Deliverable report

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Contents

1 Preface

The main objective of LignoCOST is to jointly establish a network in which relevant information packages are produced with a focus on sustainable lignin production and valorisation at industrial level (https://LignoCOST.eu/). The LignoCOST action has been structured in 5 working groups (WG) of which WG4 is dedicated to investigating value chains of selected lignin-based products. This deliverable reports the findings concerning the value chain of phenol formaldehyde resins in which lignin is already used in commercial scale to partly replace phenol.

The objective of this task is to evaluate the commercialisation potential of lignin-based phenol formaldehyde resins (LPF resins):

- Current state of art – Opportunities and barriers from market and technical point of view
- Value chains – Required processing steps & stakeholders

Task force leader: Tiina Liitiä (VTT) since June 2021, Anna Kalliola (VTT) from July 2021
Task force members: Hanne Wikberg (Fortum), Ewellyn Capanema (RISE), Per Tomani (RISE)

2 Evaluation criteria for commercialisation potential

Market potential:

- Drivers for lignin use
- Current commercial production and actors
- Market volumes & product segments
- Estimated phenol & product prices

Technical requirements & potential challenges for commercialisation

- Lignin requirements – Applicability of different lignin types
- Technical product requirements / specifications
- Key technical challenges for commercialisation
- Upgrading technologies to improve lignin quality for PF resins (TRL levels, production costs, actors)

Environmental impacts
Legislation, regulations, certifications
Barriers for commercialisation
Value chains: processing steps, key actors & potential gaps
Final conclusions: SWOT for commercialisation potential

3 Drivers for lignin use

- **Sustainable and safe alternative to toxic phenol with high availability in future**
  - **Environmental impacts:** Significantly reduced carbon footprint and global warming potential
  - **Occupational safety:** Reduced demand of toxic phenol and formaldehyde
- **Cost competitiveness and stability**
  - Lower cost raw material compared to phenol
    - Although additional operation cost needs to be considered
  - Price not fluctuating according to oil price unlike phenol price
- **Legislation & Regulations**
  - No pressure for phenol substitution from legislation
  - Regulations for formaldehyde emissions in final product, although lower formaldehyde use does not necessarily mean lower emission.
  - In some countries (e.g., in Finland) the environmental impact is one selection criteria among the price and technical performance in public procurements

4 Current commercial production and actors

The following information on LPF resins and products with LPF resins was updated 20.3.2023.

- **Latvijas Finieris** (in co-operation with **Stora Enso**) has developed (2017→) a new green glue RIGA ECOlogical used for RIGA **plywood products** https://www.storaenso.com/en/newsroom/news/2020/6/developing-a-lignin-based-resin-for-plywood, https://www.storaenso.com/en/newsroom/news/2022/3/lignin-based-glue-used-in-plywood-production, RIGA ECOlogical also by **Plytech** for **birch plywood** https://www.plytech.co.nz/plant-based-glue

- **Rolkem** has used **Stora Enso**'s lignin since late 2015 in phenolic resin production **for plywood and impregnation of technical papers for laminates**. https://www.storaenso.com/en/newsroom/news/2019/2/aiming-at-future-with-100-bio-based-resin

- **Stora Enso**'s lignin, Lineo® by Stora Enso, replaces fossil-based glue in **plywood**. Polish plywood manufacturer **Paged** has started collaborating with Stora Enso to meet their customers' demands for bio-based and more sustainable plywood. https://www.storaenso.com/en/newsroom/news/2023/2/stora-enso-lignin-replaces-fossil-based-glue-in-plywood

- Together with RISE, **IsoTimber** and **Moelven**, **Stora Enso** has been working on the most recent development of NeoLigno – 100% fossil-free structural boards and building elements. https://www.storaenso.com/en/newsroom/news/2022/7/100-percent-fossil-free-structural-boards-and-building-elements-with-neoligno

- Finnish plywood manufacturer **Koskisen** is the first company to start using the bio-based binder NeoLigno® by **Stora Enso** in its new sustainable product family. https://www.storaenso.com/en/newsroom/news/2022/1/the-first-fully-bio-based-furniture-board-in-the-world

- **UPM** has been using **LPF resins** in the WISA® plywood production **since 2017**, and offers UPM BioPiva™ lignin with their proprietary, industrially proven resin technology to resin producers and their customers worldwide **for plywood, impregnation and mineral wool**. (UPM web pages)

