Road map 2014 to 2025: Swedish lignin-based carbon fibre in composite materials of the future

Carbon fibre is strong and light and has many applications. Today, the demand for carbon fibre is mainly limited by the high cost. As a result, the material is currently primarily used in products where performance is more important than price. By introducing a cost-effective lignin-based carbon fibre, the market could increase considerably. With this road map, we show how this will be possible in just ten years.

Targets

By 2025 we will have:

• developed a new high-value Swedish product from wood raw materials: lignin-based carbon fibre, for use primarily in advanced composite materials,

• developed Swedish R&D, research infrastructure and production expertise throughout the value chain, from forest-based raw materials to high quality carbon fibre for use in advanced construction materials,

• created a demand for and use of lignin-based carbon fibre in several different applications, and

• made a significant contribution towards establishing industrial carbon fibre production in Sweden.

Background

• The bio-based economy is now established as a concept, and large investments are expected to be included in Horizon 2020, EU’s Framework Programme for 2014-2020 and the EU initiative Bio-based Industries Public-Private Partnership (BBI PPP).

• The Swedish pulp and paper industry faces considerable challenges, with a trend of decreasing demand for writing and printing paper.

• The automotive industry will be affected by forthcoming specific legal requirements for high energy efficiency, which will involve a radical technological shift towards lightweight, electric and electric hybrid cars that can only be achieved with new lightweight technology.

• The wind turbine of the future, with higher energy performance, will be made possible through the development of light, stiff, strong, cost-effective materials.

• New concepts for non-mechanical, load-bearing carbon fibre have been developed:
  o Batteries that use commercial carbon fibres as active electrodes.
  o Storage of hydrogen gas with activated carbon fibres made from lignin.
  o Thermal insulation at high temperatures.
Today’s commercial carbon fibre: applications and market

The current global production of carbon fibre is approximately 50,000 tonnes. Carbon fibre is used in applications where high mechanical performance and low weight are more important than low cost (see Figure 1 below). Carbon fibre is therefore currently used primarily in applications with a demand for high mechanical performance, such as sports equipment, aircraft, satellites, Formula 1 cars, pressure vessels, specialized tools, wind turbine components and for reinforcing concrete in areas with a high risk of earthquakes. With a lower price, the market for carbon fibre would be considerably larger than it is today. Growth is high, even with today’s relatively high carbon fibre price, and by 2020 the use of carbon fibres is expected to more than double. The most significant growth in volume is anticipated to be in the wind power industry. There is also a large potential in the automotive industry, where a lower price is crucial in terms of growth in volume.

Figure 1. Use of carbon fibre in 2011 and forecast for 2022 (tonnes).

There is not a great number of manufacturers of carbon fibres, and these are dominated by nine companies (Figure 2), based mainly in the U.S., Japan and Germany. Toray and Zoltek have recently merged, and are now the world’s dominant manufacturer of carbon fibre. One new player with a high level of ambition is AKSA in Turkey, 50% of which is owned by Dow. Other new ambitious players include SABIC in Saudi Arabia and HCC in Russia. BMW owns 50% of SGL.

Figure 2. Major manufacturers of carbon fibre and their estimated share of global capacity in 2011.
Potential future applications for lignin-based carbon fibre

Current research shows that lignin-based carbon fibre can be optimised for both structural (load-bearing) and non-structural applications. Timewise, the non-structural applications are probably closer to a market launch. Potential applications for lignin-based carbon fibre include:

**Structural applications**

- High-performance carbon fibre, e.g., aviation and aerospace (very long term).
  - Carbon fibre composites are widely used today in aviation and aerospace applications. These applications demand a high level of performance. Use of lignin-based carbon fibres will only be considered when high specific stiffness and strength can be achieved.

- Medium-performance carbon fibre, e.g., the automotive industry (medium term, may involve a mixture of the polyacrylonitrile (PAN) and lignin-based carbon fibre) and to replace fibreglass (short term).
  - The use of carbon fibre composites in vehicles is expected to increase significantly during the next few years. Lignin-based carbon fibres with high stiffness may hasten the broad use of composites in cars by a favourable price in combination with rational production technology.
  - There are requirements in EU’s End of Life Vehicles Directive (ELV) for the automotive industry to maintain a low ash content of residual products, which can be achieved by replacing fiberglass with carbon fibre in composites.

**Non-structural applications**

- Thermal insulation.
  - Carbon fibre is an excellent thermal insulator and could therefore be used in the near future as insulation materials within the construction sector and other sectors.

- Electrodes for batteries.
  - By making carbon fibres electrically conductive, they have the potential to be used as electrode materials in batteries. In particular, they can be used in the new carbon fibre battery concept in which the fibre is coated with a thin polymer electrolyte, which has been developed by Swerea SICOMP. A patent application has been submitted for this concept.

- Hydrogen gas storage.
  - Lignin-based carbon fibres can be processed so that they have a very high pore volume which can be used for gas storage. A very high capacity for the storage of hydrogen gas has been achieved in trials carried out by Innventia.

