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# High-Value Opportunities for Lignin: Unlocking its Potential

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As the biochemical industry emerges[1], it is bringing out new products and replacing existing ones made from oil. Bio-based chemicals are expected to grow significantly and increase their share in overall chemicals production to an estimated 9 per cent of all chemicals in 2020.[2]

As bio-refiners are focusing on biofuels, they prefer to use feedstock with high sugar content, such as bagasse from sugarcane or sweet sorghum, corn stover and grasses.

Wood, in contrast, has lower sugar content, which is also more difficult to access. Therefore, it remains underused as a feedstock for biofuels and biochemicals.

Wood is made of three main components—cellulose, hemicelluloses and lignin—and various extractives in small quantities. Once extracted, cellulose and hemicelluloses can be easily processed into C5 and C6 sugars, which are then processed further using well-known routes to produce various biochemicals and biofuels (e.g., ethanol).

Representing 20–35 per cent of wood in weight, lignin is a much more complex polymer than cellulose or hemicellulose, and has been considered a low-quality and low-added-value material. For example, as of 2010, the pulp and paper industry alone produced an estimated 50 million tonnes of extracted lignin, but only 2 per cent of it (1 million tonnes) was commercially used[3] for low-value products such as dispersing or binding agents; the rest was burnt as a low-value fuel. Overall, the lignin business today represents roughly 300 million dollars. The total lignin availability in the biosphere exceeds 300 billion tonnes and annually increases by around 20 billion tonnes.[4]

**The industry is just beginning to scratch the surface of lignin's potential: it could become the main renewable aromatic resource for the chemical industry in the future.**

The purpose of this Market Insight is to provide information on lignin potential. During our analysis work, we have identified key barriers and analysed different ways to lift them. In particular, we explored four promising lignin applications.

[1] 0.3 billion tonnes of organic chemicals yearly produced by the chemical industry, Haveren *et al.,* 2008
[2] *The Future of Industrial Biorefineries*, World Economic Forum, 2010
[3] *Renewable Chemicals Factsheet*, NNFCC, 2011
[4] Gregorová et al., 2006

# Lignin potential

Lignin is the most abundant natural raw material available on Earth in terms of solar energy storage. It represents 30 per cent of all the non-fossil organic carbon on Earth. Lignin can be used as a green alternative to many petroleum-derived substances, such as fuels, resins, rubber additives, thermoplastic blends, nutra- and pharmaceuticals. It is also known to be the only renewable source for industrial aromatics production.

Lignin can be found in other plants, such as cereal straws, bamboo and bagasse, but it is in wood that lignin content is the highest in terms of weight: 20–35 per cent in wood compared to 3–25 per cent in other lignin sources.

Lignin structure, purity, properties and, therefore, cost largely depend on the feedstock but also on the delignification process. The only company able to produce proven, consistently pure lignin with a clearly defined structure has a capacity of only 500 tonnes per year[1].

As illustrated in the following table and chart, the type of process used to produce lignin will dictate the value of the products that can be derived from it. Typically, kraft and organosolv lignins are two suitable candidates, whereas ligno-sulphonate will most likely lead to lower-value chemicals, which require more complicated processing.

**Fig. 1: Lignin types, volumes, purity and potential applications, 2011**

| Lignin Type | World Annual Production (MT) | Lignin Purity[2] | Potential Products |
|---|---|---|---|
| Low-purity lignin | 50,000,000 | Low | Energy<br>Refinery (carbon cracker) |
| Ligno-sulphonates | 1,000,000 | Low-medium | Refinery (carbon cracker)<br>Cement additives |
| Kraft lignin | 60,000[3] | High | Bitumen<br>Refinery (carbon cracker)<br>Cement additives<br>Biofuel<br>High-grade lignin<br>BTX<br>Activated carbon<br>Phenolic resins<br>Carbon fibres<br>Vanillin<br>Phenol<br>Phenolic resins |
| Organosolv lignin | 1000[4] | High | Activated carbon<br>Phenolic resins<br>Carbon fibres<br>Vanillin<br>Phenol derivatives |
| High-grade lignin | N/A | Very high | Carbon fibres<br>Vanillin<br>Phenol derivatives |

