COMMERCIAL VIABILITY ANALYSIS OF LIGNIN BASED CARBON FIBRE

by

Michael Chien-Wei Chen
Master of Applied Science, University of British Columbia, 2009
Bachelor of Applied Science, University of Waterloo, 2005

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Name:	**Michael Chien-Wei Chen**
Degree:	**Master of Business Administration**
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Supervisory Committee:

Dr. Stelvia Matos
Senior Supervisor
Adjunct Professor, Strategy

Dr. Elicia Maine
Second Reader
Associate Professor, Technology and Operations Management

Date Approved:

Abstract

Lignin is a rich renewable source of aromatic compounds. As a potential petroleum feedstock replacement, lignin can reduce environmental impacts such as carbon emission. Due to its complex chemical structure, lignin is currently underutilized. Exploiting lignin as a precursor for carbon fibre adds high economic value to lignin and encourages further development in lignin extraction technology. This report includes a preliminary cost analysis and identifies the key aspects of lignin-based carbon fibre commercialization based on the TCOS framework. Technologically, melt spinning and shorter oxidation time give lignin carbon fibre a cost advantage and environmental benefit. Organizationally, lignin-based carbon fibre is patentable. The challenges are seeking financial gains and demonstrating the societal benefits. Commercially, lignin carbon fibre has a cost advantage and positive consumer perception. Successfully addressing TCOS uncertainties can potentially open the door for lignin as a carbon fibre precursor, a $2.25 billion market in 2020.

Keywords: Lignin; Carbon Fibre; Nanofibre; Commercialization; TCOS

Dedication

To my family, John Chen, Jane Chen and Robert Chen; and my wife, Tammy Lee.

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Table of Contents

List of Figures

List of Tables

Glossary

Lignin	Lignin is a complex aromatic alcohols commonly derived from wood. It is the second most abundant natural polymer in the world
Polymer	Polymer is a large molecule or macromolecule, composed of many repeated subunits.
CFRP	CFRP stands for carbon fibre reinforced polymer or carbon fibre reinforced plastic. It is a strong and lightweight composite material which contains carbon fibres.
Pre-preg	Pre-preg stands for pre-impregnated composite fibres. It is often in the form of a weave for easy bonding with other components. Bonding agent such as epoxy is already present on the surface.
OEM	OEM stands for original equipment manufacturer. It manufactures products or components that are purchased by another company and retails under that purchasing company's brand name
TCOS Framework	TCOS is a business strategy analysis method which started by Dr. Jeremey K. Hall and Dr. Michael J.C. Martin. It incorporates technological, commercial, organizational, and societal uncertainties.
Epoxy	Epoxy is the cured end product of epoxy resin. It has strong mechanical properties and is used in a wide range of industrial applications.
EMI	EMI stands for electromagnetic interference. It is the unwanted effects in the electrical system due to electromagnetic radiation and electromagnetic conduction.

1: Background and Overview

1.1 Objectives

The sponsor of this project is the TCOS Lab at the Beedie School of Business at Simon Fraser University. Currently, the TCOS framework is being applied to a Genome Canada funded project, Harnessing Microbial Diversity for Sustainable Use of Forest Biomass Resources, to explore the potential of biocatalysts for improving production efficiencies and reducing environmental impacts such as carbon emissions.

One of the high value applications of such technology is to allow forest biomass to replace petroleum feedstock for carbon fibre (CF). This project is performed in collaboration with the laboratory of Dr. Frank Ko in the Department of Materials Engineering and Dr. Lindsay Eltis in the Department of Microbiology and Immunology at the University of British Columbia (UBC). The focus will be on direct melt spinning method for the lignin carbon fibre and electrospinning method for carbon nanofibre.

The objective of this report is to investigate the uncertainties surrounding the commercialization of lignin-based carbon fibre using TCOS framework. TCOS stands for Technological (T), Commercial (C), Organizational (O) and Societal (S). This report focuses on the commercial, the C aspect of the TCOS methodology, and develops a preliminary cost analysis comparing lignin-based carbon fibre with conventional PAN-based carbon fibre. The purpose of this analysis is not to determine the actual manufacturing cost but to assess manufacturability and cost in the early design stage.

Lignin carbon fibre and nanofibre technologies are still in the preliminary stage. Even though producing carbon fibre from different precursors requires different processing conditions, the essential features are very similar. For lignin carbon fibre, a comparison method can be implemented by comparing with PAN-based carbon fibre. Since there is no comparable technology available for lignin carbon nanofibre, intuition method will have to be utilized.

Regarding costs identification, simple cost modeling will be used. Simple Cost modeling enables a cost comparison between functionally comparable components that are made with competing materials or processing methods (Maine & Ashby, 2002). It identifies cost drivers, factors that have direct and indirect impact to the processing steps, which add most to the unit cost (Maine & Ashby, 2002). The cost analysis is based on the U.S. dollar ($) and includes the following steps:

- Identify key inputs, processing steps and outputs
- Identify key equipment required and its capital cost
- Determine probable yield and scrap rate
- Determine rate-limiting step

The methodology includes primary data collected from open ended interviews with primary and secondary stakeholders related to the lignin carbon fibre development and secondary data from the academic literature, governmental and company reports. The interviewees include both academic and industry leaders throughout the lignin carbon fibre value chain. Appendix A shows the interviews that have been conducted.

This report contributes to the project sponsors and their collaborators' efforts in developing lignin-based carbon fibre and carbon nanofibre by identifying relevant TCOS uncertainties with the support of quantitative data from cost analysis. In particular, the early information on commercial, organizational and societal issues may help the science team led by Dr. Frank Ko and Dr. Lindsay Eltis shape the technology that is environmentally beneficial for more effective technology diffusion. Furthermore, some of the lessons learned in this report may be applicable to other aspects of the larger Genome Canada funded project.

1.2 TCOS Framework and Market Identification

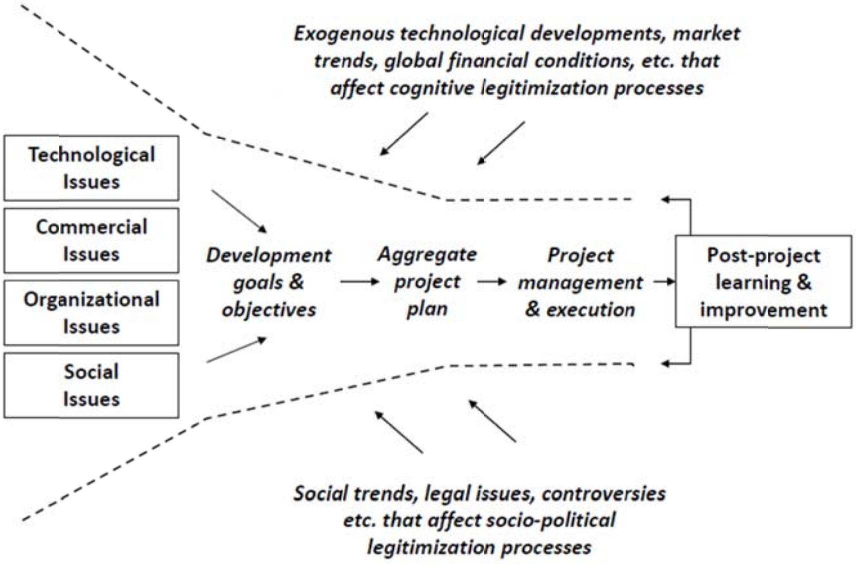
Innovation can be defined as the successful commercialization of an invention. An invention can only be considered a viable invention when it has overcome four areas of uncertainties: technological, commercial, organizational and societal (TCOS) (Hall & Martin, 2005; Hall, Matos, Silvestre, & Martin, 2011). Each of the four categories is not independent of one another but correlated. A brief overview of these four uncertainties is shown below:

- Technological uncertainty: the invention must be technologically feasible, based on corporate scientific and technological competences.
- Commercial uncertainty: the invention must be commercially viable, where it can compete successfully in the market place.
- Organizational uncertainty: the invention should be congruent with the firm’s overall strategy and capabilities, complement to its assets and ability to protect intellectual property.
- Societal uncertainty: the societal impact on or from diverse secondary stakeholders must be recognized and accommodated.

Hall and Martin (2005) further suggest that the issues identified within each of the four categories can be classified into levers, i.e. technology positive attributes that should be explored, and hurdles, i.e. challenges that need to be overcome.

Freeman defines primary stakeholders as those that have a direct impact on the technology; secondary stakeholders are defined as those that are not directly involved but may directly influence the development of technology via primary stakeholders. Closer tie between the technology developer and both primary and secondary stakeholders at early stage of the technology development can provide great opportunities to address concerns identified (Hall & Martin, 2005; Hall et al., 2011). Figure 1.1 shows the TCOS framework.

Figure 1.1 TCOS framework for exploring risks and uncertainties of an invention



Source: created by author, with data from Hall, Matos, Martin, & Bachor, 2012

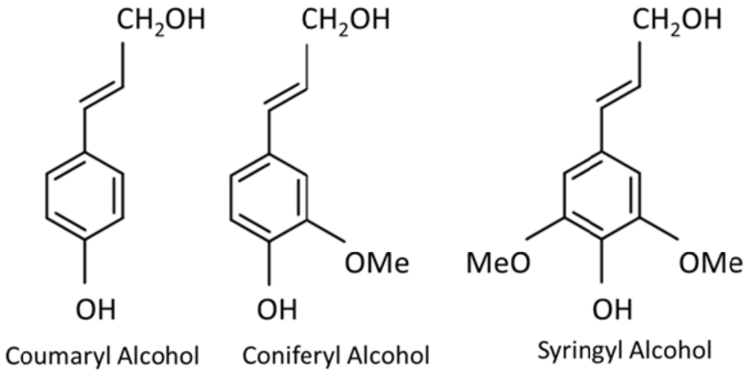
Lignin-based carbon fibre is an example of process innovation where the new technology is set to improve supply chain productivity, enable new products or enhance cost/performance, whereas a product innovation typically refers to an assembled product, and can be sold to a customer when manufactured (Maine, Lubik, & Garnsey, 2012). The key for new ventures to commercialize a new process technology is to create value for their customers. To achieve that, the first task is market identification and selection (Maine et al., 2012). Here, market is defined as potential buyers (and existing sellers) in a unique industry segment, such as automotive, consumer electronics, biotech/healthcare, etc. The TCOS analysis framework is applied to recognize such market.

1.3 Lignin and Its Potential Applications

1.3.1 What is Lignin?

Lignin is a complex polymer of aromatic alcohols known as monolignols. It is a constituent of the cell walls of almost all dry land plant. Lignin is the only large-scale biomass source of an aromatic functionality. It is composed of up to three different phenyl propane monomers, shown in Figure 1.2, and its composition differs with different lignin sources. For example, coniferyl alcohol occurs in all species and is the dominant monomer in softwoods. Hardwood species contain up to 40% syringyl alcohol units while grasses and agricultural crops may also contain coumaryl alcohol units ("What is Lignin?," 2010).

Figure 1.2 The three phenyl propane monomers in lignin



Source: created by author, with data from "What is Lignin?," 2010

There are many possible bonding patterns between individual units that make the understanding of lignin extremely difficult. For this reason, our knowledge of lignin is far less than most other natural and synthetic polymers.

Lignin is the second most abundant natural polymer in the world, surpassed only by cellulose. In nature, lignin and cellulose work together to provide structural function in plants. Cellulose is the primary loadbearing element, and lignin provides stiffness and rigidity. Both lignin and cellulose are abundant in the plant cells, fibres and vessels. This mixture of components is called lignocellulose.

Lignocellulose is made up primarily of cellulose, hemicellulose and lignin. Cellulose and hemicellulose are polysaccharides which are easily broken down and can be fully utilized to make commercial products such as paper and textile. In contrast to cellulose, which is a linear polymer, lignin is made up of heterogeneous complex aromatic polymer which protects it from degradation (Norberg, 2012). This has made the lignin inconsistent in quality and functionality. For this reason, lignin is treated as a waste by-product from pulp and paper industry and is used as fuel for the recovery boiler.

1.3.2 Lignin Degradation and Purification

In order to use lignin as raw material, lignin has to be isolated from lignocellulose. Lignin can be derived from various sources such as cereal straws, bamboo, bagasse and wood. In terms of weight, the lignin content in wood is the highest, roughly 20% to 35% while other sources only contain around 3% to 25% (Smolarski, 2012).

The price of lignin depends on the type of feedstock and the degradation and purification process adopted, as they determine the lignin structure, purity and consistency. Typically, kraft and organosolv lignins are suitably candidates for high value applications whereas lingosulphonate lignin most likely is used for lower-value products, Table 1.1.

Table 1.1 Lignin Type and their Use

Lignin Type	**Annual Production (*tonnes*)**	**Lignin Purity**	**Potential Products**
Low purity	50,000,000	Low	Energy, Refinery (carbon cracker)
Ligno-sulphonates	1,000,000	Low to medium	Energy, Refinery (carbon cracker)
Kraft	60,000	High	Bitumen, Refinery (carbon cracker), Cement additives, Biofuel, High-grade lignin, BTX (Benzene, Toluene and Xylene), Phenolic resins, Carbon fibres, Vanillin, Phenol
Organosolv	1,000	High	Activated carbon, Phenolic resins, Carbon fibres, Vanillin, Phenol derivatives

Source: created by author, with data from Smolarski, 2012

In addition to kraft and organosolv, steam-explosion lignin is another lignin degradation process available for carbon fibre applications (Norberg, 2012). Steam explosion and organosolv processes have been known in the pulping industry for decades and have a better environmental impact than kraft or sulphite processes. However, these processes have not been adopted in the industry largely due to the unfavourable economics against competing pulping methods. In contrast, kraft lignin is widely accessible at the industrial scale from the waste stream of kraft pulp and paper industry. Our stakeholder interviews (see appendix A) indicated that a strong driving force behind the investment of advanced lignin treating process for many pulp mills is not to make lignin products but to decrease lignin waste and increase pulping capacity. For these reasons, this report focuses on kraft lignin process as a precursor of lignin-based carbon fibre development for the North American market.

Kraft Lignin

In terms of industrial chemical modification of lignin, the kraft pulping process is the dominant global process. The objective of the chemical pulping process is to remove enough lignin to spate cellulosic fibres one from another, producing a pulp suitable for the manufacture of paper and other related products (Chakar & Ragauskas, 2004).

White liquor consisting of an aqueous solution of sodium hydroxide and sodium sulphide is added to the chipped wood at high temperature, and cellulose is produced from the wood by dissolving almost all lignin and a large part of the hemicelluloses into the spent liquor i.e. black liquor. The cooking procedure is regulated with respect to time, temperature and alkalinity which are suited depending on the source of wood and the target of pulp types. After cooking, the pulp is processed by washing, bleaching and drying, and is further converted into paper, board or tissue grades (Norberg, 2012).

The black liquor is a waste by-product which is underutilized and commonly used as a fuel source for heat generation. One of the widely adopted processes for isolating large quantities of kraft liginin from black liquor is known as LignoBoost® developed by Innventia and Chalmers University of Technology. In 2008, the technology was sold to Metso which together with Innventia developed the technology to industrial scale.

Kraft pulping is widely adopted because it can produce pulp stronger than other pulping processes. Fully bleached kraft pulp is often used to make high quality paper with superior strength. Kraft pulping can also use wider range of fibre sources than most other pulping processes, including very resinous types like southern pine, and non-wood species like bamboo and kenaf (Chakar & Ragauskas, 2004).

The first produced carbon fibre originating from hardwood kraft lignin was reported by Kadla (Norberg, 2012). There are two major types of kraft lignin, softwood kraft lignin and hardwood kraft lignin. Due to the chemical composition, each one has its strength. Hardwood lignin melt spins well but stabilizes slowly. Softwood lignin stabilizes well but does not melt spin. To overcome these challenges, various purification and modification techniques are under development for kraft lignin.

1.3.3 Lignin Applications

Although around 50 million tonnes of lignin are produced annually from the pulping process; however, only approximately 1 million tonnes are isolated and sold each year for industrial applications. In general, these markets are low volume niche applications. They can be divided in three main groups, Biofuel, macromolecules and aromatics as shown in Table 1.2 (NNFCC, 2009).

Table 1.2 Main applications of Lignin

	Volume	**Value**	**Application Examples**
Power/fuel	High	Low	Bio-ethanol, Bio-butanol
Macromolecules	Medium	Medium to High	Phenolic resins, Carbon fibre precursor Polyurethane foams
Aromatics	Low	High	Vanillin, BTX

Source: created by author, with data from Chapple, Ladisch, & Meilan, 2007; Smolarski, 2012

Among these applications, the most technically challenging but also the most economically rewarding products are carbon fibre and aromatics. For example, while the low value application, i.e. lignin burned as fuel after recovery, is estimated at \$400 per tonne, carbon fibre application has the highest potential to add value to lignin at \$21,700 to \$800,000 per tonne. This represents up to 2,000 times more value recovered from lignin. The overall size of the carbon fibre precursor market is estimated to be \$2.25 billion (50% of the carbon fibre tow market).

1.4 Lignin Carbon Fibre and Carbon Nanofibre

1.4.1 Background

Lignin Carbon Fibre

Carbon fibres are currently manufactured from polyacrylonitrile (PAN) precursors while small amounts are derived from pitches, notably mesophase (MPP). However, due to the high cost of these petroleum-based precursors and their associated processing costs, carbon fibre remains a specialty product. Its use has been limited to aviation, high-end sporting goods, automobiles and special industrial applications (D. A. Baker, Gallego, & Baker, 2012; X. Huang, 2009). Research and development on low-cost carbon fibre manufacturing have been limited to a small number of organizations owing to the magnitude of the effort required which includes equipment, expertise and funding source.

In 1965, Otani et al. described several methods of forming fibre from lignin (hardwood kraft, softwood kraft, and alkali softwood lignin) by both melt spinning and dry spinning, and their conversion to carbon fibre, graphite fibre and activated carbon fibre. They were able to obtain hardwood kraft lignin fibre of 20 μm to 30 μm diameters at rates of 15 m/min and strength of 0.785 GPa. They have also reported to produce carbon fibre with 1:1 mix of alkali-pulped softwood lignin and alkali-pulped softwood lignin with strengths up to 0.686 GPa (D. A. Baker & Rials, 2013).

There was a short movement of commercialization of lignin carbon fibre by Nippon Kayaku in the early 1970s under the trade name of Kayacarbon (Fukuoka, 1969). The precursor fibre was produced by dry spinning of an alkali lignin solution.

Kayacarbon left the market since the petroleum based precursors have been developed more rapidly which delivers higher strength at cheaper price.

