixture is then processed through recovery units to separate the fractions into high-quality biochemical products	patented aldehyde assisted fractionation (AAF), a mild lignin extraction method that prevents lignin from condensing during extraction from biomass Bloom received 2.9 MEUR investment from Yokogawa in 2020 to build a 50 kt/a pilot plant however status of the pilot plant has not been disclosed	KU Leuven University is developing a lignin-first biorefinery concept for simultaneous biomass fractionation and lignin valorization, the BIOCON platform Based on reductive catalytic fractionation (RCF), it is an active stabilization approach that solubilizes lignin from biomass and catalytically depolymerizes it to monomers and oligomers
Products	Cellulose, natural sugars and lignin	Depolymerized lignin and sugars	Depolymerized lignin and sugars
Feedstock	Hardwood, softwood, sugar cane bagasse, straws, grasses	Hardwood and Softwood	Hardwood Biomass
Advantages	High-purity natural lignin from spruce softwood, with a low molecular weight (<1,000 g/mol) and solubility in a range of common solvents	The company focuses on; textile fibers from cellulose fraction, bio-plastics from hemicellulose	Partnered with VITO in the Flemish Government funded Moonshot initiative, to further develop catalytic processes to produce functional bio-based aromatics from biomass and lignin (PILLAR)
Capacity	Pilot plant/ small batch quantities	Pilot plant	Pilot plant
Target lignin application	Phenol replacement in resins and composites. For materials, coatings and chemical additives	fuels, cosmetics, and fragrances from lignin	Application testing done for adhesives, polymers, coatings and lubricants
Example mill	N/A	N/A	N/A

Biorefinery lignin market could grow significantly depending on the estimated lignin value in different end uses and announced projects

VIEW TO CURRENT BIOREFINERY LIGNIN PRICING

- Biorefinery lignin market volumes are assumed to depend on the current player's project actualization
  - In low scenario, UPM (Leuna) is the only new commercial scale market entrant. Avantium, Lixea and Bio-Sep operate pilot-scale facilities, but Essity has ceased production in Germany
  - Base scenario reflects the supply pipeline as presented in Phase I, but additionally includes a 5 kt/a facility by Lixea
  - High scenario depicts several additional 10 kt/a facilities, commenced by e.g., Bio-Sep and Lixea
- In value-based market analysis, high-quality biorefinery lignin is assumed to achieve price levels of higher-value applications
  - In low and base scenarios, refined lignin replaces carbon black, and the market value is based on the forecast price of heavy fuel oil
  - In high scenario, market value is based on estimated lignin price when lignin is substituting fossil graphite in anode materials production[1]

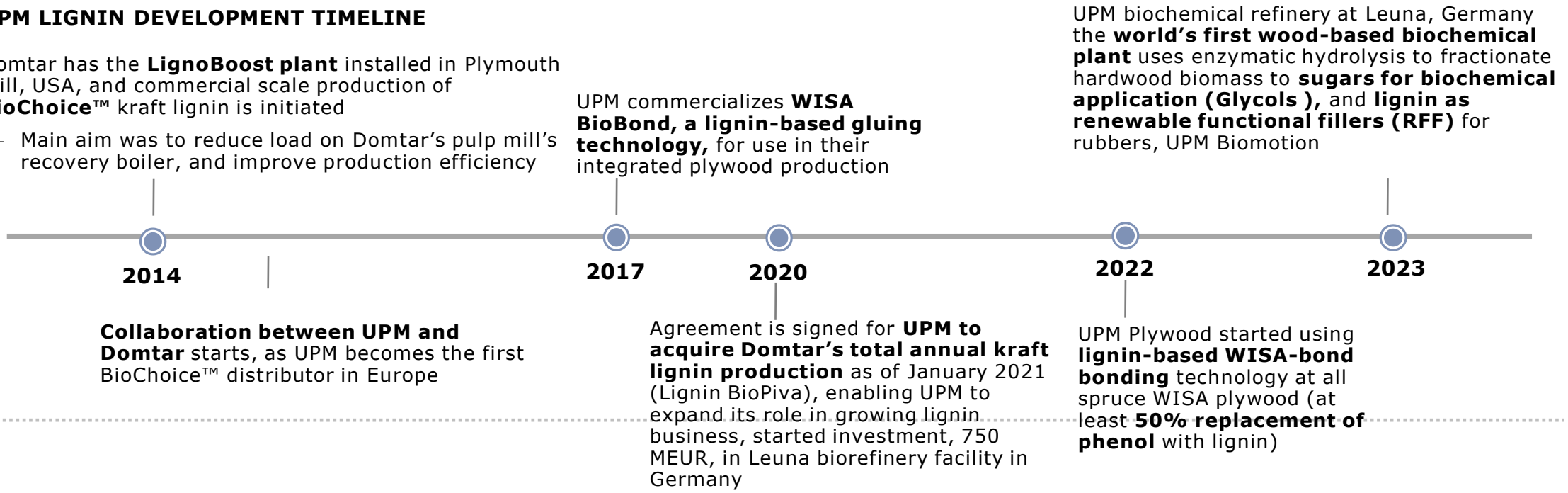
MARKET LIGNIN VALUE BY END-USE

- Biorefinery lignin lacks the estimate for 2022 market price, as this lignin type is not commercially available
- As a low case for current lignin value bitumen replacement for asphalt could be estimated at ~ 650 CAD/t
- Future price forecasting can assume that main commercial end use for biorefinery lignin is as a renewable substitute for carbon black, replacing heavy fuel oil raw material
- The forecast high case can assume that biorefinery lignin could successfully replace graphite in the production of battery anodes

1. Subject to R&D success

After strong start in 2013, Domtar's focus on lignin business has diminished, but now UPM is proceeding active product development with Domtar's lignin

UPM LIGNIN DEVELOPMENT TIMELINE



Lignin-based products development

UPM's lignin products are mainly used in **adhesives**; other applications under development include composites, rubber products, polymer foams, chemicals, and carbon fibers

