Deliverable report

Deliverable Data		
Deliverable number	D4.1 & D4.2	
Dissemination level	LignoCOST members	
Deliverable name	Value chains for lignin valorization: lignin-based carbons	
Work package	WG4	
Lead WP/Deliverable beneficiary	Per Tomani, RISE/whole consortium	
Deliverable status		
Submitted (Author(s))	20/03/2023	Omid Hosseinaei
Verified (WP leader)	25/03/2023	Per Tomani
Approved (Coordinator)	18/04/2023	R.J.A. Gosselink

Contents

Summary

The high carbon content of lignin makes it a renewable and low-cost precursor for making different carbon materials. Recent concerns about global warming and transitions from petroleum-derived materials to sustainable materials resulted in significant attention to lignin as a green carbon precursor. Here, some of the most important carbon materials and their current market status shave been evaluated. The status of lignin-valorization toward commercial production of these materials has been described. The opportunities, including main drivers, main efforts, and challenges for the commercialization of these products have been presented. Most lignin-based carbons are still in the research stage but the huge market growth for carbons, especially in energy-related applications and lightweight materials, has encouraged many companies and start-ups to invest in the production and commercialization of lignin-based carbons.

Introduction

The objective of this WG is to describe the lignin value chain in lignin valorization. Here, market opportunities related to the most important lignin-based carbon products will be evaluated. Also, the stakeholders will be identified and the current state-of-the-art status will be described. In this evaluation, a few most promising and common lignin-based materials were selected for value chain study. We focus on different lignin-based carbons in this report as materials with potentially very diverse and fast-growing applications.

Carbons are in different forms and have a wide range of applications from lightweight materials to adsorbents, coatings, electronics, and energy-related applications The need for portable energy storage units and concerns about global warming and environmental pollution have made these materials even more important due to their application in making batteries. The most common current carbon sources are petroleum-derived materials or materials from mining such as graphite. However, the transition to developing sustainable materials created a unique opportunity for lignin as a renewable carbon precursor. Lignin is an excellent renewable carbon source due to its high carbon content and aromatic structure. Lignin has been studied for producing a wide range of carbon materials including carbon fibers, carbon nanofibers, carbon foams, graphite, and graphene (Figure 1).[1–5]

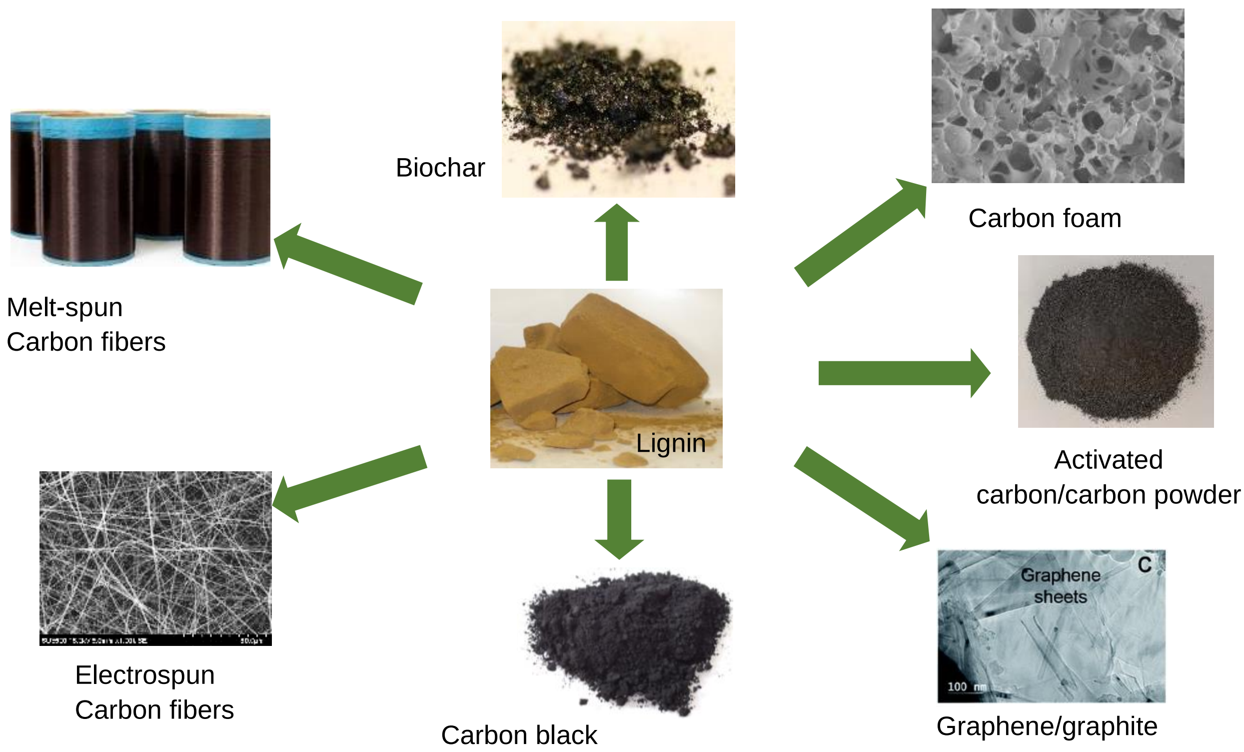


Figure 1. Examples of possible different lignin-based carbons.

These carbon materials can have different forms and morphology with a wide range of applications (Figure 2). Need to mention these materials are currently mostly in the lab-scale or pilot-scale production. However, efforts are ongoing to commercialize lignin-based carbons and in some areas, such as lignin-based carbon fibers, it has been focused on since several decades ago. Since carbon materials are very diverse we will focus on some of them which are the most common and important ones with more potential opportunity for lignin: carbon fiber, carbon for energy storage including graphite and graphene, activated carbon, and carbon black.

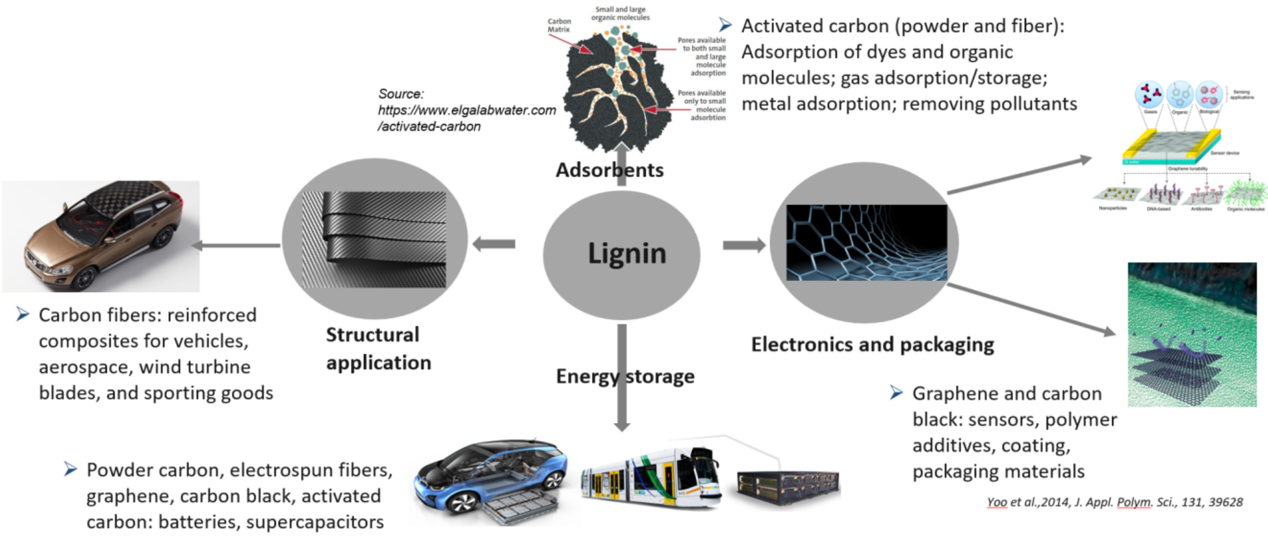


Figure 2. Potential application of lignin-based carbons.

Value chains for selected lignin-based carbons

Carbon fibers

Commercial carbon fibers

Carbon fibers, as lightweight high-modulus fibers, are considered one of the most significant industrial materials in modern-day technology. The main application of carbon fiber is for producing lightweight composites with various applications such as the automotive industry, civil construction, aerospace application, wind energy, aviation, and offshore (Figure 3).[6] The application of carbon fiber is not limited to lightweight composites, and it has expanded to the energy storage industry.[7]

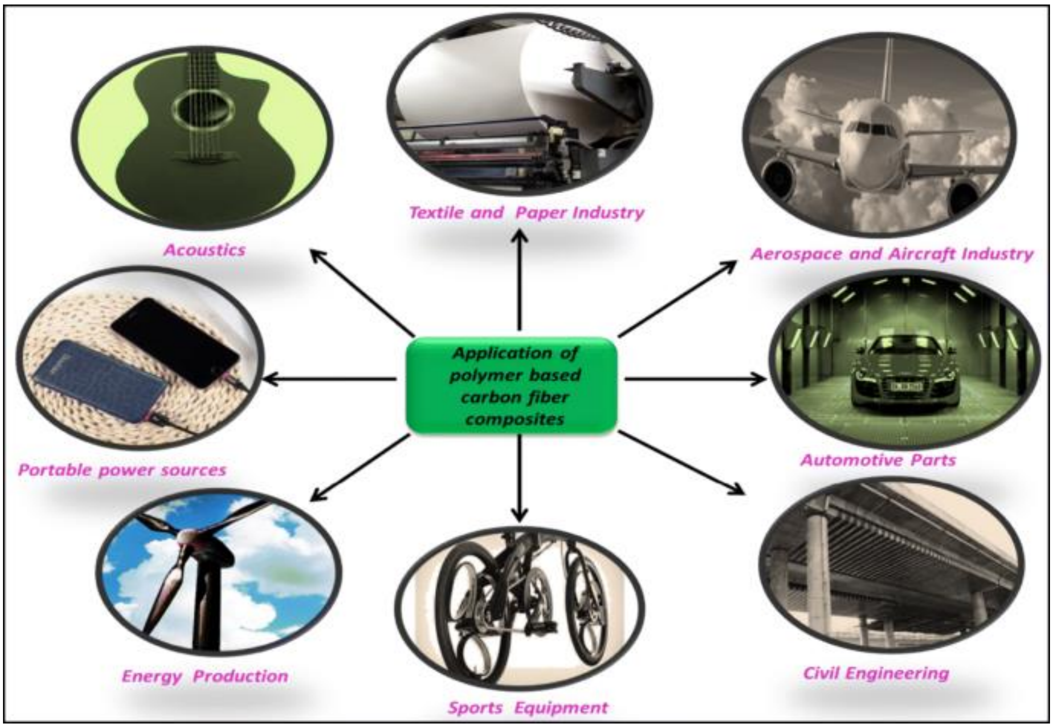


Figure 3. Different applications of carbon fibers.[6]

