Coal to Carbon Fiber (C2CF) Business Case Analysis Report

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1 Executive Summary

The carbon fiber market continues to grow driven by innovations in materials, technologies, and associated cost reductions. Historically, the defense and aerospace industry has been a major consumer of carbon fibers. On the supply side, the carbon fiber market is highly concentrated with the top ten producers accounting for more than 88% of global production capacity (Mordor Intelligence, 2021). Foreign producers dominate this tight group of suppliers. This creates a situation of dependence for the United States, and could result in an unacceptable supply risk for materials critical to national security.

Coal is a rich source of carbon and other valuable materials (*e.g.*, rare earth minerals), and is abundant and cheap in the United States. To increase domestic capacity for carbon fiber production, the creation of domestic coal-to-carbon-fiber (C2CF) supply chains that produce carbon fibers from Western coal are currently being considered. In addition to reducing dependency on foreign sources, the hope is that by using coal pitch rather than polyacrylonitrile (PAN) as the carbon fiber precursor material, the cost of producing carbon fibers could be significantly reduced. In this report, we propose a two-stage C2CF supply chain: In the first stage, known as the coal-to-pitch plant, coal pitch is produced as the byproduct of an environmentally-friendly coking process, the Ekocoke™ process. In the second stage, the pitch is converted into fibers in a spinning system and used as precursor material to make low-cost carbon fibers for the production of injection-molded composite components. The second stage is called the carbon fiber (CF) conversion plant.

In this report, we study the proposed C2CF supply chain from a business and economic standpoint. We build an integrated cost model to analyze productions costs and explore the market potential for coal-based carbon fibers produced through the C2CF supply chain in order to address the following questions:

1. Given the current state of coal processing and CF manufacturing technologies, is it possible to produce carbon fibers from coal domestically for less than $5/lb? If so, at what scale?
2. What are the main cost drivers of the United States C2CF supply chain?
3. Is there enough demand for coal-based carbon fibers to justify investments at the needed scale?
4. Which market(s) would support such a scale?

Our findings are:

- Provided that demand for coke remains strong, the economic viability of the coal-to-pitch plant (Stage 1 of the C2CF process) is robust. Given current prices, the proposed coal-to-pitch plant can produce large quantities of pitch (up to 13,000 tons per year) at the cost of ¢9 per pound or $180 per ton. By comparison, the retail prices of pitch and PAN are ¢60 per pound and $3 per pound, respectively. Thus, the coal-to-pitch plant can produce CF precursor material at a fraction of current prices.
- As a result, the proposed C2CF supply chain is able to produce carbon fiber for $5/lb. We identify several plausible scenarios that could bring the price down further to about $4.50/lb. Our approach minimizes the precursor cost leaving capital costs and energy as the next avenues for additional cost reductions.
- In our model, the cost of the spinning system that converts pitch pellets into pitch fibers amounts to ¢83/lb or 15% of the CF unit production cost. This is a significant number. Perhaps the conventional wisdom which holds that simply replacing PAN with a less expensive precursor

would be enough to reduce the CF production cost by half is flawed. Comparing pelletized (or powdered) pitch to PAN that is already in fiber form is not a fair comparison. As it turns out, replacing PAN with coal pitch is only part of the answer.

- Production cost is not the same as selling price. Based on our model, the selling price of coal-based carbon fibers would have to be at least $7.5/lb to make the CF conversion line financially attractive. High margins (in the order of 50%) are needed to cover the large upfront investment cost of the CF conversion line. Note that the CAPEX of the CF conversion line ($121M) is almost the same as the CAPEX of the coal-to-pitch plant ($142M) although the two plants operate at drastically different scales.
- The drone market, even on the fast-growing consumer and commercial segments, is not large enough to support a CF conversion line of the needed scale.
- By contrast, in the massive US automotive market, a single use case could provide enough volume for at least one CF conversion line, and potentially many lines. Future work should focus on finding an automotive use case that best exploits the characteristics of the pitch-based fibers to deliver unique value.

There are several limitations to this work. First, our work is at the level of the concept design. More details are needed on start-up costs, ramp-up costs, and operating costs (specifically energy and labor). The technologies used in the C2CF supply chain are proven technologies at pilot scale. However, they still need to be fined-tuned and tested at industrial scale. Another limitation is that our calculations rely on single point estimates for the three main portions of the C2CF supply chain: (1) coal-to-pitch, (2) spinning system and (3) CF conversion line. Our estimates have not been subjected to competitive pricing. In the recent past, equipment prices have been going down due to increased competition in the manufacturing equipment industry. As the CF industry continues to grow, we expect to see further reductions in equipment costs.

Based on our findings we make the following recommendations:

- More precision is needed around the equipment and infrastructure costs. For the coal-to-pitch plant, the detailed design and cost estimates created by Combustion Resources should be verified by an independent consultancy. For the CF conversion line, the cost estimates are rough orders of magnitude. The concepts need to be further developed and verified by independent consultancies. Special attention should be given to the spinning system, which converts coal pitch into fiber mat, since research and development in this area are more limited.
- Several avenues have been identified to reduce the CF production cost, especially in the areas of capital and energy costs. These avenues need to be pursued in detail to assess the potential cost savings more precisely. Public funding or the conversion of existing PAN-based CF conversion lines to pitch could defray the high upfront investment costs. The use of microwave technology or renewable energies could reduce the energy cost.
- On the demand side, a clearer understanding of the demand for pitch-based carbon fibers is required. Which use cases require high stiffness? How much stiffness is needed? For these use cases, what would be the demand for pitch-based carbon fibers for various levels of stiffness and at various price points? A clearer understanding of the relationship between material properties, prices and demand is needed to determine the optimal size of the C2CF supply chain.
- If the time comes to launch the C2CF supply chain, we recommend a phased-approach in which the coal-to-pitch plant is built first and run for some time. Knowing actual revenues, costs and

material properties in the first stage of the C2CF supply chain would provide more clarity for the decisions surrounding the construction on the CF conversion plant, which is much riskier. Until the CF conversion line is built, the pitch can be sold as is. One potential use of pitch is as a carbon matrix in carbon/carbon composites. Such composites are well-suited to structural application at very high temperatures (*e.g.*, reentry vehicles of intercontinental ballistic missiles, or carbon/carbon brakes). We also recommend the use of risk sharing contracts to avoid unnecessary competition within the C2CF supply chain and maximize the chances of success for the C2CF supply chain.

We are encouraged by the increased interest we've seen during the course of this project about the concept of coal-to-carbon-fiber, and are hopeful American engineers and entrepreneurs will come up with innovative and profitable solutions in this important area of research.

2 Introduction

Carbon fibers (CF) have excellent material properties including high stiffness, high strength-to-weight ratio, durability, corrosion resistance, low coefficient of thermal expansion, and electrical conductivity, that make them a go-to material for many industrial applications (See Table 1). For example, in the wind energy industry, carbon fiber is gradually replacing fiberglass because it is stiffer and stronger. The use of carbon fiber in aircrafts and drones has led to significant weight reductions, which have dramatically improved fuel efficiency and range.

Table 1– Industrial Applications of Carbon Fibers

Industrial Applications	Share of Global Demand
Wind energy	23%
Aerospace	20%
Sporting goods	12%
Automotive	10%
Pressure vessels	10%
Short fiber applications (*e.g.*, compounding for injection molding)	8%
Construction and infrastructure	8%
Other	9%

Source: Pichler (2021)

Carbon fibers' distinctive properties have led to many applications that are not only unique but also critical and essential to the United States energy, defense and transportation industrial bases. Carbon fibers are found in many military products such as aircrafts, drones, helicopters, and body armors, making the United States government a primary consumer of carbon fiber (IBISWorld, 2021). In recent years, vulnerabilities in the supply chains for carbon fibers (as well as other critical minerals) were exposed by the Covid-19 pandemic. The resulting risks were addressed in a 2021 Executive Order:

> "Critical minerals are an essential part of defense, high-tech, and other products. From rare earths in our electric motors and generators to the carbon fiber used for airplanes—the United States needs to ensure we are not dependent upon foreign sources or single points of failure in times of national emergency."
> -- Executive Order on America's Supply Chains, February 24, 2021)

The domestic carbon fiber market is projected to grow at a compound annual growth rate of 2.3% between 2021 and 2026. Already the United States consume about 60% of global CF output, and Japan provides much of that (IBISWorld, 2021). We are dependent on foreign sources for carbon fiber and this dependency appears to be growing. **To decrease dependency on foreign sources for carbon fiber, America needs to build up its capacity for domestic CF production.**

Limiting factors in the development of the CF market in the United States and elsewhere are: (1) the cost of the raw material (known as precursor); and (2) a capital and energy intensive process for converting the precursor into carbon fibers. Ninety five percent of carbon fibers are made from polyacrylonitrile (PAN), an oil-based synthetic fiber (Pichler, 2021). PAN represents about 54% of the CF manufacturing cost (Ellringmann et al., 2016). To reduce costs, less expensive precursors such as rayon (an organic textile fiber), petroleum pitch or coal pitch are utilized but their use remains limited.