In 2020, UPM made a 660 MUSD (550 MEUR) investment decision on a **new biochemicals facility** in Germany, where the product portfolio is to also include lignin derivatives in the form of **functional fillers**

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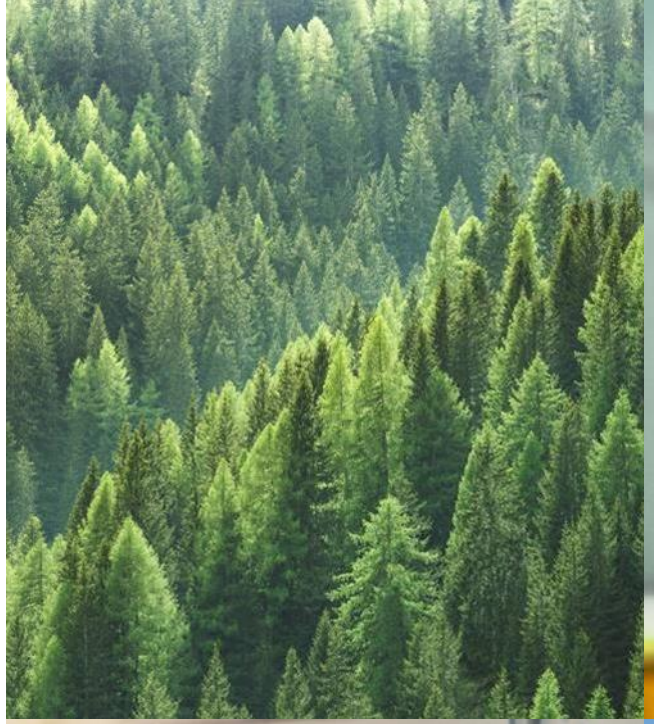

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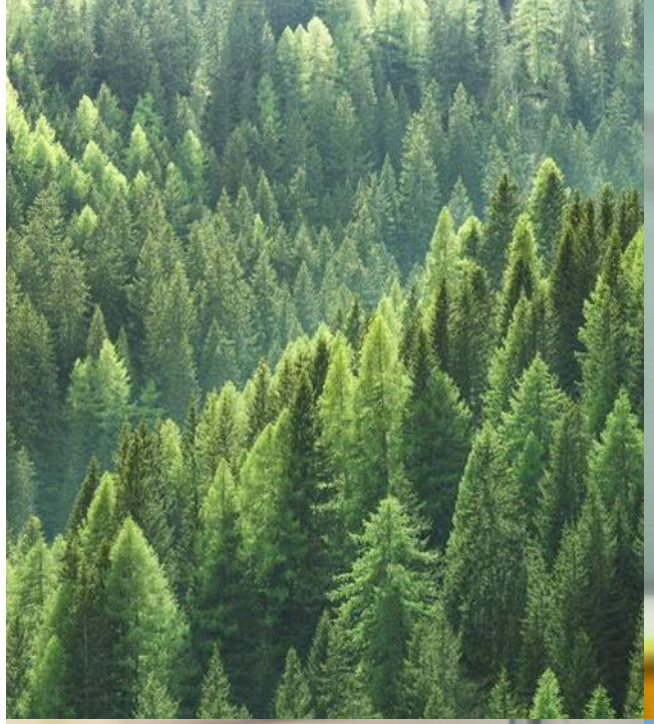


Developments in technical R&D, legislation, and competing products define the kraft lignin market in future

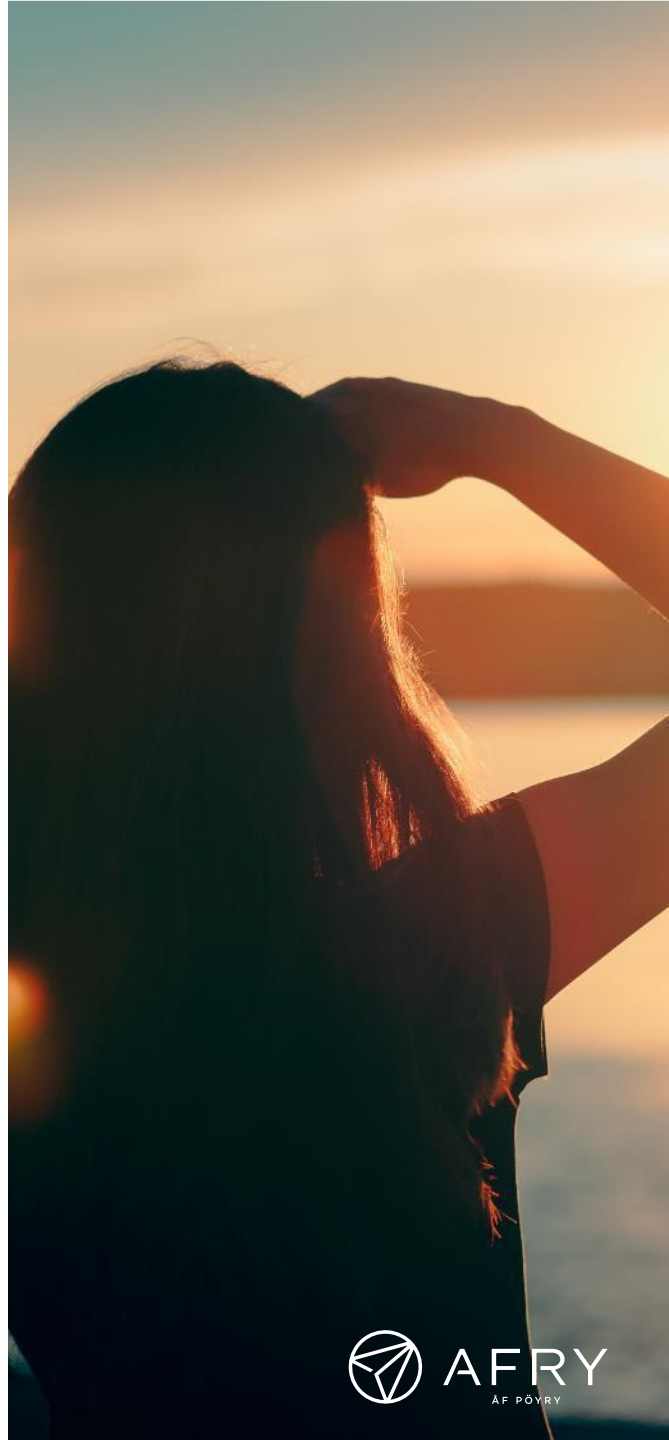
Global kraft lignin demand is mostly driven by regional legislation and product standards, public sector policies, brand owner sustainability demand, and a supply gap in the dispersants market left by decreasing lignosulfonates manufacturing