The carbon fiber production is expected to exceed 194 ktons in 2022, with a market size of $ 48.7 billion, at a CAGR of 6.6% in the past decade.[8] Figure 4 shows the market size of carbon fibers based on different areas of application. The largest user of carbon fiber is wind turbine manufacturers (~23% of the market). CF reinforced polymers (CFRPs) production is expected to exceed 194 ktons in 2022. All market segments grow—increasing demand (CAGR: 8–12%).[6,9]

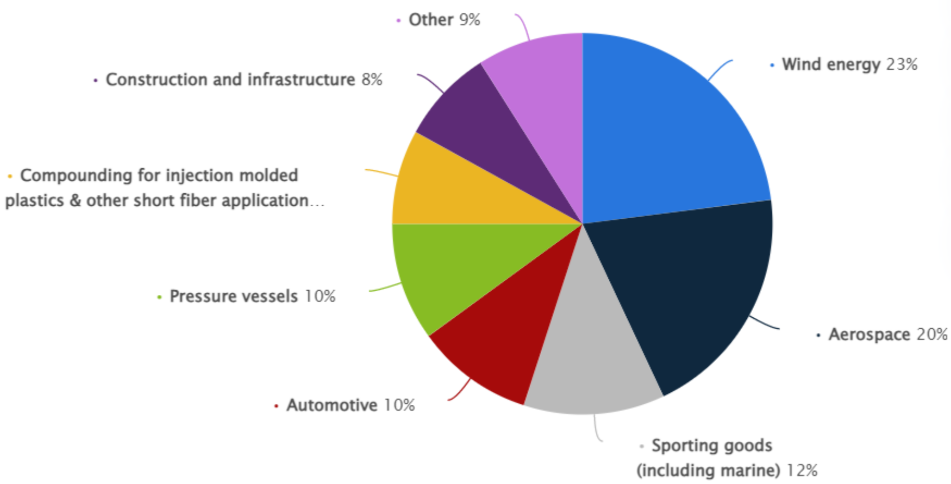


Figure 4. The market size of carbon fibers (source: Statiska 2022).

The main precursor for manufacturing carbon fiber is polyacrylonitrile (PAN) which is a petroleum-based synthetic polymer. PAN-based carbon fibers make up about 90% of total carbon fiber globally manufactured. Pitch-based carbon fibers make up almost the rest of the market plus a small production of rayon-based carbon fibers (Figure 5).[9] Pitch is a polycyclic aromatic hydrocarbon derived from petroleum residue oil or coal tar. PAN-based carbon fiber dominates structural reinforcement applications because of its intermediate modulus and high tensile strength. Other potential precursors are lignin, lignin/cellulose blends, nanocellulose, polyethylene, and bio-PAN.

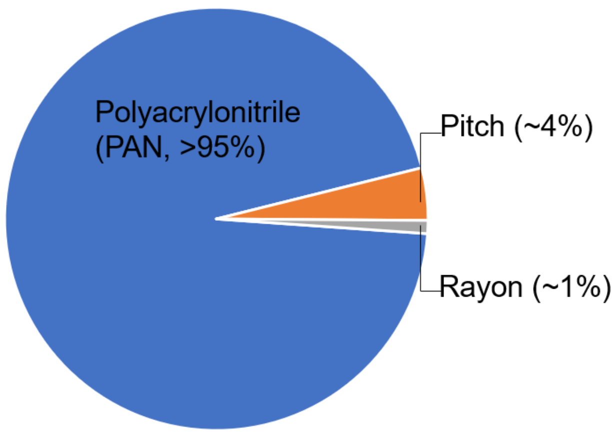


Figure 5. Commercial carbon fiber precursors.[9]

The average cost and energetic cost for the PAN-based carbon fiber are 30 €/kg and 183–286 MJ/kg, respectively.[8] Precursor accounts for more than 50% of the carbon fiber production cost (Figure 6).[10] However, a low-cost, high-volume, mid-range-performance carbon fiber is needed for most applications such as the automotive industry. In addition, international efforts toward decreasing environmental pollution and CO_2 production are pushing toward using renewable precursors for producing carbon materials.

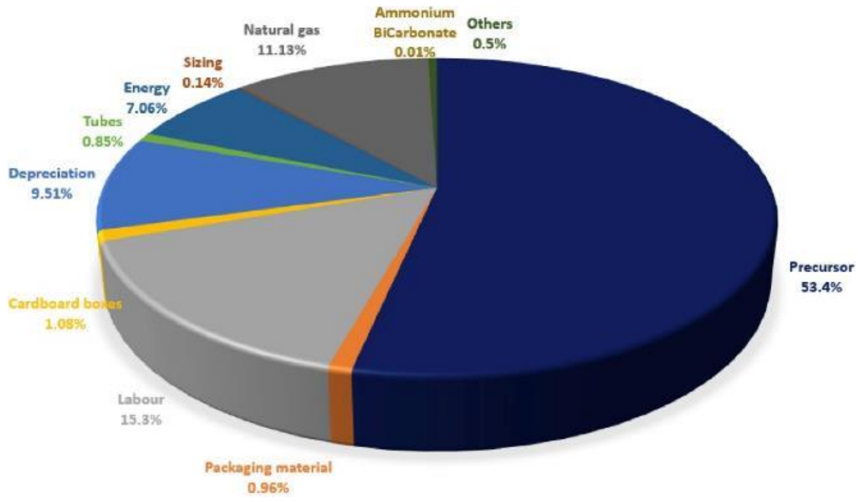


Figure 5. Commercial carbon fiber precursors.[10]

The Carbon fiber market is dominated by few companies and there are not many players in this market (Figure 5). This can be a disadvantage for developing lignin-based carbon fiber since these companies can resist the willingness toward changing precursors for producing a more sustainable carbon fiber.

Figure 5. Main commercial producers of carbon fibers.

The market analysis data shows that the demand for carbon fiber is rapidly growing (Figure 5). Therefore, there is a great expansion of the carbon fiber industry toward different products, especially the huge automotive industry. However, the expected growth of production capacity is less than market growth. This creates a great opportunity for low-cost and low-carbon footprint carbon fibers which are preferable for common applications such as lightweight composites for cars. Other precursors, such as lignin, can play an important role in the expansion of carbon fiber production and application toward daily-use products.

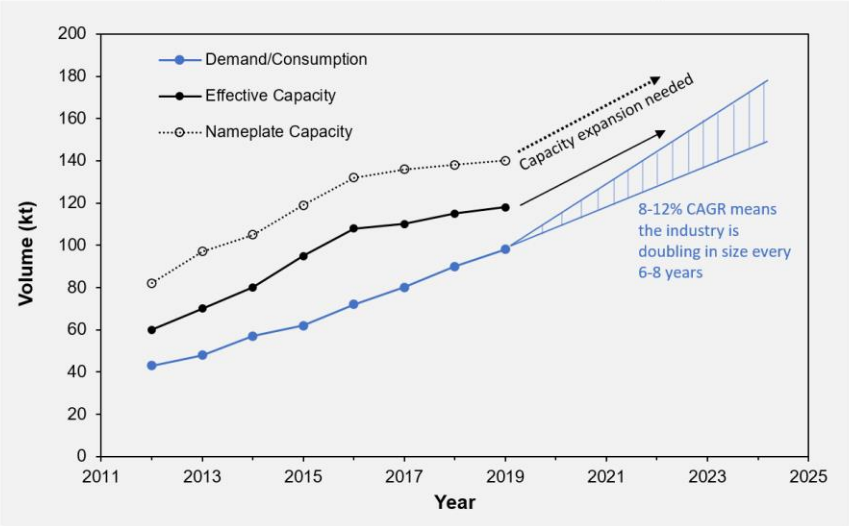


Figure 5. Demand and production capacity of carbon fibers.[9]

The carbon fiber market is not limited to only fibers and it includes other forms of products such as fabrics, prepeg, and carbon fiber reinforced polymer (CFRP) which are suitable forms for composite manufacturing. Carbon fiber producers control/produce ~70% of carbon fiber prepreg and ~80% of carbon fiber pultrusion markets (Table 1). The carbon fiber market (95 kt carbon fiber) is worth ~€2.5B, but the downstream activities add €4B on top of it.[9]

Table 1. Carbon fiber production and downstream business.[9]

Company	Precursor production	Carbon fiber production	Fabrics	Prepreg	CFRP
Toray	X	X	X	X	X
Mitsubishi	X	X	X	X	X
Teijin	X	X	X	X	X
Hexcel	X	X	X	X	-
SGL	X	X	X	X	X
HengShen	X	X	X	X	X
ZhongfuSY	X	X	-	-	X
DowAksa	X	X	X	X	X
Solvay (Cytec)	X	X	X	X	X

Lignin-based carbon fibers

The high demand for lightweight materials and concerns about global warming are the main drivers for developing sustainable and low-cost carbon fibers. Lignin has been at the center of these efforts for producing a renewable carbon fiber precursor. Different forms of lignin-based carbon fibers have been manufactured at both research- and pilot-scale. Wet-spinning, melt-spinning, and electrospinning are the main fiber spinning techniques that have been used for manufacturing lignin-based carbon fibers (Figure 6). Melt-spinning is considered to be the most cost-effective method for fiber spinning due to the high production speed and lack of need for solvent removal and recovery. Carbon fibers from melt-spinning and wet-spinning are considered suitable for structural application and developing lightweight composites. However, carbon fibers from the electrospinning process are submicron fibers in form of nonwoven mats and suitable for non-structural applications such as energy storage or as adsorbents.

