Energy Media: The Politics of Solid-Phase Bitumen

Life Cycle of Carbon Fibers: Final Report

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Introduction

This semester, we have been working with Professor Darin Barney and his Ph.D. student, Hannah Tollefson, from the Department of Communication Studies at McGill University, to fulfill a technical complementary chemical engineering course, CHEE 494. They are currently working on a project called *Energy Media: The Politics of Solid-Phase Bitumen*, sponsored by the Social Sciences & Humanities Research Council of Canada (SSHRC). The project examines emerging non-combustion uses for bitumen extracted from the Alberta oil sands and their environmental, economic, and political implications.

We were brought on to this research project to assist with interpreting and verifying scientific and technical data. The first stage of the project involved generating annotated transcripts of selected interviews that Dr. Barney and Hannah had with scientists, engineers, entrepreneurs, and research officers pursuing these innovations. The completed transcripts included interviews with Bryan Helfenbaum (Executive Director of Advanced Hydrocarbons at Alberta Innovates), Paolo Bomben (lead of the Bitumen Beyond Combustion Program at Alberta Innovates), Simon Park (Mechanical Engineering Professor at University of Calgary) and Md Golam Kibria (Assistant Professor in the Department of Chemical and Petroleum Engineering at University of Calgary).

In the second stage of the project, we reviewed documents that provided background information on the topic. These included the Bitumen Beyond Combustion (BBC) White Paper Report by Alberta Innovates [1] and the *Life Cycle Analysis of Asphaltene to Carbon Fiber* by Amit Kumar et al. [2]. Amit Kumar is a Professor of Mechanical Engineering at the University of Alberta and an Alberta Innovates Research Chair.

Now, in the final stage of the project, this report will investigate scientific claims made in Kumar's *Life Cycle Analysis of Asphaltene to Carbon Fiber* [2] from a critical engineering perspective. We will develop a clear sense of the means by which life cycle analyses of prospective materials are conducted, current life cycle of carbon fibers, claims regarding the life cycle of carbon fibers made from asphaltenes[1] derived from Alberta bitumen, and the specific assumptions made in the analysis.

While the principal resource of this report is the analysis by Kumar, we will also reference selected engineering and scientific literature on carbon fiber and material life cycle analysis more broadly. Additionally, we conducted an informative interview with Sarah Jordaan, Associate Professor of Life Cycle Assessment and Industrial Ecology in the Department of Civil Engineering at McGill University. With her help, we were able to verify and validate different assumptions made throughout the analysis.

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[1] Asphaltenes are defined as the fraction of bitumen that is soluble in toluene but insoluble in n-alkanes. Because of this definition, there is no single molecule that defines an asphaltene.

BBC White Paper Synopsis

The Bitumen Beyond Combustion (BBC) White Paper by Alberta Innovates is a major component of Dr. Barney's research. Understanding its contents and purpose will help contextualize the work we've done this semester.

Bitumen is the heaviest grade of crude oil and is present in the Alberta oil sands as a mixture of sand, clay, and water. Bitumen is comprised of light and heavy fractions and is richer in the latter than other crude oils. When sent to the refinery, the heavy fraction of bitumen requires more processing than conventional crude oils to turn into gasoline. The BBC program investigates ways in which the heavy fraction of Alberta bitumen can be diverted away from use in fuels and can instead be used to generate high-value products, such as:

- Bitumen-derived asphalt binder
- Bitumen-derived carbon fibers (our focus)
- Bitumen-derived activated carbon

According to the BBC paper, this not only increases the monetary value of the barrel, but also reduces GHG emissions in three ways. First, the bitumen is being diverted from combustion – up to 47% of the barrel can be used to produce non-combustion BBC products (listed above). Second, these products would displace higher-GHG-intensity products currently in the market. For example, a 52% life cycle reduction in GHG intensity has been claimed for bitumen-derived carbon fiber relative to polyacrylonitrile- (PAN) based carbon fiber (the typical precursor to carbon fibers). Lastly, downstream emissions will be reduced – for example, asphalt binder from bitumen increases road longevity, and carbon fiber can be used for lightweight vehicles.

In this report, we will investigate some of the scientific claims being made about the emissions- and energy- reductions that come with the production of bitumen-derived carbon fiber (CF). We will start with a general overview of how LCA is performed for prospective materials (our definition for materials not yet in production at scale). Then, we will review current knowledge of LCA of carbon fibers, and finally, we will investigate claims made about the emissions reductions from CF produced from Alberta bitumen. We will finish by reviewing assumptions used in life cycle analyses of CF from bitumen and make some recommendations for future work.

Principles and Framework of General Life Cycle Analyses

This section will introduce how life cycle assessments (LCA) are conducted as well as the extent to which the methods were adhered to in Kumar's *Life Cycle Analysis of Asphaltene to Carbon Fiber* [2].

Life cycle assessment (LCA) is an increasingly important tool to evaluate a product's environmental impacts and socio-economic performance. It is a system-based approach that assesses the material and energy inputs and flows at each stage of a product's life. The International Organization for Standardization (ISO) provides standardized principles and frameworks for LCA as well as guidelines and requirements. ISO 14040:2006 states that an LCA can assist in identifying opportunities to improve the environmental performance of products at various points in their life cycle, informing decision-makers in industry, government, or non-government organizations, selecting relevant indicators of environmental performance, and marketing [5].