- **Starting from May 2022**, the lignin-based WISA® BioBond bonding technology **is being used in all UPM's WISA spruce plywood products**. WISA BioBond is UPM Plywood's proprietary bonding technology in which at least 50% of fossil-based phenol in the glue is replaced with wood's own natural bonding agent, lignin. UPM is the first plywood manufacturer in the world to adopt such a lignin-based solution in its entire range of spruce products. https://www.upm.com/about-us/for-media/releases/2022/06/upm-plywood-is-taking-another-step-with-wisa-biobond-to-help-builders-meet-sustainability-targets/

- **Prefere resins** started industrial production of high-quality **lignin-based phenolic resins** 2017. Initially, Prefere started using Lignin as a binder **for plywood materials**, in which up to 90% of the phenol can be replaced by lignin. In 2020, Prefere resins developed a **lignin-based resin for phenolic foam**. In the future, Prefere will not only use lignin as renewable raw material. Even for important raw materials as methanol and phenol, bio-based versions are already in development. They will be available at reasonable prices within the next 15-20 years. https://prefere.com/en/company/the-lignin-story

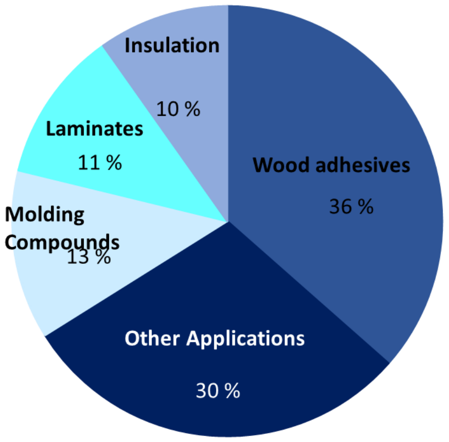
- **Arpa** lauched first **lignin-based laminates** (HPL Bloom, Fenix NTM Bloom) with 50% phenol substitution **for interior design** (spring 2019) https://www.fenixforinteriors.com/en/news/bloom-technology-fenix-ntm%C2%AE-and-arpa-hpl-selected-adi-design-index
- **Chimar** and **UPM** have partnership on lignin based phenolic resins suitable for plywood and HPL production https://chimarhellas.com/partnerships/lignin-based-resins/

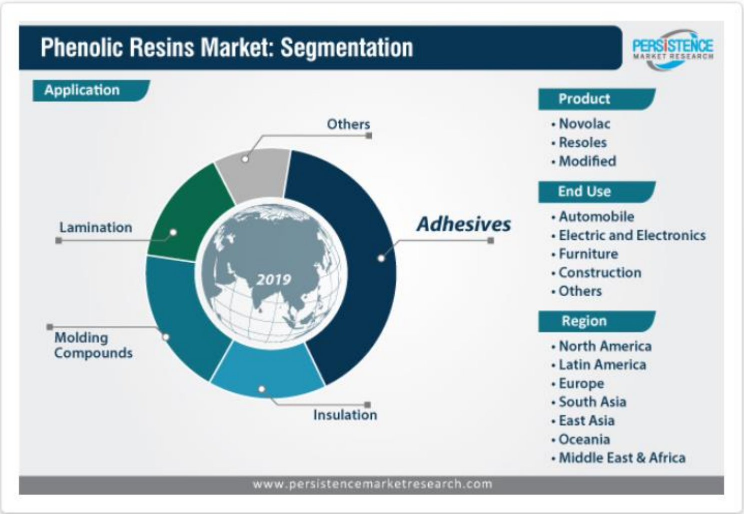
5 Market volumes & product segments

High volume market (~7 Mt/a) with increasing demand. Corresponds to ~2 Mt/a max. lignin volume at 100% substitution (Phenol ~60% of total solids, 50% DS in resins).

Main product segments (considered in the value chain)

- Wood adhesives
- Molding compounds
- Laminates
- Insulation





https://www.persistencemarketresearch.com/market-research/phenolic-resins-market.asp
MarketsandMarkets "Phenolic Resins (Resols, Novolac and Others) Market for Wood-adhesives, Molding Compounds, Laminates, Insulation and Other Applications: Global Industry Perspective, Comprehensive Analysis, and Forecast, 2014-2020
CEH marketing research 2005