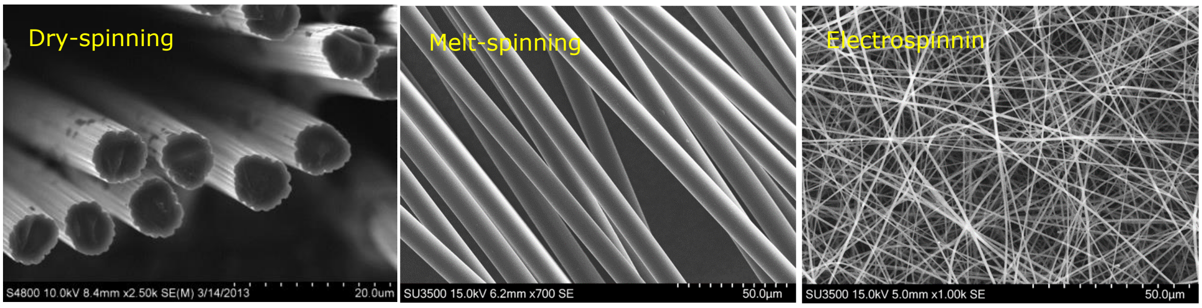


Figure 6. Lignin-based carbon fibers from different spinning techniques.[1,11,12]

The properties of the current lignin-based CF are in line with the properties of other low-modulus carbon fibers from isotropic pitch and cellulose (Figure 7). Amorphous carbon structure and lack of orientation are the main reasons for the low tensile properties of the current lignin-based carbons. These properties are much lower than current state-of-the-art PAN- or mesophase pitch-based carbon fibers (Figure 7). The automotive industry recommendations are prices in the range of $11–$15.40/kg, a tensile strength of 1.72 GPa, and a tensile modulus of 172 GPa.[13] Therefore, improving the properties of carbon fiber will provide an opportunity for using these materials in both automotive and wind energy industries. Need to mention carbon fibers have advantages compared to glass fibers due to their lower density. Also, low-modulus fibers have some market share currently as providing impact resistance in composites.

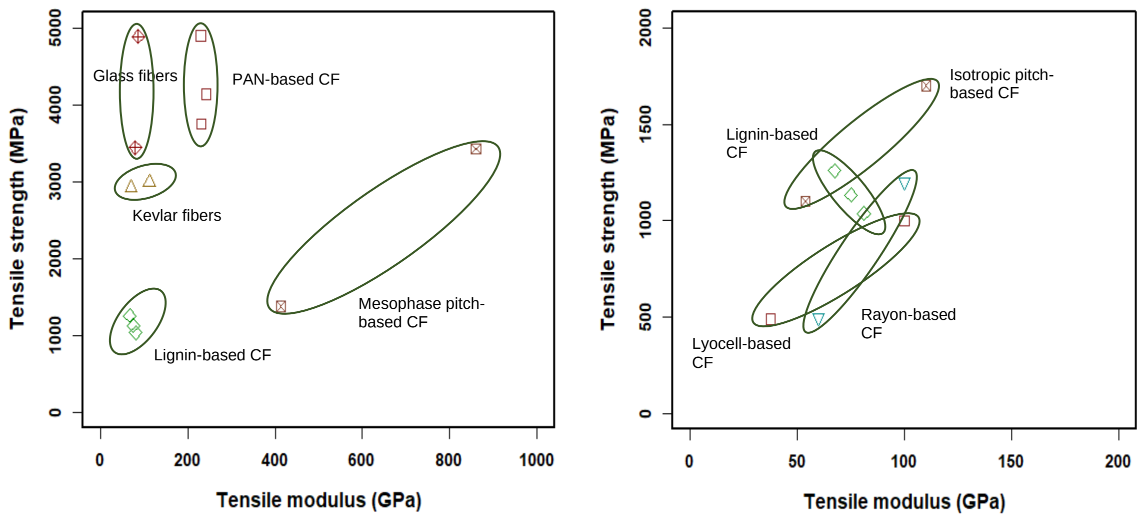


Figure 6. Tensile properties of current lignin-based carbon fibers vs different commercial structural fibers: left) lignin-based carbon fibers vs high modulus fibers; right) lignin-based carbon fibers vs low-modulus fibers. (Data related to lignin-based carbon fibers are from melt-spun fibers produced at RISE and data for commercial fibers are from manufacturers' databases)

Looking at the structure of different carbon fibers shows the impact of orientation on the stiffness of carbon fibers as mesophase pitch-based carbon fibers have the highest stiffness due to their highly ordered structure. On the other hand, the morphology and structure of lignin-based carbon fiber are more like a turbostratic structure which can be seen in PAN- and isotropic pitch-based carbon fibers (Figure 7).

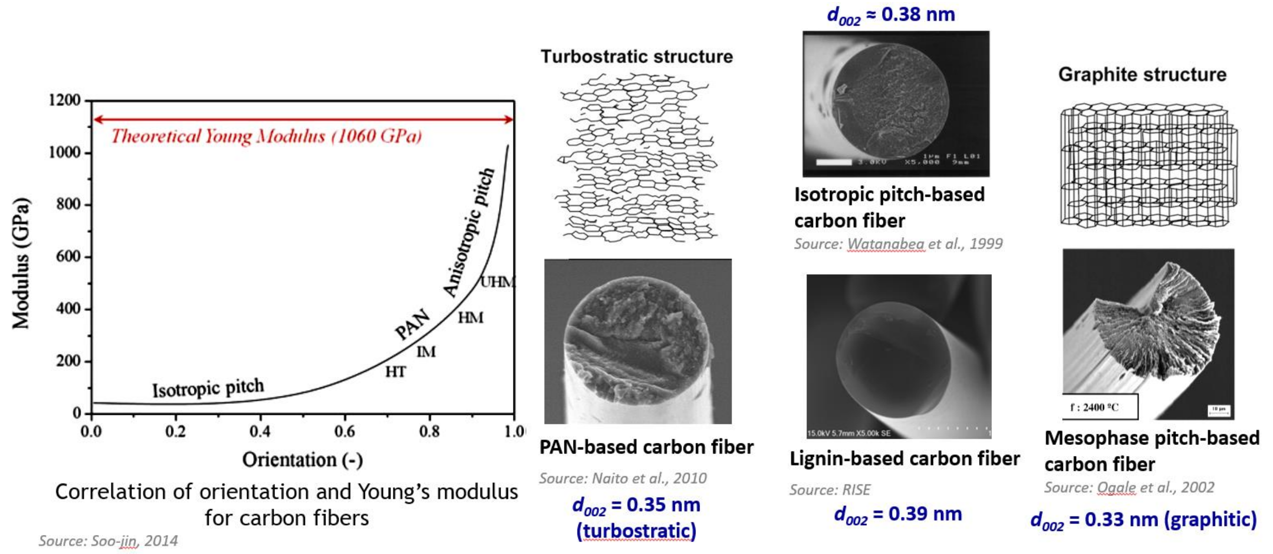


Figure 7. Structure of different carbon fibers. (d_{002}: interplanar spacing in (002) crystal lattice structures; data for isotropic pitch and lignin-based carbon fibers are from fibers carbonized at 1000 ˚C).

Commercialization of lignin-based carbon fibers

The main drivers for developing lignin-based carbon fibers are:

- The global movement toward decreasing environmental pollution and CO_2 production by using sustainable materials instead of petroleum-based materials.
    - A study showed that the climate impact of a lignin-based carbon fiber sample is estimated to be 1.50 kg CO_2 eq/kg while it is between 19.3–38.9 kg CO_2 eq/kg for PAN-based carbon fibers and 1.98 kg CO_2 eq/kg for glass fibers.[14]
- Lignin is a renewable, abundant, high-carbon content, and low-cost precursor.
    - The estimated annual production of lignin from only the pulp industry is 70 million tons (without considering emerging biorefineries for bioenergy production).[3]
- Increasing demand for lightweight materials (especially for the automotive industry).
    - The automotive industry requires low-cost, high-volume, mid-range-performance carbon fibers to produce lighter and more fuel-efficient cars.
- Concerns related to releasing toxic gasses, such as hydrogen cyanide, during the conversion of PAN.