Even though the development of lignin carbon fibre can be traced back as early as 1969 (Otani, Fukuoka, Igarashi, & Sasaki, 1969), one of the key driving forces behind the development of lignin carbon fibre in recent years is government regulatory changes on fuel consumption. In 2012, the U.S. government legislated through updated Corporate Average Fuel Economy (CAFE) standards that the average fuel economy of cars and light trucks sold in the U.S. for model year 2017 will be 35.5 mpg and will increase to 54.5 mpg for 2025 models. The most effective way to increase fuel economy is to decrease vehicle weight (Berkowitz, 2011). Currently, PAN-based carbon fibre reinforced composites could offer up to 60% weight reduction at ten times the cost. Because more than 50% of the manufacturing cost is the cost of precursor, which fluctuates heavily with the oil price, Department of Energy has invested well over $100 million over the last 10 years to examine possible routs of low cost precursor alternatives. Lignin-based precursor is one of the most promising contenders (D. A. Baker & Rials, 2013; X. Huang, 2009).

Oak Ridge National Laboratory (ORNL) is one of the most active research groups studying lignin-based carbon fibre. In 2011, Oak Ridge Carbon Fibre Composites Consortium was established to accelerate the development of low cost carbon fibre reinforced composite materials. The consortium has 52 plus members across the entire carbon fibre value chain from raw materials to downstream applications. One of the objectives set by the consortium is to manufacture a lignin-based carbon fibre with a tensile strength of 1.72 GPa and a modulus of 172 GPa that is suitable for the automotive industry.

Lignin Carbon Nanofibre

One of the first technical records related to the production carbon nanofibre, defined as carbon fibres that have a cross-section diameter in the 100 nanometres range, is from 1889 on synthesis of filamentous carbon by Hughes and Chambers (Hughes, 1889). The carbon filament was grown through gas pyrolysis and subsequent carbon deposition and filament growth. The true appreciation of the fibres came much later when the structure could be analyzed by electron microscopy in the early 1950s. The Japanese company Nikosso attempted the first commercialization of vapour grown carbon nanofibre in 1991 under the trade name of Grasker (Morgan, 2005).

Besides vapour grown, electrospinning is an alternative approach of producing carbon fibres with submicron cross-section diameter. The first documented electrostatic spinning of a polymer solution into nanofibres was in 1902 by J.F. Cooley and by W.J. Morton. Since then electrospinning has raised much interest in the manufacturing of nanofibres in part due to the low cost and ease of setting up electrospinning equipment (D. A. Baker & Rials, 2013). It is also the most convenient and scalable technique for nanofibre production. The process has been successfully scaled up and used in the production of industrial products such as air filter media. Prof. Frank Ko's research group at UBC is applying electrospinning technique to produce nano precursor fibre which later turns into carbon fibre through the conversion process.

Carbon nanofibre has unique properties such as high specific surface area and superior directional strength. It can be applied in the electrical, electronics industry, and the energy storage area as brush contact in commutator brush, switches, electrodes in capacitors and batteries, and electromagnetic interference (EMI) shields (Lin, Yingjie, & Ko, 2013). It is a radical generic technology, and, as such has huge value potential but slow adoption into new applications (Maine & Garnsey, 2006).

1.4.2 Technical Overview

Carbon Fibre

Carbon fibre is defined as a fibre containing at least 92 wt% carbon while the fibre containing at least 99 wt% carbon is usually called a graphite fibre. Carbon fibre generally has excellent tensile strength, low densities, high thermal and chemical stabilities in the absence of oxidizing agents, good thermal and electrical conductivities and excellent creep resistance.

Carbon fibre generally comes in the form of woven textile, pre-preg, continuous fibres, rovings, and chopped fibres. To further process the composite parts into final product, the composite parts can be produced through filament winding, tape winding, pultrusion, compression moulding, vacuum bagging, liquid moulding, or injection moulding (X. Huang, 2009).

Carbon fibre is grouped into a wide range of categories based on its modulus of elasticity (Price, 2011). Price also varies dramatically among different categories. High and ultra-high stiffness fibre is made for the aerospace industry at around $2,000 per kg. They are expensive and used in specialized applications such as airfoils. Standard modulus fibre can be as low as $22 per kg for the civil infrastructure industry. Table 1.3 shows the classification of carbon fibre and its applications.

Table 1.3 Classification of carbon fibre and its applications

	Modulus of Elasticity	**Price**	**Applications**
Low Modulus	40 GPa to 200 GPa	Less than $20/kg	Non-structure usage
Standard Modulus	200 GPa to 275 GPa	$20/kg to $55/kg	Automotive, Sporting goods, wind turbine, Pressure tanks,
Intermediate Modulus	275 GPa to 345 GPa	$55/kg to $65/kg	Pressure tanks, Wind turbine
High Modulus	345 GPa to 600 GPa	$65/kg to $90/kg	Aviation, Military
Ultra-High Modulus	600 GPa to 965 GPa	Up to $2,000/kg	Aerospace, Military

Source: created by author, with data from Eberle, 2012; Price, 2011

Carbon Nanofibre

There are clear differences between carbon fibre, carbon nanofibre and carbon nanotube. One key difference between fibre and tube is the aspect ratio (length/diameter). Fibre is defined as a one-dimensional filament with an aspect ratio greater than 100. Tube has aspect ratio less than 100. The diameter of a carbon nanotube is generally less than 10 nm. Carbon fibre generally has a cross-section diameter from 5 µm to 10 µm. Carbon nanofibre bridges the gap between these two limits. Generally, the diameter of carbon nanofibre is around 0.1 μm (Endo, Iijima, & Dresselhaus, 1996). Due to differences in production techniques, carbon nanotube comes in the form of power like substance; carbon nanofibre in the form of non-woven mat; and carbon fibre is often bundled together to form a tow which may be used by itself or woven into fabric. Currently, there is no carbon nanotube made from lignin.

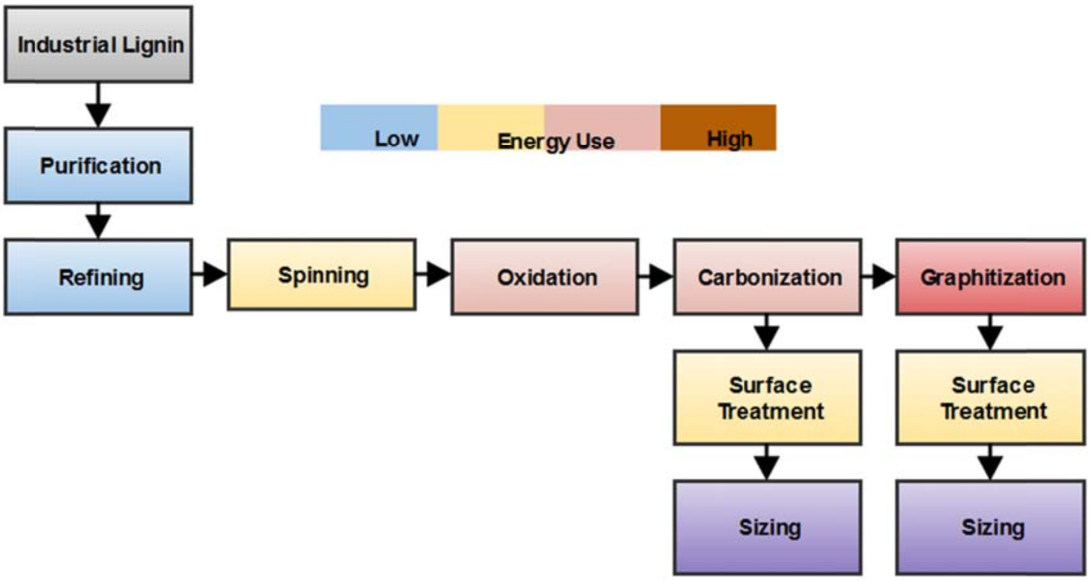
Carbon nanotubes experience a greater magnitude of Van der Waals forces due to their smaller size, while these forces are less intense in carbon nanofibres. Due to this difference in forces, carbon nanotubes need the intervention of chemical dispersants or functionalization techniques to help and maintain dispersion. However, carbon nanofibres are able to stay in the dispersed state for a longer time and do not require costly processing methods. For this reason, carbon nanofibres are normally much cheaper than carbon nanotubes. Carbon nanofibres generally are priced between $220 per kg and $1,100 per kg. On the other hand, carbon nanotube prices vary between $220 per kg and $1,650 per kg depending on purity ("Comparative study of carbon nanotubes and carbon nanofibers," 2011).

Recent studies on lignin-based carbon fibre reported tensile strength of about 1 GPa (Lin et al., 2013; Norberg, 2012; D. C. Warren, 2009) which represents only a fraction of tensile strength achieved when using the commercial PAN-based carbon fibre that ranges between 3 GPa to 7 GPa. An alternative to compensate for this deficiency is to explore other areas of application such as those focused on the functional properties of lignin carbonfibre. Due to nano-scale and high carbon content, carbon nanofibres exhibit remarkable properties between the characteristics of the bulk and yet close to the quantum limit such as high electron conductivity similar to that of carbon nanotube (Endo et al., 1996). Despite lower strength properties, lignin carbon nanofibres have significant potential for the next generation of carbon fibre applications due to high surface to volume ratio and superior conductivity.

1.4.3 Lignin Carbon Fibre Processing Steps

Even though producing carbon fibre from different precursors requires different processing conditions, the essential features are very similar. In addition to the lignin purification and refining steps shown in section 1.3.2, the carbon fibre manufacturing process includes spinning, oxidation, carbonization, graphitization, surface treatment and sizing, Figure 1.3.

Figure 1.3 Lignin carbon fibre production steps



Source: created by author, with data from D. A. Baker & Rials, 2013

<u>Spinning</u>

Precursors are converted into polymer fibres by various spinning methods. Some of the most common spinning techniques are:

- **Melt spinning:** extruding a melt of the polymer.
- **Melt assisted spinning:** extruding a homogeneous polymer solvent blend in the form of a homogeneous single-phase melt.
- **Dry spinning:** extruding a solution of the polymer in a volatile organic solvent into a circulating hot gas environment in which the solvent evaporates.

- **Wet spinning:** extruding a solution of the polymer in an organic or inorganic liquid into a coagulating liquid; this precipitates the polymer which is then drawn out as a fibre.
- **Dry-jet wet spinning:** extruding a solution of the polymer into an air gap, followed by a coagulating bath.
- **Electrospinning:** extruding submicron fibres from a liquid through electrical charge.

All methods involve pumping the melt or solution of the polymer through holes in a spinneret. The spinneret holes match the desired filament count of the carbon fibre (Chung, 1994; McConnell, 2008).

Because PAN decomposes below its melting temperature, melt spinning is not possible. PAN-based fibres are commonly formed by either wet spinning or melt assisted spinning process. Both processes involve the use of organic solvent. In melt assisted spinning, a solvent in the form of hydrating agent to decrease the melting point of PAN is used. With a low melting point, the polymer can be melted and pumped through a spinneret (Chung, 1994). In wet spinning, the dissolved precursor is immersed in a liquid coagulation bath and extruded through holes in a spinneret. The wet-spun fibre is drawn by rollers through a wash to remove excess coagulant, then dried and stretched to the correct fibre specification (McConnell, 2008).

Direct melt spinning is the most common method under investigation for the newly developed lignin fibre. Its production process requires the extrusion of only the pure polymer precursor directly into fibre form, eliminating the extra expense of solvent recovery and providing a more environmentally sound solution. For melt spinning, lignin has to reach purity greater than 99% and particles size non-melting particles no larger than 1 micron (Eberle, 2012).

The process requires the lignin to be prepared in such a way that allows low melt flow temperature so it can be melt spun without polymerizing during extrusion. It also needs a high glass transition temperature for the fibre to stabilize at an acceptable rate. The glass transition temperature is maintained above the oxidation temperature so that the fibre crosslinks and stabilizes without infusion. Spinning conditions, treatment temperatures, and temperature ramping profiles need to be carefully controlled to obtain carbon fibre with required strength.

Another important carbon fibre production method is electrospinning. It is an alternative to the melt spinning technique which is used to produce fibres in the diameter from 0.03 mm to 1 mm range. Electrospinning has been recognized as an efficient technique for the fabrication of fibres in submicron diameter range, 0.1 μm, from polymer solutions or melts.

In a typical process, an electric potential is applied between a droplet of polymer solution or melt held at the end of a capillary and a grounded collector. When the applied electric field overcomes the surface tension of the droplet, a charged jet of polymer solution or melt is ejected. The jet grows longer and thinner until it solidifies or collects on the collector. This fibre morphology is controlled by properties such as solution conductivity, concentration, viscosity, molecular weight, and applied voltage, etc. (Lin et al., 2013).

Oxidation (Stabilization)

Before fibre reaches the carbonizing stage, it needs to be chemically altered from the linear bonding to a more thermally stable ladder bonding structure. This process is also often referred to as oxidation which is accomplished by heat. The spool passes through oxidation ovens where temperature ranges from 200°C to 300°C (392°F to 572°F) (Cavette, 2006). The process combines oxygen molecules form the air with the fibre to cause the polymer chains to start crosslinking and thus increasing the fibre density. For PAN-based fibre, the density can increase from approximately 1.18 g/cc to approximately 1.38 g/cc. During the heating process, the fibre will generate its own heat (exothermic reaction) so the oxidation oven’s temperature and airflow has to be carefully controlled and monitored to prevent overheating. The oxidation process takes from 30 minutes to 120 minutes for PAN-based fibre (McConnell, 2008).

Carbonization

Once the fibres are stabilized, they are heated to a temperature of about 1,000° C to 3,000°C (1,832°F to 5,432°F) for several minutes in a specially designed furnace, filled with an inert gas mixture that does not contain oxygen. The lack of oxygen prevents the fibres from burning (Zoltek, n.d.). The gas pressure inside the furnace is kept higher than the outside air pressure, and the oven is well sealed to keep oxygen and air from entering. As the fibres are heated, they begin to lose non-carbon atoms and various types of impurities in the form of gases such as water vapor, ammonia, carbon monoxide, carbon dioxide, hydrogen, and nitrogen (Cavette, 2006; Zoltek, n.d.). As the non-carbon atoms are expelled, the remaining carbon atoms become tightly bonded along the axis of the fibre. Depending on the process, sometimes two separate furnaces may be used to carbonize the fibre at two different temperatures to better control the process. After the carbonization process, the finished fibre contains more than 90% carbon (McConnell, 2008).

Graphitization

The terms carbon and graphite are often used interchangeably by mistake. In reality, they are different. Carbon denotes fibres carbonized at about 1,315°C (2,400°F) and that contain 93% to 95% carbon. Graphite is graphitized at 1,900°C to 2,480°C (3,450°F to 4,500°F) and contains more than 99% elemental carbon (McConnell, 2008). Graphitzation step is not always included after carbonization. Its usage depends on the final usage of the produced carbon fibre.

Surface Treatment

After carbonizing, the fibres have surfaces that do not bond well with the epoxies and other materials. To give the fibres better bonding properties, the surface needs to be slightly oxidized and treated to introduce small surface roughness which also enhances the mechanical bonding property. The oxidation can be achieved by immersing the fibres in various gases such as air, carbon dioxide or ozone, or in various types of liquids such as hypochlorite or nitric acid. The fibres can also be surface treated electrolytically. The surface treatment process is usually carefully controlled to avoid surface defects which could cause fibre failure (Cavette, 2006).

Sizing

After the surface treatment, the fibres are coated to protect from damage during winding or weaving. Coating materials are chosen to be compatible with the adhesive later in the manufacturing process. Typical coating materials include epoxy, polyester, nylon and urethane. The coated fibres will be loaded into spinning machine and twisted into tows with various sizes (Cavette, 2006; McConnell, 2008).

Tow is thus a bundle of individual fibre filaments that create a larger stand – similar to yarn but not twisted as twisting makes the bundle weaker. Tow is typically woven together into cloth or a weave. The bundled filaments are identified as “tow size”. There are several variations of tow-sizes; the most common ones are 3k, 6k, and 12k. “k” stands for thousands. For example, 6k tow means there are 6,000 individual filaments.

1.4.4 Lignin Carbon Fibre Value Chain

The carbon fibre value chain in the composite industry includes a number of highly integrated steps from the production of the precursor to the post use phase (Table 1.4). Appendix B shows the current progress and key members of the value chain. The key characteristics of these steps are discussed next.

Table 1.4 Lignin carbon fibre value chain

Process Flow	→				
Value Chain	Precursor	Carbon Fibre Production	Composite Formulation	Applications	Post Use
Categories	PAN, Textile PAN, Lignin	Thermal Process, Plasma Technology, Microwave Technology, Surface Treatment	Resin Design, Pre-pregging, Veils, Weaving, Moulding, Filament Winding,	Automotive, Wind Energy, Military, Aviation, Oil & Gas, Construction, Sporting Equipment	Waste Recycling, Post Use Recycling

Source: created by author, with data from "Oak Ridge Carbon Fiber Composites Consortium," 2014

Precursor and Carbon Fibre Production

The value chain starts with the production of carbon fibre precursor such as PAN, Lignin or Textile PAN. The precursor is then turned into carbon fibre yarn via the production process (spinning, oxidation and carbonisation). The productions of carbon fibre precursor and carbon fibre yawn are covered in section 1.3.2 and 1.4.3 1.4of the report, respectively.

Development of Composite Formulation

The next key step in the value chain is the development of composite formulation which includes the carbon fibre fabrics, resin matrix and carbon fibre composites manufacturing processes. In order to have a wide adaptation, carbon fibre yawn needs to be further processed into fabrics. Pre-preg is one of the most common forms of carbon fibre used by processors, holding at least 40% of the global market. There are two main types of pre-pregs, unidirectional pre-pregs, which draws continuous filament carbon fibre uni-directionally, and multi-axial pre-pregs, which contains multi-axial weaves of carbon fibre. In both cases, the carbon fibre woven cloth is impregnated with resin. Besides pre-pregs there is also production of carbon fibre veils, non-woven chopped carbon fibre. Unlike pre-pregs, which are used for their high physical strength, carbon fibre veils can be used in a variety of applications to give specific properties such as increasing conductivity of composite parts (NetComposites, 2009). Veils would potentially be the primary format for the commercialization of carbon nanofibre due to electrospinning technique.

Proper resin matrix must be used to cope with the composites and manufacturing process. In most thermoset pre-pregs, epoxy is the dominant resin used. The main factors used to determine what resin grade to use are the processing temperature and operating temperature. Processing temperature is the temperature composite tools, such as an autoclave, an oven or the platens on a compression moulding press, can operate. Operating temperature is the temperature the finished composite will be required to withstand. A commercial aviation component will need to withstand higher operating temperatures than a carbon fibre bicycle frame would (Johnson, 2014).