For the purpose of reducing dependency on foreign sources, coal pitch is a good candidate as a CF precursor because coal is especially abundant and cheap in the United States (EIA, 2022), especially in the West. If pitch can be produced economically from Western coal, such a process could help significantly reduce the cost of CF manufacturing. Moreover, the replacement of coal by cleaner sources of energy in the power-generation industry is causing domestic coal production to plummet. As a result, many coal communities throughout the country are suffering. Over the last 10 years, employment in the coal mining industry decreased from 90,000 to 50,000 (Das & Nagapurkar, 2021). Coal is a rich source of carbon and other valuable materials (*e.g.*, rare earth minerals). Burning coal to generate electricity is perhaps not the best use of this valuable resource. Finding new, safe and environmentally-acceptable uses for coal could actually create jobs in coal-mining areas and benefit society at large (Strong, 2021).

The second cost driver is the process that converts the precursor material (*e.g.*, PAN fibers) into carbon fibers. To produce carbon fibers the precursor material goes through a series of manufacturing steps, including very high temperature thermal processes that consume a lot of energy and do not scale easily. As depicted in Figure 1, the CF manufacturing steps include pretreatment, oxidation, carbonization, graphitization, surface treatment, sizing, and winding. At the end of the manufacturing process, carbon fibers can be sold as fabrics (which could be impregnated with resin, a product commonly called a prepreg), wound filaments, or chopped/milled pieces.

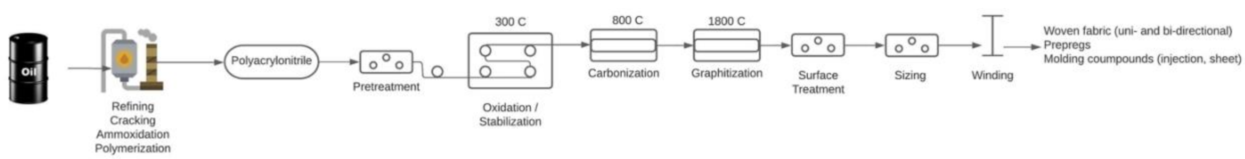


Figure 1—PAN-based Carbon Fiber Manufacturing Process

The oxidation/stabilization stage is a process bottleneck because residence times can be as high as two hours. Although residence times in the carbonization and graphitization stages are much shorter (typically only a minute or two), the high temperature ovens also limit the quantity of material that can be processed by the CF conversion line since the openings of conventional ovens can be no greater than 10 feet wide by a few inches high.

Moreover, many idiosyncrasies and closely guarded intellectual property in the CF manufacturing process complicate the matter. A few examples are:

- The physical properties of the fibers depend on the precursor being used, and the CF conversion line must be tailored to the type of precursor being processed. PAN-based fibers are stronger than pitch-based fibers; however, pitch-based fibers are stiffer.

- Each CF conversion line is also designed to achieve a specific format, grade or type of fiber depending on the needs of the industrial application for which it is built. The most popular format is 'tow' in which thousands of fibers are bundled together into a single strand, which is then wound on a spool for transportation and storage. Alternatively, it is possible to produce carbon fibers in a mat format, in which case the fibers are randomly meshed together on a conveyor belt. The dimensions of the mat (up to 10 feet wide by a few inches high) are determined by the size of the ovens.
- To achieve different levels of stiffness and strength, different temperatures may be applied at the graphitization stage.
- Sizing, which is the process of covering the fibers with a protective coat to shield them during winding and transportation, may involve a different resin depending on the industrial application.
- Carbon fibers are sold as continuous, woven, pre-impregnated, chopped or milled fibers.

In short, carbon fibers are highly technical products that are produced in small to moderate volumes for very specific uses under proprietary methods. This explains why the industry is concentrated around 15 manufacturers globally (Das et al., 2016). Several of these companies are also vertically integrated (i.e., they produce their own CF precursor).

The presence of a concentrated industry organized to serve high-end niche markets increases the dependence risk for the United States and does not encourage competitive pricing.

While customers in the wind energy, aerospace and sporting goods industries can afford to pay between $10 and $15 per pound for the distinctive properties of carbon fibers (Das & Nagapurkar, 2021), willingness to pay in the automotive industry is less than $5 per pound (Blanchard, 2021). This is because of intense market competition driven by huge production volumes as well as competition from traditional materials. The auto industry produces tens of millions of vehicles every year. By contrast, only about 3,000 commercial aircrafts are produced in a given year. A small saving on one automotive component generates huge financial benefits. Moreover, carbon fiber must compete with well-established commodities such as fiberglass, steel or aluminum. Except for the high-performance automotive segment, it is not clear that the superior properties of carbon fibers are worth the extra cost. To be widely adopted in the automotive industry the price of carbon fiber must go down. However, with a market 55 times smaller than the fiberglass market, current production volumes are not enough to bring prices down. **This is the well-known chicken and egg situation in the CF market: Higher volumes are needed to bring prices down; but prices won't got down unless the volume increases.** Can we escape this conundrum? What needs to happen to bring the price of CF down to less than $5/lb?

In this report, we present the results of an economic study of the production of low-cost carbon fibers from Western coal in a process known as the coal-to-carbon-fiber (C2CF) supply chain. The study was conducted in the context of a Utah Defense Manufacturing Community grant to address the following mandate:

> "The use of coal as the source to manufacture carbon-fiber and the advanced manufacturing process (C2CF) will reduce the costs by at least half. The benefit to DoD is costs low enough for attributable aerial

vehicles such as swarm drones. Under this task, grants and other research vehicles will be identified and pursued to further commercialization of C2CF for defense programs."

Our overall research objectives are to answer the following questions:

1. Given the current state of coal processing and CF manufacturing technologies, is it possible to produce carbon fibers from coal domestically for less than $5/lb? If so, at what scale?
2. What are the main cost drivers of the United States C2CF supply chain?
3. Is there enough demand for coal-based carbon fibers to justify investments at the needed scale?
4. Which market(s) would support such a scale?

3 Coal-based Carbon Fibers: At What Cost?

To answer the first question, we begin with a description of the proposed low-cost C2CF supply chain and then build an integrated cost model to estimate the cost of producing one pound of pitch-based carbon fiber using the C2CF process.

3.1 The Proposed Low-Cost C2CF Process

The proposed C2CF process consists of two main parts: The first part, known as the coal-to-pitch plant, produces mesophase coal pitch as the byproduct of a clean coke manufacturing process. The second plant is the carbon fiber conversion plant. It converts the mesophase pitch produced by the coal-to-pitch plant into carbon fibers (See Figure 2). Let us review each of these plants.

High value carbon products such as pitch can be extracted from coal through carbonization, gasification or liquefaction processes. (For an example of coal liquefaction, see the ongoing work of the Western Research Institute and Ramaco Carbon in Wyoming; Ramaco Carbon, 2021). In this report, we use improved carbonization techniques in coke ovens to extract pitch from Western coal. Specifically, the proposed C2CF coal-to-pitch plant implements the Ekocoke™ patent (Combustion Resources, 2021), a thermal process that efficiently separates thermal coal into its solid, liquid and gaseous components to create clean metallurgical coke and other valuable byproducts including mesophase pitch. Metallurgical coke is a reducing agent abundantly-used in the steel and chemical industries. The main advantages of the Ekocoke technology are economic and environmental: (1) the process is highly efficient since solid and gaseous byproducts are recycled in a closed system; (2) the process is able to process low-grade, thermal coal and to recycle coke fines and waste coal, which currently represent a significant environmental hazard; and (3) metallurgical coke is a widely-used commodity. The Ekocoke process was successfully deployed at pilot scale in a testing facility built in Carbon County, Utah.

The proposed Ekocoke™ plant includes the pitch extraction and upgrade in a stirred batch reactor to produce spinnable mesophase pitch. If the coke could pay for the plant, this approach would essentially provide mesophase coal pitch at a fraction of the cost.

The CF conversion line is similar to a traditional PAN-based conversion line except that the pitch, which comes in pellets, must first be melted and spun into fibers before oxidation.

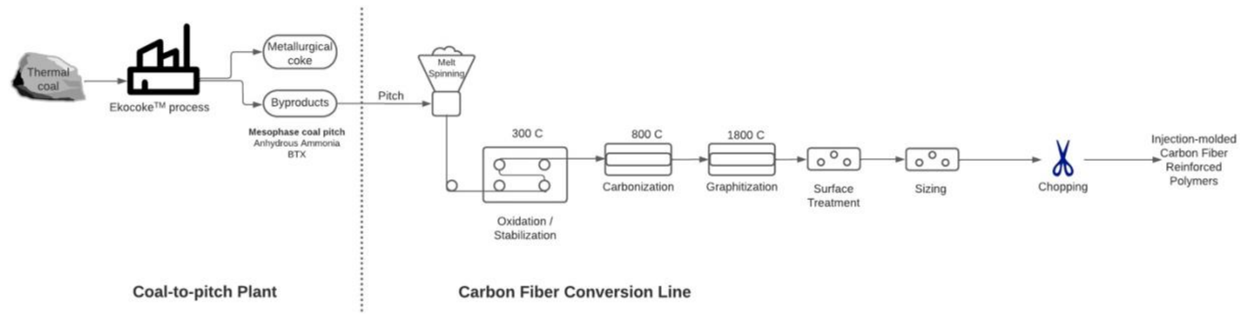


Figure 2—Proposed C2CF Manufacturing Process

Three main design characteristics of the C2CF supply chain were chosen to reduce the cost of manufacturing carbon fibers:

1. Low-cost precursor: As indicated earlier, the CF precursor can represent as much as 54% of the CF costs. Reducing the precursor cost may generate important savings. The mesophase coal pitch produced by the Ekocoke process is significantly less expensive than PAN (less than ¢60/lb for pitch compared to about $3/lb for PAN). Moreover, the coal pitch has a higher carbon content than PAN leading to a higher yield of the CF conversion line when pitch is used as the precursor (75% yield) instead of PAN (45% yield). The low yield of the PAN-based process results from the presence of non-carbon elements that are removed during oxidation and carbonization.

