

Lignin-Derived Carbon Fiber as a Co-Product of Refining Cellulosic Biomass

Matthew Langholtz and Mark Downing
Oak Ridge National Laboratory

Robin Graham
Argonne National Laboratory

Fred Baker
Big Island Carbon

Alicia Compere and William Griffith
Oak Ridge National Laboratory, retired

Raymond Boeman and Martin Keller
Oak Ridge National Laboratory

ABSTRACT

Lignin by-products from biorefineries has the potential to provide a low-cost alternative to petroleum-based precursors to manufacture carbon fiber, which can be combined with a binding matrix to produce a structural material with much greater specific strength and specific stiffness than conventional materials such as steel and aluminum. The market for carbon fiber is universally projected to grow exponentially to fill the needs of clean energy technologies such as wind turbines and to improve the fuel economies in vehicles through lightweighting. In addition to cellulosic biofuel production, lignin-based carbon fiber production coupled with biorefineries may provide \$2,400 to \$3,600 added value dry Mg⁻¹ of biomass for vehicle applications. Compared to producing ethanol alone, the addition of lignin-derived carbon fiber could increase biorefinery gross revenue by 30% to 300%. Using lignin-derived carbon fiber in 15 million vehicles per year in the US could reduce fossil fuel consumption by 2-5 billion liters year⁻¹, reduce CO₂ emissions by about 6.7 million Mg year⁻¹, and realize fuel savings through vehicle lightweighting of \$700 to \$1,600 per Mg biomass processed. The value of fuel savings from vehicle lightweighting becomes economical at carbon fiber price of \$6.60 kg⁻¹ under current fuel prices, or \$13.20 kg⁻¹ under fuel prices of about \$1.16 l⁻¹.

KEYWORDS: lignin-based carbon fiber, biofuels, value chain analysis

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INTRODUCTION

Carbon fiber (CF) composite material is valued in high-performance applications for its strength, stiffness, and light weight. Since the 1960s it has been used in the construction of aircraft, sports equipment, racecars, and other niche applications. In 2009, global CF demand was estimated at

30,000-35,000 Mg, and is projected to more than triple by 2019 with growth in advanced aircraft and wind turbine construction [1, 2]. Nearly all CF currently produced is petroleum-derived polyacrylonitrile (PAN) or petroleum- or coal-derived pitch [3]. Prices for CF from PAN are relatively high and volatile, about \$33.00 Kg⁻¹, influenced by the price

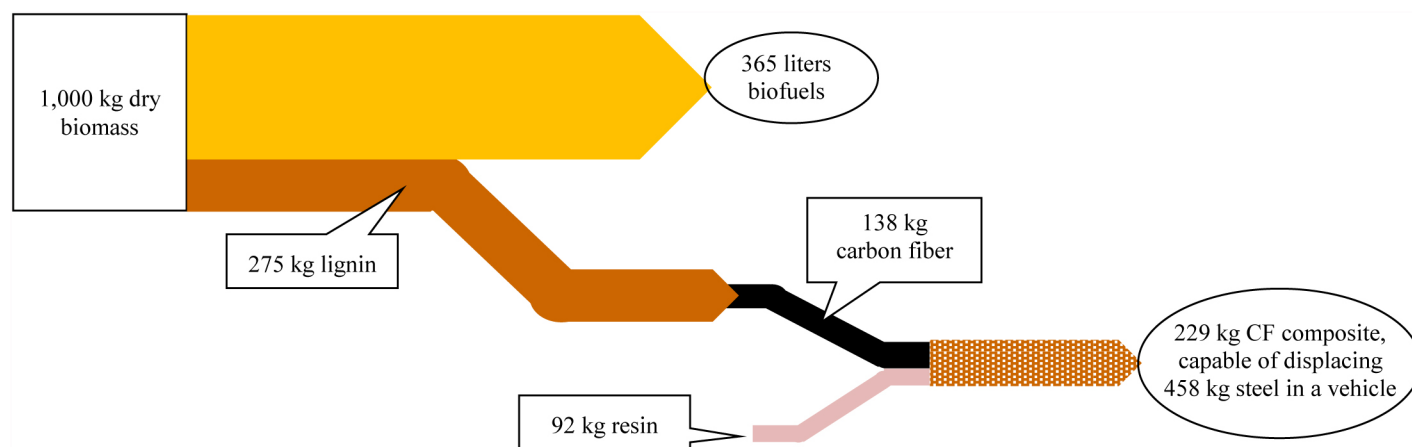


Figure 1. Schematic flow of 1 Mg dry biomass into primary components and products. 1 Mg of biomass can produce about 365 liters of biofuels and 138 kg carbon fiber. CF in turn can be used to construct CF composite, which can displace steel in vehicles, reduce vehicle weight, and improve fuel economy. Assumes lignin content of 27.5%, midpoint between hardwoods and softwoods [12].

of oil and fluctuating demand [4]. CF can also be produced from the lignin fraction of biomass. An example is CF derived from kraft lignin from the pulp and paper industry.