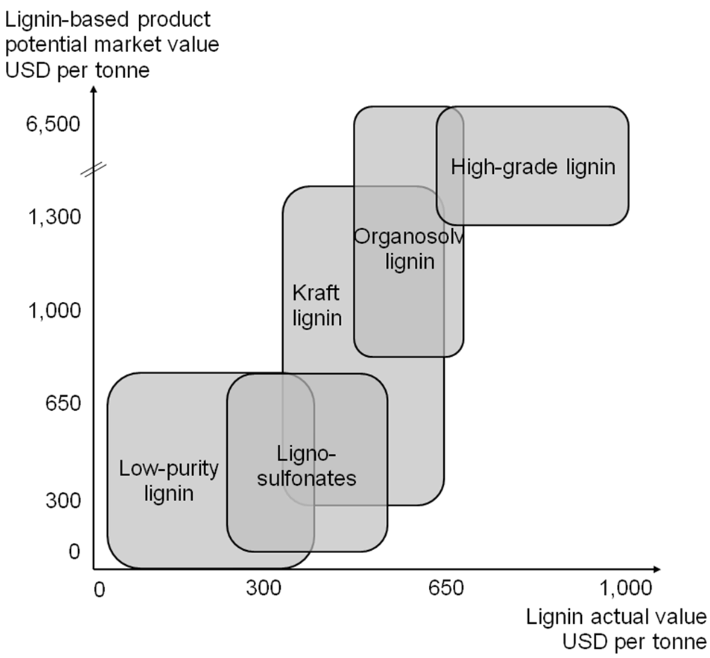
Source: *Lignin As A Renewable Aromatic Resource For The Chemical Industry*, Gosselink, 2011

[1] CIMV BioLignin™
[2] Presence of residual carbohydrates, ash and proteins depends on feedstock and process
[3] Currently, only MeadWestVaco produces Kraft lignin commercially.
[4] Organosolv lignin is mostly produced in pilot plants by CIMV (France) and Lignol (Canada).

As different types of lignin lead to different types of applications, it can be observed from the following chart that there is a strong correlation between the price of each type of lignin and the added value of the products derived from it.

Additionally, kraft lignin covers a large range of applications, including high-value ones, and is considered mid-range in terms of price. It is also readily available in enough quantity from pulp and paper producers to start feeding industrial demand. It is thus considered a good intermediate between ligno-sulphonates and organosolv lignin.

**Fig. 2: Mapping of lignin value vs. lignin-based product value, by lignin type**




Source: *Lignin As A Renewable Aromatic Resource For The Chemical Industry*, Gosselink, 2011

Furthermore, the processing technologies of kraft and organosol lignins are at very different stages of development, resulting in different yields, specificity levels and capital expenditure requirements. These differences bring to light one of the barriers that stand in the way of lignin development: the lack of mature technology.

# Barriers and potential lifts

As shall be illustrated in the case studies in the next section, taking advantage of lignin's full potential in an industrial production setting relies on the following factors:

- Technology maturity
- Interest from game-changing investors
- Funding options

## Technology maturity

Current commercial uses of lignin are only as a macromolecule, whereas the main potential lies within aromatics, for which depolymerisation processes for lignin are still in early R&D. The output of technological improvements would bring increased yield and selectivity.

***Low yields and specificity***

At present, technologies do not allow the production in one same step of any pre-determined selection of chemicals. A choice has to be made between producing fine chemicals with increased functional groups or bulk chemicals with decreased functional groups. For example, oxidative depolymerisation will produce vanillin but very few phenols and no BTX, whereas hydrodeoxygenation will produce phenol and benzene, but no vanillin.

Both processes will yield a consequent amount of unwanted chemicals that will be disposed of, showing that the percentage of lignin utilisation as feedstock still needs to be greatly improved.

Moreover, the yields of commercially produced chemicals remain very low compared to what has been achieved for almost 20 years on the research side. For example, the commercial yield of vanillin from lignin is estimated to be around 1 per cent[1], whereas yields of 13 per cent have been published in research papers[2]. Researchers estimate that yields could still be improved by a factor of 10 for BTX and by a factor of 8 for phenol.[3]

The most immediate solution lies in technology improvement, focusing on yield, specificity and costs, which will require substantial R&D effort and, therefore, funding.

***Need for new concepts involving complex processes***

One of the key processes to produce aromatics is by controlled depolymerisation and extraction of pure chemical monomeric substances. It is considered complex to carry out, as highly reactive aromatics have a tendency to quickly rearrange and form tar- and char-like polymers. Paradoxically, current techniques show a better aromatics yield with impure lignin than with highly pure lignin, which means that the reactor design itself has to be rethought.

