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Review

A critical review and meta-analysis of energy demand, carbon footprint, and other environmental impacts from carbon fiber manufacturing

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ABSTRACT

The demand for carbon fibers and carbon fiber-reinforced polymers (CFRPs) is rapidly growing due to their outstanding mechanical properties and potential to enhance sustainability, particularly for lightweighting applications. However, carbon fibers are typically produced from fossil-based feedstocks, involve energy-intensive processes, and have limited options for sustainable end-of-life management or circularity. Despite these challenges, the energy demand and lifecycle environmental implications of their production remain poorly understood. Here, we conduct a critical literature review and meta-analysis of carbon fiber manufacturing, revealing significant variations in reported energy demand, carbon footprint, and lifecycle inventory data. Our analysis makes two novel contributions. First, we identify key underlying factors driving these variations. Second, we highlight that carbon fiber, far from being a homogeneous product, has grades varying substantially in mechanical properties, end-use markets, energy intensity of manufacturing processes, and therefore environmental impacts—an aspect often underrepresented in life cycle assessments. We assert that current data are insufficient for reliably evaluating environmental impacts, posing a risk of misleading decision-making. Addressing this gap requires new lifecycle inventory datasets clearly incorporating carbon fiber heterogeneity and key influencing factors identified in this study. Additionally, we propose actionable recommendations, including a checklist, to advance sustainability in the carbon fiber sector.

1. Introduction

In recent years, carbon fibers have emerged as a "game-changing" material in modern engineering and manufacturing thanks to their exceptional properties, including high strength, superior tensile modulus, and low density (Huang, 2009). Depending on the type of fiber used—such as its grade (standard, intermediate, or high modulus) and form (continuous or chopped)—carbon fibers can exhibit specific tensile strengths approximately 5 to 20 times greater than aluminum and 2 to 10 times greater than steel (Zhang et al., 2023). Because of these remarkable properties, carbon fibers are extensively used as reinforcement in highly engineered polymeric composite materials, known as carbon fiber-reinforced polymers (CFRPs). Within CFRPs, the embedded fibers serve as the primary load-bearing components, while the polymer matrix supports load transfer, fills the gaps between fibers, solidifies the entire structure, and protects it from external damage (Pakdel et al., 2021).

CFRPs were initially adopted in high-end sectors such as aerospace and defense but have gradually expanded into other industries, including automotive, renewable energy, pressure vessels, and construction. As shown in Fig. 1, global demand for carbon fiber increased by 168 % from 2010 to 2023 and is projected to grow by an additional 144 % by 2030. This growth is reflected across various sectors. For instance, in the wind energy sector, demand for carbon fiber increased by 167 % from 2010 to 2023 and is expected to rise by an additional 113 % by 2030. The introduction of carbon fiber into wind turbine blade manufacturing has facilitated the development of larger, higher-capacity turbines, increasing their rated power output from 1 MW to 15 MW or more (Vestas, 2024). Glass fiber-reinforced composites (GFRPs) are widely used in blade manufacturing but have structural

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constraints that limit blade size and, consequently, power output. In contrast, CFRP's superior mechanical performance allows for longer blades and greater swept areas, ultimately enhancing wind turbine power generation capacity (Spini and Bettini, 2024). Meanwhile, carbon fiber demand in the pressure vessel industry has exploded from a virtually negligible application in 2010 to a significant market of 14,000 t per year in 2023 (10 % of the overall market for carbon fiber). A further 230 % increase in carbon fiber demand is expected for pressure vessels by 2030. CFRPs are extensively utilized in Type IV pressure vessels and are being further developed for broader adoption in Type V vessels (Air et al., 2023), such as those used in stationary and mobile hydrogen storage tanks (e.g., for hydrogen fuel cell vehicles), contributing to the development of a low-carbon energy system (Benitez et al., 2021).

As the use of carbon fibers has expanded, environmental concerns have been voiced (Das, 2011; Witik et al., 2011). The manufacturing process is energy-intensive and relies on non-renewable petroleum feedstock resources, such as polyacrylonitrile (PAN) precursors (Morgan, 2005). While lightweight can reduce use-phase energy consumption in transportation applications, these benefits are counteracted by a high manufacturing burden and lack of recyclability at end-of-life. In light of this, life cycle assessment (LCA) is a valuable tool for quantifying the potential environmental impacts of these materials throughout the life cycle, supporting informed decision-making, and avoiding unfavorable burden shifts (ISO 14040, 2006; ISO 14044, 2006).