There are four main groups of carbon fibre composites manufacturing process. 1) Compound moulding process, 2) Pultrusion and filament winding process, 3) Resin transfer moulding (RTM) process, and 4) Pre-preg layup process. Each manufacturing process has its own advantages and trade-offs in terms of the capital cost, cycle times, and the ability to mould complex parts.

Based on interviews with lignin carbon fibre experts (see appendix A), it is important for lignin carbon fibre to adopt the existing composite formulation at early stage of launch to minimize customer resistance. For example, as described in Maine and Garnsey (2006), when an innovation requires process innovations by their customers, they are more difficult to commercialize.

Applications

The next stage of the value chain is the application of carbon fibre. There are three major markets for carbon fibre, automotive, aviation and wind energy. For carbon nanofibre, the major markets would be energy storage areas such as electrodes in capacitors and batteries, and EMI shields. Details of these applications are included in section 5.2.1.

Reuse

The last stage of the value chain is the reusing of carbon fibre. Like paper, carbon fibre is currently described as down cycling rather than recycling. Recycled fibres get shorter and shorter; this reduces the strength of the composite material. Potential use of recycled fibres includes thermoplastic and thermoset moulding compounds, and nonwoven sheet reinforcements. Currently, the recycling industry for carbon fibre is not financially viable. However, there is potential for the recycling of carbon fibre to become profitable as technology progresses.

2: Technology Feasibility

2.1 Levers

2.1.1 Lignin Precursor Chemical Structure Advantage

From the information provided by industry experts (see appendix A), the chemical structure of lignin has several advantages over the current PAN precursor which will reduce the carbon fibre production cost. Table 2.1 shows the potential benefits of lignin precursor when compared to conventional PAN precursor. Clearly, there are production rate, manufacturing space, and environmental benefits of the lignin precursor manufacturing over the incumbent PAN precursor manufacturing. These advantages come from two main factors: melt spinnability and stabilization rate.

Table 2.1 Estimated benefit from lignin precursor for carbon fibre production

Parameter	Solution Spun PAN	Melt Spun Lignin
Energy per kg of CF	~$ 704 MJ	~$ 554 MJ
CO_2 emitted per kg of CF	~31 kg	~24 kg
Production Line length	~180 m	~120 m
Precursor Spinning Speed	~200 m/min	~600 m/min
CF Production Speed	15 m/min to 20 m/min	20 m/min to 25 m/min*
Environmental Toxicity	High	Low

*The production speed improvement is estimated as a 25% efficiency increase in oxidation. Source: created by author, with data from Das, 2011; Eberle, 2012; Imhoff, 2013

First, lignin is melt spinnable. Lignin has low enough melting temperature at which liquid flows under low shear but high enough glass transition temperate for fibre oxidation to proceed at an acceptable rate. With melt spinning, solvents can be avoided in fibre production. As described above, PAN decomposes below its melting temperature, melt spinning is not possible for PAN based precursor. Wet spinning and melt assisted spinning processes are the common spinning techniques for PAN based precursor; in both cases, PAN has to be dissolved in organic solvents. Solvent recovery is complicated and expensive. Wet spinning and melt assisted spinning processes are also more time consuming than melt spinning process. See Table 2.1 for details.

Second, lignin will have the capability to stabilize much faster than PAN fibres since lignin is already substantially oxidized. The difference could be from hours to minutes (D. A. Baker & Rials, 2013). The rate-limiting step in the carbon fibre production is the diffusion of oxygen into the fibre filament during oxidation step. The fibre filament used in the PAN process is a very dense material; oxygen takes time to penetrate through this dense structure into the inner part. With lignin, the oxygen is already in place so the need for homogeneous diffusion of oxygen atom is much less. The oxidation step can potentially combine with carbonization steps to simplify the carbon fibre production; this means shorter production line, lower energy cost and increase in throughput in given equipment.

2.2 Hurdles

2.2.1 Inefficient Bio-refinery Process

Traditionally, bio-refinery process focuses on biofuels production, and this process prefers to use feedstock with high sugar contents such as sugarcane, corn and bagasse. Wood is being overlooked as a feedstock for biofuels and biochemical due to low sugar content. For this reason, the industry and technology for lignin usage is still in the early stage of development (Smolarski, 2012).

Current bio-refinery technology does not allow the production of any pre-determined selection of chemicals in one same step. 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 produces vanillin but no BTX (benzene, toluene and xylene isomers) whereas hydrodeoxygenation produces BTX, but no vanillin. Both processes have low efficiencies, as they generate large amount of waste by-products that need to be disposed.

The utilisation of lignin refinery process still needs to be greatly improved (Smolarski, 2012). The yields of commercially produced chemicals from lignin remain very low. For example, although Borregaard is the world's largest vanillin producer, its commercial yield of vanillin extracted from lignin is only 1%. Researchers believe that the yield can potentially be 13% and the yield for BTX can still be improved by a factor of 10 (Smolarski, 2012).

2.2.2 Complex Lignin Structure and Lack End Product Consistency

The main challenge for researchers is finding low cost lignin precursors that produce carbon fibre with a consistent quality. In contrast to pitch and PAN precursors, lignin has a complex 3-D heterogeneous chemical chain structure that is still not clearly understood by scientists. Various industry leaders such as MeadWestvaco, Innventia and FPInnovation, have joint forces with ORNL researchers in developing a low cost purification process to control impurity levels in kraft lignin. Such inconsistencies have implications to high processing costs. For example, the purification process costs are estimated to be at least \$2.2 per kg (X. Huang, 2009), and combined with the lignin raw material cost, the total cost of melt spinnable lignin is more than \$3.3 per kg (far from the anticipated goal of \$1.1 per kg). The purified lignin precursor is still not comparable to its petroleum counterpart in terms of quality consistency. Processing costs are further explored in the commercialization section of this report.

ORNL studies have shown that the purified hardwood lignin is melt spinnable (Eberle, 2012). However, its melting point is about 130 °C, thus low temperature oxidation is required which reduces the oxidation rate significantly. Softwood lignin has shown to have a better potential as its carbon yield is higher than that of hardwood lignin (X. Huang, 2009). However, softwood lignin has a more cross-linked structure, thus it is not melt spinnable without modification.

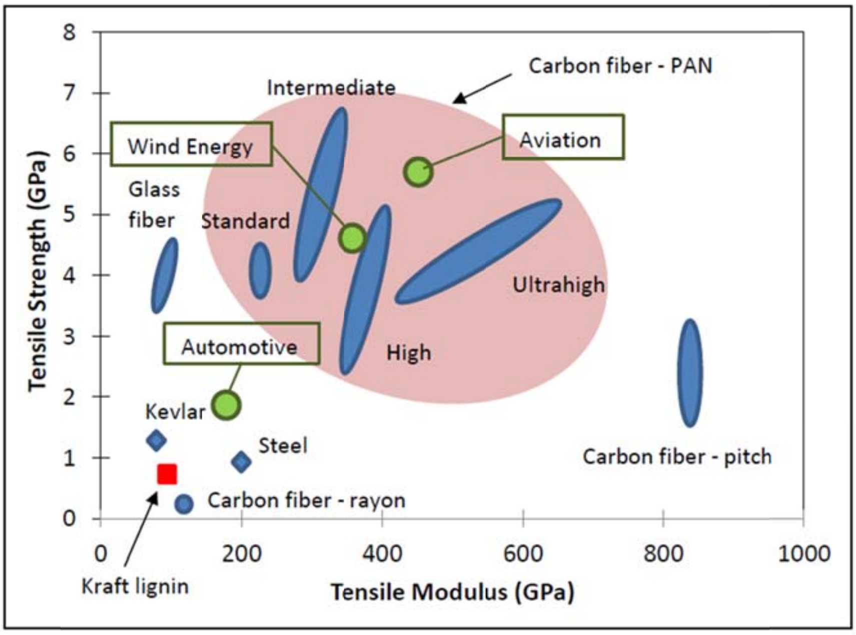
The industry representatives pointed out that lignin carbon fibre development is still in the early stage. Consistency of the final product still needs to be improved. Even though the strength of current lignin carbon fibre is good enough for some of the auto industry applications such as body panels, one of the biggest challenges to adopt lignin-based carbon fibre is the high batch-to-batch variation, i.e. lack of end product consistency. Variation in physical strength is currently one of the key barriers for the adaptation of lignin-based carbon fibre in the automotive industry.

2.2.3 Lack Physical Strength

Lignin-based carbon fibre has only half to a third of the tensile strength obtained by PAN-based carbon fibre. Recently, the ORNL in the U.S. has manufactured lignin-based carbon fibre with strength and modulus reaching 1.07 GPa and 82.7 GPa (typical ORNL lignin carbon fibre strength: 0.48 GPa, modulus: 48 GPa) (Lin et al., 2013; Norberg, 2012; D. C. Warren, 2009). Commercial PAN-based carbon fibre tensile strength is in the range between 3 GPa to 7 GPa (Lin et al., 2013).

The automotive industry requires a tensile strength of 1.72 GPa and a modulus of 172 GPa to be considered attractive for wider utilization which is the lowest requirement for mass adaptation when compared to the wind energy industry and the aviation industry. Figure 2.1 shows the properties of carbon fibre with different precursor types and the tensile strength and modulus requirements of the three major industrial applications: automotive wind energy and aviation.

Figure 2.1 Carbon fibre properties and requirement



Source: created by author, with data from Eberle, 2013; Lin et al., 2013

2.2.4 Electrospinning Technology Challenges

Industrial electrospinning equipment is still in the early stage of the development. A main shortcoming with electrospinning is the low fibre output per spinneret. To produce nanofibres through electrospinning, it is essential to prevent beads formation at the end of the tip. This means that solvent could make up more than 70% of the solution mass depending on the polymer and solvent system. Thus, only a fraction of the solution that passes through the spinneret contributes to the mass of the fibre produced. Melt extrusion has also been tested to increase productivity, but the feed rate per nozzle is still limited to prevent solution dripping out (Teo, 2014).

Another complication in the electrospinning process is related to electric field disturbance for multiple spinnerets. As the solution ejects from the tip of the spinneret under the influence of the electrostatic charges, it spreads out to form an expanding cone, which will interfere with neighbouring jets if the spinnerets are placed too close to one another. This forces the number of spinnerets to reduce in conjunction with the amount of fibre that can be deposited at one time (Teo, 2014).

Electrospinning still lacks affordable equipment setups that can guarantee accuracy and reproducibility needed for many advanced applications and active polymer materials. This has added complications in commercializing lignin carbon nanofibre (Persano, Camposeo, Tekmen, & Pisignano, 2013). Production scale up modelling and experimentation with pilot plants can address these issues (Maine & Ashby, 2002; Taleb, Maine, & Kjeang, 2014).

3: Organization Appropriability

3.1 Levers and Hurdles

3.1.1 Patentable Applications and Uncertain Technology Transfer

Organizational levers related to lignin-based carbon fibre include potential for patenting and trade secrets. Although lignin-based carbon fibre is patentable, current technological challenges may handicap its development given that its short-term commercial viability is unclear (Hall et al., 2011; Martin, 2007). Such technological uncertainties reduce the likelihood of value creation by a new venture (Maine & Garnsey, 2006).

Such uncertainties also exacerbate a university's Technology Transfer Office (TTO)'s ability to act as a protector or propagator that can influence the legitimization process of a new technology (Jain & George, 2007). Most university TTOs struggle to balance their dual responsibilities of commercializing their universities' research seeking financial gains and at the same time demonstrate that their publically funded research produces societal benefits. According to an industry expert (see appendix A), the likelihood of users adopting both a new material and a new process all at once is low.

One possible way to build legitimacy for lignin carbon fibre is to emphasize its positive environmental characteristics, i.e. the potential social benefits when compared to petroleum based carbon fibre (Hall, Matos, Bachor, & Downey, (Forthcoming)). Such benefits are discussed further in the social levers section of this report.

According to a carbon fibre policy expert (see appendix A), it is also important to develop a collaborative strategy with the participation of incumbent market players. Such collaboration has important implications for organizational aspects of the technology, as it may facilitate access to complementary assets needed to develop and implement the technology, such as capabilities, access to pilot plants and market, etc. (Hall et al., (Forthcoming); Maine & Garnsey, 2006). Efforts in establishing collaborative research are being made. For example, ORNL has hosted the Carbon Fibre Composites Consortium.

3.1.2 Large Capital Investment and Extensive Technical Support

The carbon fibre manufacturing process is difficult and expensive. A world class carbon fibre production line costs minimum of $25 million for equipment alone. This is one of the major reasons why carbon fibre producers are limited worldwide (McConnell, 2008).

Embracing carbon fibre is technically challenging. An industry expert stated during the interview that in order to convince end users to adopt carbon fibre as part of their products, extensive training and collaboration are required for designers and engineers to understand carbon fibre material. In most cases, carbon fibre producers would need to provide knowledge assistance and technical support to the end users. The support includes the carbon fibre reinforced plastic (CFRP) manufacturing process integration. Aluminum companies like Aluminum Company of America (Alcoa) have been very successful in the lobbying effort with the automotive industry. Even though CFRP parts have some superior performance, it is difficult for a composite company to provide the same degree of lobbying as Alcoa's. Training and lobbying efforts require significant amount of capital investment through each individual organization. This has brought in the industry collaboration between companies. For example, BMW has a long term partnership with SGL in carbon fibre development for the automotive industry.

Collaboration between academia and industry is also important. Several consortiums have been established worldwide on the lignin-based carbon fibre applications. International Lignin Institute was established in 1991 with headquarters in Switzerland to encourage collaboration among its members on extracting highest possible value from lignin. Lignin networks have also been created in both Netherlands and Canada. In Canada, there is Lignoworks that intends to create technology platforms for novel materials and chemicals based on lignin to replace fossil-fuel based products. The U.S. has Carbon Fibre Composites Consortium to build a network of collaborators along the lignin carbon fibre value chain.

4: Societal Acceptability

4.1 Levers

4.1.1 Bring Fuel Efficiency to the Automotive Industry

One of the key driving forces behind the development of lignin carbon fibre in recent years is government regulatory changes on fuel consumption. In 2012, the U.S. Government legislated that the average fuel economy of cars and light trucks sold in the U.S. for model year 2017 will be 35.5 mpg and will increase to 54.5 mpg for the model year 2025. That is double of the 2011 standard of 27.3 mpg. For European Union (EU), manufacturers are obligated to ensure that their new car fleet does not emit more than an average of 130 g of CO_2 per km by 2015 and 95 g per km by 2020. This is a sharp improvement over the 2011 standard of 135.7 g per km. In terms of fuel consumption, the 2015 target is 42 mpg and 57 mpg for 2020 (Berkowitz, 2011; “Road transport: Reducing CO2 emissions from vehicles,” 2014). Reducing the weight of the vehicle to improve the fuel economy and to reduce emission has become a must for manufacturers to achieve compliance with legally binding environmental standards. CFRPs offer weight reduction and superior strength. However, PAN-based CFRPs are too costly for mass production vehicles. Low cost lignin-based CFRPs become the potential solution.

4.1.2 Well Positioned Within the Bio-refinery Process Encourage by Government

As a part of the overall U.S. energy policy, the Renewable Fuels Standard mandates to reach the production of 36 billion gallons of fuel for transportation from renewable sources by 2022. To accomplish this goal, 16 billion gallons of the renewable fuel will be required to be produced from lignocellulose (D. A. Baker & Rials, 2013). One of the main barriers to the development of biomass to liquid fuel conversion process is price competitiveness with conventional oil refinery. In a mature oil refinery business, feedstock represents 50% of the total cost; this is true for petroleum based fuel and corn-based biofuel. In order to be successful, lignocellulose based bio-refinery will have to follow the similar trend. One way to reduce costs associated with biofuel production is to produce co-products with higher value than the fuel itself. Carbon fibre is considered a key high value co-product from this process. Because of this strategic importance, there is a growing effort in lignin purification development and the supply of high quality lignin feedstock (D. A. Baker & Rials, 2013).

4.1.3 More Environmentally Friendly Comparing to PAN Based Process

When the first carbon fibre conversion plant came online, operating costs were not critical design parameters and neither were the environmental effects of production. Today, the manufacturing of carbon fibre is heavily regulated by the environmental community, and producers are continually looking to reduce energy demands of this heat intensive process (Grzanka, 2013).

PAN precursor fibre is traditionally prepared by a solvent based polymerization process such as wet or melt assisted spinning. The solvent used is sodium thicocynate or dimethylacetamide. Unlike the PAN precursor, lignin precursor is melt spinnable. Melt spinning does not involve the use of solvent which leads to a potentially cheaper and more beneficial process for the environment (Das, 2011; Wilms, Seide, & Gries, 2013).

The oxidation and carbonization process have several environmental complications that pose immediate danger to human if proper consideration to emission control is not given. For PAN-based precursor, the furnaces have the potential to emit hydrogen cyanide (HCN) and ammonia (NH_3) which are immediately dangerous to human health in small quantities. Other pollutants of concern for carbon fibre producers include volatile organic compounds and greenhouse gases such as carbon monoxide (CO), carbon dioxide (CO_2) and nitrogen oxide (NO_X). These pollutants not only harm the environment, but also have a direct correlation to the energy consumption at each plant since by-products are generally incinerated on-site before venting into the atmosphere (Das, 2011; Grzanka, 2013). Even though lignin-based carbon fibre will also release volatile organic compound as the PAN precursor would, the oxygenated nature of lignin requires less oxidation time and no HCN emissions. This means a more efficient and cheaper conversion process comparing to PAN-based fibre.

4.2 Hurdles

4.2.1 Difficulties with Carbon Fibre Recycling

When used as a composite, Carbon fibre is difficult to recycle. CFRP is neither biodegradable nor photodegradable. Carbon fibre is a product designed to last for generations. While product durability is high, it becomes a disposal problem when the product reaches its end of life.

In contrast to other materials such as steel, recycled carbon fibre is not as strong as the virgin material. As a result, carbon fibre composites recycled from vehicles aren't suitable for manufacturing more vehicles. Although unused carbon cloth can be cut down into strips and turning into phone cases, laptop shells and some decoration pieces, these represent only a small portion of carbon fibre waste (Schelmetic, 2012).

Until not long ago, composite materials were generally disposed in landfills or burned. As both U.S. and EU tighten environmental regulations, this is becoming a less viable option. EU law drawn up in 2000 states that 95 % of each vehicle manufactured after January 2015 must be reused or recovered (Schelmetic, 2012). In 2004, most EU member states made it illegal to dump composites into landfills (Schelmetic, 2012).

Considering that a recycling process can only be adopted if it is financially viable, carbon fibre case is not attractive yet. Compared to efficient recycling processes such as aluminium cans where only 5% of the energy used to produce a can from virgin aluminium is used to recycle, carbon fibre still has a long way to go (Suciu, 2012).