2. Economies of scale: Ignoring market considerations for now, we base our cost and revenue estimates on the largest feasible production capacities in order to take full advantage of economies of scale. For the coal-to-pitch plant, the maximum design capacity is 250,000 tons of coke per year. Such a plant would produce about 13,000 tons of pitch per year (Combustion Resources, 2021). For the CF conversion line, we choose the mat format to maximize the annual output at 3,850 tons of CF per year (Bagwell, 2021).

3. Injection molded composites: We focus on injection molding as the primary technique for producing carbon fiber reinforced parts in high volume. With typical cycle times measured in seconds, injection molding is well suited for the production levels needed to bring costs down.

In the next sections, we develop the detailed cost model of the C2CF process. We begin with the coal-to-pitch plant.

3.2 Economics of the Coal-to-pitch Plant

As mentioned earlier, we assume the largest feasible design capacity of the coal-to-pitch plant to maximize economies of scale, namely 250,000 tons per year of metallurgical coke output. Such a plant would consume about 450,000 tons of coal per year as well as other secondary inputs. In addition to producing metallurgical coke and mesophase pitch, the coal-to-pitch plant also produces Benzene Toluene Xylene (BTX), natural gas, coal tars, sulfuric acid and anhydrous ammonia, which is used as a fertilizer where acidic soils are found.

The plant flow rates and process equipment costs were calculated by Combustion Resources (a Utah engineering consultancy) using the Aspen Icarus Process Evaluator, which combines PRO/II simulation results with a proprietary database of equipment acquisition and installation costs. Note that some of the front-end equipment costs were based on quoted equipment from manufacturers.

Inputs are bought in the spot market at retail price. Table 2 gives the annual raw material costs. Thermal coal represents more than 95% of the total raw material costs and more than 99.9% of the tonnage. (For details, see the cost model in Excel format in the electronic appendix.)

Table 2—Annual Raw Materials Cost of the Ekocoke Coal-to-pitch Plant

Raw Materials	Price per ton	Flow Rates (tons/month)	Annual Costs (Price * Flow Rate * 12)
Thermal coal	$40.00	36,032.04	$17,295,379.20
Caustic Soda (Anhydrous Ammonia)	$5,400.00	6.12	$396,576.00
Phosphoric Acid (Anhydrous Ammonia)	$2,882.00	6.12	$211,654.08
Sodium Hydroxide	$900.00	17.28	$186,624.00
Citric Acid	$3,580.00	0.58	$24,809.40
Rapeseed oil	$898.00	1.44	$15,517.44
MDEA	$6,936.00	0.04	$2,996.35
Total Cost per Year			**$18,133,556.47**

The plant produces 250,000 tons per year (or about 20,823 tons per month) of metallurgical coke. The Ekocoke processing technology views coal as a treasure trove of valuable chemicals rather than as simply a fuel to be burned to produce heat. The process efficiently separates coal into its solid, liquid and gaseous components that are collected as either high-value products themselves (*e.g.*, metallurgical coke), or as feedstock material for the production of downstream high-value products (*e.g.*, CF precursor). The various products of the coal-to-pitch plant with their estimated prices, flow rates and revenues are listed in Table 3. We assume that byproducts are sold at 50% of the retail price. This very conservative assumption allows for byproducts to be sold to chemical distributors.

Table 3—Annual Revenues of the Ekocoke Coal-to-pitch Plant by Products

Products	Price per ton	Flow Rates (tons/month)	Annual Revenues (Price * Flow Rate * 12)
Coke	$275.00	20,823	$ 68,715,108.00
Anhydrous Ammonia	$1,960.00	354	$ 8,331,724.80
Sulfuric Acid 98%	$678.92	1,015	$ 8,270,875.01
Mesophase pitch	$600.00	1,104	$ 7,952,256.00
Benzene Toluene Xylene (BTX)	$370.00	1,482	$ 6,579,014.40
Natural gas			$ 6,294,664.29
Coal Tar	$390.00	1,027	$ 4,806,734.40
Total Revenue per Year			**$ 110,950,376.90**

Although metallurgical coke is the primary product of the plant (62% of revenues and 81% of the tonnage), Table 3 demonstrates the variety of valuable chemicals contained even in ordinary, thermal coal. This type of coal is plentiful and easy to mine in the Western United States. Of special interest for us is the mesophase pitch byproduct. The coal-to-pitch plant is expected to produce about 13,000 tons of pitch per year for revenues of about $8 million (7% of total revenues), based on a selling price of $600 per ton, or ¢30 per pound.

While the selling prices in Table 3 are taken at half the average retail price, we wanted to know for comparison purposes what the unit production costs were for the two main products of interest: coke and pitch. To do so, we computed the per unit marginal costs of each product. Operating and material costs during the first year of operation are $32,659,811 (See Table 5). Coke and pitch account for 61.9% and 7.2% of revenues, respectively. This leads to the results presented in Table 4. Even by selling products at half the retail price, the coal-to-pitch plant operates within comfortable margins.

Table 4—Unit Costs, Prices and Contributions for Coke and Pitch

	Variable Production cost	Selling price	Contribution
Metallurgical coke (per ton)	$80.95	$275.00	$194.05
Mesophase pitch (per lb)	9¢	30¢	21¢

To estimate the financial viability of the plant, we assume a 5-year investment horizon, with a cost of debt of 10% per year, a loan duration of 7 years, a cost of equity of 15% per year, a debt to investment ratio of 75% and federal and state corporate tax rates of 21% and 4.95%, respectively. With these assumptions, the weighted average cost of capital (WACC) is 9.30%. Moreover, we assume that costs and revenues increase by 3% annually. (See Section 9 for the full list of our model parameters and assumptions.)

The total investment cost is estimated at $141,780,000 in 2021 dollars. This cost includes the land and various buildings, the process equipment and installation costs (including piping, civil, structural steel, instrumentation, electrical, insulation, paint, subcontracts, overheads, contract fees and contingencies).

Annual operating costs are $14,103,160 in 2021 dollars. These include labor, maintenance and utilities. The annual cash flows over the 5-year investment period are given in Table 5. It is assumed that all products are sold. Table 6 summarizes selected financial metrics of the investment.

Table 5—Annual Cashflows of the Ekocoke Coal-to-pitch Plant (2022—2026)

	2022	**2023**	**2024**	**2025**	**2026**
Revenues from coke	$ 68,715,108	$ 70,776,561	$ 72,899,858	$ 75,086,854	$ 77,339,459
Revenues from pitch	$ 7,952,256	$ 8,190,824	$ 8,436,548	$ 8,689,645	$ 8,950,334
Revenues from other byproducts	$ 34,283,013	$ 35,311,503	$ 36,370,848	$ 37,461,974	$ 38,585,833
Total revenues	**$ 110,950,377**	**$ 114,278,888**	**$ 117,707,255**	**$ 121,238,473**	**$ 124,875,627**
Operation & maintenance costs	$ (14,526,255)	$ (14,962,042)	$ (15,410,904)	$ (15,873,231)	$ (16,349,428)
Raw materials costs	$ (18,133,556)	$ (18,677,563)	$ (19,237,890)	$ (19,815,027)	$ (20,409,478)
Depreciation	$ (20,254,286)	$ (20,254,286)	$ (20,254,286)	$ (20,254,286)	$ (20,254,286)
Loan payments	$ (21,183,443)	$ (21,183,443)	$ (21,183,443)	$ (21,183,443)	$ (21,183,443)
Earnings before tax	**$ 36,852,837**	**$ 39,201,554**	**$ 41,620,733**	**$ 44,112,486**	**$ 46,678,993**
Tax	$ (9,563,311)	$ (10,172,803)	$ (10,800,580)	$ (11,447,190)	$ (12,113,199)
Earnings after tax	**$ 27,289,526**	**$ 29,028,751**	**$ 30,820,152**	**$ 32,665,296**	**$ 34,565,794**

Table 6—Selected Financial Metrics of the Ekocoke Coal-to-pitch Plant

Net present value (hurdle rate, r = WACC = 9.30%)	$82,459,688
Net present value (hurdle rate, r = 15%)	$66,361,477
Internal rate of return (IRR)	77.3%
Payback period (years)	1.3

To evaluate the robustness of the project from a financial standpoint, we consider the following what-if scenarios:

- Scenario #1: The pitch is sold at the full retail price (¢60/lb) rather than half the retail price. This scenario is favorable to the coal-to-pitch plant but goes against the goal of reducing the cost of producing carbon fibers.
- Scenario #2: The plant is unable to sell the pitch while still selling the other byproducts.
- Scenario #3: The plant is unable to sell any of the byproducts. This scenario answers the question of whether the plant would be viable if it only produced coke.
- Scenario #4: This scenario is a variant of scenario 3 in which the coke is sold at the full retail price ($550/ton) rather than half the retail price.

The same financial measures used to evaluate the baseline coal-to-pitch plant were used to measure the financial viability for each of the four scenarios. The results are presented in Table 7.