Several studies have investigated the energy demand and environmental impact of carbon fiber and CFRPs, but the results vary widely. For instance, the cumulative energy demand (CED) ranges from 286 to 1132 MJ per kg of carbon fiber (e.g., Sunter et al., 2015; Suzuki and Takahashi, 2005), while greenhouse gas (GHG) emissions range from 19.29 to 69.12 kg CO_2-eq per kg of carbon fiber (e.g., Benitez et al., 2021; Kawajiri and Sakamoto, 2022). Recent studies have provided valuable insights that help explain the variations in energy demand and environmental impact. Hermansson et al. (2019) conducted a meta-analysis comparing the energy demand and climate change impacts of different types of carbon fibers, including PAN-based, lignin-based, and recycled carbon fibers, highlighting significant differences among them. Ghosh et al. (2021) compared energy demand data from the literature on carbon fiber production and indicated that relatively few studies have been published. Most are over a decade old and lack a clear definition of the scope of their reported data. Groetsch et al. (2021a) also compared energy demand data from the literature and noted that the evaluation and comparison of results are challenging due to inconsistencies in data reporting. Furthermore, Tornabene et al. (2024), Moutik et al. (2024), and Balcioglu et al. (2025) assessed the quality of multiple inventory data sources for carbon fiber production. Prenzel et al. (2023) examined the differences in environmental impacts of carbon fiber production across different geographic locations, while Pender et al. (2025) focused on temporal and technological changes in carbon fiber manufacturing.

However, there are still gaps in fully understanding carbon fiber's energy demand and environmental impact. First, existing studies rely on datasets that are often incomplete. Publicly available data sources (e.g., commercial databases, academic literature, and company reports) lack methodological harmonization and are inconsistently reported, making it challenging to collect comprehensive data for a thorough assessment of carbon fiber's energy demand and environmental impacts. Second, while methodological inconsistencies (e.g., variations in system boundaries, functional units, and allocation methods) and outdated data are often discussed and recognized as sources of variability, a more fundamental challenge lies in the inherent heterogeneity of carbon fiber. This includes differences in production scale, grade (e.g., mechanical properties, fiber forms, and tow sizes) and precursor (e.g., PAN or pitch). Little attention has been given to how this heterogeneity affects energy requirements and environmental impact results, which may lead to the misconception that carbon fiber is a single homogeneous commodity, i.e., all carbon fibers are the same from an LCA perspective. This misconception may cause researchers and practitioners to select non-representative data and report misleading conclusions in energy and environmental analyses. Third, although existing studies acknowledge considerable data variations, they provide limited guidance for stakeholders on analyzing and interpreting these data, conducting robust

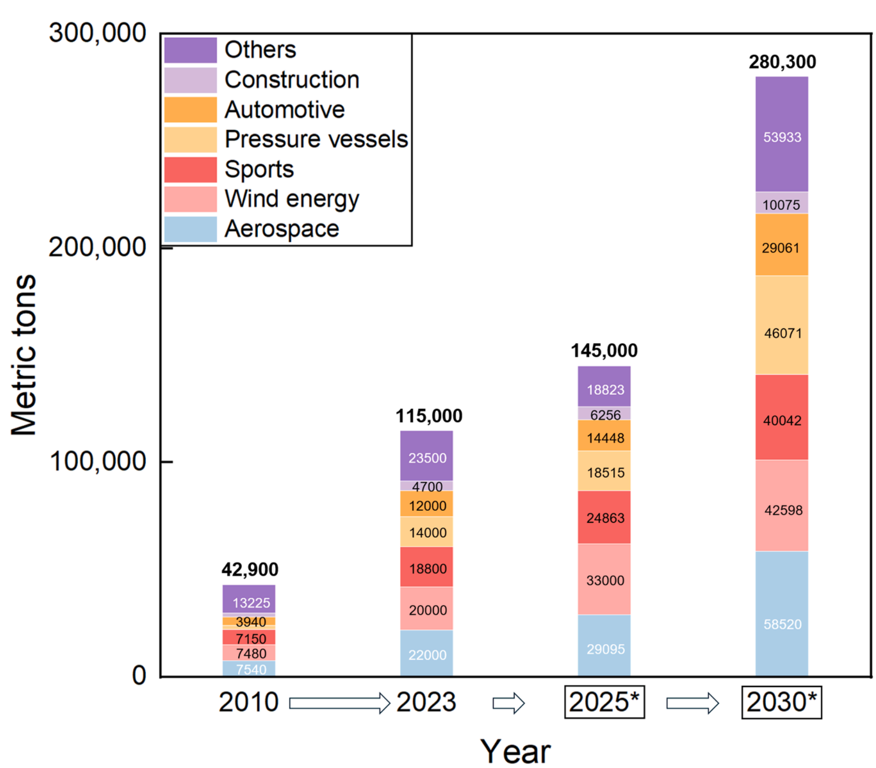

Fig. 1. Global demand for carbon fiber (adapted from CompositesWorld (2023)). Values for global demand in 2025 and 2030 are based on predictions.

analyses (e.g., LCA), incorporating carbon fiber heterogeneity into decision-making, and enhancing environmental sustainability in this sector.

Here, we aim to bridge these gaps by integrating and analyzing a broad spectrum of carbon fiber energy demand and environmental impact studies with consideration of technical attributes. The intent is to offer a more thorough assessment of variations in carbon fiber data and provide researchers with comprehensive and up-to-date datasets. Beyond commonly discussed issues (e.g., methodological inconsistencies and outdated data), we identify key underlying factors that drive these variations. Most importantly, these factors indicate that carbon fiber is not a homogeneous product but varies substantially across mechanical properties, end-use applications, manufacturing energy intensity, and, consequently, environmental impacts—an aspect that is often not effectively communicated to the LCA community or consciously shared. We assert that current data on carbon fiber are insufficient to reliably quantify environmental impacts, which could lead to misleading outcomes. To address this, we provide actionable recommendations to enhance sustainability in the carbon fiber sector, including a checklist that outlines key factors for stakeholders to consider in future decision-making.