There are two ways in which the assessment can be conducted. The first is a cradle-to-gate approach which addresses the potential environmental impact of a product from the raw material acquisition to carbon fiber production before transportation to the final use. The main components in this analysis are the impact of the materials, production, and transportation [6]. The second approach is cradle-to-grave, which encompasses all the aspects of the cradle-to-gate analysis plus those from the product's use, end-of-life treatment, recycling, and final disposal.

The *Life Cycle Analysis of Asphaltene to Carbon Fiber* (Kumar) report aims to quantify and compare the greenhouse gas (GHG) emissions and energy consumption data between the production of carbon fiber from crude oil-derived polyacrylonitrile (PAN) to the production from bitumen-derived asphalt. It uses the simulation model, literature review, and data-intensive spreadsheet models developed for the precursor and carbon fiber production for both pathways. Monte Carlo simulations were performed to assess the uncertainty of the GHG emissions in the asphaltene-based carbon fiber (ACF) pathway. In this case, simulation models make sense as a way to generate data because asphaltene-based carbon fibers (ACFs) are still in the early stages of development, so there are few experimental results. The Monte Carlo, also known as the statistical simulation method, is guided by statistical probability theory to provide a very precise numerical calculation method. Combining the Monte Carlo method with LCA solves the uncertainty problem of the LCA method in environmental impact assessment, providing a more scientific and reasonable basis for decision-making of prospective materials [7].

The scope of the study is to compare the two life cycles using the cradle-to-gate method, meaning the differences in performance and recyclability were not considered. The cradle-to-gate approach allowed Kumar to determine the impact of the resources by each process on the GHG emissions throughout their life cycle.

Current Knowledge of the Life Cycle of Carbon Fibers

PAN Pathway

In this section, we focus on LCA techniques specific to carbon fibers. We will analyze the processing steps that are commonly included in LCAs, and attempt to draw general boundaries that most LCA studies use. This will help identify differences between methods using traditional PAN precursors to new methods using asphaltene precursors.

Multiple sources cite the following four steps in carbon fiber production from PAN: (1) precursor production, (2) stabilization (or oxidation), (3) carbonization, (4) surface treatment [8, 9, 10]. Briefly, this is what is involved in each step:

1. Precursor production: Acrylonitrile (AN) is first polymerized by mixing with solvents and catalysts. This is then dissolved in a solvent, such as DMSO, DMF, or DMAC, to prepare a “dope” solution. This is then transferred to a coagulation bath and spun into filaments. Lastly, the filaments are stretched in pressurized steam to orient the molecular chains along the fiber axis. This then gets finished, dried, and spun on a spool [9].
2. Stabilization/oxidation: The fiber is oxidized at temperatures of 200-300°C, which stabilizes the PAN precursor. This is the most time-consuming step in the manufacturing process [9].
3. Carbonization: After stabilization, the precursor fiber can now withstand higher temperatures. In the carbonization process, pyrolysis is performed between 500-1600°C. This volatilizes (evaporates) most non-carbon impurities in the precursor (such as methane, hydrogen, CO_2, and ammonia). Only 50-55% weight of the original precursor will remain, containing >98% carbon [9].
    a. Additional heat treatment over 1600°C is sometimes applied, called graphitization. This will increase Young’s modulus of the fiber but will decrease its tensile strength [10].
4. Surface treatment: Surface treatment is done to enhance the mechanical properties of the fiber, typically by electrochemical oxidation. Then, a sizing layer (epoxy or resin) is applied to the surface to enable weaving and handling [9].

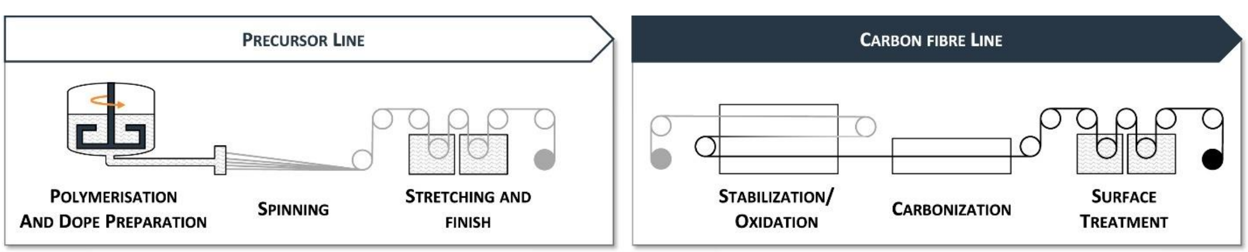


Figure 1: Production method for carbon fibers made from polyacrylonitrile (PAN) precursors [9].

LCAs involving the production of carbon fiber typically encompass these steps. However, in contrast to steel and aluminum, where life cycle inventories are provided by associations such as the World Steel Association and International Aluminum Institute, associations related to carbon fibers do not provide such life cycle resources [9]. Commercial databases also lack datasets on carbon fibers, and scientific literature is limited as well [9]. Despite this, we have compiled some data on the LCA of carbon fibers - below are some graphics that show the typical system boundaries drawn for such assessments.