Efforts on the commercialization of lignin-based carbon fibers

Commercialization of lignin-based carbon fibers has been investigated since the 70s but still, there is no commercial lignin-based carbon fiber. The following are the most noticeable efforts:

- Nippon Kayaku (Japan): They made the first commercial lignin-based carbon fiber in the 1970s under the trade name of Kayacarbon (status: *discontinued*)
    - Based on dry spinning alkali lignin and PVA
- Bayer AG (Germany): Published patents on producing lignin-based carbon fibers in 1973 and 1974 (*discontinued*)

- Based on dry-spinning lignosulfonate with PEO or acrylic acid–acrylamide
- Zoltek and Weyerhaeuser (USA): Zoltek and Weyerhaeuser worked together on producing low-cost carbon fiber from a lignin-PAN blend (status: *started in 2011, discontinued*)
  - Based on wet-spinning PAN and kraft lignin
- Stora Enso (Finland): Works, in collaboration with Cordenka, on the development and commercialization of carbon fiber from a lignin-cellulose blend (NeoFiber®) (status: unknown)
  - Based on wet-spinning kraft lignin and cellulose viscose
- Volkswagen AG (Germany): Published a paper on producing lignin-based melt-blown carbon fibers (status: *published in 2015, discontinued*)
  - Based on melt-blowing hardwood lignin

Main challenges in the commercialization of lignin-based carbon fibers:

- Variations in lignins based on botanical source, geographical environment, refinery process, and separation technique.
- Technological challenges in scaling up such as spinnability and conversion rate.
- Not reaching to desired tensile properties for structural applications.
- Reducing the price of commercial PAN-based carbon by developing more efficient and cheaper technologies such as plasma oxidation or cheaper precursors (textile-grade and melt-spinnable PAN).
- Losing the sustainability edge by increasing efforts for developing bio-based PAN.

Carbon in energy storage

Graphite

Based on the predictions, the energy rate demand will increase from 14 TW in 2010 to 28 TW in TW as a result of the increasing world population (Figure 8).[15] This equates to 130,000 TWh or the equivalent of 10^{10} tons of oil yearly which can dramatically increase CO_2 emission. Therefore, the development of renewable energy technologies is critical for achieving this goal without intensifying global warming. Renewable energy sources such as wind, solar, and biomass are scattered and to make the best use of these resources and have a continuous supply good energy storage systems are needed. Electrochemical energy storage technologies, especially Li-ion batteries, are the dominant systems for storing energy and using it in portable devices. The anode electrode in Li-ion batteries is made from graphite which currently comes from mining or petroleum/coke.

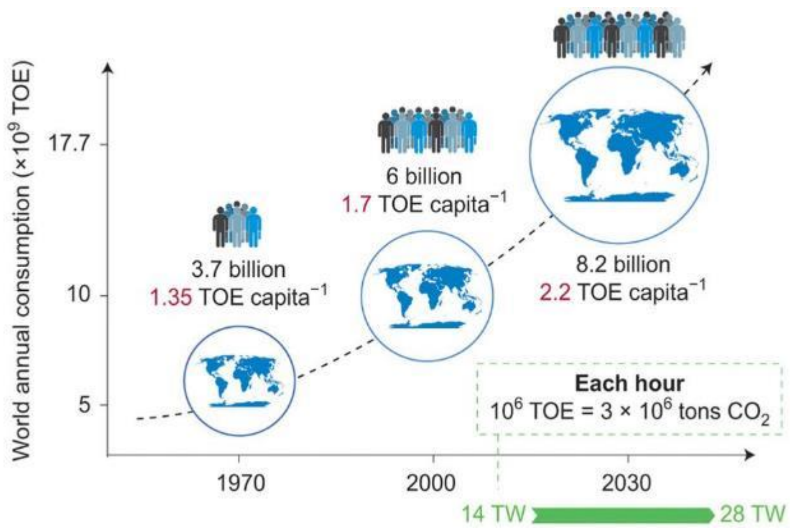


Figure 7. Past, present, and forecast of the world's energy needs (TOE = ton of oil equivalent).[15]

Natural graphite is produced by mining and synthetic graphite is made from hydrocarbon sources such as petroleum or coke. Graphite is divided into different groups based on its source and specifications (Figure 8).[1]

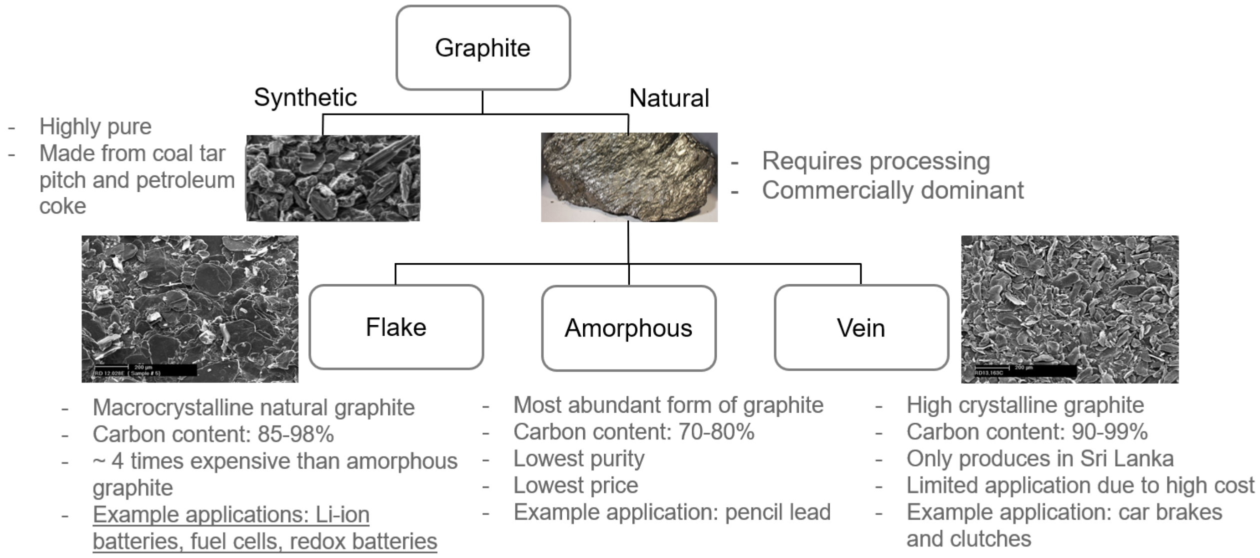


Figure 8. Different types of graphite and their specification and application.

Graphite has very diverse applications in different areas (Figure 9). However, developing Li-ion batteries is the main factor for increasing demand for graphite. It is expected that the battery industry will be the largest consumer of graphite in the coming years.[2]

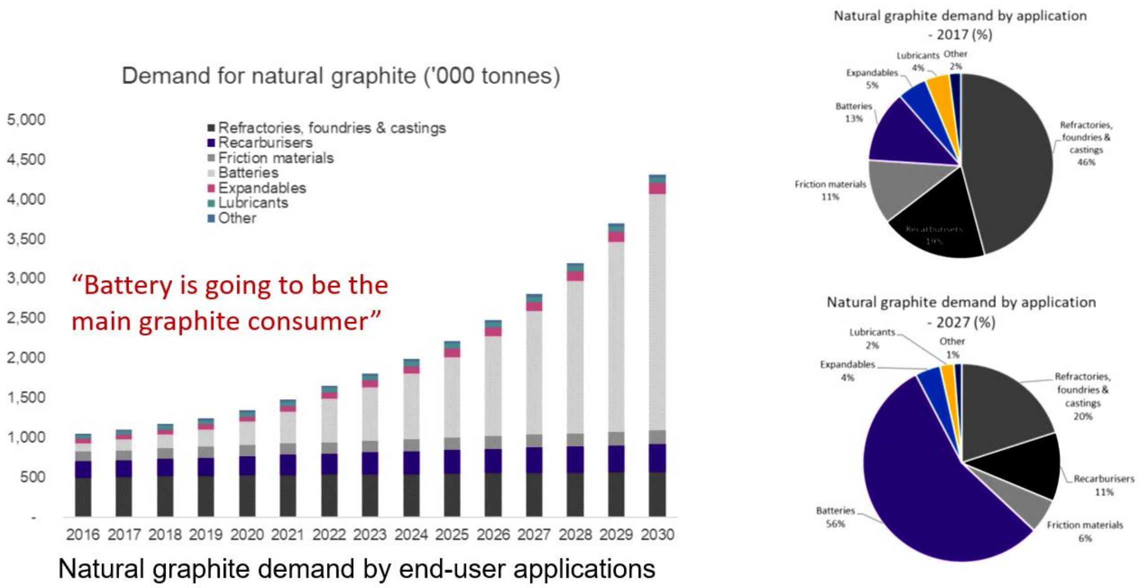
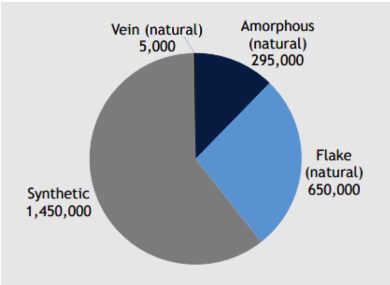


Figure 9. Current and forecasted market and demand for graphite.

[1] Sources: https://www.azom.com/article.aspx?ArticleID=1630; https://www.acarbons.com/types-and-varieties-of-graphite; https://asbury.com/resources/education/science-of-graphite/natural-flake-graphite/

[2] Source: Tirupati Graphite, Prospects for Natural Graphite Flake, accessed 15 November 2019, https://www.tirupatigraphite.co.uk/pdf/Fast-market-Graphite-Market-report.pdf

The total production of graphite was 2.43 million tons (0.95 million tons natural and 1.48 million tons synthetic graphite) in 2018. The price of natural flake graphite price (94%-97% pure) is $1,050/t for large-size flakes, $900/t for medium, and $745/t for small flakes. The current anode market is 160,000 tons (in 2018).[16] Synthetic graphite has a larger market share and the main current producers of graphite are listed in Figure 10.[3]



Global graphite market in 2016

Main synthetic graphite producers:

- Kaifeng Carbon
- Nippon Carbon
- Tokai Carbon
- Graphite India Limited
- HEG Limited
- Asbury Carbons

Main natural graphite miners:

- Syrah Resources
- Mason Graphite
- Graphite One
- Northern Graphite
- Magnis Resources
- Focus Graphite

Figure 10. Graphite market and main producers.