In 1996, the U.S. pulp and paper industry produced 208 million cubic meters of pulpwod [5]. During the kraft pulping process, lignin is separated from cellulose, and can then be purified and spun into CF. The exact price of lignin-based carbon fiber produced commercially is unknown, but is estimated to be about \$11.00-15.00 Kg⁻¹ [4, 6, 7, 8]. However, commercial kraft lignin must be washed and desalted, which compromises fiber strength [9]. An alternative source of lignin to produce CF is from biorefineries that produce liquid transportation fuels from the cellulosic and sugar components of biomass.

Second-generation biofuels, i.e. fuels derived from lignocellulosic crops rather than food crops, are expected to play an increasingly important role in future energy strategies. The economic success of lignocellulosic biorefineries hinges on the market for various co-products such as polymers, bioplastics, chemicals, and potentially lignin-based CF, in addition to a sustained market price for biofuels [10, 11]. Non-food biomass such as crop residues or dedicated herbaceous or woody biomass crops contain 5%-30% lignin, with woody feedstocks containing 20%-30% lignin [12]. Coupling the production of biofuels with lignin-based CF can provide synergistic benefits, improving overall profitability and facilitating improved fuel economies through vehicle lightweighting [13]. The flow of materials and products potentially derived from 1 Mg of dry biomass is illustrated in Figure 1. Lignin from biorefineries is purer than lignin than from kraft processes, which reduces losses from washing and desalting [9]. Stacking values of these products and services greatly increases the total economic benefit that can be derived from biomass and can help drive a paradigm shift in renewable fuels and fuel economy. Here we quantify

economic benefits of producing CF with lignin from second-generation biorefineries in a value chain analysis.

ASSESSMENT OF POTENTIAL ADDED VALUE

To evaluate stacked economic benefits of using lignin-based CF from biorefineries, we perform a value chain analysis of a biorefinery that produces cellulosic biofuel and CF from woody biomass. We assume products and benefits to include cellulosic biofuel, lignin-based CF, fuel economy savings from vehicle lightweighting, and associated CO₂ emissions reductions. We quantify added value derived on a per-ton biomass basis for low (i.e. pessimistic), high (i.e. optimistic), and reference cases (Table 2).

Cellulosic Biofuels

Assuming a yield of about 365 liters Mg⁻¹ biomass [14] and a price of about \$0.46 liter⁻¹ [14], the value of cellulosic biofuel production from a ton of biomass is approximately \$170.00 dry Mg⁻¹ (Table 2 row 3).

Lignin-Based CF

Assuming a lignin content of biomass is about 28% [12], a CF yield from lignin is 50% [15], and a CF price of \$13.20 kg⁻¹ [6, 7], CF from the lignin by-product at the biorefinery is estimated to add a value of \$1,600.00-\$2,000.00 from the same Mg of biomass (Table 2 row 7).

Fuel Economy Savings from Vehicle Lightweighting

A major variable in the analysis is vehicle weight reduction (Table 2 row 9), which in turn drives improved fuel economies (row 10). For purposes of this analysis, it is assumed that 10 kg of steel are replaced by 5 kg of CF

composite material, which in turn is comprised of 3 kg of CF and 2 kg of resin [16]. Further, each 10% reduction in vehicle weight yields about 4.5%-8% improvement in fuel economy [17, 18]. Improved fuel economy from vehicle lightweighting with CF from the same Mg of biomass is estimated to save the consumer a present value of \$740.00-\$1,600.00 over the life of the vehicle, discounted at a rate 6.0% (Table 2 row 19).