Numerous collaborative efforts have been developed to investigate possible solutions for carbon fibre recycling. For example, BMW and Boeing have collaborated to look seriously into this issue, and Airbus is leading a similar sustainability project called the Process for Advanced Management of End of Life of Aircraft (PAMELA). For the current technology, reusing carbon fibre is described more as down cycling rather than recycling. Recycled carbon fibre is used mostly as low value fillers for various industrial products. A more financially viable process has to be developed to cope with massive adaptation of carbon fibre in increasing number of applications ("Airbus Sets

Carbon Fiber Recycling Goal ·," 2014, "Boeing, BMW to Partner on Carbon Fiber Recycling," 2012).

4.2.2 Health Concerns

Like glass fibre, carbon fibre can be easily broken by stretching. The fibre can easily become a fine dust through cutting, machining or mechanical finishing and can then be released into the surrounding atmosphere. These micro fibres have the potential to stick into human skin or the mucous membranes causing irritation. During sizing and making of CFRPs, epoxy or other resin can also cause chemical irritation. Many of the solvents used in advanced composite processes are volatile, flammable and irritating to skin and eyes. In the case of carbon nanofibre like all other nanotechnology, the main concerns are skin irritation and inhalation of the submicron particles. Since carbon fibre and carbon nanofibres are conductible, airborne dust can cause short circuits and electric shock ("Use of carbon fibre composites," 2009).

The information collected is not entirely negative. The safety concerns are preventable as long as material safety datasheet is followed and personal protective equipment is worn. Equipment that may get in contact with carbon fibre dust must be fully insulated ("Use of carbon fibre composites," 2009). In the case of electrospinning, the most commonly used nanofibre production technology, the situation is very favourable. Elmarco Inc., an electrospinning equipment producer, conducted a detailed monitoring of the nanofibre content in the air during industrial nanofibre production. The results show that no contamination was found. Electrospinning uses a strong electric field that prevents the escape of fibres. In addition, it also catches small particles from the air around the equipment similar to the technology like home air purifiers ("Are nanofibers dangerous?," 2012).

4.2.3 Stringent Government Import and Export Regulation

Research programs are increasingly international, generating significant export control complexities with researchers collaborating across borders, nationalities and different legal jurisdictions. Based on our interviews with the regulatory experts, importing the latest high-tech equipment, licensing the cutting-edge technology, and exporting carbon fibre to overseas partners are all subject to import and export regulations. Since carbon fibre can be applied to the aviation and military industries, there is a higher uncertainty of whether the technology can travel across borders.

Regulations may vary from country to country but the foundation is often based on the Wassenaar Arrangement. The full name of the agreement is The Wassenaar Arrangement on Export Controls for Conventional Arms and Dual-Use Goods and Technologies. There are 41 participating states such as the United States, Japan, South Africa, Spain, Switzerland, France, Germany, Canada, United Kingdom, etc. The Arrangement focuses primarily on the transparency of national export control regimes. The participating state has to be a producer or exporter of arms or sensitive industrial equipment, maintaining nonproliferation policies and maintaining fully effective export controls ("The Wassenaar Arrangement," 2014). Even though the Wassenaar control lists do not have binding legal force throughout the participating states, the participating states often incorporate the full agreement into their national export control regimes (Vermeer, 2013).

The Arrangement works with two different control lists: the List of Dual Use Goods and Technologies and the Munitions List. Munitions List contains items designed for military use. The List of Dual Use Goods and Technologies, with 9 categories, contains goods that can both have military and civilian use. Carbon fibre for structure use falls under category 1 of the The List of Dual Use Goods and Technologies classified by specific modulus and tensile strength. Carbon fibre for EMI shielding also falls under category 1 of The List of Dual Use Goods and Technologies but classified by absorbing frequencies and conductivity ("The Wassenaar Arrangement," 2014; Vermeer, 2013).

Based on the current performance achieved by lignin carbon fibre, there will be minimal restrictions. However, as the performance improves, the uncertainty of regulatory restriction will increase. Having a lignin precursor champion sits on the regulatory committee would be a way to ensure adequate voices are heard during regulatory development.

5: Commercial Viability

5.1 Carbon Fibre Supplier Overview

In 2012, the global nameplate capacity of carbon fibre was 112,000 tonnes, comprised of 72,000 tonnes of small-tow fibre and 40,000 tonnes of large-tow fibre. By 2020, the global nameplate capacity will be 169,000 tonnes, comprised of 115,500 tonnes of small-tow fibre and 53,500 tonnes of large-tow fibre (Sloan, 2013). Tempering these figures is the knockdown effect which is the difference between the nameplate capacity of a carbon fibre line and the actual production capacity (Sloan, 2013). Actual output is always smaller than nameplate output due to inefficiencies in the production process. The details of the knockdown effect that affect actual output are shown in Table 5.1.

Table 5.1 Global carbon fibre production nameplate capacity vs. actual output

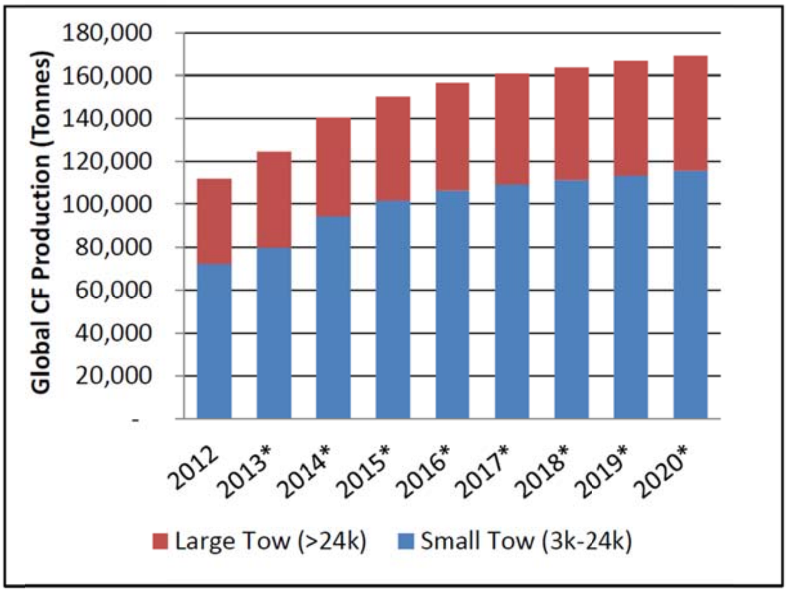
Year	**Nameplate Capacity (tonnes)**	**Actual Output (tonnes)**	**Knockdown**
2012	112,000	67,200	60%
2016*	157,000	106,760	68%
2020*	169,000	121,680	72%

*2016 and 2020 data are based on estimation. Source: created by author, with data from Sloan, 2013

Due to the complex process and high technical content of carbon fibre production, global carbon fibre capacity is still mainly concentrated in the Japanese and U.S. enterprises. Japan's Toray, Toho and Mitsubishi Rayon, mainly engaged in the production of PAN-based small-tow (<24K) carbon fibre, accounted for two-thirds of the global total small-tow carbon fibre capacity in 2012. Toray is the largest carbon fibre manufacturer in the world with an annual capacity of 18,900 tonnes in 2012 (Jahn, Karl, & Witten, 2012; Sloan, 2013).

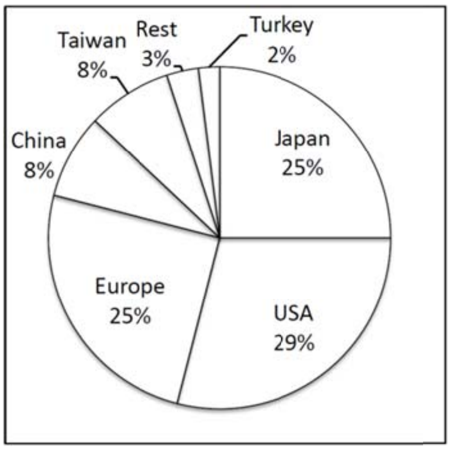
U.S.'s Zoltek and German's SGL, mainly engaged in the production of large-tow (>24K) PAN-based carbon fibre, accounted for about three-quarters of the global large-tow carbon fibre capacity in 2012. Japan's Kureha, mainly engaged in the production of pitch-based carbon fibre, is the largest pitch-based carbon fibre producer in the world. Its annual capacity was 1,800 tonnes in 2012. The estimation of the global carbon fibre production capacity is shown in Figure 5.1. The breakdown of the installation capacity by region is shown in Figure 5.2. The U.S. has the largest installed carbon fibre capacity (approximately 29% of the world production). Europe and Japan together account for approximately 50% of the global output. China accounts for approximately 8% of the global output (Jahn et al., 2012).

Figure 5.1 Global carbon fibre production by tow size



*2013 - 2020 global capacity is based on estimation. Source: created by author, with data from Sloan, 2013

Figure 5.2 Regional breakdown of carbon fibre nameplate capacity



Source: created by author, with data from Jahn et al., 2012

China's carbon fibre industry is having a rapid development. Its carbon fibre capacity has a compound growth rate of 46.2% in 2008-2012, reached 14,500 tonnes in 2012. In addition, there are approximately 38,000 tonnes of carbon fibre capacities under construction in China. However, the immature technology of Chinese carbon fibre manufacturers resulted in low quality, high production costs and poor profitability. In 2013, China’s actual carbon fibre output was only about 3,000 tonnes with the import dependency rate of approximately 76% (“Global and China Carbon Fiber Industry Report, 2012-2015,” 2013).

Because of carbon fibre’s high strength to volume ratio, it is not just high in market value but also in strategic value. In terms of supply side, there are collaborations between existing companies and the establishment of new companies funded either by governments or by private sectors. For example, Hyosung (pronounced “cho-sung,” Seoul, S. Korea), SABIC (Riyadh, Saudi Arabia), DowAksa (a joint venture of Dow Chemical, Midland, Mich., and AKSA, Istanbul, Turkey), Alabuga Fibre LLC (Moscow, Russia), Kemrock Industries (Gujarat, India) and the government of Iran. All of these new supply sources provide (or will soon provide) industrial-grade fibre intended for use in markets other than aviation (Sloan, 2013).

5.2 Levers

5.2.1 Large Potential Market

In recent years, the carbon fibre production capacity has been growing steadily at annual rate of 18% to meet the demand of carbon fibre composite materials from different industries such as aviation and military, wind turbine blades, civil construction, lightweight cylinders and pressure vessels, offshore tethers and drilling risers, medical, automobile, sporting goods, etc. In terms of application, over 98% of carbon fibre produced is processed into composite materials. The carbon composite market develops roughly at the same pace as the carbon fibre market (Jahn et al., 2012). Table 5.2 shows the breakdown of carbon fibre usage in in terms of volume.

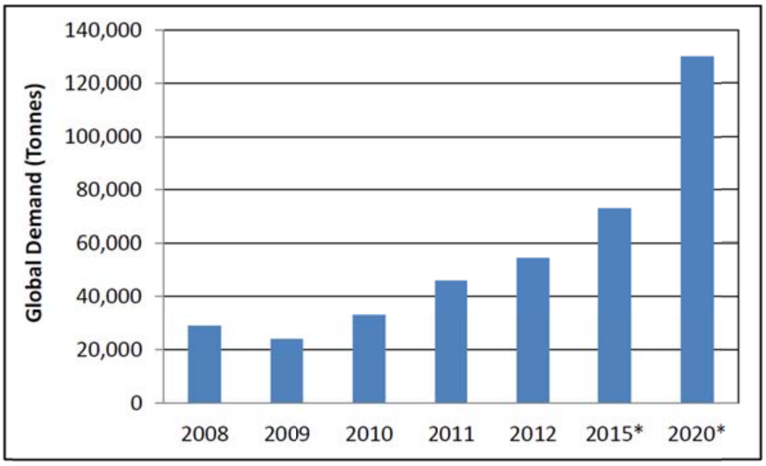
Table 5.2 Carbon fibre applications and usage in terms of global usage in volume

Industry	**Global usage in terms of volumes (%)**	**Application**
Industrial	67%	Automotive, Wind turbine, Construction, Pressure vessels.
Aviation	17%	Aircraft, Military
Sporting Goods	16%	Gold club, bicycles, helmet

Source: created by author, with data from Smolarski, 2012

The global carbon fibre demand has a compound annual growth rate of 14% between 2008 and 2012. The global demand for carbon fibre tow reaches 46,000 tonnes and 54,500 tonnes in 2011and 2012, respectively (“Global and China Carbon Fiber Industry Report, 2012-2015,” 2013). It is predicted to rise to 130,000 tonnes by 2020. See Figure 5.3 for details. In terms value, the sales of carbon fibre tow in 2011 were $1.6 billion. The sales are expected to reach approximately $4.5 billion by 2020 (Smolarski, 2012).

Figure 5.3 Global demand for carbon fibre



*2014 - 2020 global demand is based on estimation. Source: created by author, with data from Jahn et al., 2012

PAN-based precursor dominates 80% of the current carbon fibre market. Lignin-based precursor is expected to be an alternative to PAN. This section will go over three fast growing potential markets (automotive, wind energy and aviation) for lignin-based carbon fibre and one of the fast growing markets (EMI shielding) for lignin nanofibre.

Automotive

The automobile industry is seen as one of the most important drivers for the carbon fibre market. Taking consumption of approximately 2,000 tonnes in 2010 as the base, conservative analysts are forecasting annual growth of 15% for the sector (Jahn et al., 2012). As discussed in section 4.1.1 (social levers), the main driving force is the changing regulation that forces the automotive industry to improve fuel economy and reduce CO_2 emission.

The automotive industry is a large volume market for carbon fibre. Interviews with automotive industry representatives (see appendix A) suggested that until 2025 there would be a large growth in the use of carbon fibre as structural components. The industry is still in the early stages of a long-term adaptation of carbon fibre to structural and semi-structural production vehicle components. Adoption has taken longer than projected (Maine, 1997), partially due to a delay in the government tightening of CAFE regulations.

Carbon fibre usage has also been hindered by production scale up issues, primarily, high fibre processing costs and lack of high-speed composite fabrication techniques (X. Huang, 2009). The cost of low to standard modulus carbon fibre suitable for automotive applications is estimated to be around $40 per kg (Red, 2013). After including the CFRP manufacturing cost, the component used in vehicles increases to approximately $95 per kg. This contrasts starkly with $4 per kg for regular steel, $8 per kg for high strength steel and $9.5 per kg for aluminium (Jahn et al., 2012). Beyond lowering production costs, a key to the automotive adaptation of carbon fibre composite components and system is designing for parts integration (Maine, 1997). When eliminating additional assembly steps for metal parts, carbon fibre composites can enjoy an overall systems cost advantage, particularly for small production volume car models (Maine, 1997).

According to estimates provided by the ORNL, if the carbon fibre price can be $11per kg ($5 per pound) with a tensile strength of 1.72 GPa, and a modulus of 172 GPa (D. A. Baker & Rials, 2013), the potential global carbon fibre market size in 2017 for auto industry will be about $1,525 million (Eberle, 2013). The detail of this estimate is in Table 5.3.

Table 5.3 Carbon fibre demand for the automotive industry in 2017 at $11/ kg

Vehicle Type	# of Vehicle	Expected Use of CFRP	Demand for CF (tonne)*	Market for CF ($)
Super Cars	6,000	100%	590	$7 million
Super Luxury Car	600,000	10%	45,900	$506 million
Luxury Cars	4 million			
Regular Cars	92 million	1%	91,810	$1,1012 million
Total	97 million		138,300	$1,525 million

* The demand is estimated to be 3 times the current carbon fibre demand. Source: created by author, with data from Eberle, 2013

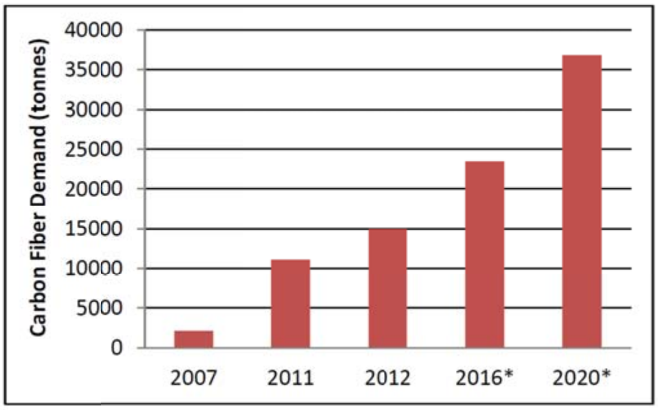
BMW is currently the most active automotive company in CFRP development for mass production vehicle. BMW and SGL Group have joined to form SGL Automotive Carbon Fibres (ACF). The joint venture produces all the CFRP for the i3 and i8 model on two production lines at Moses Lake, Washington with estimated volume of 30,000 units annually. After already investing $100 million to increase capacity, BMW has announced that another $200 million expansion will complete in 2015. The plant at Washington will be the world's largest carbon fibre plant (Ramsey, 2014). BMW executive Dr. Klaus Draeger states that, "As part of an intelligent mix of materials, we will apply carbon also beyond our BMW i and BMW M models in the future," and will be able to do so "at competitive costs and in large quantities." The company is planning to apply CFRP to the rest of its product lines (Ramsey, 2014).

Wind Energy

Next high potential market for carbon fibre is wind energy. The global wind turbine market is estimated to be $26 billion dollars with a 3.2% estimated annual growth. The economy of scale for wind generation is defined by turbine size rather than by project size. In theory, it is less expensive to build fewer larger turbines than additional smaller turbines. As modern utility scale wind turbines increase in size, new materials and manufacturing methods are required because as blades get longer, weight plays an increasingly negative role in turbine efficiency. For blade length greater than 45m, carbon fibre is often used to solve this problem.

Currently, wind turbine blades constructed from Glass Reinforced Polymer (GFRP) dominate the industry, but producers are making the move to carbon fibre alternatives due to their greater rigidity and lower weight. With this shift in manufacturing materials, combined with the increasing deployment of wind farms across the world, carbon fibre demand for the wind energy industry is expected to jump from 11,130 tonnes in 2011 to 37,000 tonnes in 2020, making it one of the single largest carbon fibre end user segment in the world (Dvorak, 2013; Sloan, 2013). See Figure 5.4 for details. The potential market size for standard-modulus fibre in the wind energy application would be $1.1 billion, assuming the fibre used in turbine blades costs $30/kg.

Figure 5.4 Global annual demand for cabon fibre consumed in wind turbine blade



* 2016 and 2020 global demand for carbon fibre used in wind turbine is based on estimation. Source: created by author, with data from Dvorak, 2013; Sloan, 2013

The U.S. is the largest supplier of carbon fibre turbine blades. GE Energy, the largest wind turbine supplier in the U.S., consumes approximately 3,000 metric tonnes of carbon fibre in 2012 (Stephenson, 2012). Other turbine manufacturers such as Vestas Wind Systems A/S in Denmark and Gamesa Technology Corp. in Spain also embraced carbon fibre years ago, using it in select structural parts of their blades and taking advantage of the lightweight blades throughout the turbine system (Wood, 2012).