6 Estimated phenol & product prices

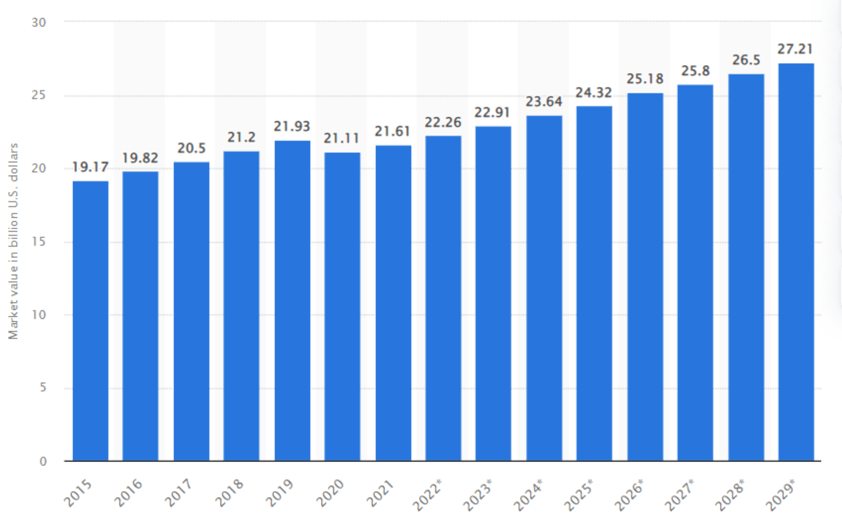
6.1 Phenol price the benchmark for cost-competitiveness

Phenol price is fluctuating according to oil price (700-1300 €/t)

- Increase of phenol price cannot be translated into product price
- High impact on profitability
- Stable lignin price highly attractive and one of the key drivers

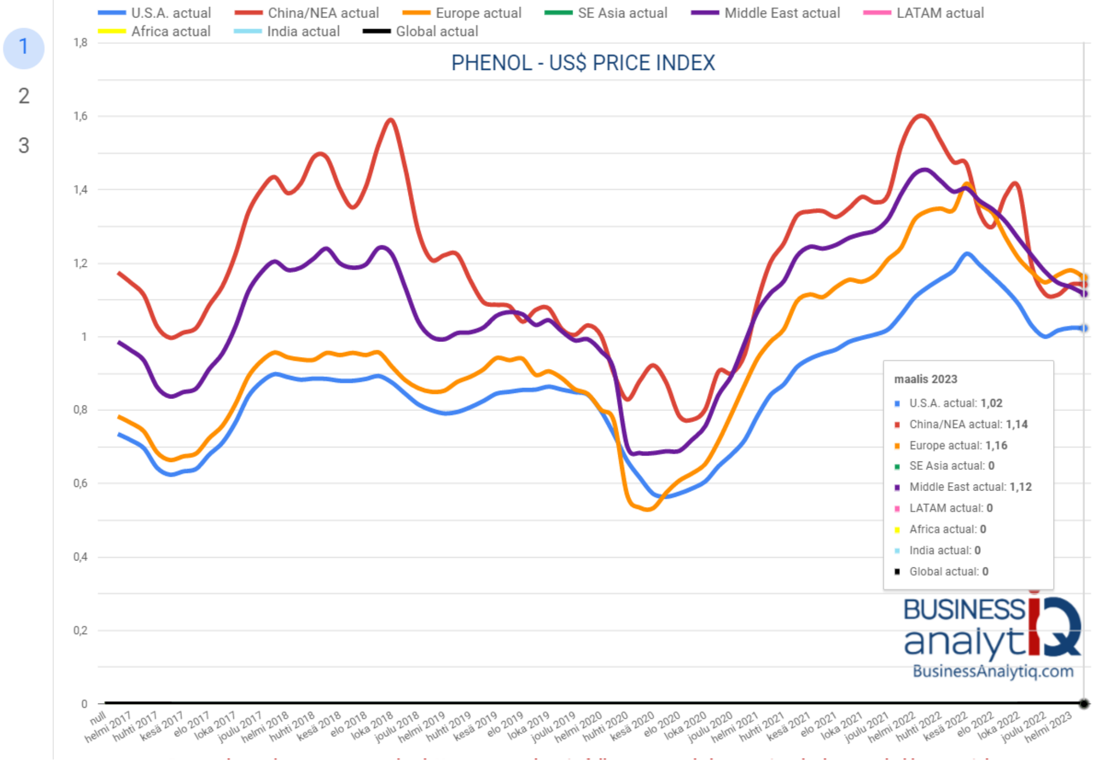
The following price information was updated 26.3.2023.