Batteries

Li-ion batteries can be found in almost all portable electronic devices and electric cars. Current producers of Li-ion batteries and their production capacity are shown in Figure 11.[4] Among all devices using Li-ion batteries, electric vehicles have the fastest-growing market and are expected to be the largest consumers of Li-ion batteries (Figure 12).[5]

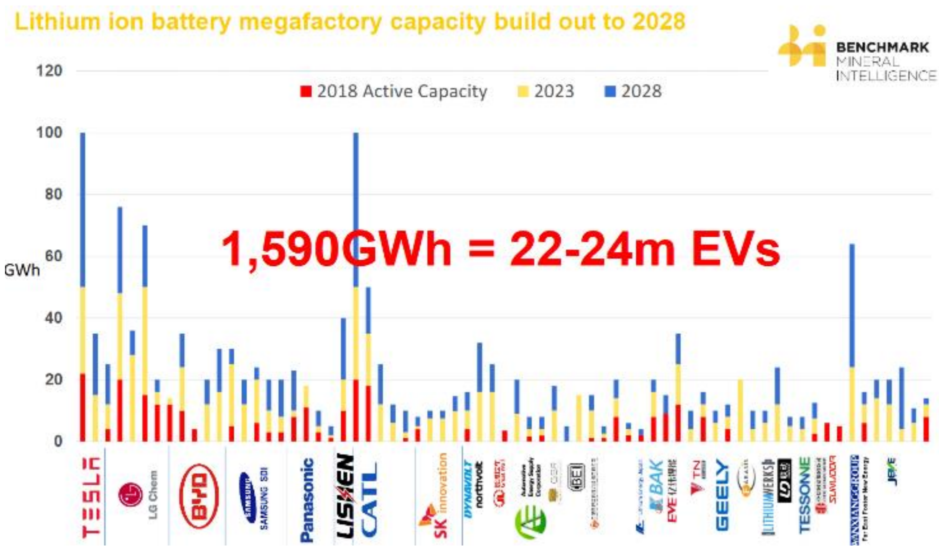


Figure 11. Production capacity of main Li-ion battery manufacturers.

[3] Sources: Argus Media Report, Argus White paper: Getting graphite prices right, accessed 15 November 2019, https://www2.argusmedia.com › media › Files › white-papers; Tirupati Graphite, Prospects for Natural Graphite Flake, accessed 15 November 2019, https://www.tirupatigraphite.co.uk/pdf/Fast-market-Graphite-Market-report.pdf

[4] Source: Source: A Look At The Top 5 Lithium-Ion Battery Manufacturers In 2019, accessed 11 November 2019, https://seekingalpha.com/article/4289626-look-top-5-lithium-ion-battery-manufacturers-2019

[5] Source: Bloomberg NEF, Electric Vehicle Outlook 2019, accessed 11 November 2019, https://bnef.turtl.co/story/evo2019/?utm_medium=Newsletter&utm_campaign=BNEF&utm_source=Email&utm_content=wirmay21&mpam=21051&bbgsum=DM-EM-05-19-M21051

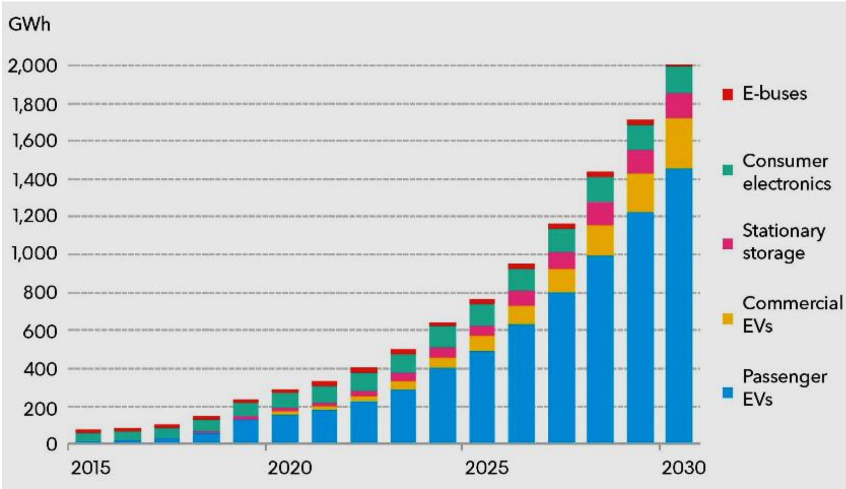


Figure 12. Lithium-ion battery demand in different sectors.

Electric vehicles' Li-batteries need a significant amount of graphite which is about 35-50 kg for a fully electric sedan (Figure 13).[6] Fast-growing electric car markets and expanding it to trucks and busses are the main reason for making this industry the main consumer of graphite.

	2017 unit sales (global, thousands)	Lithium ion battery size	Anode Material per unit (natural & synthetic combined)	Natural Flake Graphite per unit (40 - 50% yield per kg of anode material)
Plug in Electric Vehicle	~400	5 - 20kWh	5 - 20kg Balanced proportion of natural and synthetic graphite	10 - 30kg
Full Electric Vehicle	~400	30 - 45kWh	30 - 45kg Balanced proportion of natural and synthetic graphite	35 - 50kg
Electric Commercial Truck	~120	40 - 70kWh	40 - 70kg Balanced proportion of natural and synthetic graphite	40 - 80kg
Premium Electric Vehicle	~150	75 - 100kWh	75 - 100kg Higher proportion of synthetic graphite	40 - 50kg
Electric Bus	~105	150 – 350kWh	150 – 350kg Balanced proportion of natural and synthetic graphite	150 – 380kg

Figure 12. Li-ion battery sizes and consumed graphite in current vehicles.

Supercapacitors

Supercapacitors are another type of energy storage device that stores and release energy by reversible adsorption and desorption of ions at the interfaces between electrode materials and electrolytes. Supercapacitors are different from batteries in terms of rapid charge and discharge rates, high power density, and long cycle life. Unlike batteries, both electrodes of supercapacitors are made from carbon. The main component of supercapacitor electrodes is porous carbon in combination with other carbonaceous materials such as graphene, carbon nanotubes, activated carbon, graphite, etc. The automotive industry, consumer electronics, and transportation are the main users of supercapacitors and it has a fast-growing market (Figure 13).[7]

[6] Source: Syrah Resources, Syrah Resources and Graphite Market, Macquarie Bank Australia Conference, May 2018
[7] Sources: Source: IDTechEX, Supercapacitors: Applications, Players, Markets 2020-2040, viewed 3 December 2019, https://www.idtechex.com/en/research-report/supercapacitors-applications-players-markets-2020-2040/661; Business Wire, Supercapacitor Market - Global Forecasts Based on End-Users and Opportunity Assessment by

CAGR: Compound annual growth rate

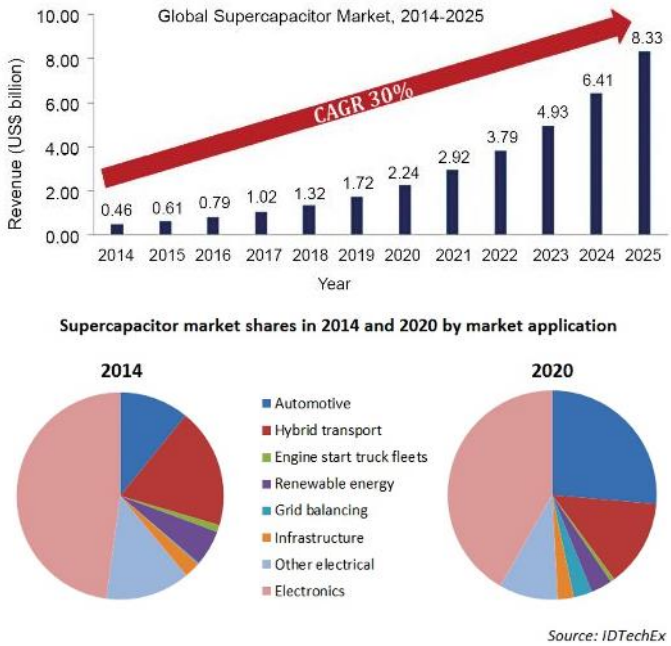


Figure 13. Global supercapacitor market.

The main producers of supercapacitors and their main characteristics and application are shown in Figure 14.[8]

Company	Country
Ioxus	USA
Maxwell Technologies[1]	USA
Murata Manufacturing	Japan
Panasonic	Japan
Eaton	USA
CRRC	China
Nippon Chemi-Con	Japan
Skeleton Technologies	Estonia
Yunasko	UK
LS Mtron	Korea
Aowei	China
Supreme Power Solutions	China
CAP-XX	Australia

Main characteristics:

- Long cycle life
- High-power delivery
- Fast charge and discharge cycle
- Usually contain no heavy metals or toxic materials

Main applications:

- Backup power supply
- Automotive industry
- Wind energy (as intermittent generators)
- Electrical grids
- Public transportation (train, bus, elevators)

Figure 14. The main producers of supercapacitors.

Technavio, viewed 3 December 2019, https://www.businesswire.com/news/home/20170503006181/en/Supercapacitor-Market---Global-Forecasts-Based-End-Users

[8] Source: Thomas, Top USA and International Capacitor Manufacturers and Suppliers, viewed 3 December 2019, https://www.thomasnet.com/articles/top-suppliers/capacitor-manufacturers-suppliers/: IDTechEX, Supercapacitors: Applications, Players, Markets 2020-2040, viewed 3 December 2019, https://www.idtechex.com/en/research-report/supercapacitors-applications-players-markets-2020-2040/661

Lignin in energy-related applications

Energy-related applications, such as energy storage, are some of the most attractive areas for the valorization of lignin and a potentially large and fast-growing market for producing lignin-based materials. There are many research and developments from both academia and industry on using lignin in energy storage and electronics. Probably the most common and promising way of application of lignin in this area is by using lignin-based carbon as electrodes in batteries and supercapacitors (Figure 15). This would be a non-structural application of lignin-based carbons which is different from carbon fibers for structural applications. In non-structural applications lignin will be used as carbon materials in energy storage devices and primarily replace graphite in batteries.