The carbon fibre used in wind turbine construction is large-tow (≥24K) standard-modulus carbon fibre. The most important requirements for carbon fibre in this application is consistency, and strong compressive and transverse tensile strength (Dvorak, 2013). Today, the fibre used in turbine blades costs $20 per kg to $30 per kg which is about 15 times to 20 times of the cost of GFRP (Stephenson, 2012).

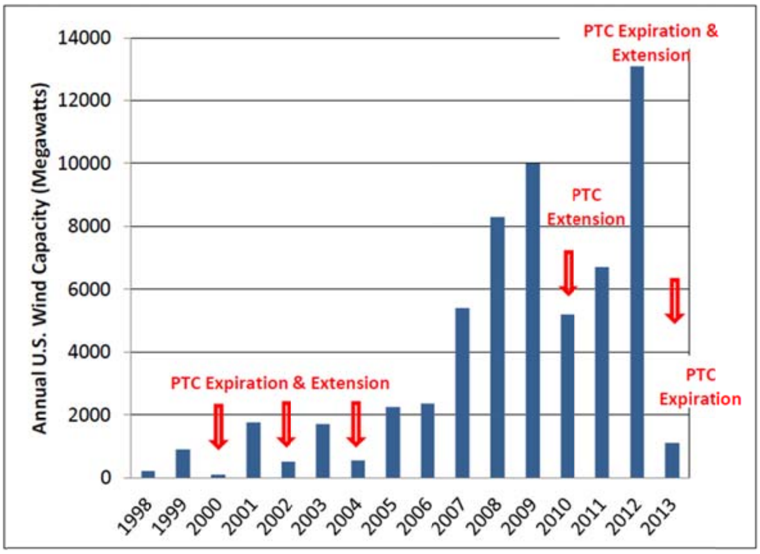
The market for wind energy is perhaps the most volatile when compared to the automotive market and the aviation market. The wind industry is strongly influenced by external factors as well as internal industry trends. Despite of the rapid market growth and technological advancement, the wind turbine prices continue to fall (20% to 35% decline since late 2008) due to the stiff competition among turbine original equipment manufacturers (OEMs) and reduced demand expectations (Wiser, 2013). However, global and regional regulations are one of the biggest external factors that influence the marketplace.

China and the U.S. are the two largest wind turbine markets in the world with 26.7% and 21.2% of the global market share respectively (Shukman, 2014). The demand for the wind energy industry is highly dependent on these government policies. For example, the recent expiration of the wind energy production tax credit (PTC) in the U.S., and Chinese government's policy of ramp-down of wind energy expansion in 2011 have put a damper on the demand (Sloan, 2013).

The PTC policy states that companies that generate electricity from wind, geothermal, and closed-loop bio-energy are eligible for a federal PTC of 2.3 ¢ per kWh for the first ten years of the facility's operation. PTC expired at the end of 2013 but a new provision was included in the American Taxpayer Relief Act of 2012 that projects under construction before January 1, 2014 are still eligible for the PTC. Combined with state renewable electricity standards, the PTC has been a major driver of wind power development in the U.S. The wind generation capacity between 2007 and 2012 in the U.S. had tripled. The majority of wind turbines installed in the U.S. is produced within the country (about 72%) which represents an annual average investment of $18 billion

("Production Tax Credit for Renewable Energy," 2014). However, PTC policy has been repeatedly gone back and forth between expiration and extension by the U.S. Congress which creates havoc to the U.S. wind industry ("Production Tax Credit for Renewable Energy," 2014). Figure 5.5 shows how PTC affects the annual installation of wind generation capacity.

Figure 5.5 Impact of Production Tax Credit on the U.S. annual installed wind capacity



Source: created by author, with data from "Production Tax Credit for Renewable Energy," 2014

China's energy supply dominated by coal has supported rapid economic development since the implementation of the reform policy 30 years ago. This has put intense pressure on resources and environment. Chinese government is now stipulating that China's energy supply needs to transition to a clean, reliable, low carbon energy source in the next two decades (Shukman, 2014). China has exceptional wind resources, estimated about 2,380 GW of exploitable capacity on land and 200 GW on the sea. In 2012, there were 76 GW of electricity generating capacity installed in China and wind energy has thus become one of the country's major focuses in energy development (Yang, 2011).

The key challenge for the wind energy development in China is lack of grid connection for new wind farms. According to the China's National Energy Administration, about 12 billion kWh were lost in the curtailment in 2012, resulting in an estimated loss of $1 billion. Solving the issues of grid curtailment is challenging since the system was designed for coal dominated power system which lacks flexibility (Qiao, 2012).

In the middle of 2011, the Chinese government introduced a new regulation "Wind Farm Development and Management Interim Rules and Regulations" which aims to improve the approval process of building new wind farms. The new regulation stated that new wind projects have to be reported to the central government and approved by the National Energy Administration before getting final approval. Projects that are not approved will not be granted grid access. Although the policy aims at solving the mismatch between the grid and wind farm planning to improve both the quality of the turbines and wind farm management, the new stringent process has significantly slowed down the development of wind farms (Qiao, 2012). With more than 20 turbine manufactures in China, the wind turbine manufactures face the challenge of overcapacity, fierce price competition, and lack of finance support for wind projects (Qiao, 2012).

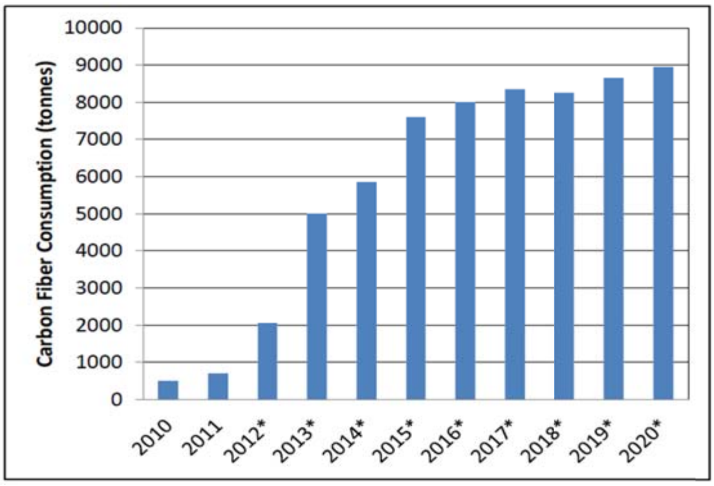
Aviation

The commercial aviation market is one of the most high profile applications of high-modulus carbon fibre thanks to the dramatically increased use of carbon fibre composites in lightweight fuel-efficient aircraft such as the two new wide body aircraft, Boeing 787 Dreamliner and the Airbus A350 XWB with 50% by weight carbon fibre composite materials. The Boeing 787 Dreamliner has been fully redesigned to incorporate the advantage of carbon fibre composite for lightweighting. For example, parts integration of its fuselage replaces 1,500 aluminium sheets and 40,000 fasteners with a one-piece carbon fibre composite fuselage. In 2013, the global airline industry's fuel bill was estimated at $210 billion (accounting for 30% of operating expenses). As the rising fuel price shrinks airline industry's profit margin to razor thin level, demand for lightweight fuel-efficient aircraft is expected to have a significant growth in the near future. The aviation industry demand for the material is estimated to climb at a Compound Annual Growth Rate of 11.8% from 7,200 tonnes in 2012 to 19,700 tonnes in 2020 (Dvorak, 2013). This demand translates into an approximate $2 billion market for carbon fibre composites in 2020, assuming the cost of high-modulus fibre is $100/kg.

The estimate volume of the commercial aviation market for carbon fibre composites is about 3,630 tonnes in 2011 and 4,010 tonnes in 2012. Beyond the wide body design of the 787 Dreamliner and A350 XWB, there are other notable uses of composite aerostructures in wing, empennage and flight control surface on single aisle commercial aircraft such as the Bombardier CSeries, the Irkut MS-21 and the COMAC C919 (Sloan, 2013).

After peaked in 2007 at 3,487 orders and bottomed out at 663 orders during the recession in 2009, Boeing and Airbus reported strong sales in 2012 with 1,203 orders and 914 orders respectively. Both companies have a healthy backlogs till 2018 (Sloan, 2013). With long backlog orders, the carbon fibre supply chain for the commercial aviation industry is expected to head to a period of stability (Sloan, 2013). Figure 5.6 shows the estimation of global carbon fibre usage in wide body aircraft.

Figure 5.6 Carbon fibre consumption in wide body aircraft



* 2012 till 2020 carbon fibre consumption is based on estimation. Source: created by author, with data from Jahn et al., 2012

On the military side, carbon fibre is key to the Lockheed Martin F-35 Lightning II fighter, the Airbus A400M airlifter, the Embraer C-390 transport, and the Eurofighter EF-2000 (Sloan, 2013). The aviation development in the military usage is dynamic. Over the last five years, the global military aviation industry has been losing altitude as western defence budgets shrunk due to recession and the tempering of combat operations in the Middle East (Sloan, 2013; Soshikin, 2013).

One of the major uncertainties of the commercial aviation market for carbon fibre is whether the composite can make it to the fuselage design for the next generation narrow body aircraft (also known as single aisle aircraft) which accounts for 70% of the word's airline fleets. Unlike the 787 Dreamliner and A350 XWB, which are wide body aircrafts with twin aisles and fuselage diameter of 5 meters to 7 meters, narrow body aircraft has fuselage of 3 meters to 4 meters. Carbon fibre is suitable for aircraft wings and many fuselages, but the skin thickness of a single aisle aircraft makes aluminium a very competitive option. As having the next generation single aisle aircraft to replace Boeing 737 and Airbus A320 is still in the drawing board, engineers are monitoring the carbon fibre industry's advancements in material and process capabilities necessary to make the design switch (Sloan, 2013).

Electromagnetic Interference (EMI) Shielding

In recent years, electrically conducting polymer and polymer based conducing composites such as carbon fibre have gained popularity for EMI shielding applications. Applications are anticipated to include parts and enclosures of consumer electronics. The market can be broken down in to conductive coating, metal cabinet, conductive plastics and laminates/tapes. The market size for each of these categories is shown in Table 5.4.

Table 5.4 Global market for EMI insulation

Type of Insulation	**2011 Market Size (US $)**	**2013 Market Size (US$)**	**2018 Market Size (US $)**
Conductive Coating	1.7 billion	1.9 billion	2.1 billion
Metal Cabinet	649 million	776 million	906 million
Conductive Plastics	504 million	520 million	609 million
Laminates/tapes	129 million	228 million	275 million
Others	1.5 billion	1.8 billion	2.1 billion
Total	**4.5 billion**	**5.2 billion**	**6 billion**

Source: created by author, with data from "Global Market for EMI/RFI Shielding To Reach Nearly $6 Billion In 2018," 2013

The global market for EMI shielding was $4.5 billion in 2011 and expected to be nearly $6 billion in 2018 (Table 5.4). The main purpose of EMI shielding is to reduce interference in operation of electronic equipment. The market demand is growing not just because of the increasing demand for electronic devices but also due to tighter safety and performance regulations ("Global Market for EMI/RFI Shielding To Reach Nearly $6 Billion In 2018," 2013). Conventional coating materials are expected to lose market share to nanomaterials in the next few years as a result of rising adoption and falling costs. There has been an increasing interest for eco-friendly shielding technology that reduces drain on natural resources and minimizes environmental concerns over existing manufacturing processes such as electroless plating ("EMI and RFI shielding material and technologies," 2014, "Global Market for EMI/RFI Shielding To Reach Nearly $6 Billion In 2018," 2013).

Comparing to carbon black, the most common material incorporated into plastic materials to improve conductivity, carbon fibre provides superior shielding performance due to its fibrous structure. However, one of the reasons why carbon fibre shielding, commonly made from PAN via electrospinning, has not been adopted in the current consumer electronic market is its high cost (D. A. Baker & Rials, 2013). See section 5.2.4 and 5.4 for more details.

The feedback from industry representatives (see Appendix A) regarding the use of low cost lignin carbon fibre as a shielding material is very positive. Besides be a low cost material, the representatives state that lignin does not evolve noxious gases during conversion and has potential for a very rapid conversion from thermoplastic lignin nanofibres to thermoset carbon nanofibres (D. A. Baker & Rials, 2013). Unlike carbon fibres used in the automotive industry and the aviation industry, strength is not the primary concern for EMI shielding application. As long as the conductivity and consistency of carbon fibre can be optimized, low cost lignin carbon fibre can fulfil the market requirement. Prof. Frank Ko's research group at UBC has recently reported achieving a breakthrough by developing a lignin-based carbon fibre shielding whose performance exceeds both the conventional PAN-based carbon fibre and metal shielding material (Lin et al., 2013). Such an achievement may allow lignin carbon fibre to capture a large segment of EMI shielding market. Assuming lignin carbon nanofibre would capture one third of the market, the potential market size would be $2 billion in 2018.

Based on the feedback from industry experts (see appendix A), it will be ideal if the electrospinning nanofibre can be combined with thermoplastics where injection moulding can be applied. Injection moulding is the most efficient way of mass production. It could potentially be the most applicable method for mass adaptation of lignin carbon fibre in the EMI shielding market.

5.2.2 Positive Consumer Perception

CFRPs are perceived as high performance material by automotive consumers. Based on the data collected from interviews with automotive industry representatives, carbon fibre parts are only used on higher performance sports cars of which consumers are willing to pay a premium price. Unlike metal parts, consumers want the carbon fibre parts unpainted for showing purposes. This phenomenon shows that the consumer is embracing the use of carbon fibre. Observability is a known enhancer of the adoption of innovation (Rogers, 2010).

5.2.3 Cost Advantage over Other Precursor Types

The estimated price for melt spinnable lignin precursor would be approximately \$1.52 per kg (adjusted for a carbon fibre yield of 55%). Ideally, the price can be lowered to \$1.1 per kg. This is substantially lower than the proposed cost of other potential precursors such as textile grade PAN at \$4.4 per kg to \$13.2 per kg (adjusted for a yield of 50%), melt-spun PAN at \$6.3 per kg (adjusted for a yield of 50%), polyolefin at \$1.57 per kg to \$2.36 per kg (adjusted for a yield of 70%). The differences in cost between lignin and the other potential precursors would increase further if the oil price increases (D. A. Baker & Rials, 2013). Table 5.5 has the details of the precursor price and production cost of each precursor type.

Table 5.5 Cost comparison of different types of low cost carbon fibre precursors

Material	Precursor Cost (US \$)	Production Cost (US \$)	Total Cost (US \$)
Conventional PAN	\$11.1/kg	\$25.15/kg	\$36.25/kg
Textile Grade PAN	\$4.4/kg to \$13.2/kg	\$12.25/kg to \$25.4/kg	\$16.65/kg to \$38.6/kg
Melt-spun PAN	\$6.3/kg	\$17.4/kg	\$23.7/kg
Polyolefin*	\$1.57/kg to \$2.36/kg	_	_
Lignin	\$1.52/kg	\$6.27/kg	\$7.79/kg

* Polyolefin is still in the early stage of development so estimation obtained on production cost. Source: created by author, with data from D. A. Baker & Rials, 2013; Norberg, 2012

5.2.4 Cost Advantage over Current PAN Process

PAN precursor fibre is traditionally prepared by a solvent based polymerization process, followed with wet or melt assisted spinning as discussed in section 1.4.3 with extrusion speed about 250 m/min. The solvent used is sodium thicocynate or dimethylacetamide with about 20% to 30% of the polymer content. Unlike the PAN precursor, lignin precursor is melt spinnable which does not involve the use of solvent.

Based on the current melt spinning speed performed in the textile industry, extrusion speed can reach 600 m/min (Das, 2011; Wilms et al., 2013). Melt spinning is a cheaper and more efficient process than wet spinning or melt assisted spinning.

Since lignin-based precursor requires less oxidation time and emits less volatile organic compounds and greenhouse gases during the conversion process, it reduces energy consumption. The energy consumption is heavily dependent on oxidation efficiency and the amount of by-products generated during conversion process. This is a huge plus to the current carbon fibre manufacturing process because the waste gas treatment for carbon fibre production is currently facing the trend of diminishing returns on economies of scale (Imhoff, 2013).

As discussed in the societal levers section, fibre conversion process produces CO_2 and HCN emissions that have impacts on the environment and human health. A comparison between estimated costs of CO_2 emission (carbon pricing), HCN emission treatment, and energy usage for PAN and lignin carbon fibre conversion is presented in Table 5.6. The estimation is based on 50k tow fibre at annual capacity of 4,500 tonnes. The estimates show that lignin precursor provides significant amount of cost saving over conventional PAN-based precursor, \$0.07 per kg for CO_2, \$0.13 per kg for HCN and \$1.50 per kg for energy reduction. As the lignin technology is still underdevelopment, the data rely on estimation of the most likely commercial production facility scenario. The thermal processing equipment is assumed to use natural gas as fuel since oxidation is the rate limiting step, and consumes most of the energy (Das, 2011). Most of the oxidation ovens on the market are using natural gas as the energy source (Imhoff, 2013). See section 5.4.4 for more details regarding the rate limiting step of carbon fibre production.

Table 5.6 Cost differences in terms of CO_2 emission, HCN emission and energy consumption between PAN and lignin carbon fibre

	CO_2	HCN	Energy Usage - Precursor Production	Energy Usage - Fibre Conversion	Total Energy Usage
PAN CF	31 kg/kg	12 g/kg	245 MJ/kg	459 MJ/kg	704 MJ/kg
Cost	\$0.31/kg	\$0.13/kg	\$2.45/kg	\$4.59/kg	\$7.04/kg
Lignin CF	24 kg/kg	~0g/kg	210 MJ/kg	344 MJ/kg	554 MJ/kg
Cost	\$0.24/kg	\$0/kg	\$2.10/kg	\$3.44/kg	\$5.54/kg
Difference	7 kg/kg	12 g/kg	35 MJ/kg	115 MJ/kg	150 MJ/kg
Saving*	\$0.07/kg	\$0.13/kg	\$0.35/kg	\$1.15/kg	\$1.50/kg

*The CO_2 cost (carbon pricing) is estimated at $10 per tonne. The HCN treatment cost is estimated at $11 per kg. Energy price is calculated based on natural gas price at $10 per 1 GJ. Source: created by author, with data from “Carbon copy,” 2013, “U.S. Price of Natural Gas Sold to Commercial Consumers,” 2014; Das, 2011; Dash, Gaur, & Balomajumder, 2009; Imhoff, 2013

If considering the “societal cost of carbon”, the damage from an extra tonne of CO_2, America’s administration estimates the cost to be $37 per tonne (“Carbon copy,” 2013). This implies that lignin carbon fibre could save $260 from CO_2 environmental impact per tonne compared to PAN-based precursor.