Three scenarios depict different outlooks for the KL market. Kraft lignin future supply development will directly correlate with higher value applications demand development and new off-takers

In the low scenario, KL market is still immature, and Ontario is the only new supplier. In the medium scenario, the market has clearly developed from today, and in addition to PF resins, dispersants and bitumen, also a few other promising applications add to the global demand

In the high scenario, global supply has more than doubled from current market, and all of it is utilized in high value products. This can only be achieved with several technical breakthroughs, favorable legislation, and a significant supply gap left by lignosulphonates

The most realistic view of KL market is that it has elements from both the low and medium scenarios. Recent mill closures could open opportunities.



PF resins, dispersants and bitumen provide the best fit for Ontario's lignin market approach

Kraft lignin can be utilized in various products – beyond solid fuels, the applications closest to commercial scale are phenolic resins and dispersants

Global Kraft lignin demand is estimated at 70-80Kt, mainly stemming from PF resins and dispersants[1]. Future demand is dependent on application specific technology development, but also on other factors such as price level and competition

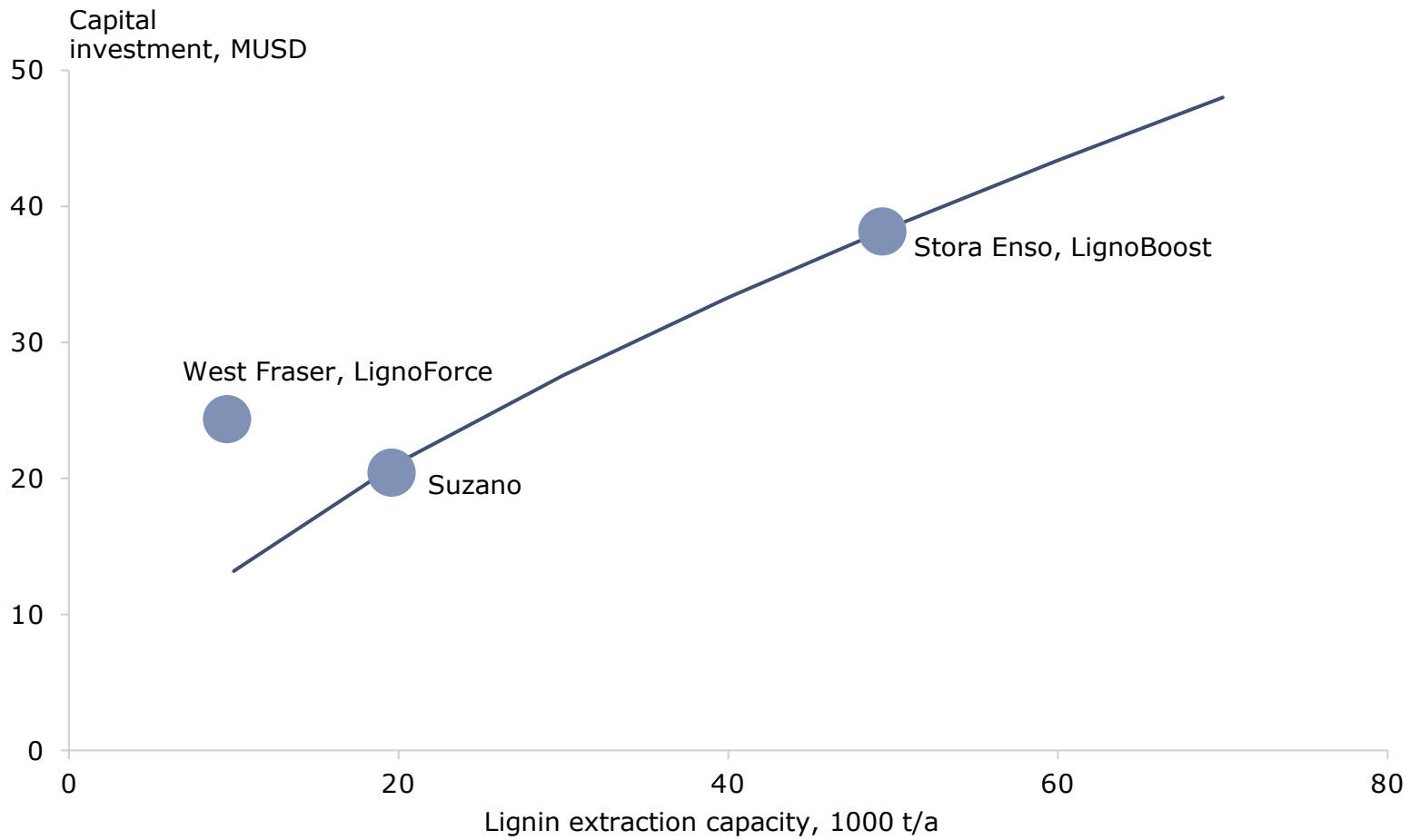
Most near-term application for kraft lignin are PF resin, dispersants, bitumen and foam with lignin-based batteries required longer development time