Supercritical depolymerisation (SD), an emerging technology that aims to produce monomer phenolic compounds, is still a field of research and remains very expensive, but shows great potential:

- This technology is already used to extract essential oils, fatty acids, lipids, and bioactive compounds from biological resources.
- $CO_2$ as a solvent can be used with SD. It is a safe and environmentally friendly solution.
- Conditions (temperature and pressure) are easier to obtain than for other processes.

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[1] Borregaard claims that it can produce 400 kg of lignin and 3 kg of vanillin from 1000 kg of wood
[2] *Determination of the Kraft Lignin Molecular Weight*, Mathias, 1993
[3] *Top Value-Added Chemicals from Biomass*, DOE, 2007

***Weak link between R&D and the industry***

Lignin is mostly unheard of, as few participants have emerged with commercial solutions based on this material. Moreover, the ties between the pulp and paper industry and the research departments of universities are focused on improving yields for their main products.

Establishing strong R&D links between universities/institutes and the industry will support the development of lignin-based applications. For example, The International Lignin Institute[1] has been created in 1991 and, more recently (2010), a dedicated lignin network in the Netherlands[2], as well as an extensive technology platform in Canada[3] have been started. A biennial international conference on lignin biochemicals was launched in 2010 as well.

## Interest from potential game-changing investors: The petrochemical industry

***Impact of biofuels***

Biorefiners may be preparing the next technological breakthrough in their labs, but concurrently, the world still requires, every day, huge amounts of chemicals that only the petrochemical industry is capable of providing. The balance of power between biorefiners and petrochemists has been established—for example, biorefiners will produce platform chemicals or even building blocks, but the rest of the process will belong to the petrochemical industry. The current observed trends are analysed as follows.

Investments in the sugar platform, favouring biofuels, have been witnessed over the past few years. This trend is backed by government mandates, especially in the USA and Europe, where clear targets have been established in terms of the biofuel as a replacement of the fossil-based fuel. This has given the biochemicals industry a competitive disadvantage compared to biofuels. Also, sugar-rich feedstock has been preferred, slowing down R&D efforts for wood-based chemicals, including lignin-based chemicals.

***Impact of petrol-based world***

However, the side effect of this trend is that more and more participants in the pulp & paper industry will start producing biofuels from black liquor, which will at the same time increase the number of lignin-rich side streams.

As technological costs decrease, it will become more and more interesting to produce lignin-based products and sell them at a much higher price than biofuel. In other words, there will be a trade-off between cheap production of commodity biochemicals (biofuel) and more expensive production of speciality and fine chemicals (mostly lignin-based).

The petrochemical industry requires ‘drop-in’ chemicals. The most advanced and almost commercial use of lignin is from CIMV’s BioLignin. It is used as a highly pure lignin macromolecule that can be ‘dropped in’ to replace phenols in a petrochemical process. Reaching a technology that makes lignin-based chemicals pure enough to be incorporated in a petrochemical process still requires R&D effort, time and funding.

As the price of oil has not been consistently high over a long period of time, it limits off-playground R&D investments from biorefiners, which prefer to stick to known technologies, focusing on the sugar platform. Therefore, the petrochemical industry has witnessed little improvement on the lignin depolymerisation front.

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[1] www.ili-lignin.com
[2] www.ligninplatform.wur.nl
[3] www.lignoworks.ca

As oil reserves continue to be found and shale gas receives increasing focus, especially in the USA, the petrochemical industry is not yet ready to make strategic moves that would compromise the barrel price equilibrium.

## Lack of funding options for biorefiners

A few funding options are available to biochemical biorefiners, but unless they have enough capital to fuel their own investments (like Borregaard, which started its biorefining business in the 1930s), they usually have great difficulty raising money.

Government mandates are at present focused only on biofuels, whereas private equity investment from the petrochemical industry is bound to the display of commercial availability.

Other ways to raise funds have dried out because of the economic conditions: banks are unwilling to raise debt levels of companies entering a nascent market. Venture capitalists have become more cautious and now systematically require a demo plant. The stock market these recent years has been uninterested in supporting the IPOs of courageous biorefiners, while others are still waiting for a window of opportunity. To cite an example, Gevo introduced its stocks in February 2011 at $15 - it was traded mostly under $6 during June 2012. Codexis, Amyris, KiOr and Solazyme were in a similar situation, with an average 56 per cent decrease from the introduction price.[1]

Among these barriers to funding, the one that seems the most likely to be partially lifted is the potential investment from petrochemical participants. Indeed, biorefiners are mostly developing drop-in chemicals, suitable for the petrochemical industry: these biochemicals require less capital investment in the procedure adaptation and less risk in end-product performance modification. For example, in the recent years, a fair number of deals have been observed.

