E4S Brief

SCENARIO MODELLING OF THE CARBON FIBER INDUSTRY IN THE TRANSITION TO NETZERO 2050

Date: 27th January 2025

Authors:
Dr. Martyn. D. Wakeman (PI) EPFL, LPAC;
Prof. Veronique Michaud EPFL, LPAC;
Prof. Karl Schmedders, IMD;
Reyhaneh Ramezani EPFL, Masters student

Keywords: Decarbonization, NetZero, Modelling, Monte-Carlo, Carbon-Fiber

In a Nutshell

Focusing on the carbon fiber industry, the key research question illuminated is: "How can mass flows be impacted via financial investment in enabling technologies to drive increases in product circularity and reductions in embodied energy in rapidly growing (double digit CAGR) end use sectors". If mass flows are not impacted then novel materials and supply chain models will not impact the cumulative CO2e of the industry. Mass flows will not be redirected without significant investment in enabling technologies, aided by government policy (for example step-wise transformation of end-of-life legislation to drive up levels of circularity).

Our work has developed a Monte-Carlo model to track versus time to 2050: i) mass flows (predictive MFA), ii) started to examine product CO2e flows (predictive LCA), and iii) monetary flows (initial work in progress) corresponding to 10-50-90 probability scenarios for different 'enablers' that are configured to represent different SSPs with corresponding market growth of carbon fiber composite products. It has take a PESTLE level trans-disciplinary approach drawing on the combined industrial and academic experience of the project team at EPFL and IMD and targeted industrial partner input.

The end goal of this project is to propose quantified sustainability initiatives and associated roadmaps (work in progress) to enable step-wise transformation of the carbon fiber value chain while it also invests to meet sustained market growth. This will require investment in new technologies, together with novel ways of collaborating in the carbon fiber value chain especially around product labelling, reverse logistics, and recycling infrastructure.

What we do and why is matters

Multiple industrial sectors need to transform products, operations, and supply chains to reduce environmental impacts and reach NetZero targets. This requires systemic change in many areas of society including industry, education, research, and policy.

The role of materials in this transition is critical including energy generation, hard to abate sectors, critical materials, and enabling technologies. Significant capital investment is needed in these supply chains, at scale, in compressed time frames; to drive increased circularity, develop lower embodied energy / CO2e products, and aid transition towards meeting NetZero SSPs. The materials sector is a key driver in our impinging planetary boundaries (including novel entities) and is in need of urgent, widespread and fundamental transformation.

This collaborative project between the IMD and EPFL targets the E4S platforms of industry transformation (especially mobility and infrastructure) also touching on reimagining managerial practices (in materials, manufacturing and logistics). The ultimate goals of this project and target audience when complete are two-fold. First to engage with the carbon fiber composites supply chain regarding our roadmap and initiatives. Secondly, for use as a sustainability strategy case study for incorporation into new lectures.

How we do it and main findings

Advanced materials in the chemical industry, illustrated here through carbon fiber, are both hard to abate (Petro-chemical derivatives) and key materials in the energy transition. Carbon fiber composites (CFRP), with their high weight specific mechanical properties and fatigue resistance, have benefits in multiple applications. For example, CFRP is used in the longer wind turbine blade spar caps, mobile compressed hydrogen storage, and is used to reduce mass and use phase emissions in highly specified aerospace, rail, and automotive products as well as increase the performance of consumer sporting equipment. However the industry still needs to decarbonize, specifically upstream scope 3 emissions in the materials value chain and down stream scope 3 emissions at end of life. Modified mass flows, for example from legislation or novel technologies, when deployed at scale, can drive reduced cumulative CO2e, which in turn are enabled by targeted financial flows.

We have established a Monte Carlo program in Python interacting with an Excel data-base to model different specific socio-economic pathways for the future adoption of carbon fiber in aerospace, wind energy, mobile hydrogen storage, infrastructure, automotive, and consumer goods. The model tracks mass flows, CO2e flows, and the associated capital investment in fixed assets. Initial work has focused on kg based CO2e product carbon footprint estimates to 2050 (Figure 1) and dynamic MFA (Figure 2). Future work will extend this to the cumulative industry sector CO2e versus time to 2050, and will map the associated monetary flows (revenue and CAPEX) versus time to 2050 to create roadmaps for the industry.

The material flow analysis starts with the historical mass flows from each market sector dating back to 1980 such that as these products reach their end of life, as a function of their durability, they can then be treated as waste or recycled in the future economy (2020 to 2050) according to different assumptions.

New parts then enter the economy from 2020 and the model tracks post industrial waste, for example with a buy to fly ratio in aerospace of 1.5:1, and at the end of life, again as a function of durability (>40 years for aerospace to a few years for consumer goods). The market adoption of carbon fiber in the different market sectors is modelled to 2050 for different assumptions (P100 is today, three sets of input variables P90, P50, P10 where P90 is most probable) which correspond to different SSPs and associated average temperature increases.