Table 7—Financial Viability of Selected Scenarios

	Scenario #1	Scenario #2	Scenario #3	Scenario #4
Net present value (r = 9.30%)	$106,463,817	$58,455,559	($45,028,768)	$162,389,895
Net present value (r = 15%)	$87,150,157	$45,572,796	($44,049,394)	$135,584,716
Internal rate of return	94.9%	59.1%	N/A	134.9%
Payback period (years)	1.1	1.6	N/A	< 1

If the pitch is sold at ¢60/lb instead of ¢30/lb (Scenario #1), the NPV increases from $82M to $106M, the IRR goes from 77.3% to 94.9% and the payback from 1.3 years to 1.1 years. While these improvements are of course welcome, they do not radically change the plant economics. In other words, **our results are not very sensitive to the price of pitch**. The results of Scenario #2 confirm this point. What happens to the pitch does not make or break the project.

However, the results of Scenarios #3 and #4 show that the plant economics are highly sensitive to the selling price of coke. Of course, when coke is sold at half its retail price, the plant cannot survive by just selling coke. However, a fair price for coke would make the plant not only viable but also highly profitable even without the contribution of the other products. This finding is driven by the fact that the bulk of the coal is converted into coke; whereas the other products are produced in relatively small quantities. **Thus, it is possible to suggest that the coke could pay for the plant and produce pitch at unbeatable prices.**

To further investigate this claim, we plotted the internal rate of return as a function of the selling price of coke when no other products are sold and while keeping everything else constant. The results are displayed in Figure 3. Starting at a selling price of about $350 per ton of coke, the plant is financially viable. Such a coke price point would support the production of coal pitch at minimal cost.

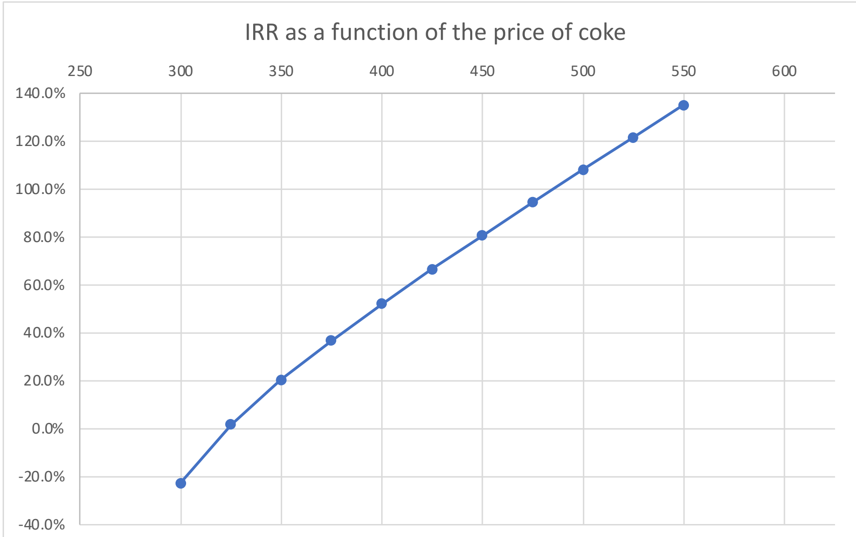


Figure 3—Internal Rate of Return of Coal-to-pitch Plant as a Function of Coke Selling Price (No other byproducts sold)

Overall, provided that demand for coke remains strong, the economic viability of the coal-to-pitch plant appears robust.

3.3 Economics of the CF Conversion Plant

We now turn to the economic feasibility of the CF conversion line. For the purpose of this study, mesophase pitch is obtained from the coal-to-pitch plant to meet the needs of a single CF conversion line. We will consider two scenarios depending on the price of pitch: ¢30 or ¢60 per pound corresponding to the baseline and scenario #1, respectively.

To build the cost model, we started from a cost estimate by Harper International (Bagwell, 2021) for a turn-key solution ranging from the oxidation operation to the sizing operation (see Figure 2). Harper International is a global leader in complete thermal processing solutions and technical services essential for the production of advanced materials based in New York. The estimate distinguishes between the acquisition and installation costs of the manufacturing equipment (CAPEX), the operating costs (OPEX) and maintenance. A separate cost estimate for the melt-spinning operation was obtained from JR Automation, a subsidiary of Hitachi, Ltd (Leftwich & Lee, 2022). JR Automation has experience in the different spinning processes for making carbon fiber. They are also able to provide turnkey integration capability for the entire CF process through carbonization and all post processing equipment including chopping. Note that the cost estimates provided in this study do not include the chopping operation.

The CF conversion plant consists of a single 10 feet (3 meter) wide production line. The pitch to fiber conversion rate is assumed to be 75%. Our choice of the mat format enables an annual output of 3,850 tons of carbon fiber for an annual consumption of about 5,150 tons of pitch. (See Section 9 for the full list of our model parameters and assumptions.)

The process begins as pitch pellets are introduced into the spinning system by means of a hopper. After being heated, the pitch goes through an extruder. From there, it is pushed through thousands of holes, then cooled down and stretched to form continuous fibers with the desired geometry, and finally laid on a conveyor belt to form a fiber mat. Unlike the tow format, which needs to be continuously stretched and pulled through the line, the mat is carried by a conveyor system as it is pushed through the line.

The various cost factors of the CF conversion line are summarized in Table 8. The initial investment cost is $121,530,000. Maintenance is 5% of the plant equipment cost annually. Operating, maintenance and raw material costs are $29,195,750 annually, assuming a pitch price of ¢60/lb.

Table 8—CAPEX, OPEX and Precursor Cost Breakdown for the CF Conversion Line (with precursor cost at ¢60/lb.)

	Spinning System (JR Automation)	CF Conversion (Harper Int.)	Total	
Plant equipment	$ 24,900,000	$ 45,815,000	$ 70,715,000	
Infrastructure	$ 5,000,000	$ 45,815,000	$ 50,815,000	
Energy cost	$ 777,600	$ 5,702,400	$ 6,480,000	per year
Operating expenses (exc. energy)	$ 1,222,400	$ 11,797,600	$ 13,020,000	per year
Maintenance	$ 1,245,000	$ 2,290,750	$ 3,535,750	per year
Precursor (coal pitch)			$ 6,160,000	per year

In Table 9, we give the per unit CF production cost. In the calculations, the finance cost consists of the loan payment for plant equipment and infrastructure (assuming a 10-year guaranteed loan at 7% per year). In light of our first research question, it would take a pitch cost of ¢27/lb to reach the target cost of $5/lb of CF. Recall that the production cost of pitch is ¢9/lb (see Table 4) and that the coal-to-pitch does not depend on the pitch for its economic viability. It is therefore feasible to obtain pitch at ¢27/lb. Lower price points are also feasible.

Table 9—Unit Production Cost Breakdown with Precursor Cost at ¢60, ¢30 or ¢20 per lb.

	Precursor cost ¢60 per lb	Precursor cost ¢30 per lb	Precursor cost ¢27 per lb
Finance cost	$ 1.65	$ 1.65	$ 1.65
Energy cost	$ 0.84	$ 0.84	$ 0.84
Operating expenses	$ 1.69	$ 1.69	$ 1.69
Maintenance	$ 0.46	$ 0.46	$ 0.46
Precursor (coal pitch)	$ 0.80	$ 0.40	$ 0.36
Production cost per lb	**$ 5.44**	**$ 5.04**	**$ 5.00**

In this section we explore other cost saving avenues that could bring the cost below $5/lb. These cost saving strategies pertain to the oven efficiencies, the spinning system, and the role of public investment to defray the upfront investment cost.

3.3.1 Oven Efficiencies

A significant contributor to operating expenses is the energy required to power the high temperature ovens. The plant is rated at about 10 MW of electric power. With a production time of 7,200 hours per year, this corresponds to a consumption of 72 GWh of electricity per year. Assuming a wholesale price of ¢9 per kWh, the cost of electricity would amount to $6.48M per year. Our model shows that a 10% saving in electricity consumption would amount to a ¢8.4 reduction of the CF production cost. A 20% saving would generate twice that amount; and a 30% saving three times that amount.

It has been posited that microwave technology may improve oven efficiency. More research is needed in this area, especially to determine how much energy could be saved by switching to microwave ovens. Future research should also explore the potential for wind and solar energy to offset some of the energy cost. Another component of operating expenses, which we did not analyze in this report, is the impact of labor costs.

3.3.2 Contribution of the Spinning System to Overall Production Costs

The spinning system is also an important driver of the equipment cost. In addition to the equipment cost itself, the system is vertically oriented, thus requiring a tall building.

The equipment portion of the spinning system alone (valued at $24.9M) accounts for 35% of the overall plant equipment cost! **This fact challenges the popular notion that reducing the precursor cost would significantly reduce the CF production cost.** The problem with this notion is that comparing the cost of the mesophase pitch to the cost of the PAN (as we have done earlier in this report) is misleading because the material forms are not the same. Indeed, since spinning is so expensive, it is not fair to compare pelletized pitch to PAN that is already in fiber form. The cost of pelletized (or powdered) pitch should be compared to the cost of pelletized (or powdered) PAN. Our analysis shows that spinning contributes ¢83 per pound or about 15% to the CF cost.

Lowering the cost of spinning pitch into fibers is an area of research that deserves greater attention. Chances are that innovations in spinning technology would also benefit other industrial applications including PAN manufacturing.