PF resins, dispersants, bitumen and foam[2], all require further modification, either on site or by the customer. Modification of KL quality to fit specific application needs, could help in finding off-take partners, especially when the application is commercial or close to commercial

Before making any final investment decision on commercial scale lignin separation, it is recommended to extract small scale samples to potential customers so that both quality requirements and interest for the product can be verified

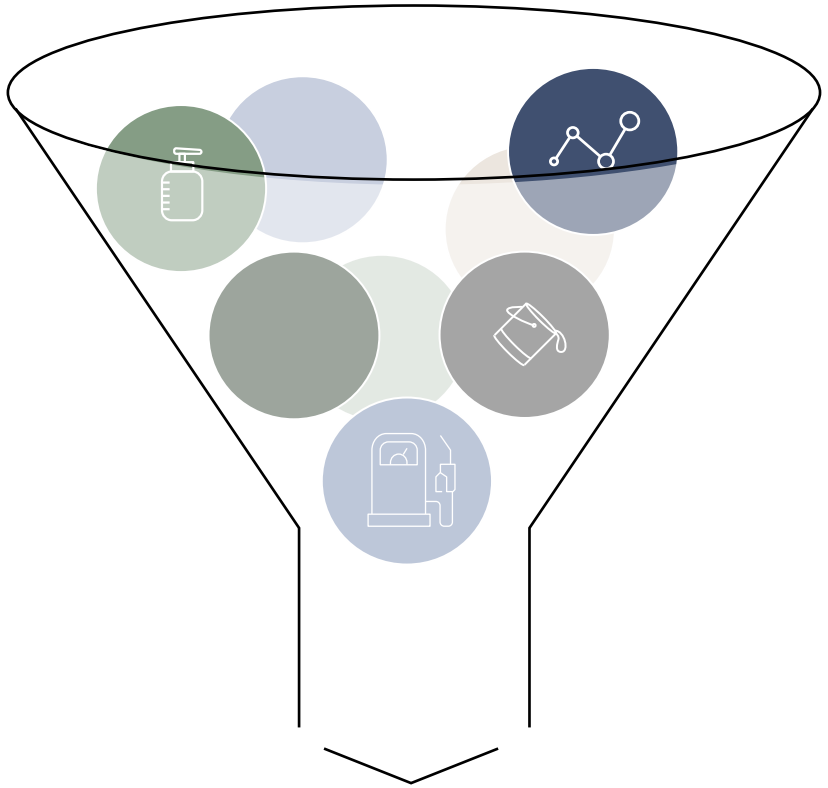
1. Current market volume for Kraft lignin as replacement for bitumen is very small, but it is actively being tested in Europe, and demand volumes are expected to grow towards 2030. Today, lignin is utilized to some extent in other road construction products.
2. Kraft lignin may need to be deodorized.

Investment costs for kraft lignin separation estimated to be 20 – 45 MUSD. Capital costs depend on the plant size and are highly mill specific



- CAPEX curve is drawn based on Stora Enso's Sunila investment (50 Kt/a, ~39 MUSD) and Suzano's 20 MUSD investment (20 Kt/a) announcement in 2015
- However, West Fraser's LignoForce process (10 Kt/a) resulted in a higher total investment than the 20Kt Suzano facility
- The differences in total CAPEX mainly result from additional rebuilds and adaptations at the site, and these are always mill specific
- Total investment is evaluated to be around 50 MUSD for a plant with 70 kt/a extraction capacity
- With 50 kt/a extraction volume, total investment is around 40 MUSD, and with 20 kt/a, it is estimated at 20 MUSD
- With a granulation and packaging plant (17 MUSD, based on Stora Enso's announced investment), the CAPEX increases from 90 USD/t (base cost for 50 kt/a plant) to 130 USD/t

Potential lignin applications for Ontario identified based on the TRL and market demand