Market value of phenol worldwide from 2015 to 2021, with a forecast for 2022 to 2029 (in billion U.S. dollars)



https://www.statista.com/statistics/1244237/global-market-value-phenol/

Phenol price index



https://businessanalytiq.com/procurementanalytics/index/phenol-price-index/

6.2 Product segments: Market volumes and estimated prices

PF product segment	Market volume, Mt/a (%) *	Max. lignin Mt/a**	PF resin price, €/t	Commercial lignin based products
Wood adhesives	2.5Mt/a (36%)	0.8	**< 1000€/t all segments (wet 50%)**	Plywood
Molding compounds	0.9 Mt/a (13%)	0.3		-
Laminates	0.8 Mt/a (11%) - 1.3Mt	0.2-0.4		Interior grades
Insulation materials	0.7 Mt/a (10%)	0.2		Mineral wool (?)

*calculated based on slide 7 data, ** assumed ~30% of wet resin (100% lignin substitution)

6.3 Additional costs of resin producer reduce cost-competitiveness

Pretreatment & Storage:

- Refining pretreatment due to agglomeration if lignin powder has low dry matter content
- Ignition/explosion risk for dry lignin due to dusting (ATEX classification for storing and handling)

Additional process steps in resin synthesis:

- Dissolution step & dosing system for lignin powder (cannot be pumped like phenol, lower dissolution rate)
- Activating treatment due to lower reactivity

Prolonged process steps:

- Lower temp and longer resing synthesis time needed to improve resin homogeneity
- Longer pressing times / higher temperature at production lines of the end-users

→ To increase cost competitiveness the additional operations should be eliminated or reactivity improved for faster process steps

7 Technical requirements & potential challenges for commercialisation

7.1 Lignin requirements – Applicability of different lignin types

Requirements (as such)

- High reactivity: Sufficient amount of available reactive sites
    - High content of phenolic units
    - Low methoxyl content (H > G > S)
    - Low degree of condensation
- Good solubility
    - As low Mw as possible
    - No polysaccharide residues (hydrolysis lignin)
    - Particle size <100-120 µm
- Alkali stability
- Good water resistance in final product:
    - Low ash & carbohydrates (especially for laminates)
    - Low content of acidic groups (e.g. -SO3)

Softwood, Annual plants > Hardwood
Spent liquor lignins >> Crude hydrolysis lignin
Kraft, soda, OS > Lignosulphonates

7.2 Technical product requirements / specifications

Plywood (50-80% lignin in LPF commercially possible)

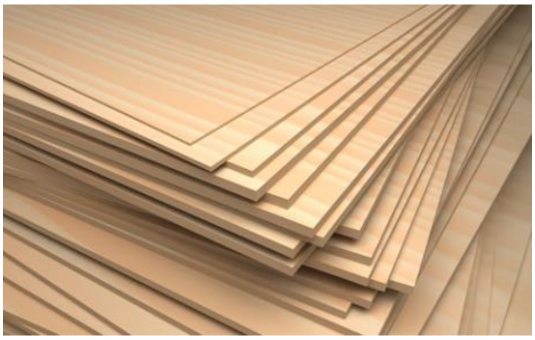
- **Product:** Highly moisture-resistant, durability, mechanical strength, low/no VOC
- **Resin:** Fast-cure enabling high production capacity

High pressure laminates (30-50% lignin in LPF commercially possible)

- **Product**: Highly moisture-resistant, durability, mechanical strength, low/no VOC
- **Resin:** Good flow, i.e. ability to diffuse through paper (low viscosity), fast-cure enabling high production capacity

Mineral woll

- **Product:** Moisture resistance, Low/zero VOC emissions, High heat stability
- **Resin:**
    - Good flow characteristics: water solubility & low concentrations for spraying
    - Elasticity and adhesion properties with the fibres for strength
    - High reactivity for curing



7.3 Key technical challenges for commercialisation

Resin production:

- **Limited lignin solubility**: powder vs. liquid, polymer vs. monomer
- **Resin heterogeneity:** Difference in initial Mw & reactivity

Production lines of plywood and laminates:

- Lower reactivity: Pressing times typically longer
- High resin viscosity / heterogeneity
    - Challenge in impregnation
    - Clogging in nozzles
- Storage stability (?)

Product performance:

- Required wet strength difficult to reach for exterior grades

Sustainable adhesives need to be • at low costs • to be easily distributable • fast reacting • long shelve life	**Means to reach 100% lignin or biobased resins:** • Further upgarding (activation, fractionation, depolymerisation) of lignin • Totally new type of resin chemistry

7.4 Upgrading technologies to improve lignin quality for PF resins

Table below summarises the upgrading technologies to improve lignin quality for PF resins as well as their TRL levels, production costs, actors.