3.3.3 The Role of Public Funding

To the extent that public funds can be used to offset the upfront capital cost, the CF production cost can be further reduced. For example, local governments can defray some of the investment costs by facilitating access to land, buildings or other infrastructures. Table 10 investigates the impact of various levels of public funding on CF production cost. When combined with energy efficiency improvements, the analysis reveals a few scenarios in which the cost is less than $4.50/lb.

Table 10—CF Production Cost (in $/lb) by Level of Public Funding and Energy Efficiency.

Precursor cost = ¢30/lb.

Level of public funding → **↓ Energy efficiency**	**None**	**$5M**	**$10M**	**$15M**	**$20M**
Baseline	$ 5.04	$ 4.95	$ 4.86	$4.77	$ 4.68
10% improvement	$ 4.96	$ 4.87	$ 4.78	$ 4.69	$ 4.59
20% improvement	$ 4.87	$ 4.78	$ 4.69	$ 4.60	$ 4.51
30% improvement	$ 4.79	$ 4.70	$ 4.61	$ 4.52	$ 4.43

Precursor cost = ¢27/lb.

Level of public funding → **↓ Energy efficiency**	**None**	**$5M**	**$10M**	**$15M**	**$20M**
Baseline	$ 5.00	$ 4.91	$ 4.82	$4.73	$ 4.64
10% improvement	$ 4.92	$ 4.83	$ 4.74	$ 4.65	$ 4.55
20% improvement	$ 4.83	$ 4.74	$ 4.65	$ 4.56	$ 4.47
30% improvement	$ 4.75	$ 4.66	$ 4.57	$ 4.48	$ 4.39

We complete the economic evaluation of the CF conversion plant by looking at the financial viability of the CF conversion plant over a 5-year investment horizon as we have done before. We show the annual cashflows assuming a precursor cost of ¢30/lb and a CF selling price of $7.50/lb (Table 11).

Table 11—Annual Cashflows of the CF Conversion Line (2022—2026) when Precursor Cost = ¢30/lb and Selling Price = $7.50/lb.

	2022	2023	2024	2025	2026
Revenues	**$ 57,750,000**	**$ 59,482,500**	**$ 61,266,975**	**$ 63,104,984**	**$ 64,998,134**
Operation & maintenance costs	$ (23,035,750)	$ (23,726,823)	$ (24,438,627)	$ (25,171,786)	$ (25,926,940)
Raw materials costs	$ (3,080,000)	$ (3,172,400)	$ (3,267,572)	$ (3,365,599)	$ (3,466,567)
Depreciation	$ (6,076,500)	$ (6,076,500)	$ (6,076,500)	$ (6,076,500)	$ (6,076,500)
Loan payments	$ (12,699,597)	$ (12,699,597)	$ (12,699,597)	$ (12,699,597)	$ (12,699,597)
Earnings before tax	**$ 12,858,153**	**$ 13,807,180**	**$ 14,784,679**	**$ 15,791,502**	**$ 16,828,530**
Tax	$ (3,336,691)	$ (3,582,963)	$ (3,836,624)	$ (4,097,895)	$ (4,367,004)
Earnings after tax	**$ 9,521,462**	**$ 10,224,217**	**$ 10,948,055**	**$ 11,693,607**	**$ 12,461,526**

Table 12—Selected Financial Measures of CF Conversion Line Investment

	Precursor cost ¢30/lb.
Net present value (hurdle rate, r = WACC = 9.30%)	$ 13,403,395
Net present value (hurdle rate, r = 15%)	$ 5.707.972
Internal rate of return	22.3%
Payback period (year)	3.0

At a precursor price of ¢30/lb the CF conversion line is viable provided that the CF selling price is at least $7.50/lb. We complete the analysis by calculating the internal rate of return of the CF conversion line for various selling prices (see Figure 4).

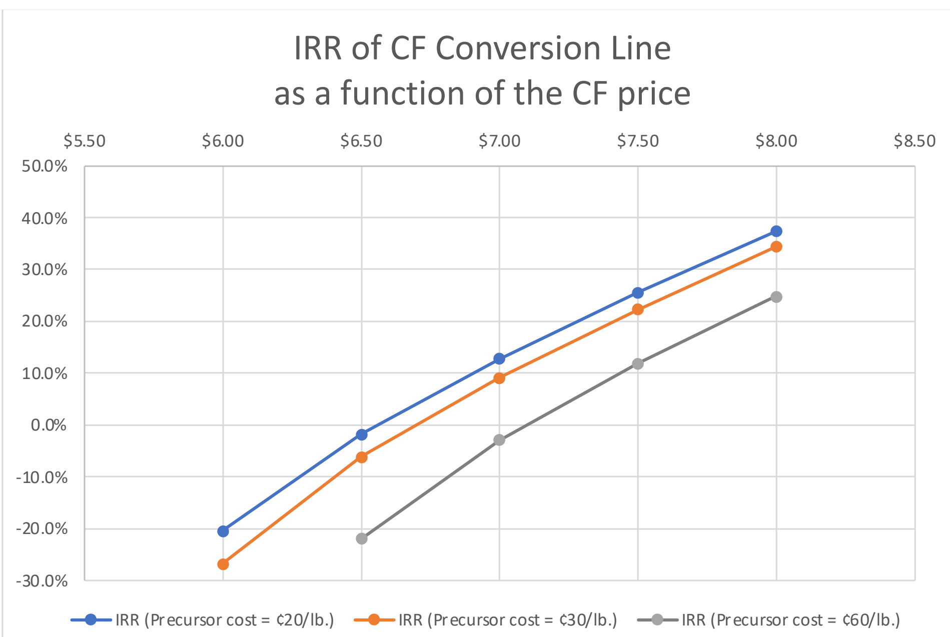


Figure 4—Internal Rate of Return of CF Conversion Line as a Function of CF Selling Price

Financial viability of the CF conversion requires a selling price of at least $7.50. Large margins (in the order of 50%) are required to cover the high upfront capital costs. Consider that a $141M investment in the coal-to-pitch plant will produce 250,000 tons of coke, whereas a comparable investment in a CF conversion line ($122M) will produce less than 4,000 tons of carbon fiber. Even though carbon fiber is a much higher value product than coke, the price difference does not make up for the huge volume gap. The cashflows of the CF conversion line are still only a third of the cashflows of the coal-to-pitch plant.

Our C2CF integrated cost model (in the electronic appendix) was used to analyze the various scenarios presented in this report. Note that the model can be used to analyze the financial viability of the C2CF supply chain as a whole or any part of it under any scenario. For example, the model can be used to evaluate the impact of state tax incentives, different debt to equity ratios, varying interest rates, etc.

4 Coal-based Carbon Fibers: How Big Is the Market?

There are very few producers of coal-based carbon fibers in the world. One of them, Mitsubishi Chemical, has been quite successful and does not face much competition for its high performance DIALEAD™ product manufactured from coal tars in Sakaide, Japan (Mitsubishi Chemical, 2021). DIALEAD™ is marketed as a high stiffness product and sold at a premium. Stiffness denotes the ability of a material to maintain its shape even after being submitted to external forces or temperature changes. High stiffness is critical in many applications such as robotic arms, optical instruments, space instruments, carbon/carbon brakes, etc., where products must maintain their shape no matter what. In scientific terms, stiffness is measured by the tensile modulus.

As depicted in Figure 5, DIALEAD™ is not as strong a material as PYROFIL™, Mitsubishi Chemical's family of PAN-based carbon fibers. However, it can be much stiffer. This is true generally of all coal-based carbon fibers. They provide higher tensile modulus but lower tensile strength than their PAN-based counterparts.

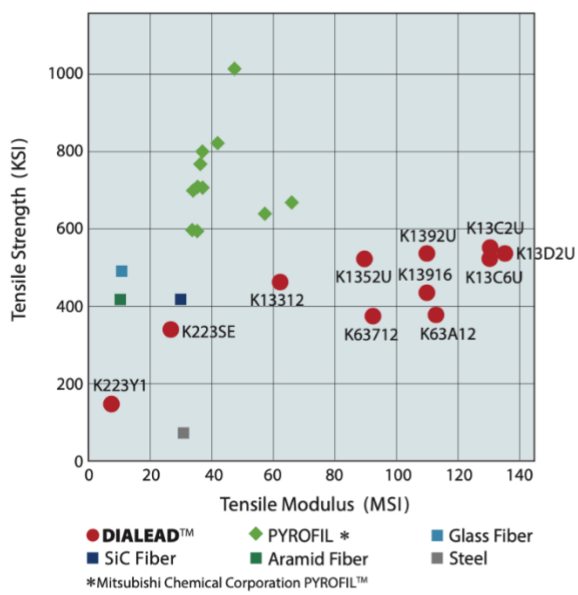


Figure 5—Tensile Properties of Materials (Source: Mitsubishi Chemical)

The development of coal-based carbon fibers rests on the discovery of new and high-volume applications for which coal-based carbon fibers provide unique and distinctive value. This value may come in the form of material properties that are better suited to the application, cost less or can be produced in high volumes. In this report, we focus specifically on injection-molded carbon fiber reinforced plastic (CFRP) components made from chopped fibers (length of about ¼ in). CFRPs are composite materials made of a polymer matrix (usually epoxy or polycarbonate) reinforced with carbon fibers. We assume a 30% carbon fiber content because research suggests it is enough to transfer most of the carbon fiber properties to the composite material. (An ongoing study at Weber State University is testing this assumption.) Note that 30% is much less than the carbon fiber content typically found in composites made from CF fabric (65—70%).