As the mass flow of carbon fiber-based products is modelled, the code includes the CO2e emissions during carbon fiber production and predicts the product carbon footprint versus time for different scenarios that include alternate rates of novel technology adoption.

These include bio-mass derived acrylonitrile as a precursor for PAN carbon fiber and lower energy carbonization using microwaves. The model also includes an evolving electrical grid mix versus time using IEA scenarios (STEPS, APS, NetZero, 100% renewable). Circularity is calculated based upon different recycling rates of post-industrial and end of life waste with associated investments.

We have pressure tested assumptions with a carbon fiber manufacturer and other players in the CFRP value chain and have presented interim results.

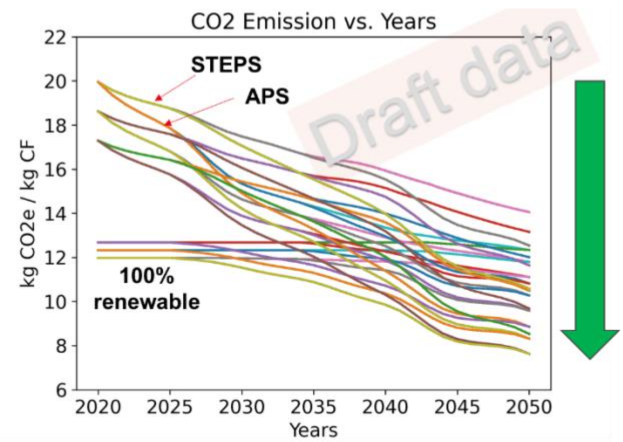

Figure 1: kg CO2e/kg CFv predicted to 2050

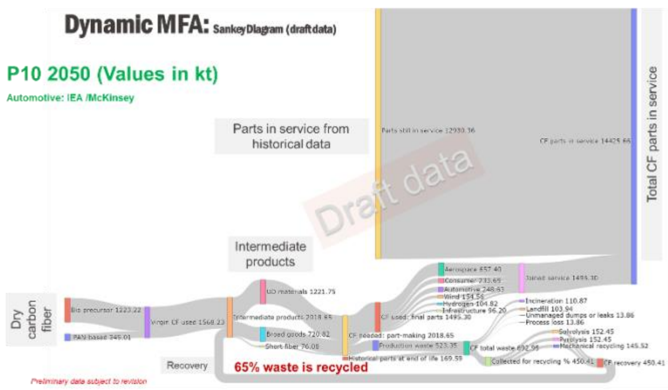

Figure 2: Dynamic MFA, P10 case (optimal), 2050 prediction (draft data)

Call for action

It is imperitive to decarbonize advanced material value chains beyond use-phase advantages alone and the industry is starting to address this. This needs to be applied to both upstream 'best carbon footprint materials', which are often used in highly specified applications and subject to significant confidentiality constraints, and to waste streams. For carbon fiber, key measures to decarbonize up stream value chains include the use of bio-based or bio-attributed acrylonitrile as a precursor for PAN carbon fiber with close to drop in equivalence in performance. Carbonization lines need to use renewable energy and increase energy efficiency. Novel collaborations and coalitions are needed to address scope 3 downstream emissions related to post industrial (part making) carbon fiber waste and improved recovery and recycling at end of life. Reverse logistic supply chains are needed with labelling of parts and collaborative approaches to building the needed infrastructure (CAPEX) and standards. Legislation will also be an important aspect driving this transformation which is needed at scale and in a compressed time frame as users of carbon fiber increasingly require improved LCA and PCF data transparency and end use customers seek to reduce their own scope 3 emissions.

"The materials sector is a key driver in our impinging planetary boundaries (including novel entities) and is in need of urgent, widespread and fundamental transformation requiring modified mass-flows together with associated capital investment in best carbon footprint materials and to drive increases in circularity." Dr. Martyn Wakeman

Learn more

An invited paper was presented at TexComp-15 in September at Leuven on "Carbon fiber NetZero 2050 Transition strategy modeling" in a specialist session on the LCA of composites.

TexComp15 (home page) - Sep 2024 - organised by CMG, KU Leuven — TexComp-15 Conference (2024)

A presentation will also be given at the JEC in Paris March 2025 in a specialized industrial trade show seminar.

Demystifying LCA: A Guide to Sustainable Composites - JEC World 2025 - English

Contact us:

Dr. Martyn D. Wakeman
Lecturer and Researcher
Laboratory for Processing of Advanced Composites
EPFL
STI IMX LPAC
MXH 146 (Bâtiment MXH), Station 12
CH-1015 Lausanne
Tél.: +41 (0)21 693 7787
martyn.wakeman@epfl.ch