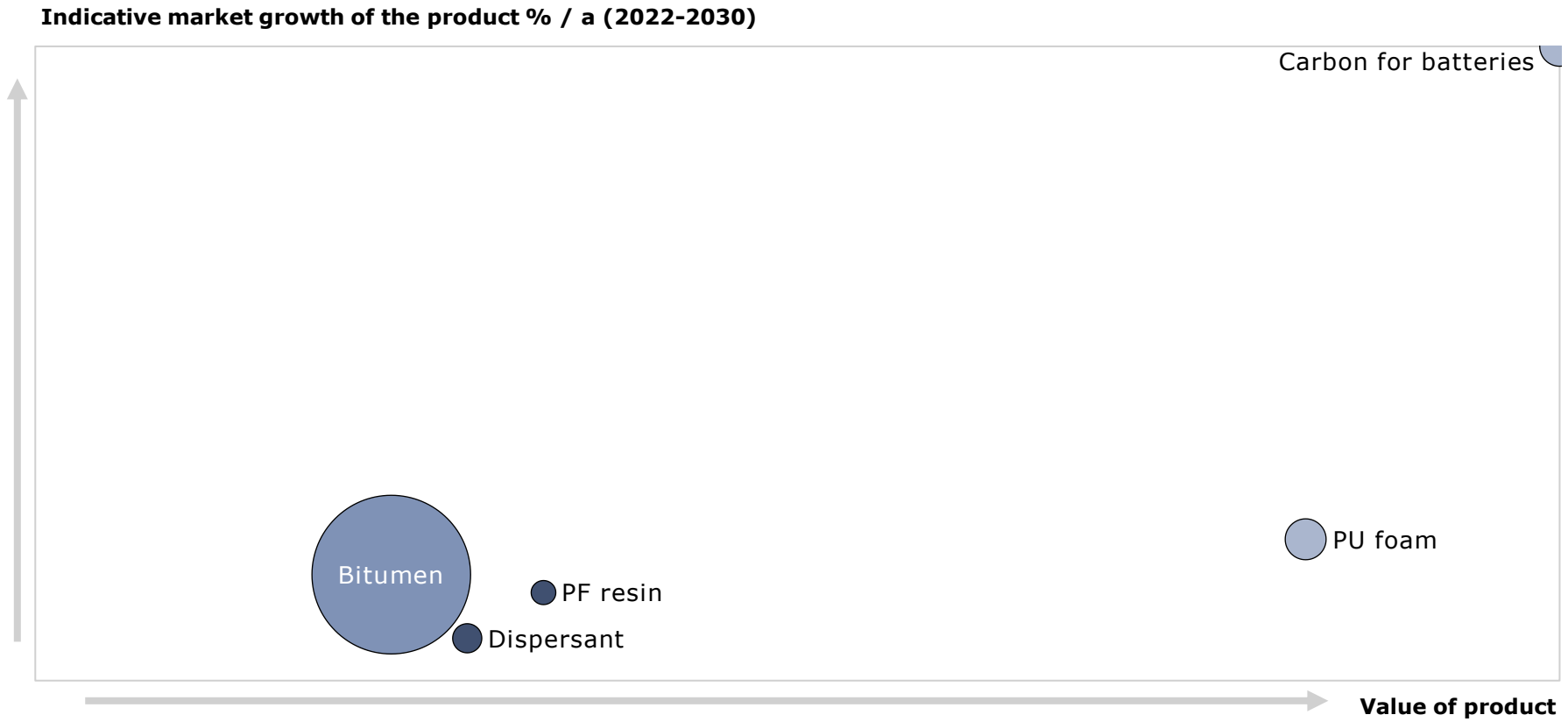


Top 4 applications

- High technology maturity, healthy market outlook, and value of the products had a high impact when choosing the top applications
  - Almost all selected products are developed by one or more of the other KL market players
  - Also, their risk profiles are considered to be smaller than for many of the excluded products
- For PF resins and dispersants, major lignin modification steps could be done off-site by the customer
- Main focus should be on PF resins and dispersants, as they are higher-value products than bitumen
  - Bitumen can serve as an extra product in case extracted lignin volumes exceed the market demand for PF resins and dispersants

1. Maximum substitution of lignin in a given application

Phenolic resin and dispersant markets represent commercial applications. Emerging PU foams and batteries could potentially provide higher margins



KEY OFF-TAKES:

- *Bubble size indicates the market size of the products in Mt[1]*
- *Bubble color indicates technology readiness*

TRL[2] 1-2 – Basic Research
TRL 3-4 – Lab scale
TRL 5-6 – Pilot scale
TRL 7-8 – Demo - scale
TRL 9 – Full Commercial

- *Carbon for batteries has the highest market growth indication in the coming years*

1. Market size indicates theoretical maximum for potential Kraft-lignin based applications. 2. Technology readiness level

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Most potential kraft lignin clients are companies with previous experience in lignin as raw material, good R&D resources and high sustainability targets

POTENTIAL OFF-TAKERS FOR KRAFT LIGNIN IN DIFFERENT END USE APPLICATIONS INCLUDE:

PF resins

- Integrated forestry companies that have in-house plywood production, and previous experience with lignin product development
- Certain PF resin producers in North America, who have current or past activity with lignin-based PF resins

Bitumen

- Potential off-takers in construction and paving in Ontario. Promising trials in Thunder Bay by Lakehead University in partnership with Pioneer Construction and FP Innovations with 5% replacement of bitumen

Dispersant

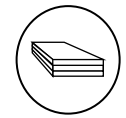
- Large multinational enterprises who have previously applied lignosulphonates in their products, significant R&D resources for product development, ambitious sustainability targets and production sites in North America

PU foam

- Foam converters that are backward integrated to blending, as these have extensive in-house chemistry expertise and testing capabilities that would enable development and partnership opportunities
  - Companies with ambitious sustainability targets, previous experience in bio-based feedstocks and those that have production sites

Batteries

- With Ontario being a hub for clean energy, the automotive industry, and EVs the demand for sustainable batteries can be significant but subject to success in R&D and commercialization

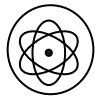


PLYWOOD PRODUCERS

PF RESIN PRODUCERS

MULTINATIONAL CHEMICAL COMPANIES WITH GOOD RESOURCES

PAVEMENT AND ROAD CONSTRUCTION



FOAM PRODUCERS WITH BLENDING EXPERTISE

BATTERY AND CAR MANUFACTURER

PF resins, bitumen, dispersants, PU foam and Li-ion batteries were recognized as most potential end-use applications for Ontario market

SELECTED PRODUCTS FOR ONTARIO

Phenol formaldehyde resins for wood adhesives

- Close to commercial scale, developing market, maturing technology
- High development activity
- High demand for sustainable product

Bitumen

- Technology under development, considerable interest from the industry
- Lignin performs well as binder without modifications
- Large addressable market

Lignosulphonate-based dispersants

- Developed market and mature technology
- Ready lignin-based product market
- Modification required to enhance solubility, price depend on properities

Rigid polyurethane foams

- Technology readiness lab to demo scale
- High competition from fossil alternatives
- Further lignin modification and investment needed from the off-taker

Carbon for batteries

- Technology readiness lab to demo scale
- High interest from car manufactures and available government incentives

PF RESINS

$+ Possibility for bio-premium

$+ A price premium over phenol price is unlikely for unmodified kraft lignin. KL would require additional processing

BITUMEN

$+ A price premium over Bitumen price is unlikely if the price of Bitumen doesn't increase drastically. A green premium and carbon tax credit can be applied due to sustainability aspects

LIGNOSULPHONATES AS DISPERSANTS

$+ Modified KL (i.e., sulfonated to make it water soluble) can obtain a price premium over lignosulfonates as KL-based dispersants perform better in certain applications

PU FOAM

$+ Kraft lignin will most likely not get a bio-premium over fossil chemicals. A discount could be applied to partially cover for development costs, but it would be case dependent