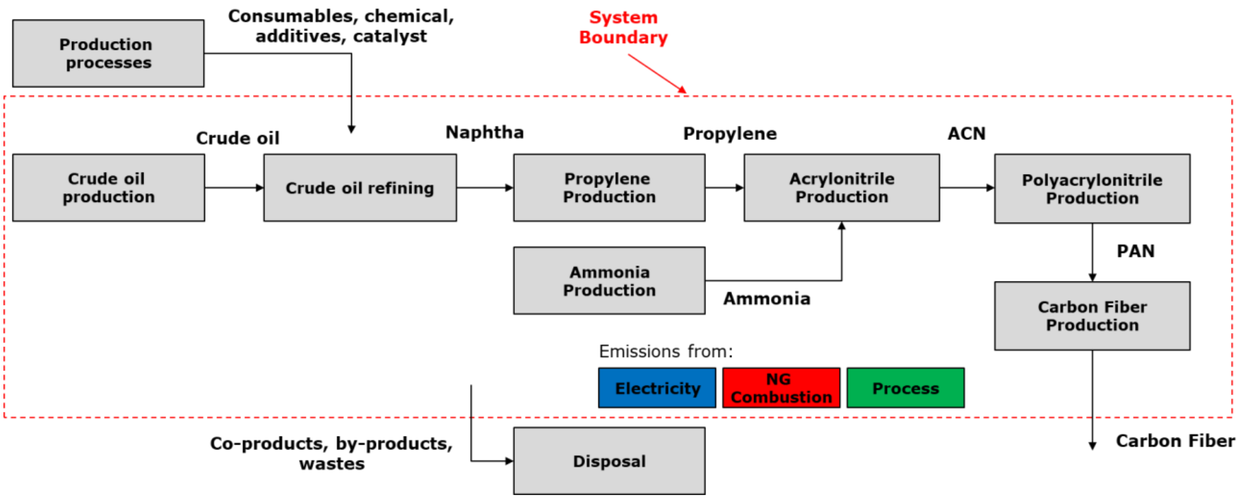


Figure 2: System boundary diagram, for the production of carbon fibers from PAN [2].

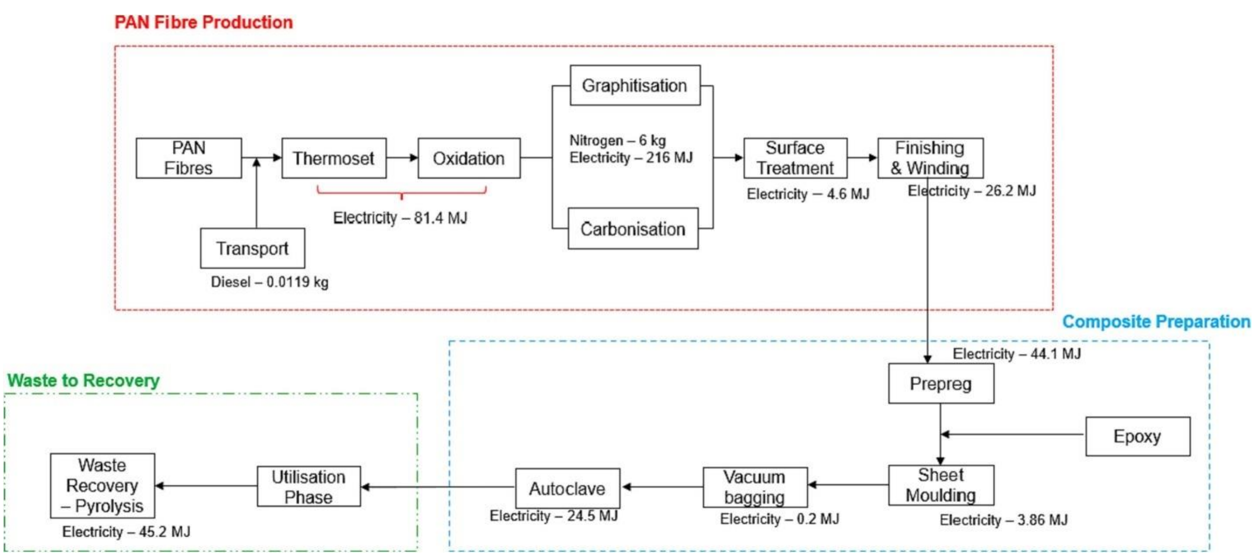
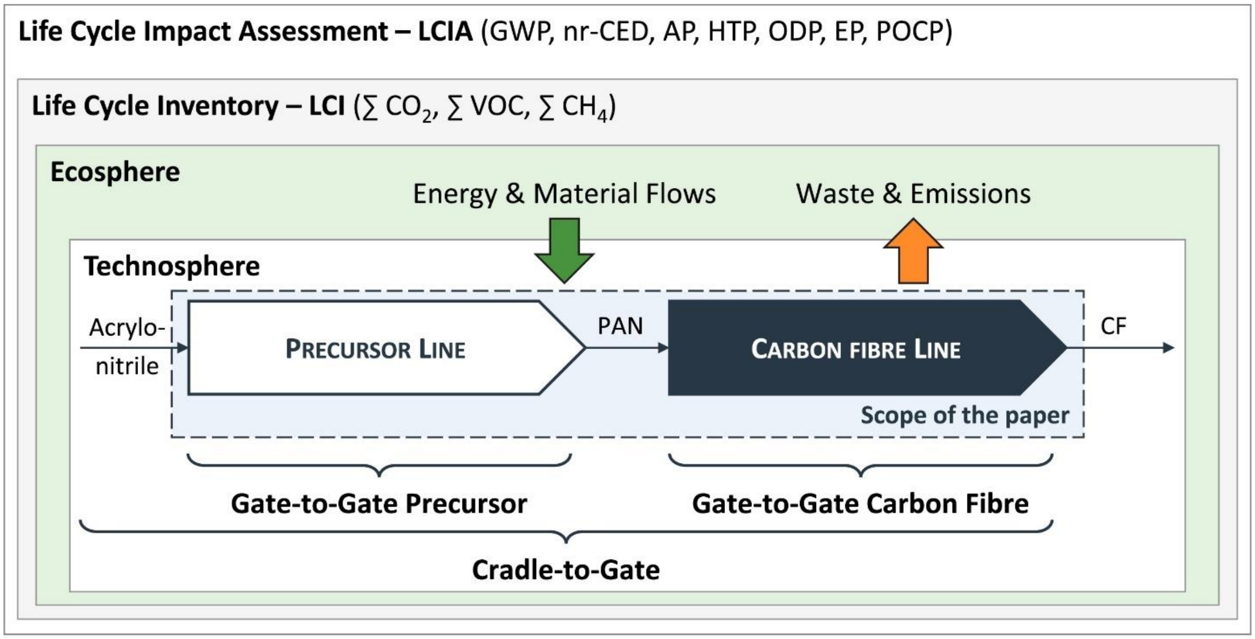