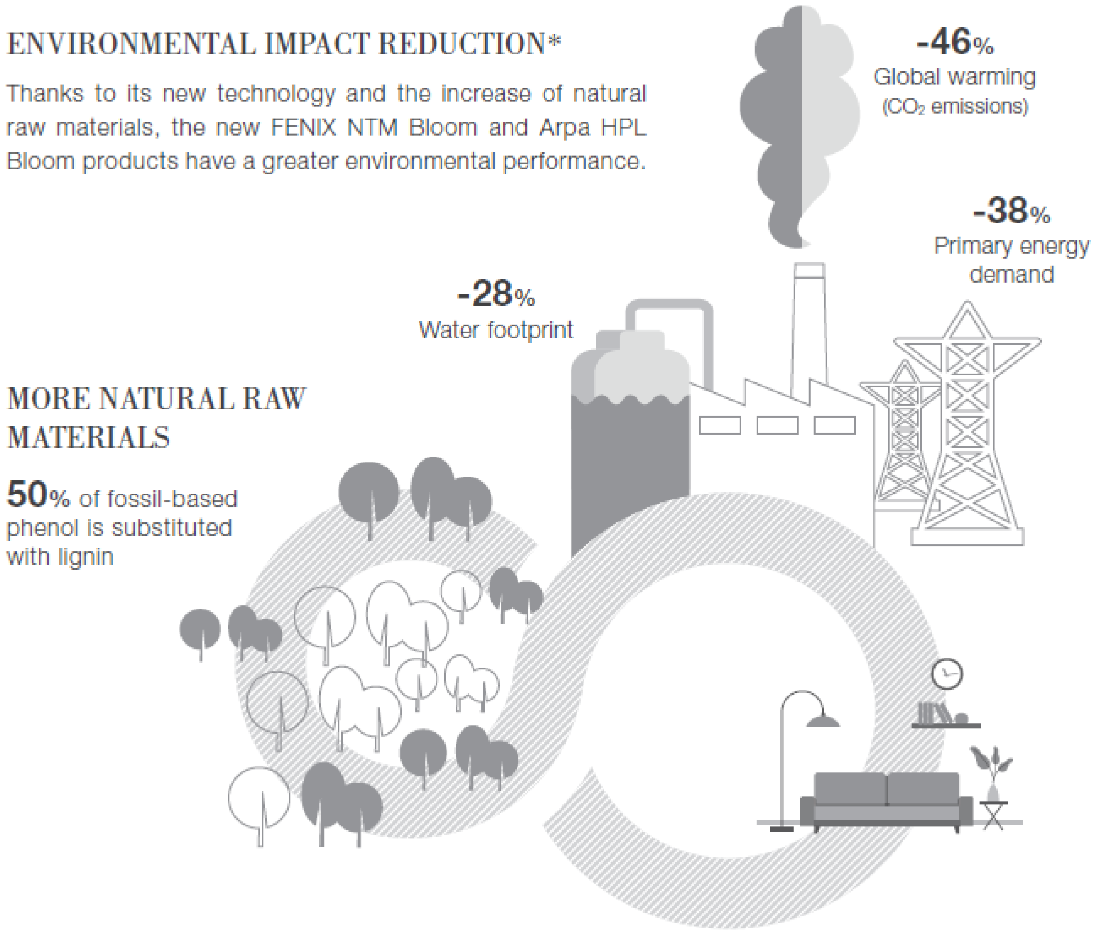
Activation mechanism	Technology	TRL / scale	Pros / Cons	Actors
Activation prior/during resin production	Alkaline dissolution, hydroxymethylation, phenolation	commercial scale	Alkaline activation/dissolution simple, phenolation requires synthetic phenol, phenolation and hydroxymethylation easy to perform by resin producer	UPM patent, Trespa patent, resin producers
Demethylation	Kraft BL heat treatment (CatLignin)	TRL 4-5, small pilot	Highly efficient activation, cost efficient No pilot production for product development	VTT patent
Fractionation	Ultrafiltration	TRL 4-5, Karatex in commercial scale at 80's	All fractions need to be utilised, contradictory results on performance, higher Opex & Capex	KCL/VTT(Karatex), KTH, VITO, ...
	Solvent extraction	TRL 5 (VTT), most at TRL 3-4		VTT, ...
Depolymerisation	BCD	TRL 5 (pilot)	Improved solubility Challenging for technical lignin; Higher yield with LigninFirst approach Effect on resin performance not known High Opex & Capex: cost competiveness for resins not known	Fraunhofer
	Catalytic depolymerisation	TRL 3-4 (LignoValue pilot plan, VITO)		KU Leuven, VITO, Vertoro, ...
	Enzymatic depolymerisation	Pilot scale, TRL 6		Metgen