$– A discount could be applied to partially cover for development costs, but it would be case dependent

CARBON FOR Li-ION BATTERIES

$+ Price premium might be given due to sustainability aspects

$– A discount could be applied to partially cover for development costs and premium for sustainability

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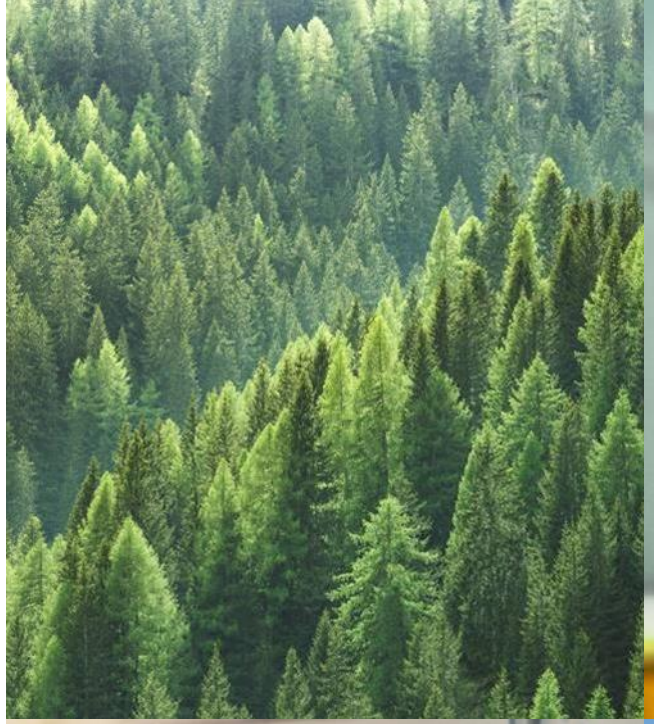
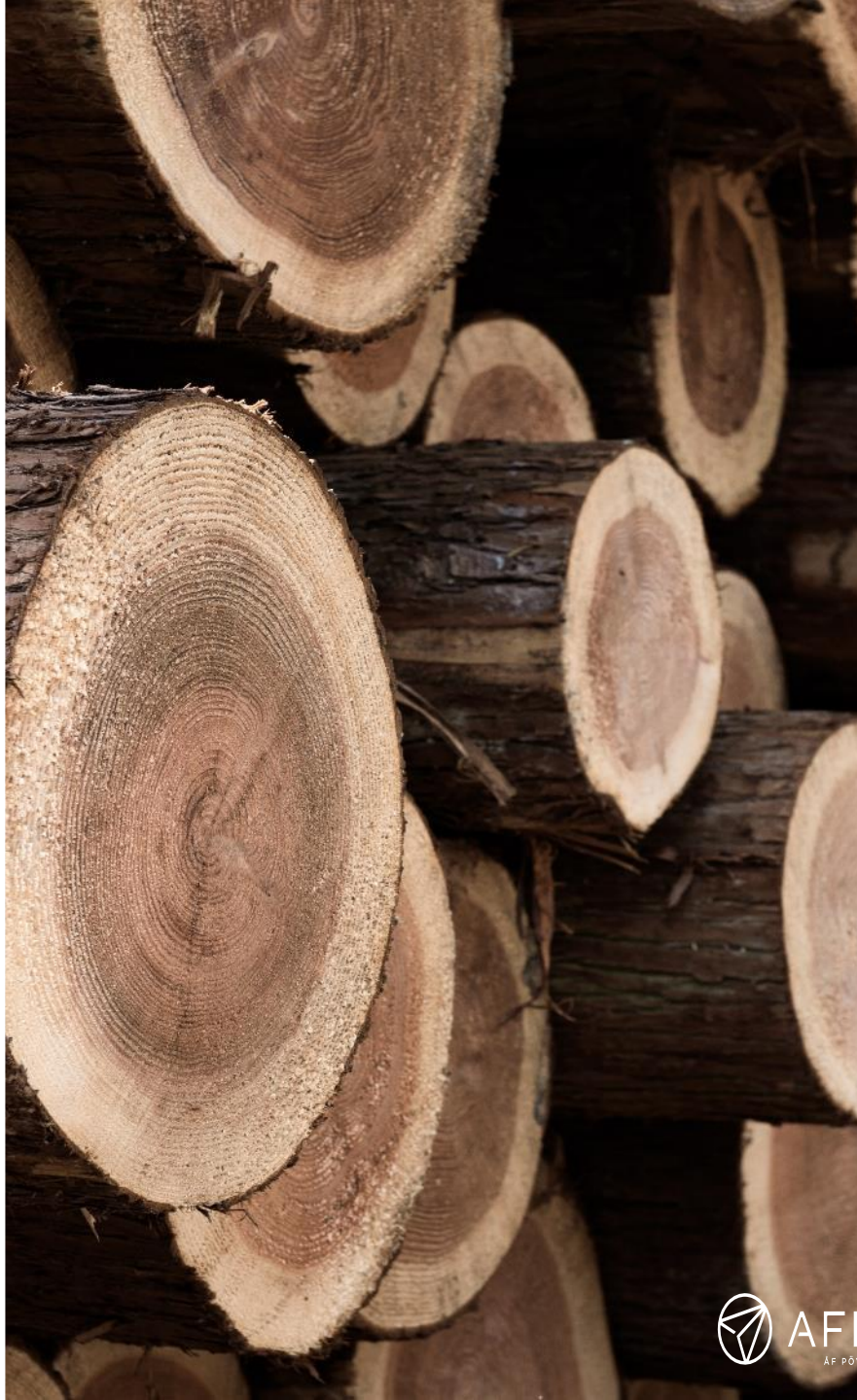