5.3 Hurdle

5.3.1 Challenges from Incumbent Technology

Automotive Industry

Based on the information collected from our interviews with the industry representatives (see appendix A), lightweight aluminium is currently the key competitor for carbon fibre parts in automotive applications. There are several reasons for aluminium to be widely used in the automotive industry. First, aluminium is a homogenous material. Unlike composites, there is a large computer aided design database for aluminium alloys. Second, the manufacturing and repairing costs for aluminium are lower. The tooling and manufacturing processes for aluminium are more similar to steel, which is widely adopted for auto industry for decades. Lastly, there is a long lasting partnership between the aluminium industry and the automotive industry ("Aluminium in the automotive industry," 2014).

In recent years, many automotive manufacturers such as Audi, Ferrari, Land Rover and Mazda are increasingly utilizing aluminium into their design. Today aluminium is the second most used material (in percentage terms) of the total weight of the car. It is used to make components of the suspension, the chassis, cylinder blocks and other engine components ("Aluminium in the automotive industry," 2014). Ferrari, high-end sports car maker, is choosing aluminium as their primary building material for the new 458 Italia super car (Carney, 2011).

Many structural auto applications do not require the mechanical properties of carbon composites, so the motivation for using them is perceived as mere weight reduction (Carney, 2011). There are multiple ways to reduce the weight of non-structural parts. For example, aluminium is still harder to repair and more expensive to make than steel, so steel suppliers are introducing stronger and lighter steel alloys to compete in the automotive market (Carney, 2011). Carbon fibre composites are most compelling for automotive applications, and show both cost and weight advantages over steel and aluminium parts in small production volume vehicle platforms, when designers take advantage of parts integration (Maine, 1997).

Aviation Industry

Aluminium-Lithium alloy (Al-Li) is the primary competitor for carbon fibre in the aviation industry. The new alloy is lighter and has better corrosion resistance than traditional aluminium. The new alloy is cheaper than the composite material (Arvai, 2010).

Al-Li is currently overtaking composites for narrow body aircraft because it provides cost advantage over composites in terms of airline operations. Narrow body aircraft, unlike wide body aircraft, fly short haul flights and operate many more take-off and landing each day. This requires a more robust airframe to withstand the stress of multiple daily take-offs and landings, as well as the pressurization cycles that inherent stresses the aircraft. Airframe can also subject to ground damage such as crushing by baggage loaders. Unlike carbon fibre composites that need x-ray devices for damage inspection, damage on the Al-Li structures can be easily determined through inspection. The repair of Al-Li is also straight forward using "scab patches" of additional material like the traditional aluminium airframes. One aircraft manufacturer mentioned that to make the composite airframe stronger and more damage tolerant the additional ply of composites would virtually eliminate the weight saving advantage (Arvai, 2010).

The competitive advantage of Al-Li also lies in its adaptation of existing aluminium manufacturing process. Composite material requires different manufacturing processes than traditional aluminium construction. Composite material requires vacuum curing in ovens and different engineering methods to attach components to an aircraft. All of these add up the operation cost for both plane manufactures and airlines (Arvai, 2010; Lownsdale, 2012).

Currently, Bombardier selects Al-Li for the fuselage of its forthcoming CSeries aircraft. A senior executive at Airbus has also indicated that his company's narrow-body replacement would not necessarily utilize composite structures (Arvai, 2010).

Wind Energy

Today, most of wind turbine blades are made with E-glass fibre. As the turbine size grows there is no question that the wind turbines industry needs to find new materials that can reduce weight while maintaining strength and stiffness. The adaptation of carbon fibre seems unstoppable. However, there are two main reasons the industry is facing difficulties in making the switch (Wood, 2012).

First, the manufacturing process for carbon is more challenging and has a relatively low damage tolerance than E-glass fibre. Carbon fibre requires perfect fibre alignment and must be cured quickly. Wind blade manufactures are forced to use more expensive pre-preg products. On the subject of carbon fibre cost, carbon fibre for wind blades costs \$20 per kg to \$30 per kg which is 15 times to 20 times greater than that of E-glass fibre (Stephenson, 2012; Wood, 2012).

Second, the wind turbine industry needs a consistent fibre supply. Large size wind turbines require large amount of standard-modulus carbon fibre. Even though the capacity of carbon fibre is much higher today than 6 years ago, there is a high uncertainty whether the suppliers are ready as the aviation and large turbine production increases (Stephenson, 2012; Wood, 2012).

Competition in the global wind energy market is fierce, especially in China, where dozens of companies are fighting for a piece of the world's wind generation market. This shrinks the wind turbine producer's profit margin dramatically. The supply concern and the high price of carbon fibre will likely continue to make some manufacturers hesitate before designing a new blade with Carbon fibre.

Electromagnetic Interference (EMI) Shielding

Metals and metallic conductive coating on plastics are the two primary incumbent technologies competing with carbon nanofibre. Metals are excellent conductors of electricity and can absorb, reflect and transmit EMI. It is the most common material for EMI shielding. Typical materials used for EMI shielding include sheet metal, metal screen, metal foam and metal paint. Beside ability to conduct electricity, metals are also excellent conductor for heat. Metal insulators are often used on electrical equipment and high-speed machinery with high build-up of static charges and heat ("EMI and RFI shielding material and technologies," 2014).

The common material used for construction of enclosures for shielding is mumetal, an alloy of 14% iron, 5% copper, 1.5% chromium and 79.5% nickel. The other metal materials used as a shield are brass, aluminium, silver, nickel and stainless steel.

All of these conductive composites have certain limitations: aluminium based has low impact resistance, and stainless steel has high density. Metal sheets are often too bulky for today's consumer electronics. Die cast enclosures of magnesium and aluminium provide significant advantages over both plastic and alternative metal housings but with a trade off on high manufacturing cost (J.-C. Huang, 1995).

Besides traditional metal casing, consumer electronic market often incorporates plastic materials-embedded metal foil as EMI shielding material. Since thermoplastics are not conductive materials, most of the energy waves are not absorbed. Plastics have been modified by ways of conductive costing, conductive fillers and intrinsically conductive polymers. Each of them has its advantages and drawbacks.

Metallic conductive coating on plastics is a well-established technique. The technology is mature and used commonly in the automotive industry and the plumbing industry as decorative. It provides weight and cost saving on comparable metal material. There are several different coating techniques such as foil laminates, conductive paints, and zinc arc spraying. The main drawbacks for all of these coating techniques are environmental pollution and cumbersome processing steps. All coating operations are secondary to the moulding operation (J.-C. Huang, 1995). This reduces manufacturing efficiency and adds up cost.

5.3.2 Conservatism in the Pulping Industry

For commercializing lignin carbon fibre, a major hurdle that needs to be solved is the lack reliable supply of cost effective high purity lignin. Due to high transportation cost, lignin has to be refined and purified at its source (pulp and paper factory). From the interview with industry experts, one of the major barriers for the implementing high purity lignin extraction process is conservatism. The pulping industry always goes for safe solutions that never fail. Even a quite simple technology like LignoBoost® is a big challenge for this industry. There is strong resistance to have process that is not part of the standard operation practice.

Given that exiting lignosulphonate markets are growing slowly and high value markets for lignin are far from markets, there are no major interests in the development for purification and fractionation of high purity lignin. Someone in the industry has to be brave enough to be the first that leads the way. Domtar, a large integrated paper producer in the U.S., has shown the successful technical implementation of lignin extraction technology in the pulp mill. Maybe there will be many followers to come.

5.3.3 Uncertainty of Carbon Fibre Supply

The market forces that drive carbon fibre supply and demand are numerous and complicated. Few indicators with little change could have the capacity substantially shift in the carbon fibre market. Current supply is approximately 67,200 tonnes worldwide (Table 5.1). Demand for this is primarily in the automotive, aviation and wind energy industry.

The Boeing 787 Dreamliner showcased the lightweighting potential and dramatic parts integration of carbon fibre polymer composites. Further adaptation in the commercial aviation industry is expected. However, lignin based precursor does not currently have the required strength for these applications. The automotive market seems to be in the early stage of a long-term adaptation. Carbon fibre usage in vehicle manufacturing is increasing. There is a large potential of using carbon fibre in the large size wind turbine blades.

Because the capital cost of fibre production is very high, existing carbon fibre producers are unwilling to invest in new capacity without firm data on future demand. The aviation industry can make long-term commitments because its order backlogs are measured in years. With fierce competition, the automotive industry and wind generation industry do not have that luxury. Lack of reliable carbon fibre supply has also hindered the adaptation of the composite material. Based on our interviews with the industry experts (see appendix A), the demand and supply of carbon fibre is becoming a chicken and egg problem in the automotive and wind energy markets.

5.3.4 Inefficient Carbon Fibre Composite Manufacturing Process

One of the keys to a successful adaptation of carbon fibre composite is the improvement of the current CFRPs manufacturing process. Currently there are several types of manufacturing techniques to make CFRPs such as resin transfer moulding, resin infusion and pressure press. Based on our interviews with the industry representatives (see appendix A), a fast production method for CFRPs needs to be developed for the automotive industry to massively adopt carbon fibre as a building material. The manufacturing pace required for the high-volume car or truck production is generally acknowledged to be one part per minute; the cycle-time is maintained for decades by auto OEMs in their metal-stamping operations. Ideally, an automotive manufacturer would prefer a process that matches the current metal-stamping efficiency (Sloan, 2012).

Several companies have leading the development to achieve this goal. Companies like Plasan Carbon Composites and SGL Group have achieved great result in reducing the cycle time of making CFRP parts. For Plasan, the cycle time of producing carbon fibre parts has reduced from 90 minutes to 17 minutes. Plasan has co-developed a new patent-pending out-of-autoclave moulding process with Globe Machine Manufacturing Co. For the first time, this work allows carbon composites to be produced fast enough for use on medium-volume production vehicles (cycle time of this process is unknown) (Lownsdale, 2012). The cycle time for the BMW process is also unknown. What is known is that it is based on RTM of woven carbon fibre fabrics, a process much faster than the hand layup/autoclave-cure methods used on CFRPs in supercars (Sloan, 2012).

One of the limiting steps for the cycle time is the rate of epoxy curing. Cedric Ball, market development manager at Momentive Specialty Chemicals' (Columbus, Ohio), says that his company has developed several fast-cure epoxies for several BMW and Audi vehicles to be as fast as 5 minutes. 2 minutes curing system is also under testing (Sloan, 2012). These are reasonable scenarios to test for future production costs.

Despite of the fast development pace on the CFRP manufacturing process, currently cycle time for carbon fibre parts is still nowhere close to the speed of metal stamping process at 1 minute per part. Challenges remain ahead. Based on the data collected from interviews, the most important requirement for lignin carbon fibre is to be compatible with the PAN-based carbon fibre moulding process since most of the current manufacturing technologies are developed around PAN-based carbon fibre.

5.3.5 Lack Industry Knowledge of Using Carbon Fibre

Unlike metals, which are homogeneous and have properties that conform to established standards, CFRPs are heterogeneous. They are composed of combinations of unlike materials such as fibre and resin (McConnell, 2008). The combination of these materials gives CFRPs 10 times the strength of steel at half the weight. However, the very same property has also made the composite parts very challenging to understand and master. Steven Carmichael, director of sales and marketing for Grafil Inc., refers that the making of CFRP is like making fine wine; the right amount of patience, finesse and processing expertise brings out the subtleties in carbon fibre that add value (McConnell, 2008).

Despite of superior strength to weight ratio, the heterogeneity of CFRPs have made the adoption of carbon fibre in the automotive industry and the aviation industry a challenging one. CFRPs cannot be used as a direct replacement for metal parts. In order to extract the maximum performance out of CFRPs, various structure components have to be redesigned (Maine, 1997). The redesigning process is time consuming and expensive. To make it even more challenging, CFRP is a relatively new technology; material engineers are still trying to understand the material property.

Based on the interviews with representatives from both the automotive industry and the carbon fibre industry, there is a large computer simulation database for homogeneous materials like aluminium or steel which have been used in the aviation industry and the automotive industry for decades. Unfortunately, it is not the case for CFRPs. The design of carbon fibre parts is often on the trial and error basis; it relies heavily on the accumulated experience which is still scarce in the mainstream vehicles and the commercial aviation industry. Unlike metals crumble on impact, composites more often shatter. There are limited computer simulation tools and database available to assist the development of mainstream vehicles using composite parts. This will increase the development cost for vehicles that meet FMVSS and EPA regulations. The same applies to the commercial aviation industry. The FAA has performed multiple tests on the new Boeing 787 Dreamliner to ensure that the design is as safe as a metal airplane (Kleiman, 2010).

5.3.6 Difficulties with Repairing Carbon Fibre Reinforced Plastics

Automotive Industry

One of the large unknown of CFRPs in mainstream vehicles is the cost of repair. The amount of CFRPs used in the in the global automotive industry is confined mostly to racing cars, super cars, and high-end luxury vehicles. The repair techniques inherited from the motorsports and the aviation industry are not directly transferable to road cars. For non-structure body panel such has the hoods and door panels, the damaged parts are generally replaced. The main issue comes to the critical support structures such as the chassis.

Currently, the only two production cars that integrate carbon fibre extensively into the chasses are the MP4-12C launched in 2011 from McLaren Automotive Ltd and Aventador LP700-4flaucned in 2011 from Automobili Lamborghini SpA. The monocoque CFRP passenger cells used in both cars are beyond the capabilities of most body shops to even evaluate, let alone repair. To solve this problem, the two companies took two different approaches. McLaren has integrated crash observing aluminium structures front and rear, to ensure that the CFRP passenger cell is well protected. The aluminium structure serves as a sacrificial element. If the first line of defence is breached and the monocoque cell suffers more than a cosmetic damage, it will need to be replaced (Malnati, 2012). Lamborghini also features a one piece all CFRP monocoque passenger cell. However, the use of CFRP is far more extensive and with less aluminium structure that serves as sacrificial element. If the damage is severe and occurs on a critical chassis component, Lamborghini will dispatch specially trained technicians to fix the car (Malnati, 2012). There are only four of them worldwide. In either case, the repair cost does not come cheap.

Both cars mentioned above are super cars with a price tag close to half a million dollar. Only 2000 units of MP4-12C and Aventador LP700-4 are produced annually (“Automobili Lamborghini - 2012 full year figures,” 2013; Siu, 2012). Automotive enthusiasts are focusing on how BMW AG intends to deal with repair of CFRP chassis components for its i3 and i8 electric vehicles, launched in 2013 with target production volumes of 100,000 vehicles annually (Lane, 2014). For mass production vehicle, the repair has to be more cost-effective to keep customers and insurance companies happy. BMW's approach is to build body panels in cheaper thermoplastics and modularize the car design for fast replacement (Lane, 2014). The strategy is to let low labour cost and cheap body panel offset against expensive chassis replacement. It is still too early to tell whether consumers and insurance companies will accept this approach (Lane, 2014; Malnati, 2012).

Aviation Industry

For the aviation industry, people are focusing on the recent incident of the fire on a 787 Dreamliner at Heathrow Airport in London. The fire has damaged the supports in a 10-foot stretch at the top of the rear fuselage. The replacement is done by replacing part of the fuselage with the new crown section. The new panel is bonded and mechanically fastened to the surrounding frames and stringers. The damaged airplane has been repaired and put back into service (Drew & Mouawad, 2013; Norris, 2014). However, there is no public information on the cost of the repair. It is commonly believed that the repair cost of the composite fuselage is much higher than that of its aluminium counterpart. The repair cost for carbon fibre aircraft in the long term will depend on the advancement of the patch-up techniques (Drew & Mouawad, 2013).

The composite materials have created new challenges for airline mechanics. Unlike aluminium, carbon structures do not dent visibly and require special ultrasound probes to identify damaged areas (Drew & Mouawad, 2013). The composite materials also require new repair techniques. There is a shortage of mechanics with the right training (Drew & Mouawad, 2013).

Wind Energy

Comparing to the previous two applications, wind turbine blades are less likely to sustain catastrophic damage as long as the wind blade materials have low weight, high stiffness and high environmental loading resistance. Since the wind generator tower is stationary, a properly designed wind turbine should work for 20 years to 25 years without repair and with minimum maintenance (Mishnaevsky Jr., 2011).

5.4 Cost Analysis

For conducting the cost analysis on lignin-based carbon fibre and nanofibre, the following steps will be preceded:

- Identify key inputs, processing steps and outputs
- Identify key equipment required and its capital cost
- Determine probable yield and scrap rate
- Determine rate-limiting step

5.4.1 Key Inputs, Processing Steps, and Outputs

The key input of lignin carbon fibre tow manufacturing process is the lignin precursor. The details of carbon fibre precursor based on kraft lignin are discussed in section 1.3.2.

The key processing steps for lignin carbon fibre manufacturing process are lignin purification and refining, polymerization, spinning, oxidation, carbonization, surface treatment, and sizing. The details are discussed in section 1.3.2 and 1.4.3.

The output from the process will be different grades of carbon fibre tow rated by modulus of elasticity. See section 1.4.2 for details.

5.4.2 Key Equipment Required and Capital Cost

Equipment and Capital Cost for Lignin Extraction

The most widely adopted process for isolating large quantities of kraft lignin is the LignoBoost® process. LignoBoost® is a complete process solution supplied by Metso for extracting lignin directly from black liquid produced by pulping mill. A LignoBoost® plant including all the equipment necessary for lignin extraction is roughly 25 × 20 × 14 m^3 in size. The lignin coming directly from the LignoBoost® plant has the property of

65% to 70% dry solid content and ash content of 0.1% to 0.5% (Bajpai, 2013). On average, the LignoBoost® plant can produce 240 kg lignin per tonne of black liquid.