Figure 3: System boundary for production of CFRP from PAN precursor. The red box encompasses the processes considered part of the LCA of carbon fibers only [11].



GWP: Global Warming Potential, nr-CED: Non-renewable Cumulative Energy Demand, AP: Acidification Potential, HTP: Human Toxicity Potential, ODP: Ozone Layer Depletion Potential, EP: Eutrophication Potential, POCP: Photochemical Ozone Creation Potential, VOC: Volatile Organic Compound, PAN: Polyacrylnitril, CF: Carbon Fibre

Figure 4: Visualization of different system boundaries that can be used when comparing life cycle inventory (LCI) data from literature [9].

Interestingly, Figure 2 (Kumar, [2]) includes the production and refining of crude oil in the system boundary, while other studies do not. Figure 4 differentiates between cradle-to-gate and gate-to-gate, where the latter does not include raw materials and intermediates; only energy and material flows related to the production process. Using this definition, Kumar performs a complete cradle-to-gate analysis, whereas Ramachandran (Figure 3, [11]) is gate-to-gate.

Der, et al (2021) [9] provide a summary of the literature on the energy intensities for each step of carbon manufacturing:

Table 1: Summary of available data on life cycle studies performed on the production process of carbon fibers. Data is from Dér, et al (2021) [9].

Study	**Energy intensity for Precursor Manufacturing [MJ/kg CF]**	**Energy intensity for CF Manufacturing [MJ/kg CF]**			
		Stabilization	Carbonization	Surface Treatment	Total CF Manufacturing
Das (2011)	245				704
Liddell et al. (2016)	394	316		25	341

Liddell et al. (2017)	312	195		24	219
De Vegt and Haije (1997)					7.56
Suzuki and Takahashi (2005)					276-478
Griffing and Overcash (2009)			4.47	0.05	4.52
Arnold et al. (2018)					255.02
Average	**317**				**286**

The sum of the averages leads to a total cradle-to-gate energy consumption of 603 MJ /kg CF. However, the reported energy demand varies widely. System boundaries vary throughout the studies; some examine cradle-to-gate, others look at gate-to-gate, and some do not specify at all. Scale also varies; Arnold et al. is based on 12k tow CF, while Das describes 50k tow (tow size is the number of filaments per tow (or roll) of carbon fiber. Thus, a 50k tow has 50 000 filaments wrapper around it). Also, the specification of fiber properties is missing. This is a major consideration addressed by Kumar [2] as well; it is not completely fair to compare the energy- and emissions- intensity of carbon fibers that have vastly different mechanical properties, which we will address further in the report.

In order to get more data to help validate the information in Table 1, we look to LCAs performed on carbon fiber-reinforced polymers (CFRPs) and extrapolate data from these LCAs to gain more information on carbon fibers. A CFRP research synthesis [4] reviewed 26 LCAs for CFRP, some of which broke down the energy use and CO_2 emissions of the CFRP production into different categories: CF production, polymer production, and CRFP production (combining the CF and polymer streams). Using the studies that did provide this granularity, we were able to extract the emissions (kg CO_2 / kg carbon fiber produced) and energy use (MJ / kg carbon fiber produced). Data is provided in Table 2, with sample calculations in the Appendix.

Table 2: Synthesis of CFRP life cycle analyses that provide data specific to the carbon fiber portion of the LCA. In many cases, the emissions or energy for CFRP production are broken down into the individual components (e.g. contribution of emissions from CF production), but the data is still given with a denominator of kg CFRP. Therefore, using the mass fraction of carbon fiber in the CFRP, we found the

emission / energy effect of carbon fiber production only. Sample calculation is provided in the Appendix. Average was calculated first for each study, then the average of those were taken to get final values (this prevents the studies with more datapoints contributing more to the overall average). All data is from LIBRE synthesis report [4], Appendix 2: Calculations.