In the next section, we turn to an analysis of two potential markets for the C2CF carbon fibers: the drone market and the automotive market. We identify specific use cases within each market and evaluate the corresponding market sizes. Our objective is to determine whether the target use cases could support the production of coal-based carbon fibers at the needed scale.

4.1 Carbon Fiber Use Cases in the Drone Market

The market for unmanned aerial vehicles (UAVs) also known as drones is growing rapidly as applications of drone technology permeate an increasing number of fields. Drones are no longer merely used for recreation or entertainment; they are also used in large-scale commercial applications such as delivering products, spraying fertilizers, inspecting bridges, power lines or other industrial installations, building communication networks, surveying the land, buying or selling real estate, or making movies. According to the Teal Group, world production of drones in the consumer and commercial markets are expected to grow from 3.8 million units in 2021 (for a value of $5.76B) to 5.3 million units by 2025 (for a value of $11.11B) (Finnegan, 2020). The bulk of that growth will be in commercial applications.

Military applications of drone technology are also expected to rise but only moderately so. Teal Group forecasts a worldwide production of 5,607 drones in 2025 estimated at $9.9B compared to 4,243 drones in 2021 (for a value of $6.8B) (Zaloga, Rockwell & Finnegan, 2020). Note that, due to the classified nature of many military projects, actual production numbers may be much larger.

Drone markets are important for the C2CF supply chain because CFRPs are a material of choice in the making of drones' structural components (*e.g.*, frame, landing gear, wings or propellers). Indeed, weight is a primary consideration in drone design. Weight reductions translate into longer range, longer flight time or increased payload, all of which create value for drone operators. CFRPs are chosen for their high strength-to-weight ratio. Based on a survey of 31 US drone manufacturers, we found that CF composites represents about 60% of the drone weight, and as much as 90% in some cases.

In 2016, the Federal Aviation Administration (FAA) issued rules to allow registered drone pilots to fly small drones, defined as weighing 55 pounds or less (including sensors and payload), only within visual line-of-sight, in the daylight, and not over people. To facilitate the development of drone applications, the FAA has shown some flexibility when considering exceptions to these rules (Finnegan, 2020). The gradual opening of the national air space to drone traffic is fueling the growth in the use of small commercial drones for routine operations. In the context of this study, we focus on the small drone use cases because they constitute 99.98% of the market in unit and 97% of the market in value today (Finnegan, 2020).

Small drones fall under several categories depending on their size and equipment (See Table 13). Small military drones are classified either as small tactical UAVs or Mini-UAVs. In the commercial space, delivery drones are heavier since they must be able to carry packages. Prosumer drones are dedicated to professional applications. They differ from Mini-UAVs by the number and quality of their sensors. Mini-UAVs are equipped with more sophisticated equipment and software than prosumer drones.

We calculated the reference weights in Table 13 based on the weight of the most popular drone in each category.

Table 13—Classification of Small Drones (Sources: Teal Group; authors)

Product Category	Reference Weight (lbs)	Reference Price	Market
Small Tactical UAV	10.5	$400,000.00	Military
Mini-UAV	6.48	$40,000.00	Commercial & Military
Delivery	21	$12,000.00	Commercial
Prosumer	10.5	$2,000.00	Commercial
Entertainment	1.4	$1,000.00	Commercial
Consumer	2.1	$750.00	Consumer

How large is each drone market and how much carbon fiber would be required to support these markets in the near future?

To answer these questions, we collect domestic forecasted drone demand data from Teal Group for 2025. We then calculate the CFRP weight per drone as 60% of the drone weight. Our goal is to determine the market size if all drones in that product category were produced using injection-molded CFRP parts. As such, we assume the CF weight is 30% of the part weight. Given these assumptions, the forecasted CF weight for all small military drones is 1.28 tons for 2025 (See Table 14).

Table 14—CF Needed to Support US Small Military Drone Market (2025)

Product	Year	Forecasted Production	Avg. Weight (lbs)	% of CFRP	CFRP Weight per unit (lbs)	CF Per Unit (lbs)	Forecasted CF Weight (lbs)	Forecasted CF Weight (Short Tons)
Mini-UAV	2025	2,200	6.48	60%	3.89	1.17	2,566.08	1.28
Small Tactical UAV	2025	-	10.50	60%	6.30	1.89	-	0.00
							2,566.08	**1.28**

It is interesting to note that in their report the Teal Group says it is "not optimistic about the plans for swarming small UAVs" because, among other things, the lives of American soldiers should not be put at risk "because the Air Force uses cheap, disposable systems." (Zaloga, Rockwell & Finnegan, 2020 : 325) Even if Teal Group underestimated the forecast by a factor of 10, the CF needed to support the military drone market in the Mini-UAV and small tactical UAV categories is insignificant relative to the output of the C2CF supply chain.

What about commercial drones?

We perform the same exercise for commercial drones. By far the largest use cases predicted by Teal Group in the United States are the general photography market followed by the consumer market. Across all applications, the domestic demand for commercial drones would require less than 1,000 tons of CF per year (See Table 15). While significant, this is still not enough to support the C2CF supply chain. At least four times as much would be needed.

Table 15—CF Needed to Support US Small Commercial Drone Market (2025)

Product	Application Domain	Year	Forecasted Production	Avg. Weight (lbs)	% of CFRP	CFRP Weight per unit (lbs)	CF per Unit (lbs)	Forecasted CF Weight (lbs)	Forecasted CF Weight (Short Tons)
Prosumer	General Photography US	2025	625,000	10.50	60%	6.30	1.89	1,181,250.00	590.63
Consumer	Consumer US	2025	1,200,000	2.10	60%	1.26	0.38	453,600.00	226.80
Prosumer	Agriculture US	2025	50,000	10.50	60%	6.30	1.89	94,500.00	47.25
Prosumer	Construction US	2025	50,000	10.50	60%	6.30	1.89	94,500.00	47.25
Prosumer	Energy US	2025	30,000	10.50	60%	6.30	1.89	56,700.00	28.35
Prosumer	Insurance US	2025	15,000	10.50	60%	6.30	1.89	28,350.00	14.18
Delivery	Delivery US	2025	5,000	21.00	60%	12.60	3.78	18,900.00	9.45
Prosumer	Other Industrial Inspection US	2025	10,000	10.50	60%	6.30	1.89	18,900.00	9.45
Prosumer	US Civil Government	2025	6,000	10.50	60%	6.30	1.89	11,340.00	5.67
Mini-UAV	Construction US	2025	7,700	6.48	60%	3.89	1.17	8,981.28	4.49
Entertainment	Entertainment US	2025	32,000	1.40	60%	0.84	0.25	8,064.00	4.03
Mini-UAV	Agriculture US	2025	6,000	6.48	60%	3.89	1.17	6,998.40	3.50
Mini-UAV	Energy US	2025	5,000	6.48	60%	3.89	1.17	5,832.00	2.92
Mini-UAV	Other Industrial Inspection US	2025	1,000	6.48	60%	3.89	1.17	1,166.40	0.58
Mini-UAV	Communications US	2025	1,000	6.48	60%	3.89	1.17	1,166.40	0.58
Mini-UAV	US Civil Government	2025	750	6.48	60%	3.89	1.17	874.80	0.44
Mini-UAV	General Photography US	2025	500	6.48	60%	3.89	1.17	583.20	0.29
Mini-UAV	Insurance US	2025	400	6.48	60%	3.89	1.17	466.56	0.23
								1,992,173.04	**996.09**

Our analysis shows that even in the very optimistic scenario in which all small military and commercial drones sold in the United States in 2025 are produced using injection-molded CFRP parts the quantity of CF needed to support these use cases falls far short of the needed quantity. Applications in other industries will need to be developed to generate enough demand for the C2CF supply chain. We look for such applications in the automotive industry.

4.2 Carbon Fiber Use Cases in the Automotive Market

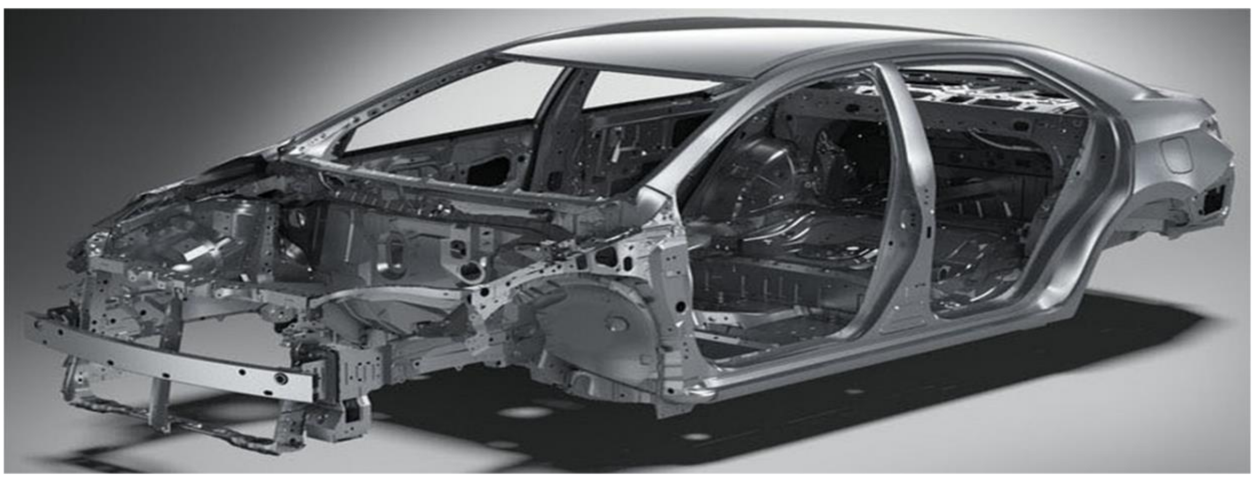
Steel remains the primary material used to make cars, even though the share of aluminum is rising due to its malleability and light weight (See Table 16). At 3 lb per vehicle (or 0.1% of the weight), carbon fiber enters the list as a tiny subset of the 'Other' category.