**Multifunctional applications**

- Separators in super capacitors.
  - The electrodes in a super capacitor are separated by a permeable separator material with electrical insulator properties. By using carbon fibre, these properties are likely to be achieved.
• Load-bearing electrodes in super capacitors and batteries.
  o Structural battery composite materials can be manufactured by using polymer electrolyte-coated carbon fibre. It is also possible to use such fibres in electrodes for structural super capacitor materials.

Figure 3 shows how a small amount of lignin extract from a modern kraft pulp mill can be used as load-bearing carbon fibre in the lightweight car of the future. It is obvious that the potential is enormous. The lignin-based carbon fibre in this example saves 50 times more energy as compared to replacing oil with lignin in combustion. It is also clearly more resource-effective to make lightweight materials from lignin as opposed to using it to replace fossil fuel in combustion.

On average, less than 1 kg of carbon fibre is currently used per car. If this quantity were to increase to 10 kg or 100 kg per car, this would correspond to the use of 80,000 tonnes and 800,000 tonnes of carbon fibre respectively per year on a global basis. In view of the fact that the global production capacity in 2011 was less than 100,000 tonnes, this shows that a shortage could arise if demand increases in a single market area.

![Image](image.png)

Figure 3. A vision of the future: lightweight cars containing carbon fibre composite made from lignin.

Technologies

Structural carbon fibres are currently mainly manufactured from the petroleum-based product polyacrylonitrile (PAN). A smaller quantity is manufactured from petroleum pitch, which is a by-product from certain oil refineries, mainly in the U.S. The supply of petroleum pitch is expected to be reduced as a result of the large-scale increase of the use of shale gas in the U.S.

The different stages of the commercial production of carbon fibre are shown in Figure 4. The first stage is spinning (extrusion) of PAN-fibres. Thermal processing is then carried out in a number of processing stages: stabilisation, followed by a carbonisation stage and high-performance carbon fibres are put through a graphitisation stage. The final stage involves the chemical treatment of the fibre surfaces to make them compatible with polymers. PAN-based carbon fibres are manufactured in a solvent-based process, while pitch-based carbon fibres are manufactured through melt spinning.
In principle, the same process stages apply for the manufacturing of lignin-based carbon fibre as for PAN-based carbon fibres. The production of lignin-based fibre allows a number of simplifications of the process compared with PAN-based fibre, and has, therefore, great potential for a more cost-effective process, making it highly competitive.

The road to achieving the targets

The targets will be achieved through a close cooperation between Innventia and Swerea SICOMP, from pulp-mill-produced lignin to lignin-based carbon fibre composites and components, in close collaboration with industrial players along the value chain Figure 5. It is important to emphasize that, although the value chain is long, two existing value chains are linked together through the production of lignin fibres. The driving force for the forest industry is a new product, and for businesses further down the value chain the driving force is the need for cost-effective, renewable carbon fibre.

Figure 4. Simplified process chart for commercial manufacturing of carbon fibres based on fibres from PAN (current) or lignin (in the future).

Figure 5. Stakeholders in the value chain for Swedish lignin-based carbon fibre that cooperate in the Vinnova-financed project: “Test bed for Swedish lignin-based carbon fibre”, 2013-2015.
Main roles of the players along the value chain

Innventia: Develops lignin quality, pre-processing of lignin, feeding extruders, melting properties, extrusion, reeling/unreeling, stabilisation and carbonisation. Innventia can also produce tailor-made lignin at its demonstration facility, LignoBoost Demo, which can be used as raw material in the carbon fibre demo facility.

Swerea SICOMP: Develops process properties for the manufacturing of reinforcement and composite components, and physical properties for various applications based on carbonised lignin-based carbon fibre on different scales for manufacturing of composites, components and application testing.

One important and thus far untapped area for development is the surface treatment of carbon fibre to create the right interaction with resins and other polymers in the finished composite. This research is currently being carried out in cooperation between Innventia and Swerea SICOMP.

The involvement of industrial stakeholders is crucial in order to achieve a demonstration value chain on site. These stakeholders have different roles along the value chain which include producing the raw material lignin, defining which product properties are required in different applications, testing components, developing production technologies, developing business models, and, in the final stage, commercialisation.

The current situation

Innventia and Swerea SICOMP currently have a high degree of expertise and advanced laboratories for the parts of the value chain on which the two institutes are focusing. Innventia’s and Swerea SICOMP’s areas of expertise complement each other, giving an academic and technological breadth that is unique in the world.