Although these deals focus on sugar-based chemicals, the same behaviour is expected from petrochemical participants when lignin processing technology is able to deliver cost-effective aromatics.

## Competition from alternative routes and feedstock for the production of aromatics

Lignin is not the only feedstock that can be used to produce aromatics. Other feedstocks have been identified in recent years, reinforcing the competition in the race towards bio-based aromatics production.

These alternative routes are using crude biomass, tannins or lignocellulosic carbohydrates for the production of aromatics.

**Fig. 3: Selected initiatives of biorefiners focusing on aromatics production**

| Company | Product | Applications | Feedstock | Commercial Production Start Date |
|---|---|---|---|---|
| Virent | p-Xylene | PTA, PET | Plant carbohydrates | N/A |
| Annellotech | BTX | Chemicals and transportation fuels | Non-food biomass | N/A |
| Gevo | Isobutanol[2] | Synthetic rubber, lubricants, PMMA, PET, PTA | Plant carbohydrates | H1 2012 |

*Source: Frost & Sullivan, 2012*

However, most of these processes are at a very early stage. It is unclear if those routes can become costs competitive as well as sustainable.

[1] Data extracted on 20 June, 2012
[2] Used to replace aromatics

# High added-value applications: case studies

The main applications from lignin can be broken down into three groups:

**Fig. 4: Main applications for lignin**

| Group | Volume | Value | Application example |
|---|---|---|---|
| Power/fuel | High | Low | • Carbon source for energy production |
| Macromolecules | Medium | Medium | • High molecular mass applications like wood adhesives (binders)<br>• Carbon fibres<br>• Polymers, e.g., polyurethane foams |
| Aromatics | Low | High | • Polymer building blocks<br>• Aromatic monomers, e.g., benzene, toluene and xylene (BTX)<br>• Phenol<br>• Vanillin |

*Source: Frost & Sullivan, 2012*

The chief challenge, but also the most rewarding, economically, lies within high-value products, among which are aromatics and carbon fibre. The difficulty resides in the diversity and the complexity of the lignin material itself. This paper focuses on four high-value lignin-based products:

- BTX, in the Aromatics group
- Phenol, in the Aromatics and Macromolecules groups
- Vanillin, in the Aromatics group
- Carbon fibre, in the Macromolecules group

Among these, BTX and phenols represent two out of the three main aromatic compounds used in the industry[1].

For each of these products, the current demand, forecasted growth and application roadmap is examined, and an analysis offered of how the petrochemical industry could take advantage of it.

## BTX

BTX is the source of approximately 60 per cent of all aromatics in volume. It represents a 100-billion-dollar market and was produced from petroleum with the following volumes in 2010[2]:

- Benzene: 40.2 million tonnes per year
- Toluene: 19.8 million tonnes per year
- Xylene: 42.5 million tonnes per year

BTX represents almost 24 per cent of the global petrochemical market in value[3]. The average price for BTX is around $1,200 per tonne. The BTX market is forecasted to grow at a 4.4 per cent CAGR[4] from 2010 to 2020.

[1] The third one is terephthalic acid, converted from p-xylene, and generated from BTX
[2] *Chemical Economics Handbook Product Review*, Sean Davis, 2011
[3] *Chemical Economics Handbook*, ICIS
[4] Annellotech, 2010

As the applications for BTX are extremely vast[1], some of the most representative examples of final products made out of BTX are offered here.

**Fig. 5: Selected applications of BTX**

| Bulk Chemical | Sample Final Product |
|---|---|
| Xylene | • Plasticisers<br>• Resins used in auto parts, coatings and furniture<br>• Urethanes used in foams and insulation<br>• Polyamide resins used in adhesives<br>• Polyester fibres used in apparel<br>• Polyethylene terephthalate (PET) used in bottles, film and other products |
| Benzene | • Bisphenol A, used in polycarbonate (eyeglasses, containers, computers) and epoxy resins (coatings, adhesives)<br>• Phenolic resins<br>• Nylon fibres<br>• Rubber chemicals, pesticides, dyes |
| Toluene | • Urethane foams used in bedding, insulation<br>• Urethane elastomers used in footwear<br>• Urethane coatings used in varnishes, adhesives, sealants |

*Source: Frost & Sullivan, 2012*

The application roadmap for BTX from lignin would be similar to that for BTX from petroleum, as lignin-based BTX would be used as a drop-in chemical. However, lignin-based BTX is still in the R&D phase and much progress needs to be made on depolymerisation techniques both in terms of yield and specificity. Researchers in this field indicate that commercialisation could begin within 10–20 years.