Biorefinery lignin extraction requires a sugar platform roadmap

- With the available 250, 000 cubic meters (0.24 million green tonnes) of Hardwood in Ontario
- **A biorefinery concept is only possible if the sugar platform and its market are well defined**
- In Europe, however, biorefineries can be found in Germany, Estonia, and Scotland. The feedstock of choice is both agricultural and wood residues
- For example, **UPM** has invested over **750 MEUR** to build a 15-hectare biorefinery site with a **220 kt** production volume:
  - Sugars (65–70% of wood) are converted to Bio-Monoethylene Glycol (BioMEG), Bio-Monopropylene Glycol (BioMPG) and industrial sugars. MEG is used to produce textiles, plastics, PET, packaging, and industrial coolants while MPG is used in composites, pharma, or cosmetics products.
  - Lignin fraction (20-35 % of wood) in the form of functional filler (~70 kt) for rubber and tire application.
  - Feedstock being Beechwood and residues from sawmills, start of production in 2021 and ramp up by 2024
  - There are major advantages to integration with an existing facility including access to onsite customers
- With a more systematic approach to enzyme solution, Fibenol is now starting up its first lignocellulosic biorefinery in Estonia. The combination of Sunburst™ pre-treatment technology and tailored enzymatic cocktails from Novozymes provides more than 90% conversion of birch wood processing residues into high-quality cellulosic sugars and co-products, including high-purity lignin LIGNOVA™



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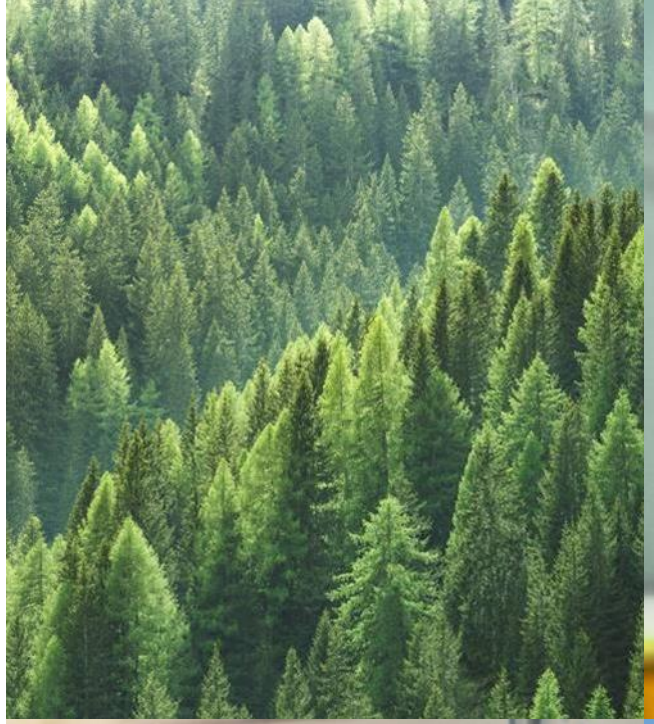

Ontario benefits from existing knowledge and high lignin volume but KL market immaturity could be a concern

STRENGTHS

- Access to large volumes of kraft lignin supply
- Willingness to put effort into developing KL end-product market
- Existing infrastructure and resources at the lignin cluster at Thunder Bay, BETC, and Lakehead University to support product development
- Ontario has a robust value chain network and innovation ecosystem through CRIBE/ Nextfor
- Flexibility in lignin extraction volumes, some the volume of lignin could be used for energy production until markets with a higher value are developed

WEAKNESSES

- Past slow-paced development resulting in an immature market still decades later
- Compared to competing jurisdictions there is low investment in commercial and product development of advanced biomaterials

S W O T

OPPORTUNITIES

- Few KL suppliers in the NA market, resulting in less competition specially with recent mill closures
- Supply gap in the lignin-based dispersants market, due to recent shut-downs of lignosulphonate production facilities
- Changing legislation and policy landscape, which can promote raw materials with lower carbon footprint, such as lignin
- Ambitious sustainability targets set by large brand owners
- Successful R&D in higher value applications, such as carbon for batteries and PU foams, there has been an initial success with CRIBE-funded commercial trials that can be expanded

THREATS

- Technical challenges related both to kraft lignin extraction at the pulp mill, and end-use applications development
- Absence of the guaranteed market demand
- Competing raw materials, both fossil- and bio-based, that can offer a better price, availability or performance properties
- Product and market development will take time

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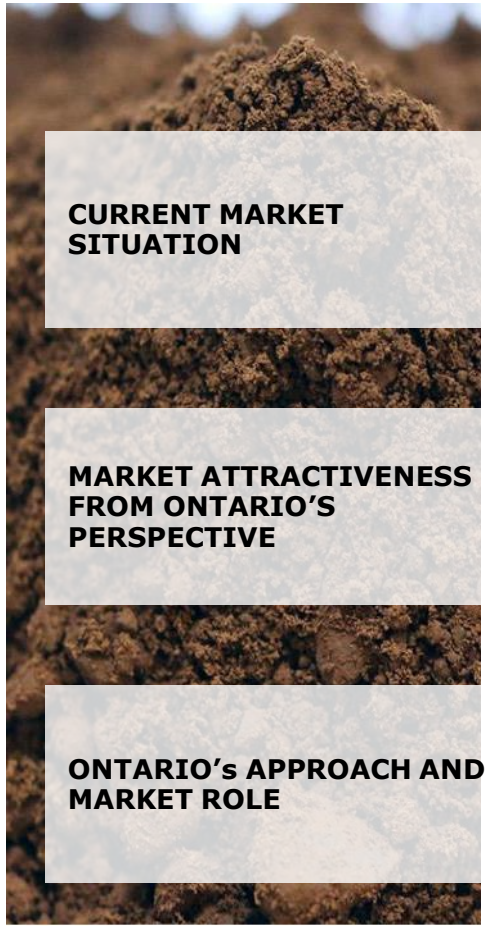
If Ontario mill decides to enter KL business, it should find suitable KL development partners and be prepared to create the market