2. Methods

2.1. Search and screening

We aim to identify studies focusing on LCA or energy demand analyses relevant to carbon fiber manufacturing. We use the Web of Science as our primary search engine and supplement this with a snowballing approach (i.e., review of citation lists in included studies) to find additional relevant studies. We screen the search results, focusing on studies that provide primary data and excluding those that rely on data from other sources. For a detailed description of the search and screening methodologies, refer to supplementary information (SI) Section 1. We systematically synthesize insights from the reviewed studies to develop an in-depth overview of carbon fiber manufacturing, as presented in Section 3.1.

2.2. Data alignment

In total, we identified 39 literature sources that report or provide values related to energy demand, environmental impact, or both for carbon fiber manufacturing. We then conducted a meta-analysis and documented the data in two ways: as reported data and aligned data. Reported data are directly sourced from the literature without modification, while aligned data are processed according to the following standard procedure to harmonize results:

1) Unit conversion: Units of reported data were converted to the metric system (e.g., BTU to MJ, lb to kg).
2) Primary energy assumption: We found that many studies do not specify whether their values in MJ represent primary energy demand or only electricity use. CED refers to the total amount of primary energy resources consumed throughout the entire life cycle of a product (Huijbregts et al., 2006). When energy demand is reported in kWh, we assume it represents onsite electricity use values. We first convert kWh to MJ and then divide the result by 30 % to estimate the corresponding CED value. This 30 % represents the typical efficiency of electricity generated from primary energy (Murphy et al., 2022). For data specified in BTU or MJ without indicating whether they represent primary or onsite energy, we assume they represent primary energy demand and use them directly in our study.
3) Normalization through production process conversion rate (yield): The conversion rate, or yield, is defined as the amount of carbon fiber produced per unit of polyacrylonitrile (PAN) processed, or the amount of PAN produced per unit of acrylonitrile (AN) processed. For products such as AN and PAN obtained from various LCI databases, we adopt life cycle impact assessment (LCIA) methods in openLCA version 2.1 to obtain CED and GHG results per kg. These results are then adjusted to a normalized output of 1 kg of carbon fiber using only the minimum and maximum conversion rates reported in the literature. Similarly, for product data reported from other literature sources, we directly adjust the data to a normalized output of 1 kg of carbon fiber using these two conversion rates.

We note differences in LCA methodologies, such as attributional versus consequential LCA (Thomassen et al., 2008). Existing literature on carbon fiber has very limited information on these methodologies, so we do not differentiate between them in our analysis. By following the above procedures, we ensure that our data are consistent and comparable across different sources, allowing for a more accurate assessment of the CED and GHG emissions associated with carbon fiber manufacturing. For detailed information on data sources and our calculations, see SI Sections 3 and 4.

3. Results

3.1. Carbon fiber manufacturing processes

This subsection provides an in-depth overview of carbon fiber manufacturing processes based on the insights gathered from our systematic literature review. There are multiple pathways to produce carbon fiber, each starting from different precursors such as PAN, petroleum pitch, lignin, and others. However, this study primarily focuses on the PAN-based pathway, as it dominates the current commercial carbon fiber market. The structure of this subsection is as follows: first, we introduce the precursors (e.g., PAN, pitch, and lignin); second, we focus on the conversion of PAN to carbon fiber; we then discuss various factors affecting the energy demand and environmental impact of carbon fiber manufacturing.

We examine the manufacturing process starting from the raw material AN to PAN and from PAN to carbon fiber, as illustrated in Fig. 2. Given the various applications of carbon fiber, this study focuses on the cradle-to-gate system boundaries, excluding its use phase and end-of-life. The end-of-life aspects of carbon fiber are discussed in Section 4. We do not focus on the upstream production processes of AN, a well-established chemical intermediate (Brazdil, 2012). Approximately 90 % of AN production follows the Standard Oil of Ohio (SOHIO) industrial route, which is based on the ammoxidation of propylene (Cespi et al., 2014).

3.1.1. Precursor

Polyacrylonitrile (PAN) precursors currently dominate commercial carbon fiber production, accounting for >90 % of output, followed by petroleum pitch (Hexcel, 2024), both of which are fossil-based materials. Producing carbon fiber from these fossil-based precursors is reported to be costly and energy-intensive (Das, 2011; Yadav et al., 2023). Therefore, there is an increasing need to find cheaper or less energy-intensive alternative precursors to match the high-level performance of PAN-based fibers (Bisheh and Abdin, 2023).