Table 16—Average Material Composition of Passenger Cars (Source: Al-Quradaghi, Zheng & Elkamel, 2020)

Material	Average Weight per Car (lbs)	Percentage
Steel	1876	63%
Aluminum	154	5%
Glass	88	3%
Plastics	251	8%
Tires	68	2%
Battery	31	1%
Fluids	110	4%
Other (e.g., paint, textiles)	401	13%
Total	**2979**	**100%**

Historically, carbon fiber has been used in high-end sports cars and supercars to reduce the vehicle's weight. More recently, carbon fiber has made inroads in several mass-produced models. CFRPs are now used to make hoods, fenders, bumpers, driveshafts, floor panels and other body panels (*e.g.*, tailgate, roof, C-pillar) but only on selected models. The full-electric BMW i3 is perhaps the first high-volume vehicle making extensive use of carbon fibers using revolutionary design principles. Overall, however, the carbon fiber content in the average passenger vehicle is only about 3 pounds (about one tenth of a percent of the total weight). There is a consensus among experts that demand for CFRPs in the automotive industry will continue to grow fueled by innovations in materials, technologies, and cost reductions. One report predicts that demand for CF from the automotive industry would quadruple if the price of carbon fiber would go down to $5/lb (Lucintel, 2020).

We identified and conducted in-depth research on 30 automotive use cases that we view as particularly promising. The list of use cases is given in Table 19. Each use case corresponds to a specific automobile component such as roof, bumper or driveshaft.



For each component, we record the material from which it is traditionally made together with the weight of the component made in the original material. We then estimate what percentage of the component could be replaced with injection-molded CF composites. In most cases, the replacement is full. However, some components (*e.g.*, tailgate) are sub-assemblies and cannot be made entirely of composites. Assuming no changes in the component geometry, we go on to calculate the new weight of the component using the replacement percentage and weight conversion ratios based on the materials' densities (See Table 17).

Table 17—Weight Conversion Ratios of Selected Materials

Material	Density	CF to Mat Ratio
Steel	8	0.188
Aluminum	2.7	0.556
FiberGlass	1.75	0.857
CF Composite	**1.5**	1

Our analysis is limited to the top ten best selling cars and pickup trucks in the United States. We round up the list with the best-selling electric vehicle, the Tesla Model 3 (See Table 18).

Table 18—List of Top Selling Vehicle Models in the United States

Vehicle Type	Vehicle Brand	Vehicle Model	2020 Sales
Pickup truck	Ford	F-Series	787,372
Pickup truck	Chevrolet	Silverado	593,057
Pickup truck	Dodge	Ram	563,676
Passenger car	Toyota	RAV4	430,387
Passenger car	Honda	CR-V	323,502
Passenger car	Toyota	Camry	294,348
Passenger car	Chevrolet	Equinox	270,994
Passenger car	Honda	Civic	261,225
Passenger car	GMC	Sierra	253,014
Pickup truck	Toyota	Tacoma	238,805
Electric vehicle	Tesla	Model 3	206,500

We use linear regression and the last ten years of sales data to calculate the 2025 sales forecast (See Table 19). For each vehicle model, we determine if the use case applies, and how many components each vehicle contains. For example, while all vehicles have a hood, only trucks are equipped with a tailgate. Similarly, each vehicle has four suspension knuckles but only one front-end bolster.

With this information, we are able to calculate the estimated CFRP gross weight for each use case, from which we can calculate the estimated CF weight (assuming a 30% carbon fiber content in the CFRP—see discussion of drones use cases). Collectively, the 30 uses cases represent a total weight of 317,360 tons of carbon fiber per year; enough to consume the output of 82 CF conversion lines!

Table 19—Carbon Fiber Needed to Support Selected Automotive Use Cases (2025)

Product	Classification	Original Material	Original Unit Weight (lbs)	CFRP %	CFRP Unit Weight (lbs)	Year	Forecast	Qty per Vehicle	CFRP Gross Weight (lbs)	% of CF	CF Weight (lbs)	CF Weight (short tons)
Brake Caliper	Non-Structural	Steel	15.2	100%	2.85	2025	5,878,895	4	67,019,397	30%	20,105,819	10,053
Floor Panel	Non-Structural	Aluminum	12.4	100%	6.89	2025	5,878,895	1	40,499,051	30%	12,149,715	6,075
Front Engine Cover	Non-Structural	Aluminum	2.4	100%	1.33	2025	5,511,040	1	7,348,053	30%	2,204,416	1,102
Front Fascia	Non-Structural	FiberGlass	10	100%	8.57	2025	5,878,895	1	50,390,524	30%	15,117,157	7,559
Gear Cooler	Non-Structural	Aluminum	7	100%	3.89	2025	5,511,040	1	21,431,822	30%	6,429,546	3,215
Hood	Non-Structural	Aluminum	36	100%	20.00	2025	5,878,895	1	117,577,890	30%	35,273,367	17,637
Motor Castings	Non-Structural	Aluminum	70	100%	38.89	2025	5,511,040	2	428,636,432	30%	128,590,930	64,295
Output Shaft	Non-Structural	Steel	3.3	50%	0.31	2025	5,511,040	1	1,704,978	30%	511,493	256
Rear Deck Lids	Non-Structural	FiberGlass	12.1	100%	10.37	2025	2,586,088	1	26,821,424	30%	8,046,427	4,023
Rear Fascia	Non-Structural	FiberGlass	10	100%	8.57	2025	2,913,340	1	24,971,488	30%	7,491,446	3,746
A Pillar	Semi-Structural	Steel	5	100%	0.94	2025	5,878,895	2	11,022,927	30%	3,306,878	1,653
B Pillar	Semi-Structural	Steel	5	100%	0.94	2025	5,878,895	2	11,022,927	30%	3,306,878	1,653
Battery Case	Semi-Structural	Aluminum	20.46	100%	11.37	2025	367,855	1	4,181,281	30%	1,254,384	627
Bumper Beam	Semi-Structural	Steel	20	100%	3.75	2025	5,878,895	1	22,045,854	30%	6,613,756	3,307
C-Pillar	Semi-Structural	Steel	5	100%	0.94	2025	5,878,895	2	11,022,927	30%	3,306,878	1,653
CFRP Stabilization Bars	Semi-Structural	Steel	5	100%	0.94	2025	5,511,040	4	20,666,399	30%	6,199,920	3,100
CFRP Wishbones	Semi-Structural	Steel	6.2	100%	1.16	2025	5,511,040	4	25,626,335	30%	7,687,901	3,844
Driveshafts	Semi-Structural	Steel	25.53	100%	4.79	2025	5,511,040	1	26,380,659	30%	7,914,198	3,957
Front Axel "Blade"	Semi-Structural	Steel	15.3	75%	2.15	2025	5,511,040	1	11,857,347	30%	3,557,204	1,779
Rear Wall Panel	Semi-Structural	Aluminum	7.19	90%	3.60	2025	1,069,087	1	3,843,367	30%	1,153,010	577
Seat Frame	Semi-Structural	Steel	33	100%	6.19	2025	5,878,895	2	72,751,320	30%	21,825,396	10,913
Seat Rails	Semi-Structural	Steel	12	100%	2.25	2025	5,878,895	4	52,910,051	30%	15,873,015	7,937
Seat Structure	Semi-Structural	Steel	10	100%	1.88	2025	5,878,895	2	22,045,854	30%	6,613,756	3,307
Tailgate	Semi-Structural	Aluminum	75	50%	20.83	2025	2,657,264	1	55,359,661	30%	16,607,898	8,304
Front End Bolster	Structural	Steel	11.3	100%	2.12	2025	4,809,808	1	10,190,780	30%	3,057,234	1,529
Rear Suspension Knuckle	Structural	Steel	21	100%	3.94	2025	5,511,040	2	43,399,439	30%	13,019,832	6,510
Steering Knuckle	Structural	Steel	21	100%	3.94	2025	5,511,040	4	86,798,878	30%	26,039,663	13,020
Suspension Knuckle	Structural	Steel	21	100%	3.94	2025	5,511,040	4	86,798,878	30%	26,039,663	13,020
Suspension Links	Structural	Steel	8.3	100%	1.56	2025	5,511,040	4	34,306,223	30%	10,291,867	5,146
Truck Pickup Box/Bed	Structural	Aluminum	400	98%	217.78	2025	3,292,807	1	717,100,157	30%	215,130,047	107,565
											634,719,697	**317,360**

The above results correspond to an ambitious scenario. We don't yet know with certainty if the C2CF material will satisfy all the requirements of the structural use cases. As for the non-structural use cases, carbon reinforcement may not be required in every case. Even if we targeted only the 14 semi-structural uses cases, there would be ample demand for multiple CF conversion lines (See Table 20).