Author / Report	**Appendix pg. no.**	**CF% (weight)**	**Emissions from CF (kg CO2 / kg CFRP)**	**Emissions Impact (kg CO2 / kg CF)**	**Energy from CF (MJ / kg CFRP)**	**Energy Impact (MJ / kg CF)**	**LCA scope (cradle-to-)**
Das (2011)	13	-	-	31	-	704	Grave
	13	-	-	24	-	670	
La Rosa et al. (2016)	17	58%	-	-	1003	1729	Gate
Maxineasa et al. (2015)	19	27%	5.4	20	-	-	Gate
	20	27%	5.3	20	-	-	
	21	13%	2.6	20	-	-	
	22	15%	2.9	19	-	-	
	23	14%	2.9	21	-	-	
Meng et al. (2017)	24	25%	23	92	371	1484	Gate
	25	50%			800	1600	
	25	50%	32	64	564	1128	
Zhou (2013)	30	61%	19	31	174	285	Gate
Average				**39**		**1026**	

The average energy intensity for these studies is higher than that of Table 1; this can partially be attributed to the difference in scope (Table 1 deals with mostly gate-to-gate, while Table 2 deals with mostly cradle-to-gate). This would indicate a significant contribution of energy from pre-production steps (e.g. crude oil production and refining, as shown in Figure 2).

Asphaltene pathway

Literature exists for producing carbon fibers via asphaltenes, including multiple studies which use Alberta bitumen specifically to produce the fibers [12, 13]. The production process stays relatively similar to that of the PAN pathway, with the addition of a pre-treatment and pre-stabilization step (see Figure 5 below). Although the production pathway is well documented in literature, life cycle assessments for the production via asphaltenes were not found, and thus we do not have quantitative data to compare to Kumar's LCA.

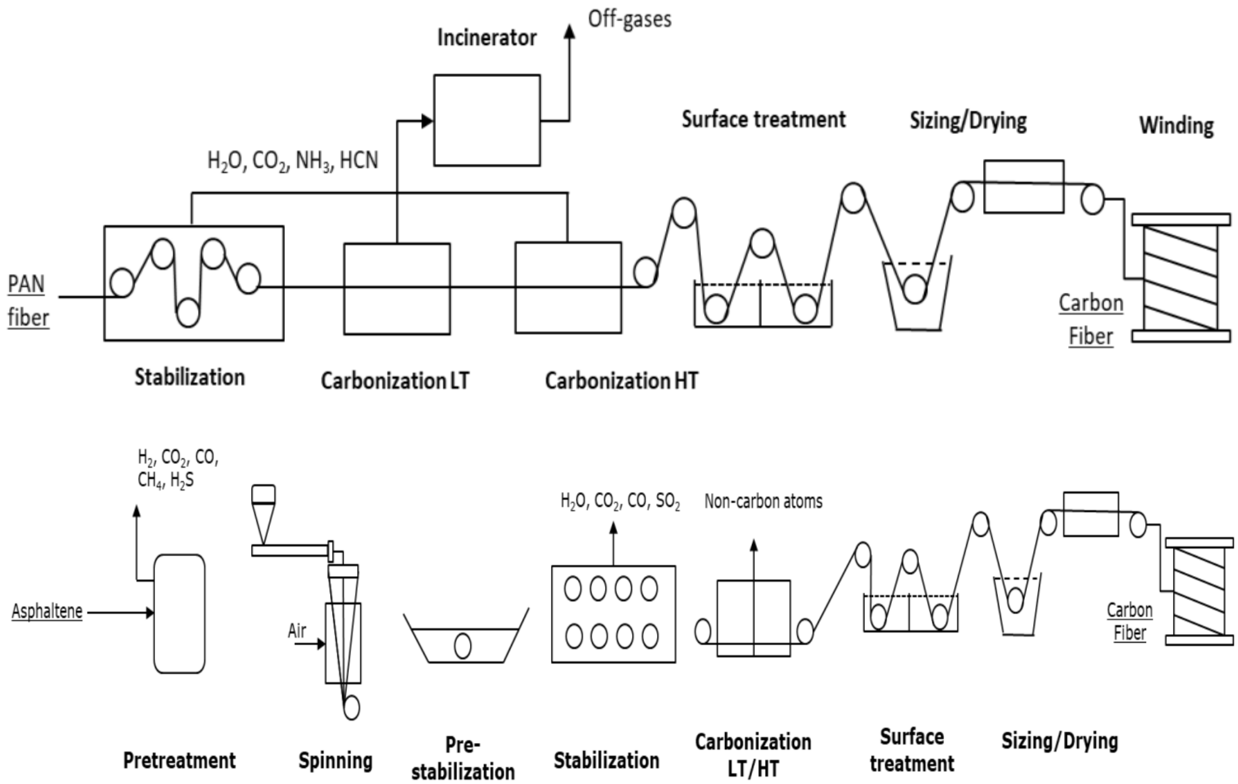


Figure 5: Production pathways for PAN-based (top) and asphaltene-based (bottom) carbon fibers (Kumar) [2].

The system boundary drawn by Kumar for the production pathway of carbon fibers from asphaltenes is shown in Figure 6 below. Note the similarity to Figure 2, including how consumables and additives are omitted from the system boundary. This is not likely a major contributor to emissions and will be discussed further in the The physical properties of ACF and PCF are also important to consider. Kumar reports a tensile strength and Young's modulus of 1000MPa and 55GPa, respectively, for ACF at lab scale. Those for PCF are 5700MPa and 290GPa, respectively – both about six times larger. The automotive industry requires 1720 MPa tensile strength – thus, ACF would not satisfy the requirements for automotive applications, and comparing it to PCF at a cradle-to-grave scope would not be effective (the two types of fibers would likely have different applications, and thus different emissions associated with their use and end-of-life).

Overall, we are confident that the claims made in Dr. Kumar's *Life Cycle Analysis of Asphaltene to Carbon Fiber* are sound. The report is very thorough and clear about what claims and data come from literature and which are calculated by the authors. The LCA boundaries appear to be drawn in a standard way, both for the PAN and the asphaltene pathway. Thus, the numbers presented in the report may be taken at face value with a high degree of confidence.