CO₂ Emissions Reductions

In addition to economic savings, improved fuel economy through vehicle lightweighting provides environmental benefits in the form of reduced greenhouse gas emissions. A vehicle that travels 240,000 km over a ten-year life, with a conventional fuel economy of 9.6 km/l, and an improved fuel economy of 11% through lightweighting saves approximately 2,900 l of gasoline, or about 6.8 Mg CO₂ emissions (see calculations in Table 3 row 11). Assuming high value of \$11.00 Mg CO₂e, the present value of potential economic benefits of reduced CO₂ emissions and steel displacement are shown in Table 2 rows 24 and 25. Potential costs of CO₂ emissions associated with CF production (Table 2 row 25) make net economic carbon-related benefits low (\$14.00-\$60.00 Mg biomass⁻¹) compared to values of CF production and fuel savings. Applying current CO₂ market prices would further reduce carbon benefits in economic terms. Total quantities of CO₂ emissions and emissions reductions per Mg biomass are shown in Table 1.

Table 1. CO₂e emissions and emission reductions (Mg CO₂e Mg⁻¹ biomass)

	Low Case	High Case	Reference Case
1 CF production ¹	-2.74	-3.29	-3.02
2 Steel displacement ²	0.57	0.68	0.62
3 Fuel savings ³	4.08	8.70	6.23
4 C sequestered in CF products ⁴	0.42	0.50	0.46
5 Net reductions ⁵	2.31	6.58	4.29

¹ Source: Assumes 24.2 units CO₂e per unit of CF production [19] * Table 2 row 4 * Table 2 row 5.

² Calculation: (Table 2 row 20*row 4*row 5) *0.5 (assumes 50% of steel is recycled, and 3 units of CO₂ produced for each unit of steel) [19].

³ Calculation: Table 3 row 11*row 15*row 16.

⁴ Calculation: Table 3 row 15*row 16*44/12 (m.w. CO₂/m.w. C). Represents C sequestered in long-lasting durable products.

⁵ Sum rows 1-4.

The opportunity cost of the fuel value of lignin for biorefineries is relatively small (Table 2 row 28), and could be displaced with alternative bioenergy strategies, e.g. gasification. Combined added values are estimated to provide from \$2,600.00-\$3,800.00 dry Mg⁻¹ biomass (Table 2 row 29, Figures 2 and 3). Table 4 illustrates these benefits in

terms of quantity per vehicle, dollars per vehicle, dollars per kg CF, and dollars per dry Mg biomass.

Table 2. Assumptions and cumulative added values and benefits of cellulosic biofuel, carbon fiber, fuel savings, and hypothetical CO₂ emissions potentially derived from 1 dry Mg of biomass

	Low Case	High Case	Reference Case
1 Cellulosic biofuel production (liters Mg ⁻¹) ¹	355	375	365
2 Cellulosic biofuel price (\$ liter ⁻¹) (2007\$) ²	\$0.46	\$0.46	\$0.46
3 Value of cellulosic biofuel (\$ Mg ⁻¹ biomass) (2007\$) ³	\$164.91	\$174.41	\$169.66
4 Lignin content of (%) ⁴	25%	30%	28%
5 Yield of CF from lignin ⁵	50%	50%	50%
6 CF Price (\$ kg ⁻¹) ⁶	\$13.20	\$13.20	\$13.20
7 Value of CF (\$ Mg ⁻¹ biomass) ⁷	\$1,653.00	\$1,984.00	\$1,819.00
8 Amount of CF used (kg car ⁻¹)	136 ⁸	163 ⁹	150
9 Vehicle weight decrease	17% ¹⁰	20% ¹¹	18%
10 Fuel Economy increase	8% ¹²	16% ¹³	11% ¹⁴
11 Fuel price (\$ liter ⁻¹) (June 2010\$) ¹⁵	\$0.72	\$0.72	\$0.72
12 Miles driven (km vehicle ⁻¹ year ⁻¹) ¹⁶	19,312	19,312	19,312
13 Fuel economy (Km liter ⁻¹) ¹⁷	9.6	9.6	9.6
14 Value of fuel economy savings (\$ vehicle ⁻¹ year ⁻¹) ¹⁸	\$109.20	\$232.96	\$166.83
15 Vehicle life (years) ¹⁹	10	10	10
16 Present value of fuel economy savings (\$ vehicle ⁻¹ at 6% discount rate) ²⁰	\$804.00	\$1,715.00	\$1,228.00
17 Kg lignin vehicle ⁻¹ ²¹	272	327	299
18 Mg biomass vehicle ⁻¹ ²²	1.1	1.1	1.1
19 Present value of fuel economy savings (\$ Mg biomass ⁻¹) ²³	\$738.00	\$1,575.00	\$1,128.00
20 kg of steel replaced by 1 kg of CF ²⁴	3.3	3.3	3.3