Several alternative precursors are currently under investigation, including lignin, asphaltene, polyolefin, and polyethylene (Bari et al., 2023; Chung, 2021; Röding et al., 2022; Souto et al., 2018). Among them, lignin is considered one of the most promising precursors due to its bio-sustainability and low cost as a byproduct from the bioethanol and paper industries (Kun and Pukánszky, 2017). Its aromatic backbone and high carbon content (over 60 %) make it a strong candidate for carbon fiber production (Beaucamp et al., 2024). Historically, lignin-based carbon fibers exhibited inferior mechanical properties compared to PAN-derived fibers. However, recent advancements have enabled the production of lignin-based carbon fibers with high strength (Bai et al., 2024; Luo et al., 2024) and high stiffness (Vaughan et al.,

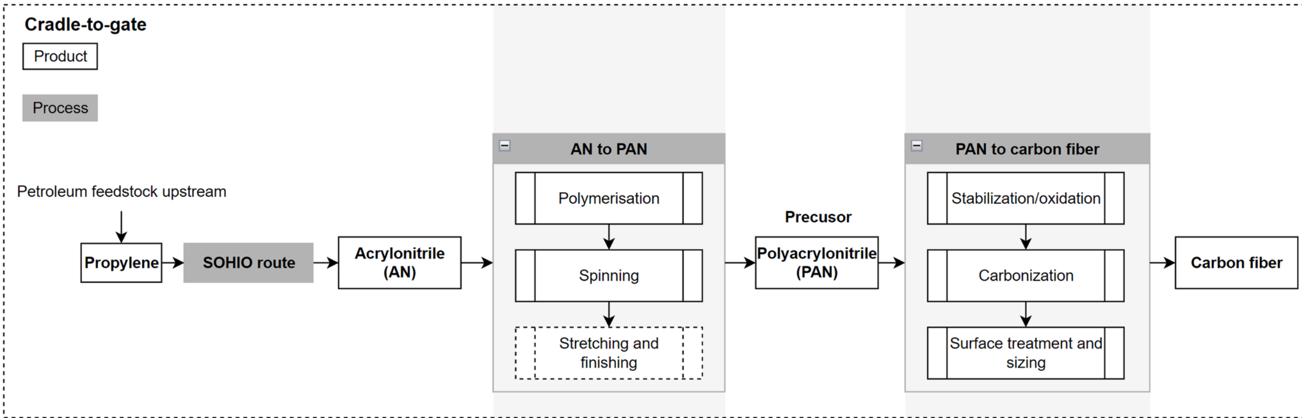

Fig. 2. Typical manufacturing processes for PAN-based carbon fiber (adapted from Dér et al., 2021; Huang, 2009; Morgan, 2005). Manufacturing carbon fiber from other precursors, such as pitch and lignin, involves different processes. In the figure, processes shown with solid lines indicate the availability of energy demand data, while those with dashed lines indicate the absence of such data. Both will be further elaborated in Section 3.2.

2025), achieving mechanical properties comparable to those of PAN-based fibers and paving the way for lignin to serve as a viable alternative to standard-modulus grade fibers (e.g., T300). Despite these advancements, the technologies associated with these alternative precursors remain at a relatively low technology readiness level (TRL 3–4, lab scale), indicating that they are still in small-scale development and have not yet achieved commercialization.

Now, we delve into the manufacturing processes specifically for the PAN precursor. PAN production typically involves polymerization, spinning, stretching and finishing, as shown in Fig. 2. Different carbon fiber manufacturers, such as Toray and Mitsubishi, employ different technological routes (e.g., polymerization, spinning), using different solvents, initiators, and comonomers to produce PAN. Nunna et al. (2019) provide a detailed analysis and comparison of these PAN manufacturing methods. It is important to note that the mechanical properties of carbon fiber are heavily dependent on the microstructure of PAN (Khayyam et al., 2020), as the orientation and crystallinity of PAN fibers directly influence the strength and stiffness of the finished carbon fibers. Thus, differences in the polymerization and spinning processes can significantly affect the final carbon fiber quality.

Different precursors yield carbon fibers with distinct mechanical and thermal properties (Huang, 2009). Pitch precursors are primarily utilized to produce high-modulus (i.e., high stiffness) carbon fiber (Aldosari et al., 2020), while PAN precursors are more commonly used standard modulus and intermediate modulus (high-strength) fibers (Al Aiti et al., 2018).

Carbon fiber production from other precursors involves different manufacturing processes as compared to PAN-based carbon fibers. For example, asphaltene-based carbon fiber requires additional pretreatment to withstand the temperatures involved in the stabilization process due to asphaltene's low softening point (Baritto et al., 2023). Similarly, lignin-based carbon fibers are processed at different temperature ranges than PAN-based carbon fiber production (Luo et al., 2024; Yadav et al., 2023). To manufacture high-performance carbon fiber from pitch, it is typically necessary to first convert its original isotropic form into anisotropic (mesophase pitch) through thermal polymerization (Huang, 2009; Kaur et al., 2016).