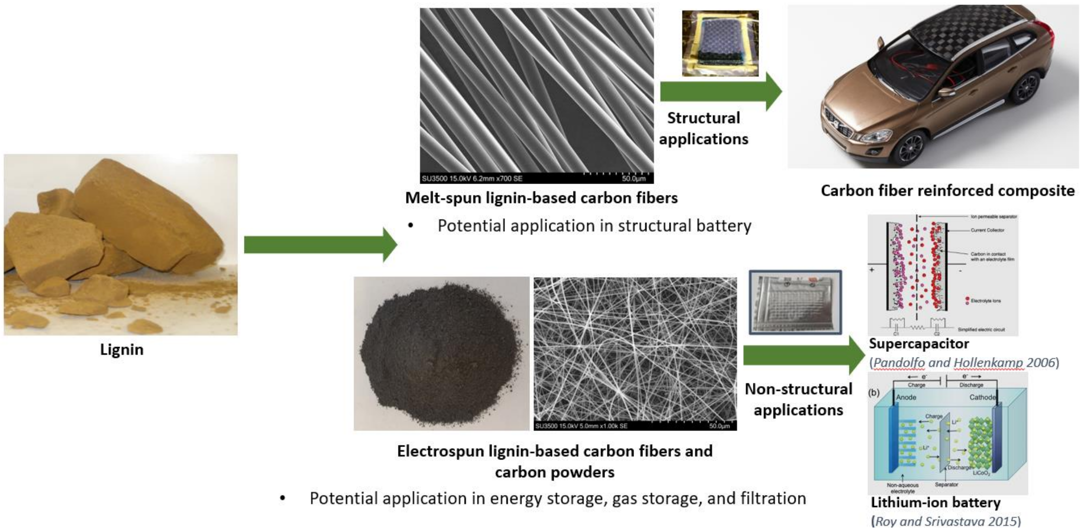


Figure 15. Structural and non-structural application of lignin-based carbons.

Lignin-based carbons can have different forms, powder or non-woven fibers when used as electrodes in batteries or supercapacitors (Figure 15). Electrospun fibers are high surface area non-woven mats that can have many potential applications (Figure 16).[17]

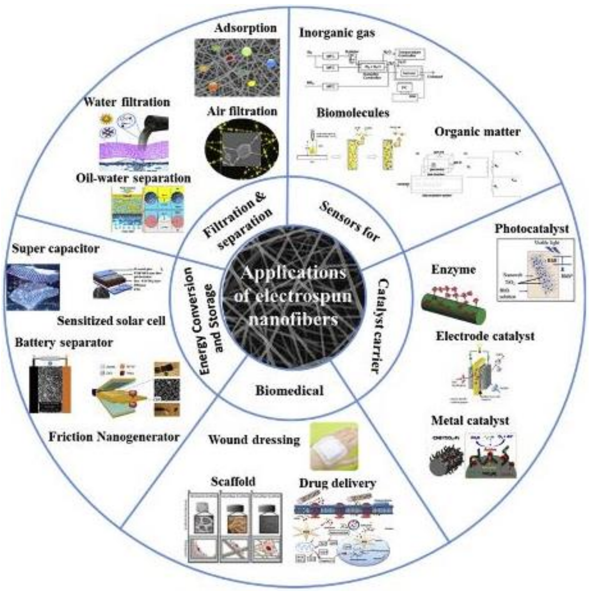


Figure 16. Potential application of electrospun fibers.[17]

Electrospun carbon fibers (carbon nanofibers) have unique properties: high surface area, high electrical conductivity, high structural stability, and high mechanical strength with flexibility. These properties make these materials a perfect choice for different potential applications when high surface area and electrical conductivity are needed such as supercapacitors, batteries, hydrogen storage, air emission control (CO_2 adsorption), filtration media, and composites. Lignin is a promising precursor for making electrospun carbon fibers and many research and development works are ongoing on this topic (Figure 17).[1,3]

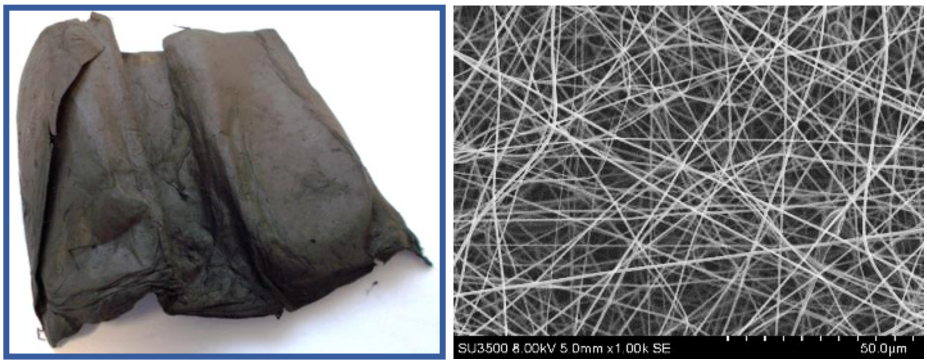


Figure 17. Lignin-based electrospun carbon fibers.

Graphite vs hard carbon

Carbon materials divide into two main groups: graphitizable and non-graphitizable carbons (Figure 18). Lignin-based carbons belong to non-graphitizabale carbons—hard carbon—and the main characteristics of these materials are:

- The graphenic sheets are discrete fragments, curved, bent, or twisted
- Turbotractic structure with random orientation of graphene layers
- Contain voids and pores
- The density of 1.4–1.7 g cm-3 vs 2–2.25 g cm-3 for graphite

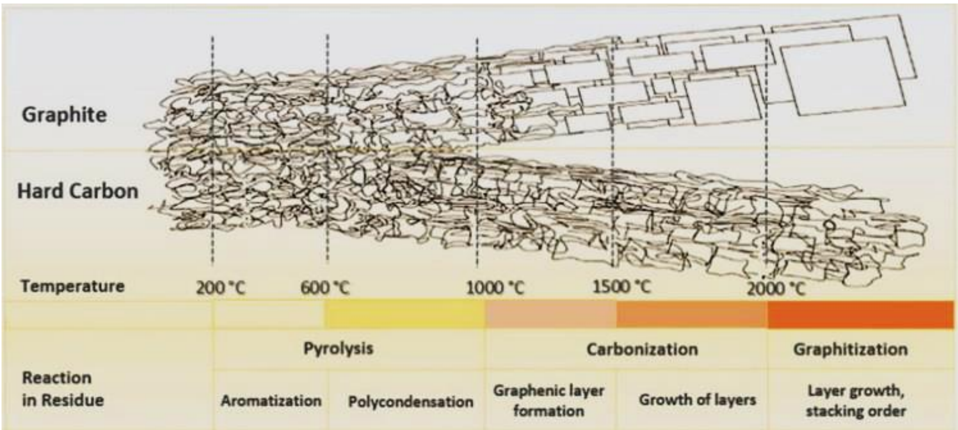


Figure 18. Formation of different carbons as a function of temperature (graphitizable vs non-graphitizable carbons).[18]

Hard carbon, due to its characteristics, performs differently from graphite when used as battery electrodes in Li-ion batteries. The theoretical capacity of hard carbon as an anode electrode is very broad due to the impact of surface morphology and porosity (Table 2).[19–21]

Table 2. Theoretical specific capacities of different negative electrode materials for Li-ion batteries.

Materials type	Theoretical capacity (mAh g^{-1})
Hard carbon	200–600
Graphite	372
Lithium Titanate (Li4Ti5O12)	175
Titanium dioxide	330
Silicon	4200

Emerging and commercialization of new battery technologies, especially Na-ion batteries can potentially create a great market opportunity for lignin-based hard carbonsHard carbon has a better performance in Na-ion batteries compared to graphite. Table 3 shows important specifications of Na and Li in battery applications.[22]

Table 3. Theoretical specific capacities of different negative electrode materials for Li-ion batteries.

Materials type	Na	Li
Cation radius (Å)	1.02	0.76
Atomic mass (g/mol)	23	6.9
Capacity (mA h/g)	1,165	3,829
Melting point (℃)	97.7	180.5
Abundance (mg/kg)	23.6×10^3	20
Distribution	Everywhere	70% in South America
Price, carbonates (US$/ton)	150	5,000

The main advantages of Na-ion batteries compared to Li-ion batteries are:

- The production cost of Na-ion batteries is lower than Li-ion batteries.
- Sodium is cheaper, more abundant, and less toxic than lithium.
- Na-ion batteries have better recyclability than Li-ion batteries.

Graphitization of lignin and lignin-based graphene

Although lignin is a non-graphitizable carbon but different methods such as catalytic graphitization and laser-induced graphitization have been tried for the graphitization of lignin and even producing lignin-based graphene (Figure 19). The graphitization of lignin can create opportunities for producing lignin-based graphene and graphite. Both graphene and graphite have many applications in areas such as energy storage, electronics, and the packaging industry.