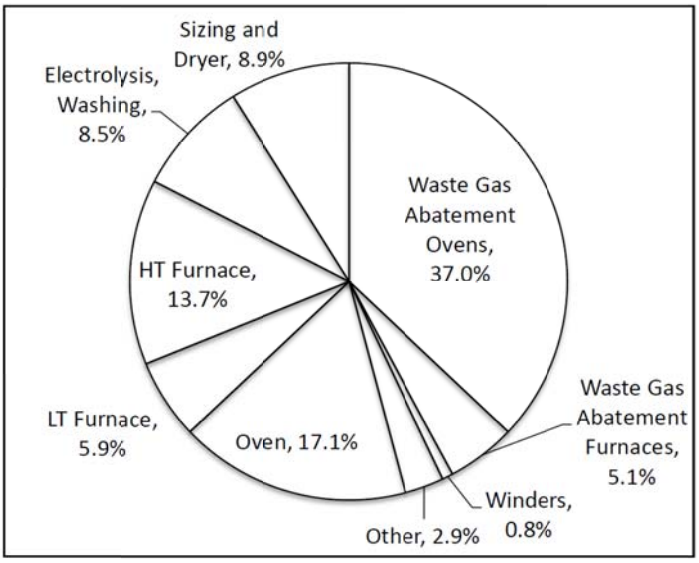
For a LignoBoost® plant to produce 50,000 tonnes lignin per year, the total investment cost is between $12 million and 18 million and the operational cost is between $60 per tonne and $110 per tonne of dry lignin (Tomani, 2010). After lignin extraction, additional processing steps are needed to prepare the lignin to be melt spinning able for carbon fibre production. The price is volatile, ranging from $0.80 per kg to $3 per kg. The industry goal for melt spinnable kraft lignin is $1.1 per kg.

Capital Equipment Cost for Carbon Fibre Production

Carbon fibre producers are very secretive about how their products are manufactured. Each producer's fibre differs from those of its competitors'. For this reason, equipment and process are custom tailored for each manufacture which makes them expensive. A single world class production line can cost a minimum of $25 million for equipment alone and take up to two years to implement. Tokyo-based Mitsubishi Rayon Co. Ltd. has spent $100 million on a three-year expansion of its Otake production facility and SGL has collaborated with BMW to build a $100 million carbon fibre manufacturing facility in Moses Lake, Wash. Each of these plants has the annual capacity of more than 2,500 tonnes (McConnell, 2008).

A representative from Harper International, an equipment provider for carbon fibre production, stated that the key equipment needed are creel stations, winders, oxidation oven, low temperature (LT) & high temperature (HT) furnace, pre & post treatment unit, and waste gas treatment unit. Figure 5.7 shows an estimate cost break down of capital equipment from Harper International. The estimated total capital cost is around $45 million exclusive facility, utilities and installation. The annual capacity of the plan is around 3,000 tonnes. The estimated deprecation cost of carbon fibre produced would be $2.14 per kg, assuming capital cost depreciation over 7 years with zero residual value (Imhoff, 2013).

Figure 5.7 Capital cost structure of carbon fibre manufacturing



*The capital cost of the whole process is estimated to be $45 million. The annual capacity is estimated to be 3,000 tonnes. Source: created by author, with data from Imhoff, 2013

Capital Equipment for Lignin Carbon Nanofibre

The main difference between carbon nanofibres and the conventional carbon fibre production is in the spinning process. As discussed earlier, conventional PAN precursor fibre is generally made by wet spinning or melt assisted spinning techniques. Industrial scale nanofibres are largely produced through electrospinning. For the conversion process (oxidation, carbonization and graphitization), carbon nanofibre and carbon fibre should fundamentally be similar (Lin et al., 2013; Norberg, 2012). However, the end product of electrospinning is in the form of non-woven mat, and is targeting different applications than the conventional carbon fibre, implying that sizing and surface treatment step will be different.

Since industrial scale electrospinning techniques and carbon nanofibre conversion processes are still in the early stage of the development, the majority of the electrospinning machines on the market are designed for laboratory and small-scale production (Luo, Stoyanov, Stride, Pelan, & Edirisinghe, 2012; Persano et al., 2013).

Depending on the setup and capacity, laboratory-scale commercial machines could start at around \$100,000 ("Electrospinning systems : RT Advanced-ETC," 2014). Industrial scale equipment will be custom built and cost in the range of millions of dollars. Table 5.7 shows a list of representing companies in nanofibre processing and their top of the line product.

Table 5.7 Representative companies in nanofibre processing

Organization, Product	Yield
Elmarco, NC Polot Line 500	0.171kg/h
MECC, EDEN	0.18 kg/h
Spur Nanotechnologies, Spin Line	0.192 kg/h
ANSTCO, ANSTCO-NF-Line-IV	0.09 kg/h
Inovenso Ltd, NANOSPINNER416	0.21kg/h

Source: created by author, with data from "Electrospinning Mass Production Output," 2012; Luo et al., 2012; Pisignano, 2013

5.4.3 Yield and Scrap Rate

Yield Rate

An important aspect in carbon fibre production is yield. Higher weight loss represents lower yield, resulting higher production costs. Depending on the chemical structure of the precursor, yields from the various processing steps will vary. For PAN precursor, the overall yield is around 45% to 50% which means that 2 kg of PAN-based precursor is required to make 1 kg of carbon fibre. Table 5.8 shows the yields obtained from each processing step with various sources of lignin precursor. Commercial tar pitch and PAN precursor are also included as a comparison. Unlike commercial tar pitch, the thermal pretreatment step has little effect on yield losses for lignin-based precursor. The large difference in pretreatment yield between lignin and pitch is due to the difference in the chemical components. Lignin precursor contains far less components with low melting point.

Table 5.8 Overall yields of different carbon fibre precursor types

	Pretreatment (%)	Spinning (%)	Oxidation (%)	Carbonization (%)	Overall (%)
HWKL*	99	95.0	94	52	45 to 50
Alcell Lignin	97	95	97	46	40
Tar Pitch	40	95	110	80	33
PAN	~99	95	~108	~54	50 to 55

*Hardwood kraft lignin is purified using the LignoBoost® process. Source: created by author, with data from D. A. Baker & Rials, 2013; Chung, 1994; Das, 2011; Hu, 2002; Morgan, 2005.

In contrast to pitch and PAN-based fibre, a slight weight loss occurs during spinning and oxidation steps of lignin-based fibre. The weight increase in pitch and PAN-based fibre is due to the formation of infused oxygen bridging and cross-linking. Table 5.8 shows that is the case of lignin-based fibres. The majority of weight loss occurs during the carbonization step: 48% for Hardwood Kraft Lignin and 54% for Alcell lignin fibres. The weight loss is substantially higher than pitch, 20% for Tar Pitch. The purpose of carbonization is to eliminate all elements other than carbon. Technical lignin and PAN, with elemental carbon contents of only 59% to 67% are expected to have substantial weight loss, while pitch has >80% carbon. Overall yields are approximately 45% for the HWKL-based carbon fibres and 40% for the Alcell lignin-based carbon fibres. Both results are higher than tar pitch's 33%. With respect to yields, HWKL and Alcell based precursor seem to be a promising option (Hu, 2002; Morgan, 2005). Based on this data, the overall yields of lignin-based carbon fibre is as good as any other precursor type with the yield rate of approximately 50%.

Scrap Rate

There is a knockdown effect during carbon fibre production. Knockdown represents the scrap rate that comes out of a carbon fibre line's stated capacity. The average knockdown for all PAN-based fibre types is about 35% which means that only 65% of a line's capacity is usable. The knockdown percentage tends to be smaller for large-tow carbon fibre and larger for small-tow carbon fibre (Sloan, 2011). Based on the estimation by Chris Red, CEO of Composites Forecasts & Consulting LLC, the manufacturing efficiency of carbon fibre tow will increase substantially over the next decade. He estimated that production efficiency was about 60% in 2012, increasing to 68% by 2016 and reaching 72% by 2020 (Sloan, 2011). Since the conversion processes between PAN and lignin-based fibres are similar, the same knockdown ratio should be applicable to lignin-based carbon fibre when technology matures.

5.4.4 Rate-limiting Steps

Oxidation is currently the rate limiting step of the carbon fibre process because its length last from 0.5 hours to 2 hours. Comparing carbonization, which takes only minutes, oxidation is the slowest and most energy consumption step in the whole process. With typical oxidation oven ranging from 500 m to 1000 m in overall heated length, oxidation has limited the production speed of PAN-based fibre, ranging from 15 m/min to 20 m/min (Stry, 2012). As discussed in section 2.1.1, lignin precursor has high oxygen content in the side chains which require shorter oxidation period at a lower temperature comparing to PAN precursor. For this reason, the cost in the oxidation process is expected to be lower (Hu, 2002). The data presented in Table 5.9 shows that costs are estimated to reduce from \$2.2 per kg of PAN carbon fibre to \$1.7 per kg when producing lignin carbon fibre.

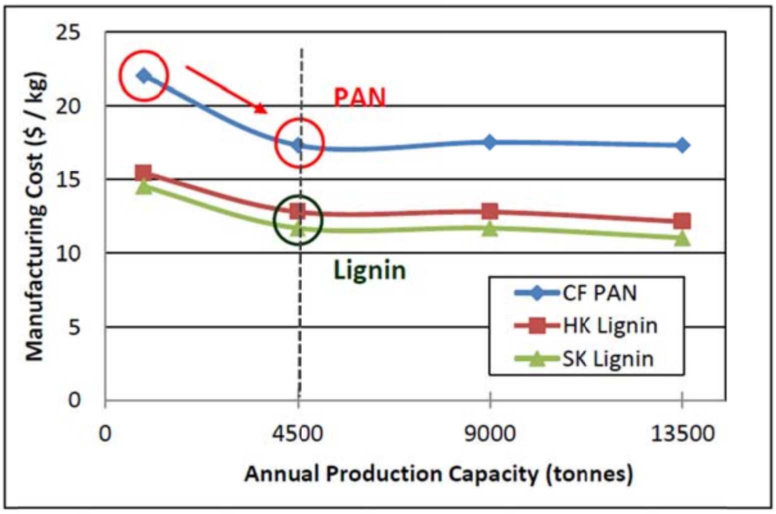
It is known in the industry that the efficiency of the oxidation furnace plays a critical role in the production process. According to Randy Strop, general manager for Despatch Industries, there are three important elements for the oxidation oven design: throughput, scalability and energy efficiency. RMX Technologies and ORNL have worked together to improve the current oxidation process with plasma based conversion process. The new process can potentially reduce the processing time by 65% (Paulauskas, 2013). The technology is suitable for PAN-based precursor, but it can potentially be used for other precursor types such as lignin in the near future according to the interviews with industry experts (see appendix A).

5.4.5 Economies of Scale

In microeconomics, economies of scale are the cost advantages that enterprises obtain due to size, output, or scale of operation with cost per unit of output decreasing as the fixed costs are spread out over the units of output (Heakal, 2013). With increasing scale of operation, companies can have advantages in bulk buying of raw materials through long-term contracts and large capital investment in production capacity (Heakal, 2013).

Interview with representative of a key industry player indicated that the conversion process for lignin-based carbon fibre resembles PAN-based carbon fibre and thus the amount of saving achieved between the two processes due to increase scale of operation should also be comparable. Based on the information provided by ORNL, the minimum efficient scale for a carbon fibre production line is 4,500 tonnes per year (Paulauskas, Warren, Eberle, Naskar, & Ozcan, 2007) as shown in Figure 5.8. The study conducted by Kline and Co. in 2007 suggests that for a conventional 900 tonnes annual capacity line, the production cost is roughly $22 per kg. If the line size were scaled-up for higher volume production, at around 4,500 tonnes per year, the point of diminishing returns would be reached. At that point the production cost would be around $17 per kg. Since the development of lignin carbon fibre is aimed for high volume production applications, the cost estimation should base on high volume capacity, 4,500 tonnes per year (Paulauskas et al., 2007).

Figure 5.8 Minimum efficient scale for carbon fibre production



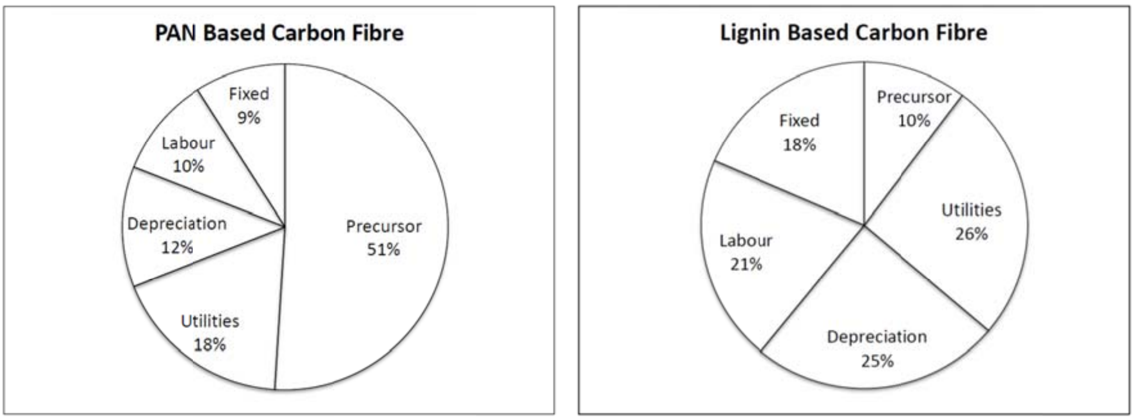
Source: created by author, with data from Paulauskas et al., 2007

5.4.6 Cost Breakdown

Raw Material, Equipment and Utility

For PAN-based carbon fibre, the cost of precursor accounts for 51% of the cost of manufacturing carbon fibres followed by 18% utilities, 12% depreciation, 10% labour and 9% represented by other fixed costs (D. A. Baker & Rials, 2013). This assumes the minimum efficient annual production volume of 4,500 tonnes (Figure 5.8). The cost breakdown for PAN-based carbon fibre in terms of raw material, equipment, and utility is shown in Figure 5.9 a). These types of cost categories are fulfilled in manufacturing cost modeling (Maine & Ashby, 2002; Taleb et al., 2014).

Figure 5.9 a) Cost breakdown for PAN-based carbon fibre (based on \$22/kg) b) Cost breakdown for lignin-based carbon fibre (based on \$11/kg)



a) b)

Source: created by author, with data from D. A. Baker & Rials, 2013

Since the processes of producing lignin and lignin carbon fibre are still under development, it’s not clear what the cost breakdown structure for lignin-based carbon fibre is like in terms of raw material, equipment, and utility. However, it is expected that the cost of precursor in the cost breakdown structure will be dramatically reduced, and the overall cost of lignin carbon fibre will be lowered comparing to the PAN-based system. Figure 5.9 b) shows the estimation of the cost breakdown of lignin carbon fibre. Based on the feedback from interviews with key industry leaders, if lignin-based precursor is used, the weight of precursor in the cost breakdown structure will be dramatically reduced (lignin precursor is estimated at \$1.1 per kg). Comparing to petroleum based precursor, lignin is already substantially oxidized. Therefore, oxidative thermo-stabilization of thermoplastic lignin fibre to thermoset lignin fibre could proceed faster than PAN-based fibre. According to the interview data (see appendix A), the difference could be from hours to minutes. The improvement will also reduce energy consumption and equipment cost (D. A. Baker & Rials, 2013). Based on the ORNL’s estimation, energy saving during oxidation could fluctuate around 30% (Das, 2011; Eberle, 2012; Imhoff, 2013). Since the carbon fibre manufacturing process is highly automated, the labour cost should remain the same for both processes.

Processing Steps

The cost breakdown of PAN and lignin-based carbon fibre in terms of the process steps (spinning, oxidation, carbonization, surface treatment and sizing) are shown in Table 5.9. The cost of spinning includes the cost of precursor.

When analyzing the cost structure between two precursor types, the biggest difference is in the cost of precursor and spinning. The estimation of $11.1 per kg is based on melt assisted or wet spinning plus the price of PAN precursor. As discussed in section 2.1.1, melt assisted and wet spinning methods are expensive due to the use of solvents and relatively low spinning speed in comparison with melt spinning. PAN precursor is also expensive and highly dependent on petroleum price.

The estimated price of lignin at $1.1 per kg is based on melt spinning ready lignin from FPInnovations's Lignoforce® Technology. Like LignoBoost®, Lignoforce® is also designed for kraft mill and has similar ash content, molecular weight distribution, etc. Since lignin precursor is still in the development stage, only few early adopters have the processing plant installed such as Domtar Corporation. The price at $1.1 per kg is an industry goal when the degradation and purification process matures (current cost for melt spinning ready kraft lignin is beyond $1.1 per kg). Representatives from ORNL and FPInnovation noted that in order to have a fair comparison between the lignin and PAN precursor costs, lignin has to be melt spinning ready; otherwise raw lignin feedstock should be compared with the cheaper raw material, acrylonitrile monomer (AN).

Table 5.9 Cost breakdown for PAN and lignin-based carbon fibre in terms of $/kg and % of overall cost

	Process Steps	Precursor & Spinning	Stabiliza-tion	Carboniza-tion	Graphitiza-tion	Surface Treatment	Sizing	Total cost
PAN Base Line (900 tonnes)	PAN (%)	51	16	23		4	6	100
	PAN, ($/kg)	11.1	3.4	5.1		0.8	1.3	21.7
PAN High Volume (4500 tonnes)	PAN (%)	59	13	19		4	5	100
	PAN, ($/kg)	10.2	2.2	3.3		0.7	0.9	17.3
Lignin High Volume (4500 tonnes)	Lignin (%)	23	26	21	23	3	5	100
	Lignin, ($/kg)	1.1*	1.7	1.4	1.5	0.7	1.3	6.6

*The cost of spinning process includes the prices of precursor. At $1.1/kg, the lignin is assuming melt spinning ready. The estimation for lignin carbon fibre is based on the more aggressive goal of reaching $6.6/kg ($3/lb). Source: created by author, with data from D. A. Baker & Rials, 2013; F. S. Baker, 2009; Norberg, 2012; D. Warren, 2011

From above analysis, it is clear that lignin precursor can potentially lower the overall cost of carbon fibre from approximately $20 per kg to as low as $6.6 per kg. Table 5.9's estimate for lignin carbon fibre is based on a more aggressive goal of reaching $3 per lb ($6.6 per kg). Based on the information provided by industry experts (see appendix A), $5 per lb ($11 per kg) is good enough to create market penetration.

6: Summary of Findings and Conclusion

6.1 Summary of Finding

Potential Market

Carbon fibre is the most economically rewarding application for lignin. The three fast growing potential markets for carbon fibre industry are automotive, wind energy and aviation. A subsector of carbon fibre is emerging with the development of carbon nanofibre, which has strong potential in EMI shielding in the consumer electronics sector. Based on the current price (approximately \$35/kg), the global market demand for carbon fibre is expected to reach 130,000 tonnes (\$4.5 billion in sales value) in 2020. Assuming that the precursor accounts for 50% of the carbon fibre manufacturing cost, the precursor market is estimated to be \$2.25 billion in 2020.

Amongst the four market segments, the automotive industry requires the lowest modulus strength with a tensile strength of 1.72 GPa, and a modulus of 172 GPa (low to standard modulus fibre). The main driving force behind the use of carbon fibre in vehicles is improving fuel efficiency forced by government regulation. If carbon fibre price can be as low as \$11 per kg, the potential global carbon fibre market in 2017 for auto industry will be 138,300 tonnes (\$1.5 billion).