Innventia, in cooperation with Chalmers University of Technology in Gothenburg, Sweden, has developed a process for extracting lignin from black liquor from the kraft pulp mill process. This process is called LignoBoost, and has been owned since 2008 by Valmet, which has sold two plants thus far. Lignin from these two facilities could in theory be converted into bio-based carbon fibre which would result in a volume that corresponds to more than half of the world’s current carbon fibre production. Many companies, Energimyndigheten and VINNOVA are interested in the LignoBoost process. Several forest industry companies are currently financing R&D in lignin and lignin-based carbon fibre at Innventia. Innventia has submitted two patent applications for lignin-based carbon fibre. Today, Innventia can manufacture continuous mono-filament lignin fibres and use this material to produce carbon fibres that are decimetres in length. By the autumn of 2014, Innventia will also be able to manufacture multi-filament lignin fibre on a small scale. A successful attempt to manufacture multi-filament lignin fibre carried out in the autumn of 2013 in cooperation with an equipment supplier is shown in Figure 6.
Equipment for manufacturing continuous lignin-based carbon fibre is not yet available, but in 2015 Innventia plans to invest in a pilot facility for the production of continuous lignin-based carbon fibre with an annual capacity of 10-20 kg. This is a very challenging and important step towards achieving the goal of a larger scale production (demo/full scale). The main difference compared with the current situation is that it will then be possible to emulate industrial production of carbon fibre on a large scale.

Swerea SICOMP currently has the necessary expertise and equipment to analyse physical fibre properties linked to various applications. Standardised test methods are used when there is sufficient access to the material, but methods for characterising individual fibres and smaller quantities of fibres have also been developed. Swerea SICOMP also has the capacity to analyse and verify the process properties of fibres for different manufacturing methods and different matrix systems, and to design, dimension and develop manufacturing techniques for composites. These skills are essential for the development of brand new fibres such as a lignin-based carbon fibre. Swerea SICOMP is in the process of building a testing and demonstration facility, “Sustainable production of composites”, which is being fitted out for the development and verification of bio-based composite materials. This is the next stage in the manufacturing process after lignin fibre manufacturing.

Innventia and Swerea SICOMP have a close strategic cooperation, and, together with representatives from industry, are planning a joint demonstration facility for the manufacture of lignin-based carbon fibre composites with an annual capacity of approximately 50 tonnes.

**Future R&D and resources needed**

It is our aim to work together to develop expertise and experimental resources in a smart way and thereby form a unique, unbroken value chain and a strong R&D environment from the forest to lignin-based carbon fibre products.

At present, the expertise and experimental resources for continuous manufacture of lignin-based carbon fibre is lacking, particularly stabilisation and carbonisation, where a continuous fibre-stretching process is required in order to achieve good mechanical properties. How environmental exposure affects mechanical performance and long-term properties is another area where additional knowledge is needed.

More information is also needed about how to surface treat lignin-based carbon fibre in order to achieve good compatibility with the polymer in the composite material and how the fibre functions in the manufacturing process. This is a specific area of great significance for the effective use of lignin-based carbon fibres in different composite systems and where Swerea SICOMP in cooperation with Innventia intends to develop tools and solutions. This will require significant effort over the course of several years on different scales (mono-, multi- and pilot scales) before the time comes to expand to demo/full scale.

Equipment is lacking for developing the technology on a continuous pilot scale. Investments are necessary in new equipment with greater capacity and performance in order to develop lignin-based carbon fibre from kraft lignin. Innventia is now working to secure this strategic investment, and place it close to Innventia’s expertise in lignin and lignin-based carbon fibre.

At a higher system level, life cycle analyses should be carried out on the entire value chain, including use and recycling. Carbon fibre production itself is an area where Innventia in particular will develop knowledge, while environmental and system-related aspects that cover the whole of the value chain are being studied as part of the close cooperation between Innventia and Swerea SICOMP.
In an estimated two to four years all the data will be collected that will be needed to inform the decision on establishing a demonstration facility for lignin-based carbon fibre including surface treatment, with an annual capacity of approximately 50 tonnes. The demonstration facility has multiple aims: to train operators, to test critical process stages, to define optimal process conditions and to test components in different applications, all of which will reduce the risks in industrial production.

**Road map for 2014-2025**

The road map is summarised in Figure 7 below, and includes the following steps:

- work on a laboratory scale and pilot scale until 2017/2018, with the goal of producing data for a demonstration facility,
- prior to industrial operation, establish a Swedish national demonstration facility for lignin-based carbon fibre, including composite manufacturing, with an annual capacity of approximately 50 tonnes of carbon fibre,
- component testing 2018-2022, and
- industrial production in Sweden by 2025.

The timetable for structural and non-structural carbon fibre can be accelerated by a major investment in both R&D and equipment. The market launch of non-structural applications can be expected to take place sooner. The speed of implementation will depend on the level of commitment of the industry during the development period.

![Figure 7: Road map for the industrial production of lignin-based carbon fibre in Sweden.](image)

In addition to these concrete steps, it is vital to secure interest from industrial players and other financial backers throughout the entire value chain in order to:

- establish the necessary properties of carbon fibre for various applications,
- finance a continuous pilot facility for R&D work,
- finance a national R&D programme,
- finance a Swedish demonstration facility, and
- set up a carbon fibre factory in Sweden.
Sources

- Information från HCC, Toho och SGL.

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