This direct use of a bio-based BTX has already gathered the attention of the petrochemical industry. For example Virent, which has developed a technology that can convert biomass into biofuels and aromatics has already partnered with Shell. Although this technology is based on sugars and starches, we expect the same interest from petrochemical participants when lignin-based aromatics become economically viable.

A strong interest from the petrochemical industry is needed to develop the emergence of an alternative source of BTX. Indeed, the biorefiners do not aim at recreating the whole value chain but instead to provide chemicals as ‘drop-ins’ to be used directly in petrochemical processes. R&D partnerships need to be put in place to help biorefiners raise their quality level to industry standards. As the petro-chemists control the downstream side of the chemical processing, they are in the best position to also help biorefiners commercialise their products. Finally, petrochemists should not wait until biorefiners are more developed to focus their interest on them. Patents get filed, biorefiners are in a limited number and yet they do not require much funding to become commercially operational. The cost of opportunity is never likely to be this low in the future.

Additionally, securing an alternative feedstock would help prepare downstream petrochemists against higher petroleum prices and volatility.

[1] *2011 Guide to the Business of Chemistry*, American Chemistry Council

## Phenol

Current phenol production volumes amount to 8 million tonnes per year. Phenol market value is around $1500 per tonne[1]. However, its main applications—Bisphenol-A, phenolic resins and caprolactam—achieve costs in the region of $1,870 to $3,120 per tonne[2].

The phenol market is expected to grow at a CAGR of 3.9 per cent over the next 10 years.[3]

Phenol is mostly produced from cumene, which is itself produced from the alkylation of benzene with propylene.

Lignin can address phenols in the following two ways:

- As a macromolecule, to replace phenol in the petrochemical process
- As a lignin-based phenol

For now, neither of these uses is commercially available. The first use is technically ready to be commercialised, but high-purity lignin still needs extensive testing from petrochemists. Partnerships between lignin producers and petrochemists could occur in the coming years.

The second use is in a lengthy R&D process involving depolymerisation technologies discussed earlier, and could take 10–20 years to be operational.

Two-thirds of phenol production involves its conversion to plastics or related materials. The following are the main applications for phenols:

- Phenol formaldehyde resins
- Polyurethane foams
- Polyurethane for automobiles

Phenol is considered a commodity and is directly affected by the price of oil. However, lignin price is relatively stable and is likely to decrease as yields improve and technology spreads. Petrochemical participants can take advantage of this upcoming change by supporting lignin producers in funding and R&D. Today, there is still no patented process for the conversion of lignin to phenol. The interest for the petrochemical industry is the same as for BTX. However, the direct use of lignin as a replacement of phenol is not new and was already commercially in place before the decline in phenol prices.[4] As oil becomes more expensive, this trend could pick up again in the coming years.

## Vanillin

Vanillin is of particular interest, as it has been commercially produced from lignin since 1937. Before 1980, 80 per cent of all vanillin produced came from lignin. In the 1980s, changes in the pulping process made vanillin production alongside pulp environmentally unfriendly. Only Borregaard, a former pulp & paper participant that had converted into a pure biorefining participant remained active in this market. Today, 20 per cent of vanillin is produced from lignin and 80 per cent from crude oil using the guaiacol route.

Global demand for vanillin was estimated at around 16,000 tonnes per year in 2010. Natural vanillin represents less than 1 per cent of the total volume but approximately 40 per cent of the market value.

Annual vanillin demand is growing at a stable annual growth rate of 2 per cent in Europe and the USA. However, the annual growth rate reaches 10 per cent in China. This quickly rising demand, combined

[1] ICIS, 2012
[2] Stewart, 2008, ICIS 2011, Global Industry Analysts 2010. fx rate used: 1.2485
[3] GBI Research, 2012
[4] The technology was already used during the Second World War to produce composites

with uncertainties on supply (50 per cent of vanilla is exported from Madagascar) is pushing up the prices of both natural and synthetic vanillin.