Wind energy is the next market with fast potential growth. It requires stronger fibre performance (standard modulus fibre) than the automotive industry but less than the aviation industry. The driving force behind wind energy generation is the need for large size wind turbine blades. Carbon fibre demand for the wind energy industry is expected to be 37,000 tonnes (\$1.1 billion) in 2020.

The aviation industry is the most critical and high profile application for high-modulus fibre. The driving force behind this application is the increasing use of carbon fibre composites in lightweight fuel-efficient aircraft. The estimated market size for carbon fibre composites in the aviation industry is 19,700 tonnes (\$2 billion) in 2020.

EMI shielding market demand is growing not just because of the increasing demand for electronic devices but also due to tighter safety and performance regulations. For carbon nanofiber, the global market size for EMI shielding is expected to be approximately \$6 billion in 2018; carbon nanofibre can be estimated to account for approximately \$2 billion in this sector.

TCOS Analysis

The key TCOS levers and hurdles identified for lignin carbon fibre and lignin carbon nanofibre are summarized in Table 6.1. While factors such as allowing for melt spinning process and shorter oxidation time represent some of the advantages of lignin-based fibre over PAN, inconsistency in its chemical characteristics and lack of technical knowledge of its application in a bio-refinery system are examples of the technological hurdles that the developers need to overcome.

Although lignin-based carbon fibre is patentable, current technological challenges may handicap its development as its short-term commercial viability is unclear. One of the most promising ways for commercializing lignin carbon fibre is to emphasize its positive environmental characteristics, i.e. the potential social benefits (societal levers). However, it is also one of the organizational hurdles faced. The university's TTO is struggling to balance their dual responsibilities of commercializing the research in seeking financial gains and demonstrating societal benefits.

Lignin carbon fibre technology is encouraged by government regulations to improve automotive fuel efficiency. There will be automotive specific safety regulations and crash testing specifications to meet. However, the technology is also under stringent international trade regulations due to its usage in the aviation industry. With shorter oxidation stage, lignin precursor has the benefit of reducing greenhouse gas and toxic gas emission. Potential health concerns over airborne fibre dust and difficulties with recycling at the end of product cycle are examples of the social hurdles confronted.

The main focus of this report is on commercialization and its interaction with other three uncertainties (technological, organizational and societal). Consumers embrace CFRPs with its connection to high performance auto racing. Shorter oxidation stage not only gives the social benefit of a more environmentally friendly process but also gives the commercial lever of a more efficient and cheaper production process comparing to PAN. Encouraged by government regulation, carbon fibre finds its way in potential markets like automotive, wind energy and aviation. However, the usage in the aviation industry has also left carbon fibre subject to stringent trade regulations. Steep challenges from incumbent technologies and the lack of reliable sources of lignin are examples of commercial hurdles that the early adopters need to overcome.

Table 6.1 Summary of TCOS analysis for lignin carbon fibre and lignin nanofibre.

Uncertainties	Lignin Carbon Fibre and Lignin Nanofibre	
Technological	Lever	● Lignin precursor has chemical structure advantage over PAN precursor type, allowing for melt spinning process. ● Lignin has the capability to stabilize much faster than PAN fibres since lignin is already substantially oxidized.
	Hurdle	● The technology for lignin usage in bio-refinery systems is still in the early stage of development. ● The complexity and inconsistency in lignin chemical structure is not fully understood. ● Electrospinning, the most promising method for nanofibre, is still immature.
Organizational	Lever	● Opportunities for patents, trade secrets and licensing. ● Opportunities for collaboration with incumbent market players.
	Hurdle	● Standard commercialization strategy deployed by TTOs may not be suitable for lignin carbon fibre technology diffusion. ● Entry barrier for carbon fibre industry is very high.
Societal	Lever	● Carbon fibre process using lignin as a precursor produces less green house and noxious gases. ● The lignin carbon fibre precursor fits well into the current bio-refinery process encouraged by the U.S. government.
	Hurdle	● Carbon fibre is difficult to recycle. ● There are concerns over possible inhalation and skin irritation of air born carbon fibre dusts. ● Tight import and export regulatory restriction due to applications in the aviation industry and the military industry.
Commercial	Lever	● Consumer embraced CFRP for its connection with high performance image especially in the automotive industry. ● Lignin is currently the cheapest precursor material under investigation for next generation carbon fibre precursor. ● Lignin precursor improves the production efficiency and reduces waste treatment cost.
	Hurdle	● Facing steep challenges from incumbent technologies. ● Uncertainty of lignin supply due to conservatism of pulp and paper industry. ● Hesitation of mass adaptation due to volatility of carbon fibre

		market. ● High barriers for customer adaptation. New manufacturing process has to be in place to embrace CFRPs. ● Lack of industry knowledge of utilizing carbon fibre. ● CFRPs are difficult to repair.

Cost Analysis

Lignin based carbon fibre precursors are expected to have a substantial production cost advantage over incumbent PAN based precursors. Process cost analysis was conducted, including estimates of achievable technological advances which would most affect manufacturing costs. The key factors that have direct and indirect impact on the unit cost of lignin carbon fibre are precursor cost, capital costs of equipment for precursor processing and carbon fibre production, scrap rate, and rate-limiting steps. The most widely adopted process for isolating large quantities of kraft lignin is LignoBoost® process. The industry's goal for melt spinnable kraft lignin is $1.1 per kg (current cost is beyond $1.1 per kg).

Carbon fibre production is an expensive process. A single production line can cost a minimum of $25 million for equipment alone. The key equipment needed are creel stations, winders, oxidation oven, low temperature (LT) & high temperature (HT) furnace, pre & post treatment unit, and waste gas treatment unit. The main difference between carbon nanofibres and the conventional carbon fibre production is in the spinning process. Unlike conventional fibre, nanofibre requires electrospinning. Industrial scale electrospinning techniques are still in the early stage of the development. Depending on the setup and capacity, laboratory-scale commercial machines could start at around $100,000. Industrial scale equipment will be custom built and cost in the range of millions of dollars.

The overall yield of lignin-based carbon fibre is as good as any other precursor types with the yield rate of approximately 50% (2 kg of precursor is required to make 1 kg of carbon fibre). The average scrap rate for all PAN-based fibre types is about 35%.

The same scrap rate should be applicable to lignin-based carbon fibre when technology matures.

Oxidation is currently the rate limiting step of the carbon fibre process. Because lignin precursor requires shorter oxidation period at a lower temperature comparing to PAN precursor, oxidation can also be improved by as much as 30%. The costs for oxidation alone are estimated to reduce from \$2.2 per kg for PAN carbon fibre to \$1.7 per kg when producing lignin carbon fibre.

From the information provided by ORNL, the minimum efficient scale for a carbon fibre production line is 4,500 tonnes per year. For PAN-based carbon fibre, the cost of precursor accounts for 51% of the carbon fibre manufacturing cost. With similar yield and scrap rate, lignin carbon fibre will reduce the cost dramatically. The overall cost of low to standard modulus fibre is expected to drop from approximately \$20 per kg to \$6.6 per kg. The cost of lignin precursor only accounts for 10% of the overall cost. Based on the information provided by industry experts, \$5 per lb (\$11 per kg) is good enough to create market penetration for the automotive industry.

Because of lignin carbon fibre's shorter oxidation time, it can reduce 7 kg of CO_2, 12 g of HCN emission, and 150 MJ of energy consumption per kg of carbon fibre produced comparing to PAN-based counterparts. This can further be converted to the savings in social costs.

6.2 Conclusion

Target Market and Course of Action

The application of the TCOS uncertainty framework and the preliminary cost analysis developed in this study suggest that the initial target market for lignin carbon fibre should be the automotive industry. Based on the challenges identified in current technology advancements, high-modulus carbon fibre applications may not be a candidate for the alternative precursor such as lignin, but it might be acceptable for automotive applications because of less stringent performance requirements in non-structural usage. Alternative precursors are not a viable option in the aviation market and wind generation market as they cannot yet meet performance requirements.

Of all potential markets, carbon fibre application in the automotive industry is considered the most stable and embraced by consumers. CFRP in sports and race cars is perceived to be a superior material that enhances performance; consumers are willing to pay at a premium price. Wind energy is considered the most volatile market. Despite of rapid growth and technological advancement, wind turbine prices have shown a 20% to 35% decline since late 2008 due to the stiff competition with OEMs turbine. Due to low profit margin and dependence on the U.S. and Chinese governmental policies, turbine manufactures are hesitant to design new blades with innovative material such as carbon fibre.

Despite a healthy backlog of orders for the commercial aviation market, carbon fibre demand for the military aircraft usage is volatile. Over the past five years, the global military aviation industry has been losing altitude as western defence budgets shrivelled. There is also a high uncertainty of whether the composite can make it to the fuselage design of the next generation narrow body aircraft which accounts for 70% of the word's airline fleets.

The market forces that drive carbon fibre supply and demand are numerous and complicated. Despite a long-term increase in demand, there is also a high chance of oversupply caused by government subsidy for its strategic value. Demand is predicted to increase to 130,000 tonnes ($4.5 billion in sales value) in 2020.

Due to limited information available on nanofibre at this early stage of development, it is too early to comment on the initial target market. However, the feedback from industry regarding the use of low cost lignin carbon fibre in EMI shielding is very positive. Currently, carbon fibres used in EMI shielding are generally made from PAN via electrospinning. The main challenges are high precursor and solvent recovery cost. Lignin carbon fibre can be very competitive in this context.

The results indicate that the key strategy for the innovators moving forward is to focus primarily on optimizing the technology in terms of lignin precursor consistency and efficiency of manufacturing process that utilizes carbon fibre. Although the strength of current lignin carbon fibre is good enough for some of the auto industry applications such as body panels, the major barrier for the automotive industry to adopt lignin-based carbon fibre is batch-to-batch inconsistency. Another challenge is that current CFRP manufacturing process is nowhere close to the metal stamping process in terms of speed.

The challenges for lignin nanofibre in the EMI shielding market are similar. Shielding performance of lignin nanofibre also suffers from inconsistency due to lignin's chemical characterises. The data indicates that if the electrospinning nanofibre could be combined with thermoplastics, a significant market application would open up in injection moulding since it is considered one of the cheapest and most efficient ways of mass production.

One of the keys for successful adaptation of carbon fibre in the automotive industry is the price. The standard modulus fibre suitable for automotive application is currently estimated at $40 per kg. It is still too expensive for the application in mass production vehicles. Based on interviews with industry experts (see appendix A), the price has to be around $11 per kg. Lignin carbon fibre has great potential to reach this goal on the assumption that melt spinnable lignin precursor can be supplied at $1.1per kg. The efficiency of carbon fibre production is improved with shorter oxidation period, and the yield and scrap rate of lignin-based carbon fibre is as good as that of conventional precursor types.

Carbon fibre is a complex and capital-intensive industry. Due to lack of required market expertise and financial capital of the commercializing venture for lignin based carbon fibre precursors, it would be sensible to out-license the technology to an incumbent firm that possesses the manufacturing and marketing capabilities. In addition to cost advantage, environmental benefits are also a major attractive point of lignin technology when compared to PAN-based carbon fibre. These aspects, combined with the establishment of strategic collaboration, may provide this technology with the required resources to overcome its hurdles for commercialization.

Future Work

The present report reflects the status of the TCOS uncertainties surrounding the lignin-based carbon fibre and provides a preliminary cost analysis for this new technology. The work was limited due to lack of data on nanofibre. As more studies are conducted in this area, future commercialization analysis will be able to provide a more complete market assessment and cost modelling for lignin-based carbon nanofibre.

In this research, only EMI shielding market has been investigated for carbon nanofibre. However, the unique properties such as high electron conductivity, high specific surface area and superior directional strength also allow carbon nanofibre to find applications in energy storage areas such as brush contact in commutator brush, switches, and electrodes in capacitors and batteries. Work remains to identify the potential beachhead market for lignin-based carbon nanofibre.

Carbon nanofibre and commercial electrospinning equipment are still in the early stage of development. Even though fibre conversion processes between carbon fibre and nanofibre are fundamentally the same, the manufacturing steps are different due to the differences in physical properties of the output. Carbon nanofibre is in the form of non-woven mat that utilizes the functional properties such as electrical and thermal conductivity. This implies that the sizing and surface treatment step will be different from conventional carbon fibre. As technology advances, parameters such as key inputs, rate limiting steps, equipment requirements, etc. can be identified. A more accurate cost analysis can be performed for carbon nanofibre.

As part of the commercial uncertainty, future supply and demand relationship of lignin should be studied. Currently, lignin is considered a waste product from the pulp and paper industry. The cost of lignin is based largely on the processing cost, targeted at $1.1 per kg by industry experts. The supply of high purity lignin is limited and unstable due to conservatism in the pulp and paper sector. As the demand for high purity lignin expands, the market structure and raw material price may start to shift. This change can influence the future utilization of lignin carbon fibre.

As the technology evolves, future TCOS analysis will be able to identify different and more accurate levers and hurdles for lignin based carbon fibre and nanofibre. The examination of these uncertainties at such early stages of development is crucial because it aims to help shape the technology for effective dissemination.

Appendices

Appendix A: Conducted Lignin Carbon Fibre Interviews

Date	**Interviewee**	**Company**
2011-12-09	Principal Scientist	FP Innovation
2012-02-15	Program Manager, Bi- refinery	FP Innovation
2012-02-23	Chief Executive Officer	Lignol
2012-03-29	New product Manager	Weyerhaeuser
2012-03-29	Director, Technology Partnerships / Open Innovation	Weyerhaeuser
2012-08-09	Scientist	FPInnovations
2013-03-05	Chief Technology Officer	Lignol
2013-04-09	Associate Professor	University of British Columbia
2013-08-06	Scientist	Weyerhaeuser
2013-08-08	Commercialization Manager	Oak Ridge National Lab
2013-08-08	Chief Technology Officer	Plasan Carbon Campsites
2013-08-14	V.P. Technology & Business Development	PlastiComp
2013-08-30	Senior Consultant	MJBradley and Assoc.
2013-09-09	Senior Scientist	Oak Ridge National Lab
2013-09-13	Postdoc Research Associate	Kessler Research Team at Iowa State University
2013-09-16	Project Manager	Södra Innovation
2013-09-16	Mechanical Engineer	Research Council of Canada
2013-09-19	Technology Development Manager	Oak Ridge National Lab
2013-09-19	Chief Executive Officer	LTI Associates
2013-09-27	Director, Business Development & Strategy	Applied NanoStructured Solutions

Appendix B: Current Progress in Lignin Carbon Fibre Development

Industries	Desired Property	Developer	Novelty
Automotive	Weight reduction	Plasan	Reduce cycle time of making CFRPs parts from 90 min to 17 min. Further improve the moulding process with Globe Machine Manufacturing Co. for medium-volume vehicle production.
		Ford Motor Company	Use CF panel on low to medium volume vehicle.
		Momentive Specialty Chemicals	5 min curing epoxies used in high-pressure resin transfer moulding process is commercial ready. 2 min curing is under trial.
		BASF & SGL	BASF and the SGL Group jointly develop reactive polyamide system for CFRPs used in the automotive industry. The system uses Thermoplastic Resin Transfer Moulding (T-RTM).
		DowAksa	Join venture of Dow Chemical Company and Aksa intended to produce low cost and higher performance carbon fibres.
		Continental Structure Plastics	Provided lightweight materials and composite solutions for the automotive, heavy truck, HVAC and construction industries. In May 2013 it has expanded production in Pouance, France.
		Faurecia	Europe's largest manufacture in automotive body panel. Currently, looking to expand existence in North America.
		Hanwha-Azdel	Investing $20 million for constructing a new plant in Bugang, South Korea for lightweight reinforced thermoplastic (LWRT) for Asia

			automotive industry market.
Wind Energy	High strength, Weight reduction	Kessler Research Team (Iowa State University)	Developing lignin-based CF for wind turbine blades. Developing resins for composites repairing.
		Sandia National Laboratories	Developing model testing for composites wind turbine blades.
Aviation	High strength, Weight reduction	Toho Tenax America, Inc	Toho's Tenax® HTS 3k, 6k and 12k fibres have been qualified to the NMS 818 dry fibre specification for aviation applications.
		ATK Launch System	The largest producer of rocket motor cases with extensive CF experience.
		SABIC Innovation	Created CF technology coupled with polyetherimide resin for aviation applications.
Pressurized Oil and Gas Storage, or Offshore structure	High specific strength	Toho Tenax America, Inc	Toho's Tenax® brand carbon fibres has been qualified and applied on offshore oil and pressure Vessels.
Civil infrastructure	High specific strength, Environmental resistance	Altus Group Precaster	Altus Group uses CF based reinforcement in precast concrete to enhance the strength and reduce the weight.
		Chomarat North America	Manufacturing nonwoven carbon composite for civil construction applications.
Non-aviation defence	High strength, Weight reduction	TorTech Nano Fibres Ltd (Plasan & Q-Flo)	Plasan, has join ventured with Q-Flo, a University of Cambridge spin-off company, to produce carbon nanotube infused fibre for body armour and armour vehicles.
Electronics	High electrical conductivity	PlastiComp	Developing carbon fibre EMI shielding material.
		National Research Council	Building carbon fibre radio antenna dish.

		Advanced Fibrous Materials Laboratory (University of British Colombia)	Developing lignin carbon nanofibre through Electrospinning. Potentially used in EMI shielding.
		Composite Materials Research Laboratory (State University of New York)	One of the pioneers in EMI shielding with carbon fibrous materials.
Thermal Management	Thermal conductivity, Flameproof	GrafTech & ORNL	First commercial application of lignin CF as high temperature thermal insulation.
Equipment and Process Development	Improve CF production efficiency	Despatch Industries	Experts in thermal process technology and oxidation oven.
		Metso Power	Purchased LignoBoost® form Innventia. First to commercialize it on an industrial scale.
		RMX Technologies	Collaborate with ORNL in plasma based oxidation process to reduce oxidation time of CF conversion.
		Harper International	Leader in oxidation oven and LT and HT slot furnaces design.
Raw Material	Low cost, High purity	Sodra	Sodra supports the development of the LignoBoost® technology.
		FPInnovation (Vancouver Canada Based)	Develop LignoForce® Lignin from kraft pulping process. The process is low capital and capable of producing high purity dry lignin.
		Innventia	Develop LignoBoost® technology with Chalmers University of Technology.
		CIMV	CIMV's Biolignin® from wheat straw is currently the only technology to market highly pure lignin macromolecule that can be used as replacement for phenols in a petrochemical process.

		Lignol	Use solvent based pre-treatment technology to produce high-yield conversion of cellulose to ethanol. Produce high purity HP-L® lignins.
		Domtar	Developed BioChoice® lignin from Southern Pine. The company has a commercial-scale lignin separation plant at its Plymouth, N.C., mill, the first U.S. based facility of its type.

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