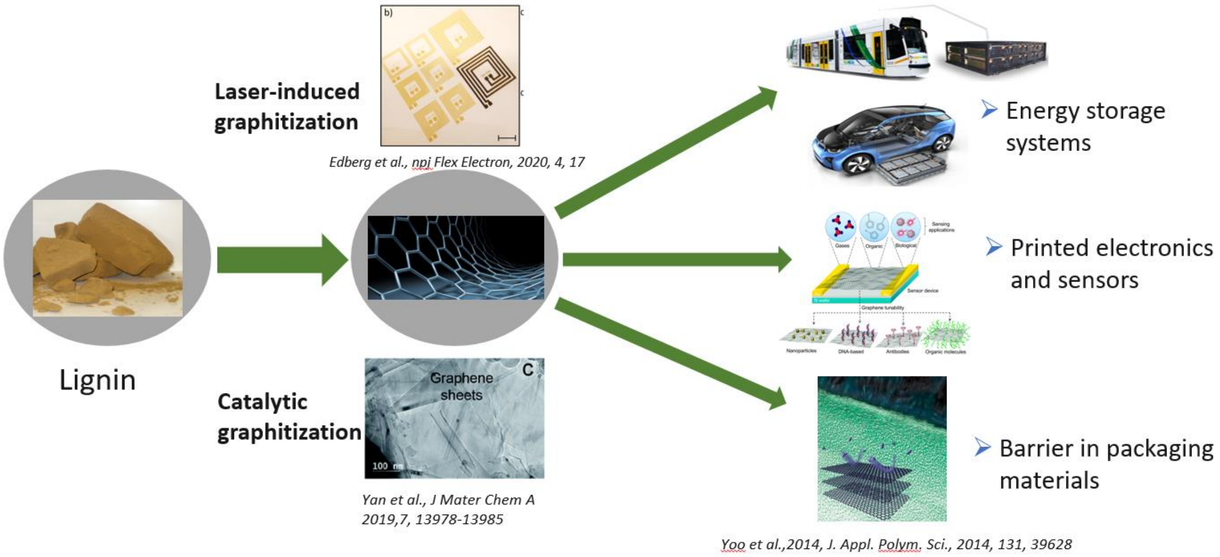


Figure 19. Graphitization of lignin and potential applications of lignin-based graphene.

Commercialization of lignin-based carbons in energy-related applications

The main drivers the for commercialization of lignin-based carbons in energy-related applications are:

- Fast-growing energy storage and renewable energy market need a sustainable source of carbon.
- Lignin is a low-cost, abundant, and renewable material with high carbon content.
- Developing new energy technologies such as Na-ion batteries, which are based on hard carbon and cheaper metals, creates a great market opportunity for lignin-based carbons.
- Environmental concerns and legislation on sustainability and reducing CO_2 emission.

The main efforts on the commercialization of lignin in the energy-related application and the production of graphene are:

- Stora Enso (Finland): Works on developing lignin-based anode—graphitized and/or hard carbon—for batteries (Lignode®) (*status: active*)
- Bright Day Graphene (Sweden): A start-up in Sweden that tries to commercially produce lignin-based graphene (status: *active*)
- UP Catalyst (Estonia): A startup in Estonia that works on the development and commercialization of sustainable graphene including lignin-based graphene (*status: active*)
- Domtar (USA): Domtar in collaboration with the United States Department of Agriculture's Forest Products Laboratory (FPL) works on producing lignin-based graphene (*status: unknown*)

The main challenges in the commercialization of lignin-based carbons in energy-related applications are:

- Lignins from different botanical sources, pretreatment, and separation process have different properties.
- Presence of impurities, especially inorganics, in lignin
- Low degree of graphitization in lignin since lignin forms a non-graphitizable carbon (hard carbon) in conventional conversion processes.
- The lower energy density of hard carbon compared to graphite in Li-ion batteries.
- Low electrical conductivity of hard carbon for sensing and electrical applications

Activated carbon and carbon black

Activated carbon

Activated carbons are high surface area carbon materials that are available in different forms such as fibers, granules, and powder. Commercial activated carbons are primarily made from coal, wood, coconut shell, lignite, and peat. These materials can have a very high surface area of up to 3000 m^2/g which makes them suitable as adsorbents in many applications (Figure 20).

Figure 20. Different applications of activated carbons.

Main activated carbon producers are located in South and South-East Asia:[9]

- MICBAC India
- Carbon Activated Corporation
- Evoqua Water Technologies LLC.
- Osaka Gas Chemical Co. Ltd.
- Jacobi Carbons
- Calgon Carbon Corporation
- Cabot Corporation
- Carbon Resources LLC
- CarboTech
- Haycarb PLC

Activated carbon has a growing market due to the need for removing contaminants from the environment (water and air). A market prediction and geographical global market for activated carbon are shown in Figure 21.

[9] Source: https://micbacindia.com/blog/activated-carbon-market-how-is-the-market-evolving/

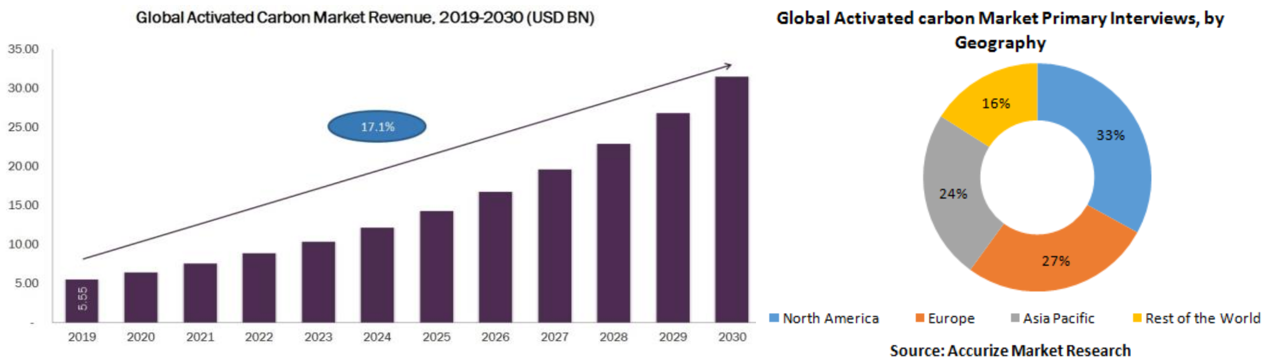


Figure 21. Global activated carbon market.[10]

Activated carbon fibers

As it was mentioned activated carbon can be in different forms including fiber. Activated carbon fibers can be produced from different precursors and in different forms (Figure 22). Activated carbon fibers have a market size of $367.1M in 2018 which is expected to grow to $583.5M by 2028 (CAGR of 4.7%.).[11]

<table>
<tr><td colspan="2">Carbon Yarn
</td><td>Carbon yarns
1.0~3.0g/m</td><td rowspan="2">Packing
High-temp.
insulator</td></tr>
<tr><td colspan="2">Carbon Cloth
</td><td>Weight
300g/㎡ 95 wt.%
Carbonized</td></tr>
<tr><td colspan="2">Activated Carbon Fibers
</td><td>Specific surface
area BET 800~2,000㎡/g</td><td rowspan="3">Air filter
Mask filter
Water filter
Electrode
for EDLC
Adsorbent
for solvent
recovery
apparatus</td></tr>
<tr><td>Activated
Carbon Felt</td><td rowspan="2"></td><td>Weight 70~200g/㎡
Specific surface
area BET 800~1,800㎡/g</td></tr>
<tr><td>Activated
Carbon Cloth</td><td>Weight 90~200g/㎡
Specific surface
area BET 800~1,800㎡/g</td></tr>
</table>

Figure 21. Different forms of activated carbon fibers.[12]

The main precursors for activated carbon fibers are:

- Pitch
- Polyacrylonitrile (PAN)
- Phenolic resins
- Cellulose (viscose)

10 Sources: Source: https://www.nextmsc.com/report/activated-carbon-market; https://www.accurizemarketresearch.com/report/activated-carbon-market

11 Source: https://market.us/report/activated-carbon-fiber-market/#major-market-players

12 Source: Gun Ei Chemical Industry Co. Ltd.

The main application of activated carbon fibers are:

- Solvent recovery
- Air purification
- Water treatment
- Catalyst carrier
- Energy

The main producers of activated carbon fibers are[13]:

- Toyobo Co. Ltd.
- Kuraray Co. Ltd.
- Unitika Ltd.
- Gun Ei Chemical Industry Co. Ltd.
- Taiwan Carbon Technology Co. Ltd

Figure 22 shows examples of activated carbon fiber products from Taiwan Carbon Technology Co. Ltd and Toyobo Co. Ltd. Specifications of activated carbon fiber products from Taiwan Carbon Technology Co. Ltd are summarized in Table 4.

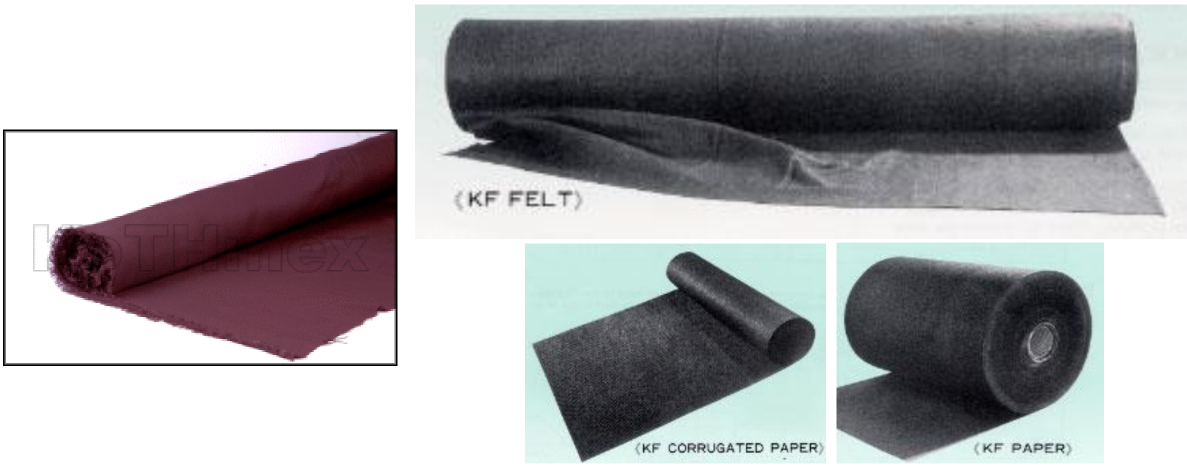


Figure 22. Examples of activated carbon fiber products from (left) Taiwan Carbon Technology Co. Ltd and (right) Toyobo Co. Ltd.