3.1.2. *PAN to carbon fiber*

As shown in Fig. 2, the first step in the PAN-to-carbon fiber process involves stabilizing the PAN precursor fibers in the presence of oxygen at temperatures typically ranging between 200 and 300 °C (Dér et al., 2021; Groetsch et al., 2023a). This step achieves thermal stability of the fibers by transforming their structure into a ladder structure, laying the foundation for subsequent carbonization (Frank et al., 2012; Khayyam et al., 2020). The stabilization process is energy-intensive and time-consuming (Khayyam et al., 2020; Morgan, 2005). After stabilization, the fibers undergo carbonization in an inert atmosphere (typically nitrogen) to remove non-carbon elements. This process occurs in furnaces through multiple temperature zones, which can be generally divided into two phases: the first phase occurs in a low-temperature zone (around 750 °C), and the second phase in a high-temperature zone (up to 1500 °C) (Benitez et al., 2021). The next step involves surface treatment and sizing, which typically involves electrolysis to enhance chemical bonding (Morgan, 2005), and the use of epoxy sizing agents to increase the carbon fiber's processability and compatibility with various epoxy resin systems (Toray, 2021).

3.1.3. *Carbon fiber grades*

Unlike many commodity metals (e.g., aluminum), carbon fiber does not have a single, widely accepted quality standard, with each manufacturer defining its own specifications. Notably, over 200 variations of fiber specifications are available in the market (personal communication with an industry expert). Therefore, carbon fibers should not be considered as a single homogeneous commodity for the purpose of energy and environmental analysis. Rather, each carbon fiber or CFRP materials, should be assumed to be a unique product, engineered with distinct properties tailored to specific end markets and applications (CompositesWorld, 2022).

In terms of mechanical properties, carbon fibers can be roughly grouped into standard modulus, intermediate modulus (high tensile strength), and high modulus categories (Toray, 2021); and within each category, there are a wide range of carbon fiber variants, each with specific properties. Carbon fibers can also be classified by tow size, where the tow size represents the number of filaments per bundle of continuous filament in the material. Tow size ranges from 1000 to 320, 000 filaments, with common tow sizes being 1 K, 3 K, 12 K, and 24 K (where "K" denotes thousands of filaments). Carbon fibers are categorized into low-tow (1K–24 K filaments) and heavy-tow (up to 320 K filaments) based on the number of filaments per bundle (Al Aiti et al., 2018).

The distinction between low-tow and heavy-tow carbon fibers is important when comparing energy demand and environmental impact. For the same level of energy demand or emissions from the production line, heavy-tow carbon fibers generally produce a greater overall mass compared to low-tow fibers, resulting in lower energy demand and emissions per kilogram of carbon fiber. However, increasing tow sizes has certain drawbacks. Although it typically reduces production costs, energy demand, and emissions, it also leads to reduced mechanical properties (e.g., strength) and increased variability in these properties (Latifi, 2021). Currently, aerospace applications primarily use low tow sizes (< 12 K) (Wang et al., 2011).

Additionally, different applications require different types of carbon fiber. For example, carbon fibers in the wind energy sector are designed to balance stiffness, strength, and cost-effectiveness (CompositesWorld, 2021; Ennis et al., 2019; Hiremath et al., 2020). In contrast, carbon fibers for commercial aerospace prioritize superior strength-to-weight and stiffness-to-weight ratios, and strict control over mechanical property variations, even at a higher cost (Soutis, 2005). In aerospace applications, even incremental improvements in mechanical performance are crucial and justify the increased expense, whereas, in wind energy, cost-effectiveness is a more significant consideration.

Manufacturing different grades of carbon fiber typically involves different feedstocks, production processes, and process settings, which can result in differences in energy demands and environmental impacts. Specifically, the strength of carbon fiber increases as the carbonization temperature increases up to 1500 °C (Huang, 2009). Beyond this 1500 °C threshold, the modulus increases, but the strength decreases (Frank et al., 2012; Kanhere et al., 2022). This means that increasing the modulus of carbon fiber (i.e., different grades) requires more energy. Additionally, to achieve higher carbon content and extreme modulus (Frank et al., 2012), PAN-based carbon fibers can be further carbonized at temperatures around 2000 °C or higher, requiring yet more energy. It should be noted that a different precursor, mesophase pitch, can be used for these high-modulus carbon fibers, as pitch is better suited for processing at high temperatures (e.g., 3000 °C) and can achieve a higher modulus than PAN. Moreover, the materials used in the process can also vary; for instance, argon or helium is often used to maintain an inert environment instead of nitrogen when producing high-modulus carbon fiber at high temperatures. This is because nitrogen becomes ionized at these temperatures and could react with other elements, potentially affecting the overall production process (Huang, 2009).

3.1.4. Production scale

Scaling is a crucial consideration in LCA because different production scales can significantly affect energy efficiency, material use, and overall environmental impact. Larger-scale production often benefits from economies of scale, which can reduce per-unit emissions and resource consumption. Kawajiri and Sakamoto (2022) adopted a power law assumption to scale impacts for the carbon fiber manufacturing process, comparing GHG emissions from lab-scale to industrial-scale production. For carbon fiber production (including PAN upstream processes), the authors predicted that scaling production from 500 to 3000 tons per year would reduce GHG emissions by 42.7 % on a mass basis, from 43.32 kg CO_2-eq to 24.83 kg CO_2-eq per kg of carbon fiber, as shown in Fig. 3a.