CURRENT MARKET SITUATION

- Currently, the kraft lignin commercial end-use applications market is small (70-80 kt) and a large share of extracted lignin is today burned as lime kiln fuel. However, there is interest in high value applications based on KL
- Future market demand is driven by the policy landscape, competing products supply gap, and brand owners' sustainability targets
- Most KL suppliers conduct in-house R&D to develop higher-value applications for lignin

MARKET ATTRACTIVENESS FROM ONTARIO'S PERSPECTIVE

- Large R&D investments conducted for years by e.g., UPM and Stora Enso is now approaching the stage where certain KL-based products have potential for larger scale market take-off in the next 10 years
- With successful market development, many applications can offer higher value for Ontario. However, further development is still required in terms of **R&D support**, **application R&D work**, **technical challenges** related to lignin extraction, and **creation of KL end product markets** and **value chains**

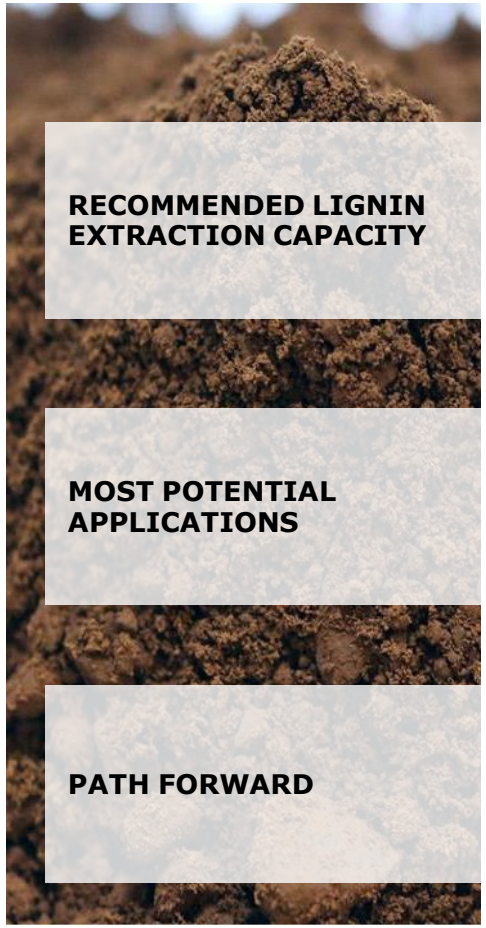
ONTARIO's APPROACH AND MARKET ROLE

- Similar to most KL producers, Ontario's kraft lignin extraction requires close collaboration with technology suppliers, product developing companies and/or research institutes, and KL off-takers
- Successful partnerships can result in well refined products with good margins and high demand

1. Most realistic view is that the market demand for KL in 2030 is in between the low and medium scenario demands, namely 125-200 kt/a. Reaching high scenario market volumes requires several technical breakthroughs, favorable legislation, large brand owners with high sustainability targets to be interested in lignin, and significant supply gap left by lignosulphonates.

AFRY ÅF PÖYRY

If Ontario mill decides to enter KL business, it should find suitable KL development partners and be prepared to create the market



RECOMMENDED LIGNIN EXTRACTION CAPACITY

- AFRY recommends capacity for lignin extraction is 10-50 kt/a. A small-scale lignin extraction to verify quality and develop strategies,
- For any larger scale investments (e.g., 76 kt), lower capacity utilization rates and/or higher lignin burning volumes can be expected

MOST POTENTIAL APPLICATIONS

- Many potential KL applications have low TRL and/or require additional lignin modification to be suitable for use
- PF resins and dispersants are the only commercial products today and they are also expected to represent largest markets for KL in future. PU foams are still under development but could potentially provide higher margins should R&D be successful. Lignin for batteries will provide the highest margin but needs R&D success

PATH FORWARD

- Collaborations with downstream partners who are already familiar with utilizing lignin in their products is recommended for a shorter time to market
- Successful market entry requires time and resources
- Government support could play a vital role in accelerating the adoption of bio-based materials made from lignin by implementing a range of policies, incentives, and initiatives
- There is an existing innovation network (CRIBE) that can be utilized to support collaboration and market development

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Lignin Roadmap for Ontario

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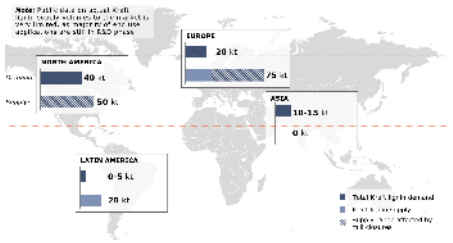
Making Future

AFRY Methodology for current kraft and biorefinery lignin market demand, and future supply-demand scenarios



Global and regional lignin demand

- Global and regional Kraft lignin market demand is estimated based on AFRY databases, public sources (e.g., trade data when available) and AFRY insight
- Since Kraft lignin is an emerging market that lacks detailed market statistics, it is not possible to give exact market data (KL volumes being supplied to different customers and what they do with these volumes is not publicly available information), thus AFRY has made an estimation on the market volume based on our best understanding of the market

Llignin supply-demand scenarios

- The Kraft lignin supply-demand scenarios towards 2030 are estimated based on AFRY insight and estimations on the volume growth of potential Kraft lignin applications.

AFRY Insight

- AFRY insight is generated through years of close industry connections and in-house knowledge building through project work, as well as coordinating and being a part of industrial ecosystems such as The Lignin Club
- AFRY coordinates the " The Lignin Club". The ecosystem consists of major global pulp producers who are extracting Kraft lignin in addition to chemical industry companies, lignin extraction technology providers and research institutions such as VTT. The lignin ecosystem is also supported by CEFIC which is the official European Chemical Industry Council.

Note: The Lignin Club Ecosystem members are presented here: https://ligninclub.fi/who-we-are/).