8 Environmental impacts

By 50% phenol substitution in HPL production (Arpa: FENIX NTM Bloom)

- ~ 50% reduction in CO_2 emissions
- ~ 30% reduction in water footprint
- ~ 40% reduction in primary energy demand

https://www.arpaindustriale.com/sites/default/files/doc_micro/arpa_bloom-hr.pdf



*** Source:** *LCA study performed by Arpa Industriale comparing standard FENIX NTM and Arpa HPL with new FENIX NTM Bloom and Arpa HPL Bloom.*

9 Barriers for LPF resin commercialisation

Lignin is not a drop-in substitute for phenol

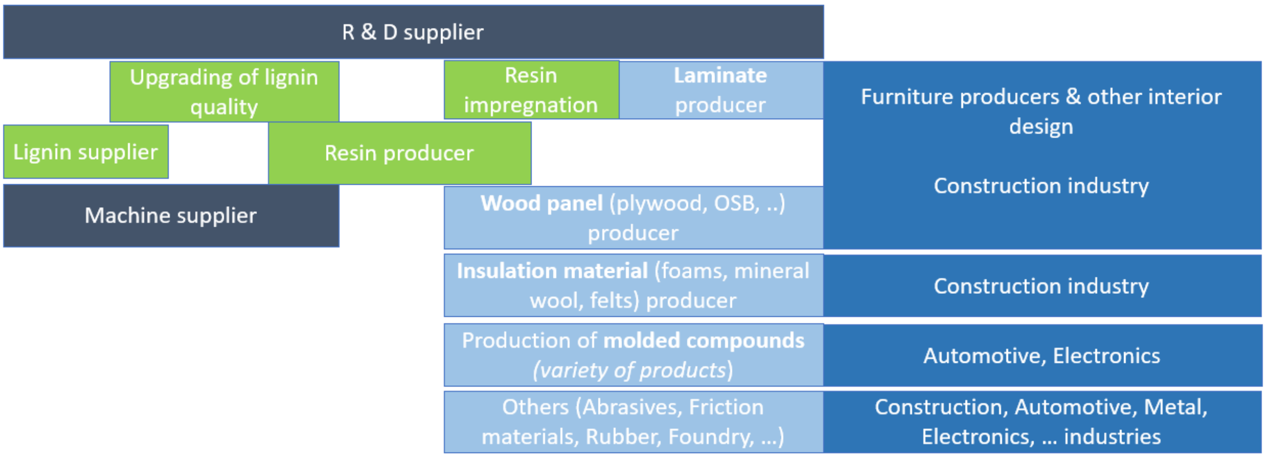
- Formulations need to be redeveloped and optimised for each lignin (even within different kraft lignins)
- Significant product development effort needed from resin producers & end-product manufacturers
    - Lack of knowledge from lignin among chemical industry, poor knowledge sharing between the stakeholders (collaboration needed)
- Investments needed for current product manufacturing lines
- Risk of increasing production costs due to additional or prolonged process steps
- Estimated time to market may be rather long (3-7 years depending of starting level)

Market acceptance & attitude of resin producers:

- Higher demand from end-users needed to create market pull for activation of resin producers
- Despite the market pull, the resin producers are not yet ready to make changes required at production lines.
    - More ’green minded’ attitude needed to make the required changes to current production
    - High research effort and investments needed - Risk too high for resin producers?
    - Lignin supply still too small / scattered, several suppliers needed to minimise risk
    - Consistency of lignin quality: kraft lignin has quite even quality; different type of other lignins (different recipes)