Table 20—Carbon Fiber Weight by Use Case Classification (in short tons)

Use Case Classification	CF Weight (short tons)
Non-Structural Use Cases (10)	117,960
Semi-Structural Use Cases (14)	52,611
Structural Use Cases (6)	146,789
	317,360

Adoption of a few of the use cases on a single model would also create sufficient demand (See Table 21). In fact, this is the approach adopted by BMW when it dedicated the 3,000 ton-per-year CF conversion line in Moses Lake, WA, entirely to the model i3.

Our results confirm the popular belief that the automotive market can absorb large quantities of carbon fiber provided that the right use cases are found and the price of carbon fiber does not exceed $5/lb.

Table 21—Carbon Fiber Weight by Model (in short tons)

Vehicle Brand	Vehicle Model	CF weight (Short tons)
Ford	F-Series	75,920
Chevrolet	Silverado	52,011
Dodge	Ram	57,947
Toyota	RAV4	23,988
Honda	CR-V	17,243
Toyota	Camry	12,671
Chevrolet	Equinox	14,898
Honda	Civic	13,430
GMC	Sierra	20,602
Toyota	Tacoma	22,290
Tesla	Model 3	6,360
		317,360

5 The Coordinated C2CF Supply Chain

If we are to solve the chicken-and-egg problem in the C2CF supply chain, we need to reduce the price and increase the scale simultaneously. This is more easily said than done. One major risk to the C2CF supply chain is a lack of coordination between the coal-to-pitch plant and the CF conversion line in the likely event where they are owned by different entities.

Consider the following decentralized C2CF supply chain: The two entities interact as one sells pitch to the other. The manager of the coal-to-pitch plant wants to maximize her plant's profits. If she can, she would prefer selling the pitch at the retail price of ¢60/lb or more. She has no incentive to sell the pitch for less. Unfortunately, the manager of the CF conversion line won't buy at that price because his plant cannot make a profit. He would buy at the price of ¢20/lb but there is no seller at that price. The C2CF supply chain breaks down. While it is able to produce and sell pitch, the pitch does not go toward CF manufacturing. It is used for other purposes. Note that in this case, the first-year profit of the coal-to-pitch plant is $33,178,171. The CF conversion line doesn't exist. Therefore, its profit is $0. The total supply chain profit is $33,178,171.

This is the well-known 'double marginalization' problem. Each company within the supply chain maximizes its own profit irrespective of what's best for the whole supply chain. As each company adds its margin before passing its product down to customers, the price paid by the end consumer gets higher and higher leading to fewer and fewer sales. When companies within the supply chain fight for margins, the size of the pie shrinks. Everyone suffers.

Fortunately, there is another way. Consider the alternative scenario in which the coal-to-pitch plant sells the pitch for ¢20/lb but receives a percentage of the sales of CF; say, 20%. At ¢20/lb of pitch, the CF production cost is less than $5.00/lb. The CF conversion line will buy pitch at $20/lb. Let's run the numbers:

The coal-to-pitch plant loses $10.6M of pitch revenues but earns $11.55M (*i.e.*, $57.75M * 20%) from CF sales. The net effect is a profit increase of $701,248 for a first-year profit of $33,879,419. The profit of the CF conversion line is $1,728,934. The total supply chain profit is $35,608,353. Everyone is better off.

The lesson here is that when setting the price for the pitch, the coal-to-pitch manager should consider the system impacts, and not just the impact on their plant's bottom line. Revenue sharing is a simple, yet effective, way to incentivize every supply chain member to think in terms of what's best for the whole supply chain, and make the pie as big as possible. It works by rewarding the coal-to-pitch plant for its effort to lower the CF price, which will maximize CF sales.

In the CF market, American companies will compete with Japanese companies who dominate the market, and are highly integrated into large conglomerates called *keiretsu*. Mitsubishi is one such vertically-integrated conglomerate. Mitsubishi Chemical produces the coal tars used to make DIALEAD™. It is, in fact, not uncommon for a Japanese firm to own stock of their suppliers or customers. Over time, this has led Japanese managers to develop deep and closely knit relationships with their supply base. Such an industrial organization aligns well with the Japanese collectivist mindset. The American industrial base is much more fragmented leading to many incentive misalignments between buyers and sellers. If unchecked, it can be a source of friction and inefficiencies putting the whole supply chain at a disadvantage. Our recommendation is to use risk-sharing contracts such as revenue sharing to give the US C2CF supply chain the best chances to succeed.

6 Conclusion

Progress is being made toward the creation of a coal-to-carbon-fiber supply chain in the United States. It begins with the creation of spinnable coal pitch. In this paper, we analyze the Ekocoke™ process as the mechanism for creating such pitch. Other mechanisms exist (*e.g.*, coal liquefaction) that also need to be investigated. The main advantage of the Ekocoke™ approach is that it allows production of mesophase pitch at lowest cost since the pitch is the byproduct of a self-sustaining coking process. The 250,000 ton-per-year Ekocoke™ plant can actually support more than one CF conversion line.

The next step consists in spinning the pitch into fibers. This is a delicate and resource-intensive process that adds significant costs that usually aren't factored in. Nonetheless, the potential for coal-based carbon fibers to be much cheaper than PAN-based fibers exists. While we show it is possible to bring the production costs down to $5/lb, it is unlikely that such cost will result in a selling price less than $7.50/lb in the short term. Therefore, finding high-volume applications that leverage the unique properties of pitch-based fibers should remain a preeminent objective of the C2CF research community. We propose the automotive industry as a market of choice for such an investigation due to the industry's high production volumes. Finding such use cases would not only provide the scale needed to bring costs down; It would also justify the price premium customers may have to pay in the short term relative to established materials such as steel, aluminum or fiberglass. One avenue of research that has not been explored in this report is to use CF reinforcement to save volume in addition to weight. For example, if the volume of an automotive component could be reduced even by a small percentage by using CFRP, the potential benefits could be huge.

To launch the C2CF supply chain, we recommend a phased-approach in which the coal-to-pitch plant is built first and run for some time. Knowing actual revenues and costs in the first stage of the C2CF supply chain would provide more clarity for the decisions surrounding the construction on the CF conversion plant, which is much riskier. Until the CF conversion line is built, the pitch can be sold as is. One potential use of pitch is as a carbon matrix in carbon/carbon composites. Such composites are well-suited to structural application at very high temperatures (*e.g.*, reentry vehicles of intercontinental ballistic missiles, or carbon/carbon brakes). We also recommend the use of risk sharing contracts to avoid unnecessary competition within the C2CF supply chain and maximize the chances of success for the C2CF supply chain.

We are encouraged by the increased interest we've seen during the course of this project about the concept of coal-to-carbon-fiber, and are hopeful American engineers and entrepreneurs will come up with innovative and profitable solutions in this important area of research.

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9 Model Parameters & Assumptions

Category	Parameter	UOM	Value	
Capacity	Production hours per year	hours	7,200	
	Coal-to-pitch nameplate output	short tons per year	250,000	
	CF conversion plant nameplate output	short tons per year	3,850	
	CF conversion lines	#	1	
Design parameters	CF conversion format	Tow or Mat	Mat	
	Filaments per tow	k	NA	
	Pitch to CF yield	%	75%	
	Line width	m	3	
	Precursor spinning speed	m/min	TBD	
	Precursor spinneret diameter	µm	TBD	
	Electricity (Carbon fiber) at startup	kW	13,000	
	Electricity (Carbon fiber) in operation	kW	8,800	
	Low Temperature Furnace	C	800	
	High Temperature Furnace	C	1800	
	Residence time (oxidation)	minutes	64	
	Residence time (low temp furnace)	seconds	68	
	Residence time (high temp furnace)	seconds	68	
Raw material costs	Rapeseed oil	$/lb	$0.45	
	MDEA	$/lb	$3.47	
	Sodium Hydroxide	$/lb	$4.40	
	Thermal coal	$/short ton	$40.00	
	Phosphoric Acid	$/lb	$1.44	
	Caustic Soda	$/lb	$2.70	
	Citric Acid	$/lb	$1.79	
Byproducts prices	Benzene Toluene Xylene (BTX)	$/short ton	$370.00	50% of retail price (source: grains.org)
	Natural gas(*)	$/MWh	$31.68	
	Coal Tar	$/short ton	$390.00	
	Sulfuric Acid 98%	$/short ton	$678.92	50% of Brenntag bulk price
	Coke	$/short ton	$275.00	
	Anhydrous Ammonia	$/short ton	$1,960.00	50% of Brenntag bulk price
	Mesophase pitch	$/lb	$0.30	or $0.60
Buildings	Space requirements	sqft	TBD	
Life expectancy	Equipment Coal-to-pitch	years	7	
	Equipment CF conversion line	years	20	
	Buildings	years	20	

	Coal-to-pitch	CF Conversion
Cost of equity	15%	15%
Cost of debt	10%	7%
Federal corporate tax rate	21%	21%
State corporate tax rate	5%	5%
Corporate tax rate	25.95%	25.95%
Ratio of Debt / Inv.	75%	75%
WACC	9.30%	7.64%
Loan duration (years)	7	10
Inflation	3% per year	3% per year