**Fig. 6: The vanillin market in 2011**

| Vanillin Type | Est. Market Volume (metric tonnes) | Est. Market Value (USD) | Est. Average Price (USD per metric tonne) |
|---|---|---|---|
| **Synthetic vanillin** | **16,000** | **192,000,000** | **12,000** |
| *- Lignin-based* | *3,200* | *38,400,000* | *12,000* |
| *- Crude-oil-based* | *12,800* | *153,600,000* | *12,000* |
| **Natural vanillin** | **60** | **36,000,000** | **600,000** |
| Total | 16,060 | 228,000,000 | 14,196 |

*Source: Frost & Sullivan, Borregaard*

Borregaard is the only company producing vanillin from lignin[1], and achieves an estimated market share of around 20 per cent in volume. It uses a well-known oxidative depolymerisation process on black liquor resulting from sulphite pulping. However, this process yields a very limited quantity of monomer phenols.

In terms of application, vanillin differs from BTX or phenols, as it is considered, not a platform chemical, but an end product. It is used directly in a large number of products as a flavour (82 per cent of its total volume), a pharmaceutical intermediate (13 per cent) or a fragrance (5 per cent).[2]

This is considered a low-hanging fruit for pulp & paper participants, as the technology is well known and has been tested by companies like Ontario Paper, Monsanto and Rayonier in the past century, before being mostly abandoned due to environmental issues.

The key to producing vanillin from lignin while being environmentally friendly is to increase the percentage of feedstock used. At Borregaard, less than 1 per cent of the wood is used for vanillin, while the other 99 per cent is used for other bio products and as an energy source. Also, the wood-derived lignin carbon footprint is around 90 per cent less than that of vanillin made from guaiacol.

It may soon be economically important to switch the production process back to lignin processing due to various factors, such as the pulp and paper industry initiating a strategic turn towards biorefining, the increasing price of oil and growing demand from Asia.

The significance of this for the petrochemical industry is that, although vanillin itself is too small a market to be regarded strategic, the concept of the full utilisation of wood to produce biochemicals should raise interest in the industry. Pulp & paper market participants with a biorefining component already consider joint ventures with petrochemists highly possible in the future.

[1] Rhodia produces vanillin from crude oil using the catechol-guaiacol process and has an estimated 55 per cent market share in the vanillin market
[2] *Aroma Chemicals from Petrochemical Feedstocks*, NEDLAC, 2005

## Carbon fibre

*"Diverting 10 per cent of the lignin potentially available in the US could produce enough carbon fibre to replace half of the steel in domestic passenger vehicles"*
– DOE report, 2007

In 2011, the global demand for carbon fibre tow in 2011 was estimated to be 46,000 tonnes, and is forecasted to rise to 140,000 tonnes by 2020. Sales of carbon fibre tow are expected increase from $1.6 billion in 2011 to $4.5 billion in 2020.[1]

In terms of applications, global sales of carbon fibre reinforced plastics (CFRPs) were estimated at $16.1 billion in 2011, and are forecasted to reach $28.2 billion in 2015 and $48.7 billion by 2020.

The first and only commercial lignin-based carbon fibre was manufactured in a small pilot plant operated by Nippon Chemical Co. from 1967 to 1973. The precursor used was lignosulphonate, a technical lignin originating from the sulphite process.

The main drawback of carbon fibre is its very high price compared to other composites and materials. The current price of carbon fibre is around $18 per kilogramme, whereas the automotive industry is not willing to consider it until the cost is decreased to $7–11 per kilogramme[2].

The main reason for this high price is that polyacrylonitrile (PAN), the precursor to almost 80 per cent of the commercial carbon fibre, represents more than 50 per cent of the overall manufacturing costs.[3] Also, PAN is converted to carbon fibres using thermal pyrolysis, a slow, energy-consuming and, thus, expensive process that is combined with stressing to achieve the right properties.

The idea is, therefore, to use lignin as an alternative to PAN. Lignin is readily available, relatively inexpensive and structurally rich in the phenyl propane group with high carbon content (60 per cent). Lignin, however, possesses several disadvantages, the most notable of which is the difficulty in recovery in a clean-pure form.

Today, ORNL[4] is at the forefront of developing lignin-based carbon fibre, expecting to produce a lignin-based carbon fibre for about $8 per kilogramme, which could be sold commercially for about $12 per kilogramme, well inside the target range. The Department of Energy awarded $34.7 million to ORNL in 2010 for the construction of a Carbon Fibre Technology Centre. In November 2011, Zoltek, global leader in the production and sales of carbon fibre for commercial applications, was awarded a $3.7 million award from the US DOE to support and accelerate lignin-based precursor fibre technology for producing low-cost carbon fibre.