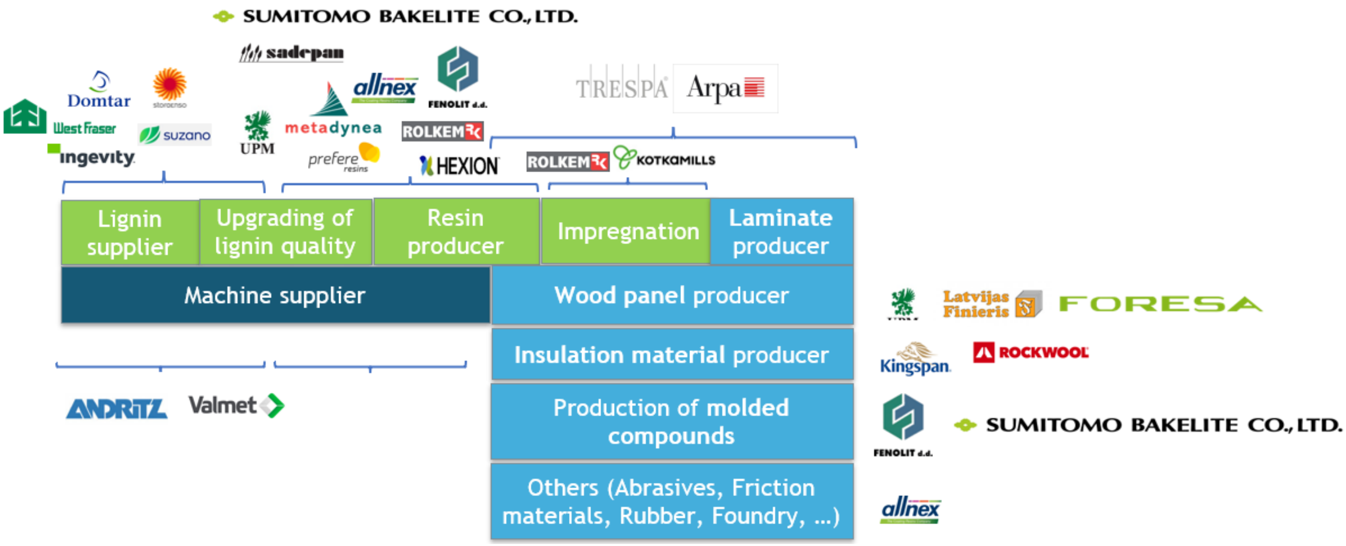
10 Value chains: processing steps, key actors & potential gaps

LPF resin value chain:



11 Lignin producers

Example of simplified value chain with potential Stakeholders:



12 Final conclusions

As conclusions, SWOT for the commercialisation potential of LPF resins was made:

Strengths
• High volumes unlike in other biophenolics
• Cost (competitiveness and) stability (lignin vs. phenol)
• Commercial production (partial phenol substitution)
• Lignin as such can be used, upgrading technologies also exist improving utilization rate
• Significant environmental benefits (i.e. lower LCA for resin and end-product)
• Improved working safety
	Weaknessess
	• Lignin is not a drop in chemical
	• Additional process stages needed
	• Varying lignin quality (different lignin types)
	  ◦ Low substitution levels with HW (requires activation)
	  ◦ Hydrolysis lignin insoluble, can be used only partially. Potential for depolymerisation.
	• Current formulation only for ~50% phenol substitution and for a few specific end-uses
	• 100% phenol substitution needs further upgrading or novel chemistry
	• Upgrading reduces cost competitiveness; pilots required

Opportunities • High market volumes, increasing CARG • Commercial LPF production already exists • High oil/phenol price fluctuations • Growing lignin offering in near future • ...	**Threats** • Research effort needed for resin/product development too risky • Investments needed for development and commercial production (resin producer, product manufacturer) too high • Lack of long-term product experience of end-users

13 Company interviews

As a last activity of the value chain investigation, company interviews were done

- to understand the full commercialisation potential for lignin-based phenol formaldehyde resins (LPF resins)
- to understand the technical challenges & barriers for commercialisation

SWOT analyses on commercialisation potential of LPF resins from different lignin producers/ potential lignin producers:

Strengths	Weaknessess
• Significant environmental benefits (i.e. lower LCA for resin and end-product) - lower LCA is also a benefit • Commercial business already • Lignin can be used as such for **LPF resin** i.e. no modification	• Lignin is not a drop-in substitute for phenol - Different lignins are not drop in for each others - fine-tuning of the recipe
Opportunities	**Threats**
• Positive Environmental benefit / sustainability also an opportunity; **Change in industial environtal!** • Accelerating demand / expanding use if phenol will be restricted! • Different types of lignin → different resins for various/different applications or replacing PU resins • WE are living n a turning point → changes • Local production more needed, global phenol chain is risky/weak • Reach • *FIND the unique selling point	• Big players dominating the market with IPR in LPF resins* • Are the properties good enought/ accepted? Niche or expanded?