Report Assumptions section.

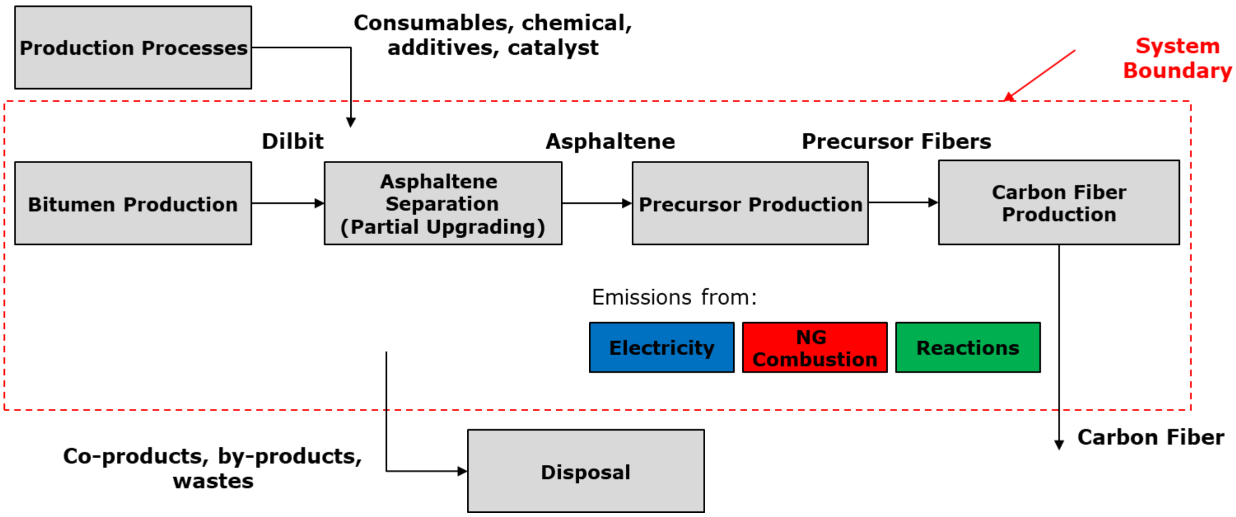


Figure 6: System boundary for the production of carbon fibers from asphaltenes [2].

Claims regarding Life Cycle of Carbon Fibers derived from Alberta Bitumen

Kumar gives the following summary table for the overall GHG emissions from the PAN and asphaltene pathways:

Table 3: Summary of LCA results for PAN and asphaltene pathways (Kumar, [2]).

Category	PAN pathway kg CO_2eq/kg CF	Asphaltene pathway kg CO_2eq/kg CF
Total life cycle	36.6	17.4
Background processes	6.66	1.24
Precursor	9.21	1.25
Carbon fiber	20.7	14.9

It shows that the PAN pathway produces over two times the emissions as the asphaltene pathway. The total LCA emissions from the PAN pathway (36.6 kg CO_2/kg CF) align with the 39 kg CO_2/kg CF we calculated in Table 2. We did not find suitable literature to compare the asphaltene pathway emissions. However, the similarity of the PAN pathway's values leads us to believe the asphaltene pathway's calculation is reputable.

Kumar also claims that the energy consumption for PAN-based carbon fiber (PCF) is 123.5 kWh/kg CF, and for asphaltene-based carbon fiber (ACF) is 29.9 kWh/kg CF, which is four times lower. The explanation given is that a major part of the energy consumption in the ACF pathway is associated with the "bitumen" stream, which is the significant light portion of the barrel that remains when the heavy asphaltenes are extracted (i.e., most of the barrel is still being used for fuel, so a proportionally large fraction of the energy consumption is associated with it). Additionally, PAN production requires solvent recovery, which is responsible for 7.1 kg CO_2eq / kg CF, almost a fifth of the total emissions from PCF production. Lastly, the PAN pathway requires additional natural gas for off-gas incineration, while the ACF pathway uses hydrocarbon off-gases to supply the required heat.

123.5 kWh/kg CF is equivalent to 444.6 MJ/kg CF – comparing this to Tables 1 and 2, where we found an energy demand of 603 MJ/kg CF and 1026 MJ/kg CF, we find that Kumar presents a slightly lower energy demand than the works cited in this report. This is likely due to the low quality of LCA data available on carbon fibers. However, in a way, it supports the validity of Kumar's analysis. The numbers do not appear exaggerated to make the asphaltene pathway appear more attractive.

It is important to note that these claims made by Kumar assume an overall ACF yield of 55%. (Yield, in this paper, refers to the mass of carbon fiber produced per unit mass of asphaltene used). According to Kumar, at a yield of 23.2%, the emissions from PCF and ACF pathways would be equal, while the maximum expected yield from literature is 60% [2, 9]. This concept is illustrated in Figure 7 below. As the yield increases (more carbon fiber is produced for the same amount of asphaltenes), the CO_2 emissions per kg CF produced decrease. This could prove to have major implications in the emergence of asphaltene-based CF. PAN-based CF has been capped at a yield of 60% with years of research, but if the ACF process can be optimized in a way that the yield is high, the specific emissions will drop, further increasing the benefits of the new feedstock. However, Kumar assumed a 55% yield for ACF, which has not yet been proven at scale. If a high yield is not achievable, the emissions savings may not be as good as Kumar has presented.