In terms of applications, carbon fibre is used in different industries:

**Fig. 7: Carbon fibre applications split by volume, 2010**

| Industry | % of total volumes | Examples |
|---|---|---|
| Industrial | 67% | Cars, civil engineering, wind energy |
| Aerospace | 17% | Aircraft |
| Sports goods | 16% | Tennis rackets, bicycles, fishing poles |

*Source: Materials Technology Publications, 2011*

[1] Materials Technology Publications, 2011
[2] Oak Ridge National Laboratory (ORNL), 2008
[3] *Development of commodity grade, lower cost carbon fiber commercial applications*, Warren, 2009
[4] Oak Ridge National Laboratory

However, the number of applications is limited due to the high cost of carbon fibre, which is itself dependent on higher demand to be able to perform economies of scale.

For petrochemists, this is another opportunity to diversify their investments. By partnering with biorefiners working on developing carbon fibre from lignin, they would accelerate the emergence of lower-cost carbon fibre and, therefore, initiate a huge demand growth.

In the long term, betting on the emergence of carbon fibre using an alternative feedstock will probably be economically more rewarding than keeping the price high and demand relatively low to keep current oil-based processes active.

Following are the requirements to rapidly expand the carbon fibre industry:

- Large investments in new, proven production methods
- Development of lower-cost precursors
- Products fit with high-volume demand

Joint ventures, R&D or commercialisation partnerships could be viable ways for petrochemical participants to help develop an alternative carbon fibre industry.

# Conclusion: What is the future for the lignin-based chemicals industry?

## Addressable markets and roadmap

Observing the four products analysed in this paper, the market potential is over $130 billion, and growing faster than the world's GDP. In 2020, this potential is expected to reach $208 billion.

**Fig. 8: Selected addressable markets of lignin-derived products, 2010**

| Product | Est. commercial date | Est. market volume (MTon) | Est. market price (USD per tonne) | Est. market value (B$) | CAGR 2010-2020 (volume) |
|---|---|---|---|---|---|
| **BTX** | 2020–2025 | 102 | 1,200 | 122 | +4.4% |
| **Phenol** | 2015[1] | 8 | 1,500 | 9.6 | +3.9% |
| **Vanillin** | Commercial since 1933 | 0.016 | 600,000 | 0.1 | +4% |
| **Carbon fibre** | 2020–2025 | 0.046 | 34,800 | 1.6 | +13% |
| **Total** | | | | 133.3 | +4.5% |
| **World GDP** | | | | | +4.2%[2] |

*Source: Frost & Sullivan, 2012; ICIS Economic Handbook, 2011; CIMV, 2012*

In 2011, an encouraging capacity scale-up from the main suppliers of lignin took place, increasing lignin production by 100,000 MT, which is expected to increase technical lignin availability by 10 per cent[3]. As the total production of lignin surpasses heat and power demand from pulp & paper manufacturers and biorefineries, researchers in the field consider this a boost that will stimulate further developments of high-value lignin applications. Also, lignin will probably receive greater attention as the price of oil continues its volatile journey and hits new price records.

The development of an economically viable lignin valorisation route for the production of aromatic chemicals or carbon fibre would necessitate much more research to optimise processing technologies. The use of high-purity lignin is also an important issue. It can be produced by organosolv technology, which requires high capital investments and has so far not reached the industrial-scale stage.

In terms of a roadmap, the next five years could see the emergence of lignin used in its polymeric form to replace phenol in petrochemical processes, through partnerships between lignin producers and petrochemical participants. Lignin-based vanillin production could also gain some momentum depending on the price of oil and demand for vanillin.
The next five years are expected to confirm these trends, but also to give momentum to new technologies for processing lignin into carbon fibre, and depolymerising lignin into phenol and BTX.

Twenty years from now, researchers and industry participants expect to see the commercial launch of biorefining factories that will produce high added-value chemicals and materials out of lignin.

These trends raise important questions for the entire galaxy of participants revolving around these products: biorefiners, technology providers, pulp & paper participants, governments and

[1] CIMV, 2012
[2] IMF, 2012
[3] As announced by Borregaard, Domsjö, Metso and CIMV in 2011

petrochemists. One of the main uncertainties lies in the ability of lignin-based products to achieve a consequent market share in their target markets.