Moreover, Groetsch et al. (2023) found that although power demand increases as the carbon fiber production scale rises from 2000 to 10,000 tons per year, the power demand per unit weight of carbon fiber decreases with increasing production scale (see Fig. 3b). For instance, at a production scale of 2000 tons per year, the power demand is 5MW, whereas at 10,000 tons per year, it is 15 MW. This represents only a threefold increase in power demand, despite a fivefold increase in production capacity, indicating that the power demand per unit weight of carbon fiber decreases with scale.

These two studies suggest that GHG emissions and power demand may not necessarily scale in the same manner, as emissions appear to be influenced not only by energy consumption but also by process efficiency improvements beyond electricity use alone. However, this relationship remains underexplored. Although general or heuristic scaling approaches have been proposed in LCA (Piccinno et al., 2018, 2016), specific studies on upscaling in carbon fiber manufacturing are limited, as further discussed in Section 4. Moreover, data from lab-scale or pilot plant capacities cannot accurately represent industrial production lines—and there is a significant difference in commercial carbon fiber production scale and the production scale for which carbon fiber environmental impact has been measured experimentally. For example, Liddell et al. (2017) conducted a bandwidth study on CFRP energy use and savings using data from an experimental carbon fiber production line (at the Carbon Fiber Technology Facility) with a capacity of only 25 tons per year. Similarly, Dér et al. (2021) and Groetsch et al. (2021a) investigated the energy consumption of carbon fiber production using pilot plants with capacities of 120 tons per year. According to personal communication with carbon fiber industry experts, the typical nameplate capacity for a single carbon fiber production line currently ranges from 1500 to 2500 tons per year, depending on the tow size and grade of carbon fiber being produced. These commercial facilities have capacities one to two orders of magnitude beyond the experimental and pilot-scale facilities that have been explored from an energy analysis or LCA perspective.

3.1.5. Operational parameters

Groetsch et al. (2023) examined the relationships among process parameters, fiber properties, emissions, and energy consumption in carbon fiber manufacturing. By adjusting the temperature profile in the oven (during stabilization) and furnace (during carbonization), as well as the process speed/heating time, the author found that the energy demand per kilogram of the final product could be reduced by up to 30 %, leading to cleaner production.

3.1.6. Geographic location of the plant

Considering the emphasis on electric process technology in carbon fiber manufacturing, the energy demand and environmental impact of carbon fiber production varies substantially by geographic location. The manufacturing process involves energy-intensive heating operations (e.g., carbonization), which are typically electric. The cleanliness of

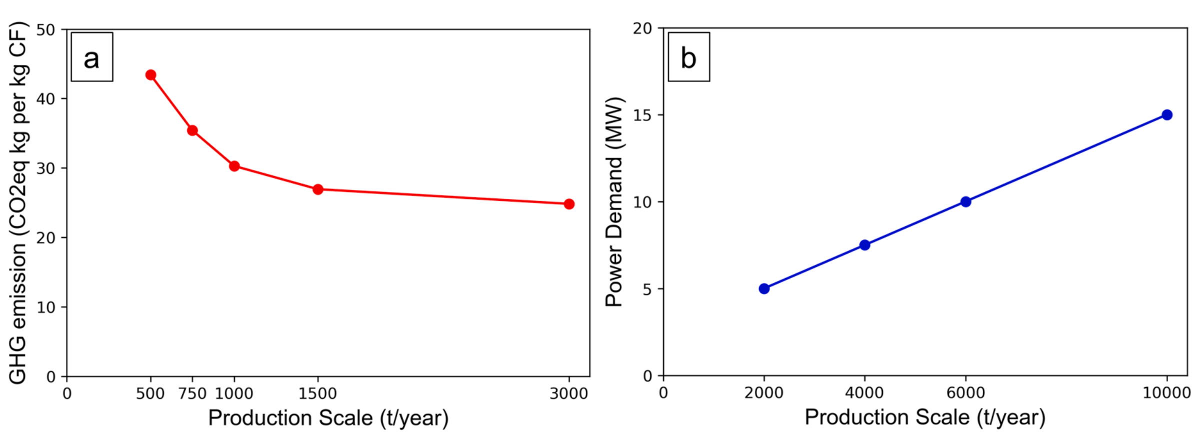

Fig. 3. Relationship between carbon fiber manufacturing production scale and (a) greenhouse gas (GHG) emissions (CO_2-eq per kg of carbon fiber) and (b) power demand (MW).

regional electricity generation therefore greatly affects the emissions associated with carbon fiber production. Fig. 4 shows the global carbon fiber nameplate (rated) production capacity by countries in 2023, with a total capacity of 290,230 t (CompositesWorld, 2023). Production is concentrated in China, the US, Japan, and Europe (EU), with notable regional variations in grid mix emissions. For example, China, which accounts for 51 % of global production, had the highest carbon intensity of electricity generation at 0.95 kg CO_2-eq per kWh. In contrast, the EU, contributing 10 % of global production, had the lowest average electricity emission rate among the top four countries, at 0.36 kg CO_2-eq per kWh—less than half of China's electricity emissions rate. This highlights the differences in emissions that could arise based on production location, even when the carbon fiber product and technology pathways are identical. Grid generation mixes are also rapidly shifting in many regions, meaning that spatiotemporal considerations can result in significant time-dependence and volatility in LCA results, especially when seeking to inform comparative assertions. Here, we consider only geographic location-based grid mix emissions. Mechanisms such as Renewable Energy Certificates (RECs) or Guarantees of Origin (GOs) can be used to reduce the market-based carbon emissions of carbon fiber (Holzapfel et al., 2024, 2023); however, this is beyond the scope of our study.