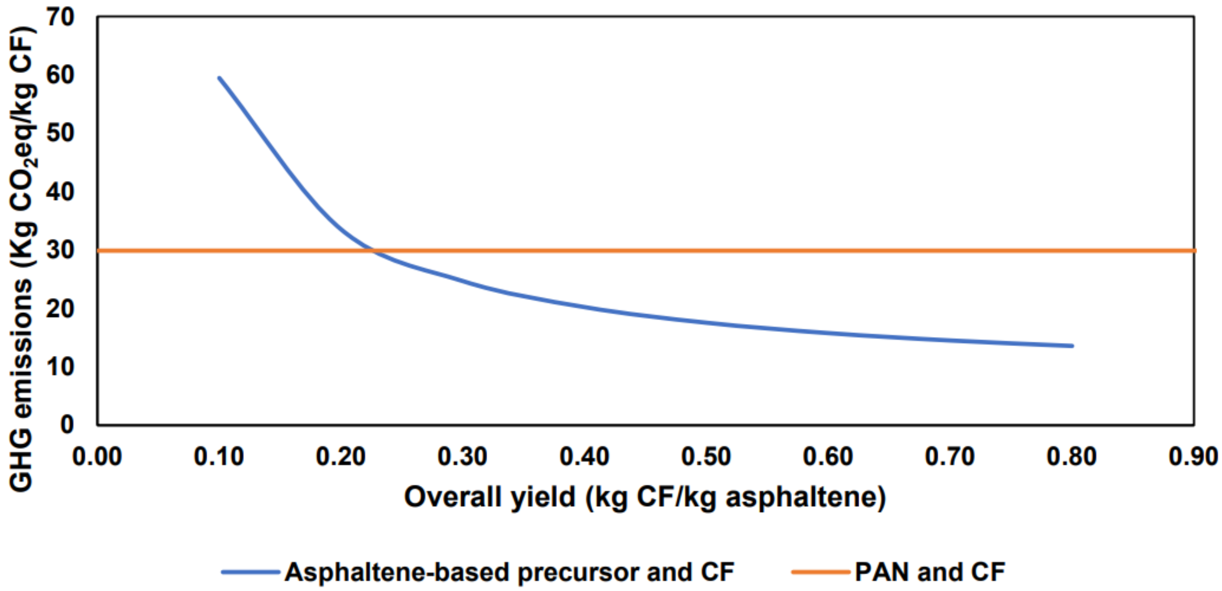


Figure 7: Tradeoff of specific emissions and yield (Kumar, [2]).

The physical properties of ACF and PCF are also important to consider. Kumar reports a tensile strength and Young's modulus of 1000MPa and 55GPa, respectively, for ACF at lab scale. Those for PCF are 5700MPa and 290GPa, respectively – both about six times larger. The automotive industry requires 1720 MPa tensile strength – thus, ACF would not satisfy the requirements for automotive applications, and comparing it to PCF at a cradle-to-grave scope would not be effective (the two types of fibers would likely have different applications, and thus different emissions associated with their use and end-of-life).

Overall, we are confident that the claims made in Dr. Kumar's *Life Cycle Analysis of Asphaltene to Carbon Fiber* are sound. The report is very thorough and clear about what claims and data come from literature and which are calculated by the authors. The LCA boundaries appear to be drawn in a standard way, both for the PAN and the asphaltene pathway. Thus, the numbers presented in the report may be taken at face value with a high degree of confidence.

Report Assumptions

Last, we will review further assumptions and estimations were made throughout the Kumar report [2]. We wanted to evaluate and validate these to ensure the life cycle analysis was still up to official standards set by the ISO. To do so, we spoke to Prof. Jordaan, Associate Professor of Civil Engineering at McGill, whose research focuses on life cycle assessments.

A large part of estimating GHGs through LCA is the effects of transportation depending on the plant location. The report assumed that crude oil is produced in the Gulf of Mexico for the PAN pathway and transported to Houston, TX, for refining. Light naphtha is transported to steam crackers in Port Arthur, TX, where propylene, ammonia, and acrylonitrile are produced. Then, acrylonitrile is transported to Decatur, AL, to produce PAN and carbon fiber. Whereas for the asphaltene pathway, all processes were assumed to be performed in Alberta, Canada. Geographical representativeness is an important topic that must be considered when making comparisons. It is important to make sure that the geographical assumptions represent what actually happens.

Throughout the report, the emissions due to transportation are not quantified, which is a significant omission in our opinion. We assume that in the PAN pathway, the crude oil is transported from the Gulf of Mexico to the United States by pipeline. Figure 3 shows the large number of lines that exist for the route discussed in Kumar's report. The most considerable environmental impact due to pipelines occurs during the construction period. Setting anchors and installing flowlines causes local disturbance to the seafloor crushing the organisms directly beneath the legs used to support the structure [14]. Light naphtha is generally also transported in "white product pipelines" that are used for refined petroleum products [15]. Due to the highly flammable and toxic nature of acrylonitrile, classified as a high-hazard chemical, it must be transported in regulated rail tank cars or road tankers [16]. Considering all the various transportation methods needed, there would be significant environmental impacts associated with the PCF pathway making them essential to be considered.