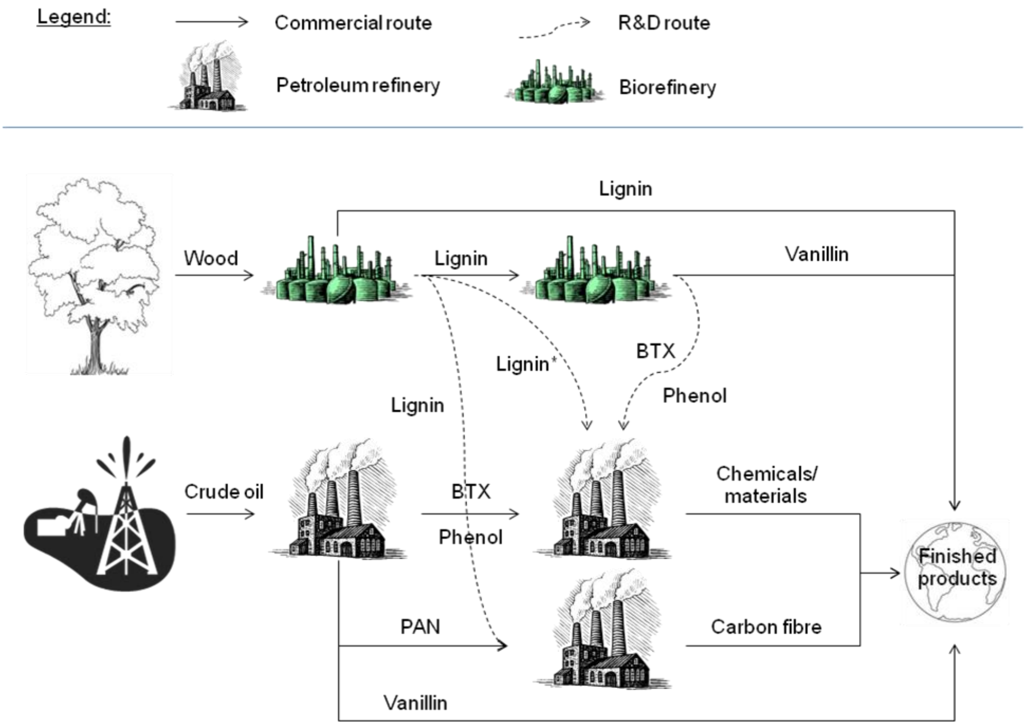
## Why petrochemists should get involved

The potential impact of petrochemists would be to accelerate this agenda by partnering on R&D or commercialisation phases, either by funding biorefiners, giving them access to R&D resources, or helping them set up a pilot plant.

As illustrated in the following graphic, the petrochemical industry will eventually find in lignin a challenger at three different levels:

- The production of platform chemicals (e.g., BTX, phenol)
- The production of intermediate chemicals (e.g., carbon fibre)
- The production of end products (e.g., vanillin)

**Fig. 9: Selected routes from wood and oil involving lignin**




* High-grade lignin as polymer, used as a replacement for phenol

*Source: Frost & Sullivan, 2012*

Therefore, it is a unique chance for petrochemists to secure a future alternative source of raw material. Being the first mover on this market can assure technology leadership, strategic partnerships and a competitive edge.

One of the key outputs of this paper is also that the petrochemical industry holds by far the highest capacity to accelerate the emergence of lignin-based chemicals. As discussed, this is not a game where the petrochemical industry will necessary lose out to the 'green' industry. The most frequent forecast heard in the industry is that biorefiners will become an increasing source of alternative feedstock for petrochemists by means of joint ventures or acquisitions. In the long term, biorefiners and downstream chemists are likely to be integrated.

In the end, what the nascent lignin-based chemicals industry proposes is to create value through focus collaboration.

Therefore the key questions for petrochemists are:

- **What is the best strategy to take advantage of the evolution of lignin-based products?**
- **Which technologies and which products should we support?**
- **Which companies are worth investing in?**
- **What should we expect in terms of revenue and competitive advantage from a closer collaboration with biorefiners in the short, medium and long terms?**

# About the author

## Nicolas Smolarski

Nicolas is a consultant based in the Frost & Sullivan Paris office and has been with the firm since 2007. Nicolas has been working with clients from the chemicals, materials and food industries, and has developed a particular interest in the bio-based segment.

Nicolas holds a Masters in Management from HEC Paris and a Postgraduate degree in Mathematics with honors from Université Paris Dauphine.

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