[13] Source: https://market.us/report/activated-carbon-fiber-market/#major-market-players

Table 4. Specifications of the carbon fiber products from Taiwan Carbon Technology Co. Ltd.

Item No.	ACF content(%)	Weight (g/m^2)	Thickness (mm)	BET (m^2/g)	Average pore (A)	Standard dimension(Roll)	
						Width(cm)	Lengh(M)
AW2001	100	45	0.3	2000	19-20	65	50
AW1501	100	70	0.35	1500	19-20	100	100
AW1107	100	150	0.6	1100	19-20	103	100
AW1109	100	115	0.4	1100	19-20	120	100
AW1114	100	100	0.4	1100	19-20	103	100
AW1112	100	95	0.35	1100	19-20	107	100

Lignin-based activated carbon

Research on lignin as a precursor for manufacturing activated carbons has a long history. Lignin-based activated carbon can be in form of powder and fiber. Lignin-based activated carbon can have a wide application for the adsorption of dyes, adsorption of organic molecules, gas adsorption/storage, and metal adsorption (Figure 23).[23]

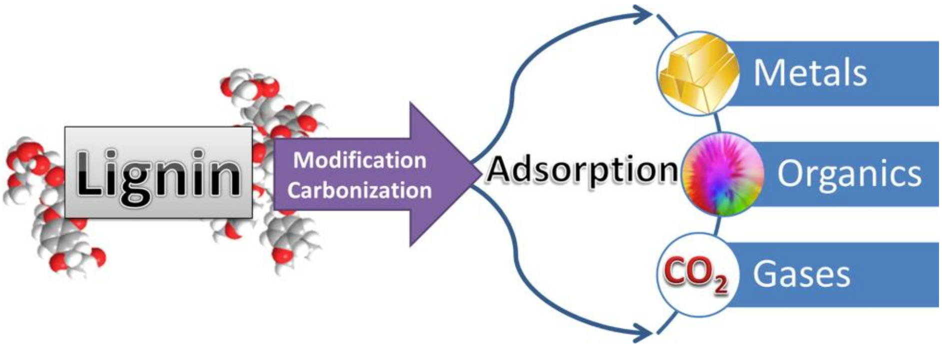


Figure 23. Application of lignin-based adsorbents.[23]

Lignin-based activated carbon can have a controlled pore structure (size and distribution) and surface functionality for the adsorption of a wide range of materials/chemicals such as heavy metals or Perfluoroalkyl and Polyfluoroalkyl substances (PFAS) from the environment (Figure 24).[23,24]

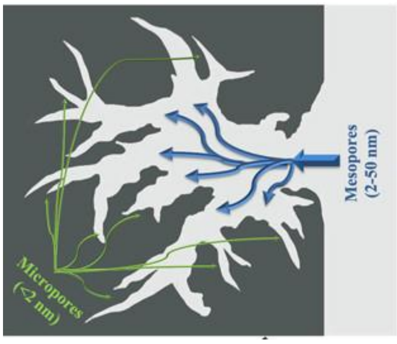


Figure 24. Schematic illustrations of pores in activated lignin-based carbon.[24]

Carbon black

Carbon blacks are spherical paracrystalline carbon particles with high electrical conductivity, high surface area, and high stability. Carbon black is made of a hydrocarbon fuel such as oil or gas. The worldwide market of carbon black is estimated at 16 million tons. About 93% of the total produced carbon black goes into rubber applications. The largest consumer of carbon black is the car industry, automobile tires, which use 73% of the carbon black production (Figures 25 and 26).[25]

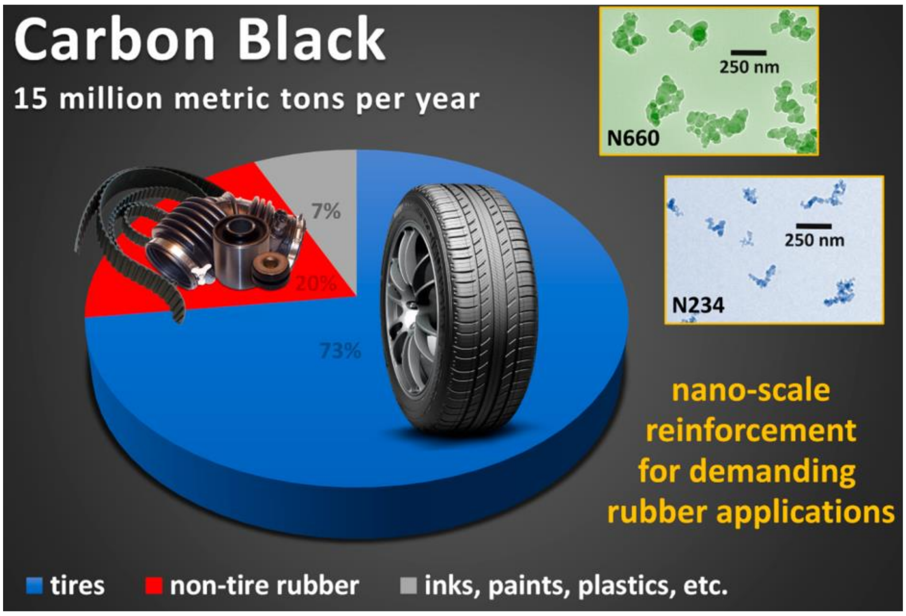


Figure 25. Carbon black market.[25]

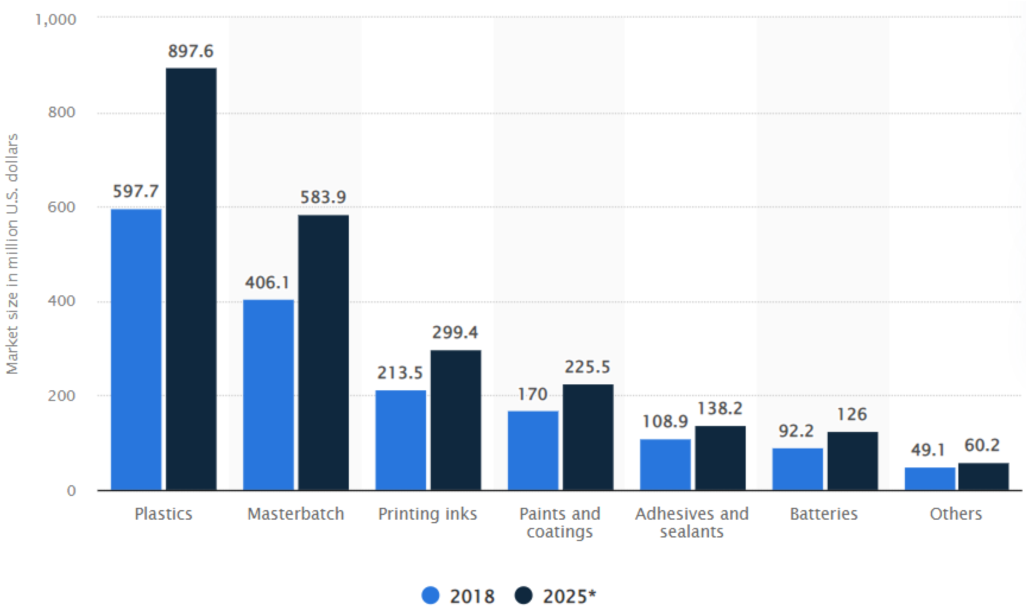


Figure 26. Carbon black market and predicted growth.[14]

[14] Source: https://www.statista.com/statistics/1285839/global-specialty-carbon-black-market-size-by-application/

The main commercial producers of carbon black are:

- Cabot Corporation (USA)
- Mitsubishi Chemical Corporation (Japan)
- Orion Engineered Carbons S.A. (Germany)
- Phillips Carbon Black Limited (India)
- Tokai Carbon Co., Ltd. (Japan)
- Birla Carbon Public Co. Ltd (India)
- Continental Carbon Company (USA)
- Himadri Chemicals & Industries Ltd. (India)
- Iran Carbon Co (Iran)
- Longxing Chemical Stock Co, Ltd. (China)
- OCI Company Ltd (Korea)
- Omsk Carbon Group (Germany)
- Ralson Goodluck Carbon Pvt. Ltd (India)
- Shandong Lion King Carbon Black Co., Ltd. (China)
- Triveni Turbines (India)

Commercialization of lignin-based activated carbon and carbon black

The main drivers for the commercialization of lignin-based activated carbons and carbon black are:

- The huge and growing market for activated carbon in different areas such as air and water filtration, gas storage, energy storage (supercapacitors), and chemicals.
- Carbon black has a big market in the rubber industry and expanding its application to energy-related applications will further increase it.
- Lignin is a low-cost, abundant, and renewable material with high carbon content.
- Environmental concerns and legislation on sustainability and reducing CO_2 emission.

There haven't been many efforts on the commercialization of lignin-based activated carbons or carbon black. In the case of carbon black, its possible production from lignin has recently been investigated. Some efforts on commercial production of lignin-based activated carbon and carbon black are:

- Sweetwater Energy (USA): A biorefinery that produces lignin based on a patented pretreatment method which later is converted to activated carbon for water treatment (*status: active*)
- UPM (Finland): UPM invested in an industrial-scale biorefinery for producing biochemicals and lignin-based functional fillers as carbon black (*status: active*)

Challenges in the commercialization of lignin-based activated carbon and carbon black are:

- Cost (especially for activated carbons): there are many cheap alternatives to lignin-based activated carbons.
- Variability in lignin will impact the properties of the final products.
- Quality of the products especially in the case of carbon black.

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