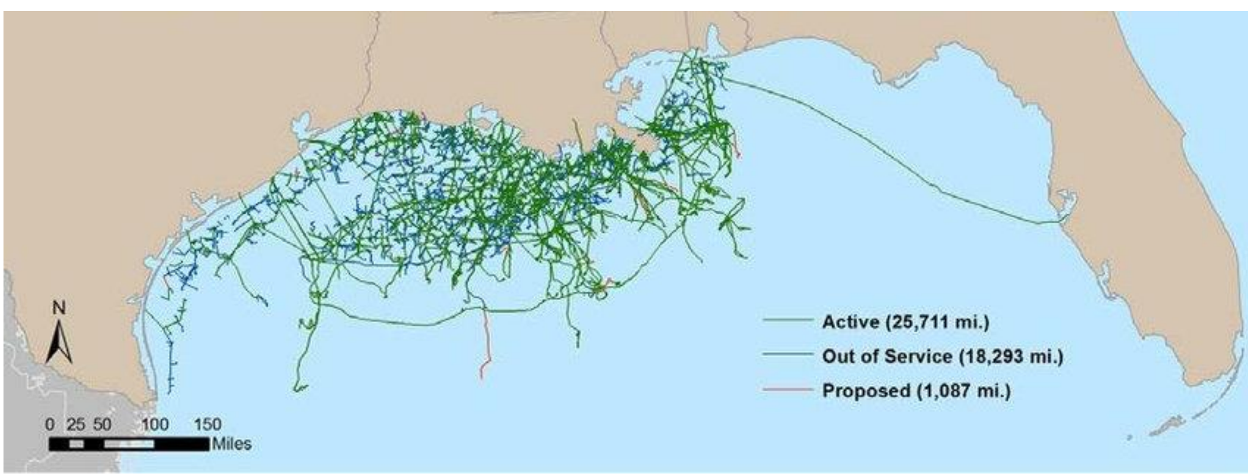


Figure 8 Status and Location of Oil and Gas Pipelines in the U.S. Portion of the Gulf of Mexico

It is essential to clarify what the system boundaries are for each pathway. The report considered the GHG emissions from the process, electricity production, fuel combustion, and cleaning of off-gases. The emissions associated with process plant construction, equipment maintenance, production of consumables, additives, catalysts, and disposal of wastes and by-products were excluded. For completeness, Kumar could have included all emissions associated with the production and construction materials. However, it makes sense that they were not because they are typically small when dealing with very large fossil-related plants (usually 5% or less). Including these emissions would have significantly increased the project's scope as well. Usually, in LCA, the focus is explicitly put on parts that can be represented as accurately as possible. Some challenges arise when trying to document where all the construction materials come from. On the contrary, upstream materials are usually dwarfed by the combustion phase, but for this process, we are dealing with non-combustibles, so the material emissions may be a bigger portion of the total process emissions, making them more important and necessary to include. For future research, it could be interesting to account for by-products whether they are harmful to the environment.

Asphaltene-based carbon fiber is currently produced on a very small scale, so they chose the functional unit for the study to be 1 kg of carbon fiber produced. In the report, Kumar claimed that a greater yield would lead to lower GHG emissions per kg of carbon fiber produced. This makes sense because large facilities in general lead to economies and efficiencies of scale. Since large heating processes are involved, more extensive facilities make it easier to develop heat exchangers for better heat integration.

Considering why the cradle-to-grave analysis was not implemented is also important. Carbon fibers are currently very difficult to recycle because of their use in composite materials. However, there may be hope that asphaltene-based carbon fibers are easier to recycle because they are derived from natural materials. We believe that Kumar chose to omit the end-of-life and recyclability because Alberta Innovates is focusing primarily on the production phase of transforming bitumen into carbon fibers and doesn't yet have the resources to examine what will happen after it reaches the market. Additionally, the end-of-life and recyclability will vary depending on the purpose of the carbon fiber. In the second part of the analysis, they performed a cradle-to-grave LCA specifically on producing carbon fiber for manufacturing vehicle parts.

Conclusion

Through our research on life cycle analyses, carbon fiber production processes and speaking with Prof. Jordaan, we were able to use this report to validate and explain some of the scientific claims that were made in Kumar's *Life Cycle Analysis of Asphaltene to Carbon Fiber*. This report has determined that while the life cycle assessment could have been more in depth, it is still credible and accurate.

The simulation-based LCA comparison was done for the purpose of helping stakeholders make informed decisions regarding the suitability of producing asphaltene-based carbon fiber in Alberta as an alternative use of bitumen. A cradle-to-grave analysis would be more thorough, however after production of the carbon fibers, the environmental impacts varies significantly depending on the purpose and use. Additionally, the carbon fibers produced from asphaltenes have lower mechanical properties than those made from PAN, so their applications will differ.

Future steps if Kumar were to continue this analysis could include changing from a cradle-to-gate method to a cradle-to-grave method, accounting for harmful by-products, and including all emissions like those from construction materials. As mentioned before, taking these next steps would significantly increase the scope and length of the research report.

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Appendix

Sample calculation for Table 2 data, using Zhou (2013) as an example:

The paper states that 61% of the CFRP's mass is from carbon fiber. Also, production of 1kg CFRP leads to 26kg of CO_2eq emitted, 19kg of which is from carbon fiber manufacturing. But, this 19 kg CO_2eq per kg CFRP produced isn't useful, since we want the emissions per kg CF only. Using the mass fraction, we can calculate that:

$$19\,\frac{kg\ CO_2eq}{kg\ CFRP}\left(\frac{1kg\ CFRP}{0.61kg\ CF}\right) = 31\,\frac{kg\ CO_2eq}{kg\ CF}$$

A similar process is applied to the energy usage.