Furthermore, carbon fiber exports are often subject to stringent regulations, such as export control and the International Traffic in Arms Regulations (ITAR) laws, due to their dual-use applications in both civilian and military sectors, highlighting the importance of the plant's geographic location (CompositesWorld, 2022; US ITAR Law, 2024). Moreover, personal communication with industry experts indicates that PAN production and carbon fiber manufacturing facilities are typically not co-located in the same plant, although a few are in the same industrial park (e.g., integrated facility). When conducting LCA or relevant studies, it is important to specify the location of the PAN and carbon fiber plant and consider transportation factors if necessary.

3.1.7. Conversion rate of PAN to carbon fiber

As explained in Section 2.2, the conversion rate, or yield, is defined as the amount of carbon fiber produced per unit of PAN processed. Reported conversion rates in the literature vary significantly, ranging from 36 % to 58 %. This variation may be due to differences in the amount of comonomers (e.g., methyl acrylate and methyl methacrylate) added during PAN production to improve its solubility and processability (Groetsch et al., 2023b; Ju et al., 2013). However, a higher amount of comonomers in PAN can lead to increased mass loss during the carbonization process, negatively affecting the conversion rate and requiring more PAN to produce the same amount of carbon fiber (Choi et al., 2018; Khan et al., 2022). Typically, the conversion rate from PAN to carbon fiber is between 45 % and 50 %, meaning that 2–2.22 kg of PAN is needed to produce 1 kg of carbon fiber. Given the significant upstream environmental impact of PAN production (Das, 2011), variations in conversion rate can considerably amplify the energy demand and environmental footprint per kilogram of carbon fiber.

3.2. Energy demand and environmental impact of carbon fiber

Section 3.2.1 presents LCI data collected during the meta-analysis, which can be used in future LCA studies to evaluate all relevant environmental impacts for carbon fiber manufacturing. During our meta-analysis, we found that most of the literature reports cumulative energy demand (CED), greenhouse gas (GHG) emissions, or both, while other environmental impact indicators are less commonly examined for carbon fibers. Therefore, we primarily scrutinized these two indicators, which are discussed separately in Sections 3.2.2 and 3.2.3.

3.2.1. Life cycle inventory data

Similar to Section 3.1, the scope of our study begins with the production of PAN from AN, followed by the manufacturing of carbon fiber from PAN. The upstream production processes of AN can be used as background data for the LCA model, and databases such as ecoinvent and Idemat provide comprehensive LCI data for these processes

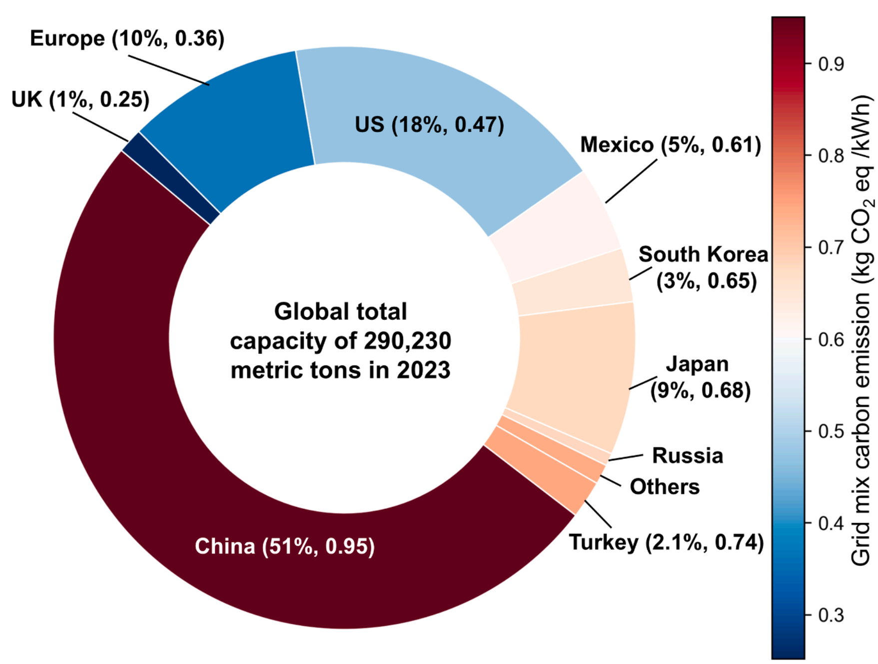

Fig. 4. Global carbon fiber nameplate production capacity by country in 2023, with corresponding grid mix carbon emissions. The donut chart illustrates each country's share of global carbon fiber production capacity. The values in parentheses represent: (1) the country's proportion of total global production capacity and (2) its grid mix carbon emissions (kg CO_2-eq per kWh), including both direct emissions during electricity generation and upstream emissions from the power plant and fuel production (more details see SI Section 2). The color gradient indicates grid mix emissions, with higher emissions shown in red and lower emissions in blue. Note that nameplate/rated capacity may differ from actual production capacity, as manufacturers with production lines operating at 1 K to 6 K tow sizes often report their capacity based on a 12 K scale, potentially leading to an overestimation of actual production (CompositesWorld, 2023).