Strengths	Weaknesses

• High volumes unlike in other biophenolics
• Cost (competitiveness and) stability (lignin vs. phenol)
• Commercial production (partial phenol substitution)
• Lignin as such can be used, upgrading technologies also exist improving utilization rate
• Significant environmental benefits (i.e. lower LCA for resin and end-product)
• Improved working safety
	• Lignin is not a drop in chemical
	• Additional process stages needed
	• Varying lignin quality (different lignin types)
	  • Low substitution levels with HW (requires activation)
	  • Hydrolysis lignin insoluble, can be used only partially. Potential for depolymerisation.
	• Current formulation only for ~50% phenol substitution and for a few specific end-uses
	• 100% phenol substitution needs further upgrading or novel chemistry
	• Upgrading reduces cost competitiveness; pilots required

Opportunities	**Threats**
• High market volumes, increasing CARG • Commercial LPF production already exists • High oil/phenol price fluctuations • Growing lignin offering in near future • ...	• Research effort needed for resin/product development too risky • Investments needed for development and commercial production (resin producer, product manufacturer) too high • Lack of long-term product experience of end-users

Strengths	Weaknessess

• High volumes unlike in other biophenolics
• Cost competitiveness (lignin vs. phenol) - will vary
• Commercial production (partial phenol substitution)
• Lignin as such can be used, upgrading technologies also exist improving utilization rate
• Significant environmental benefits (i.e. lower LCA for resin and end-product, better working safety)
• Stable quality of softwood lignin from LignoBoost, LignoForce or similar processes
	• Lignin is not a drop in chemical
	• Varying lignin quality related to different lignin types
	  • Low substitution levels with HW (requires activation)
	  • Hydrolysis lignin insoluble, can be used only partially. Potential for depolymerisation.
	• Current formulation only for ~50% phenol substitution and for specific end-uses
	• 100% phenol substitution needs further upgrading or novel chemistry (but today not a strong pull/need for it)
	• Upgrading reduces cost competitiveness
	• Kraft lignin is delivered as a solid material (powder)

Opportunities	**Threats**
• High market volumes, increasing CARG • Commercial LPF production already exists • High oil/phenol price fluctuations • Regulations/legislation in EU • Growing lignin offering in near future • Granules instead of powder	• Investments needed for development and commercial production (resin producer, product manufacturer) • Research effort needed for resin = product development • Lack of long-term product experience of end-users

Other comments and answers to our questions are:

- End of the value chain (such as furniture producers like Ikea, rubber like Nokia, automotive, construction etc) are very important to involve in the development. They have the muscles to change and meet this type of market demand.

- The main growth for LPF in Europe (short term) is in plywood. Asia & North America start to be interested. Plywood is shipped long distances. There is an increase in product qualities in EU - growth.
- As a supplier of lignin is usually not interesting to build their own LPF line.
- The main value for the PF resin producer is the competitiveness – customer demand (sustainability) is the driver. Sustainability is the main selling point within EU. The customer had/have much more interest in sustainable solutions than what the PF resin producers expected. Some lignin suppliers deliver a LCA to produce lignin to customers and calculate the CO2 footprint for 50% substitution as part of a delivery. 70-75% of the CO2 footprint is from the phenol in PF resins & this is the main selling point for lignin instead of fossil-based phenols. Another selling point and driver is the high and fluctuating phenol prices.
- Lignin modification maybe needed only if you want to reach 100% bio-based resins. 100% LPF is possible but is it needed? Today not a pull since you need to change the existing production line. Other “crosslinkers” than formaldehyde could be a way forward for 100% lignin. But is it important with 100%? 50% substitution is “standard” today for those who use lignin in their formulations. The producers LPF want a real difference in CO2 footprint, so 5% is not interesting. 60-70% is possible but today not as optimized as 50%.
- Roughly: Plywood, OSB & impregnated paper etc is together a very large market if you calculate that 50% of the phenol is replaced! 25% of the PF is phenol. 8000 ton PF resin is “normally” used by a relative large plywood production line and to substitute all phenol to lignin means 1000 ton lignin. A “standard” commercial kraft lignin separation process produces about 40 000 – 50 000 tons kraft lignin/year. Kraft lignin for the market is expected grow. Companies are looking at new and growth of production capacity. The increased cost for fossil raw materials is one driver for this development.
- Lignin is supplied directly to the resin supplier or a resin producer which have added a plywood production line. Service and technical knowhow, including how to include the lignin in the production of LPF resins need to be part of the delivery. Very good cooperation with customers is of course always important.
- Softwood kraft lignin seems to be a better raw material than hardwood kraft lignin for LPF. However, not sure about organosolv lignin. This could be of interest if the lignin price is right and the lignin is pure
- High phenol price is positive for lignin. Basically minimum 500 Euro/ton for phenol at extremely low oil price. OBS! Methanol price will of course affect the price/cost when you compare.
- The sulphur content in kraft lignin is not identified as a problem. Moist lignin is easier for the resin producer to handle than dry.
- A challenge is that new types of lignins require new adjustments in production. A guess is that it takes about 3 years to connect & reach the market for new lignin suppliers on the market. The customer for lignin is usually not updated on the opportunities. There is a need to give a lot of support to introduce this new opportunity.