(Ecoinvent, 2024; Idemat, 2024).

3.2.1.1. PAN manufacturing. Currently, only four sources have been identified that explicitly report LCI data for the AN-to-PAN manufacturing process, as shown in Table 1. For more detailed information on the LCI, including exact values for each inflow and outflow, please refer to SI Section 5. Notably, the comonomers varied among all sources that reported the comonomer; and one study Duflou et al. (2009) did not disclose this information at all. This variation suggests differences in production routes to produce PAN (see Section 3.1.1). Among the available sources, Benitez et al. (2021) provided the most detailed unit process-based LCI data.

3.2.1.2. Carbon fiber manufacturing. Table 2 lists sources that have reported LCI data for carbon fiber manufacturing using PAN as the input flow, except for JCMA (2021), which provides aggregated data that reports inflows and outflows in terms of environmental exchanges rather than direct inputs and outputs of unit processes. For more detailed information on the LCI, including exact values for each inflow and outflow, please refer to SI Section 5.

It is worth noting that the LCI data generally lack detailed information on carbon fiber grades and production scales, except for Benitez et al. (2021), Groetsch et al. (2021a), and JCMA (2021), which each specify the tow size and/or modulus for the carbon fiber studied. This lack of specificity on carbon fiber grade presents two key challenges: it is difficult to understand how energy use and environmental impact vary across different carbon fiber grades, and it is challenging to determine whether the LCI data represent an experimental or an industrial production setting. Second, the conversion rate—the amount of carbon fiber produced from 1 kg of PAN—varies across these ten sources. Benitez et al. (2021) reported the lowest conversion rate at 36 % (i.e., 2.78 kg PAN required for 1 kg of carbon fiber), while Romaniw (2013) reported the highest at 58 % (i.e., 1.72 kg PAN needed for 1 kg of carbon fiber). Third, the energy inputs and energy carriers given in the LCI datasets vary substantially. For example, the electricity requirement ranged from 0.2 MJ to 306.7 MJ per kg of carbon fiber, and the natural gas flow ranged from 2.63 MJ to 481 MJ (see SI Section 5). Finally, process emissions, such as hydrogen cyanide (HCN, a highly toxic compound) and carbon dioxide (CO_2, contributing to climate change), may occur during carbon fiber manufacturing (Groetsch et al., 2021b). However, some studies report only the output of 1 kg of carbon fiber without detailing associated emissions, which affects the accuracy of the LCA results for toxicity, climate change or other impact categories.

Table 1
LCI data for AN-to-PAN manufacturing process. Each source is categorized as basic, intermediate, or detailed based on the LCI detail level, with the rubric provided in SI Section 6.

No.	Sources	LCI detail level	Comonomer	Notes
1	Duflou et al. (2009)	Intermediate	Not specified	This LCI uses dimethylformamide (DMF) as a solvent and polydimethylsiloxane (PDMS) for protective sizing.
2	Meng et al. (2017)	Intermediate	Vinyl acetate	This LCI is adapted from several literature, expert opinions, and results from a confidential industrial dataset. It does not include a solvent.
3	USLCI (2024)	Intermediate	Methyl methacrylate	This LCI is representative only of key material and energy inputs required to produce PAN.
4	Benitez et al. (2021)	Detailed	Methyl acrylate	The authors include several steps for acrylonitrile polymerization to manufacture PAN, each with its own LCI.

Stabilization and carbonization are the primary contributors to energy demand in carbon fiber production (Dér et al., 2021; Groetsch et al., 2021a; Liddell et al., 2017). Personal communication with carbon fiber industry experts indicates that the equipment used for stabilization (i.e., ovens) and carbonization (i.e., furnaces) mainly relies on electricity rather than natural gas. Natural gas may be used for exhaust gas treatment, as noted by Groetsch et al. (2021a), though the production scale in their study is unclear. Contrary to the information gleaned from personal communications with industry experts, we found that all LCI sources list natural gas as a process input, and that most LCI sources indicated natural gas as the dominant energy carrier. Some sources even lack an electricity input entirely, instead attributing all energy consumption to natural gas. This discrepancy raises questions about accuracy of publicly available LCI information, including whether electricity is the primary energy input in carbon fiber manufacturing or whether natural gas also plays a significant role—an issue that warrants further investigation.

3.2.2. Cumulative energy demand

Fig. 5 shows the CED for products or processes from AN to carbon fiber, with all values adjusted to a normalized output of 1 kg of carbon fiber following the procedure mentioned in Section 2.2.

First, it is worth highlighting the substantial variation in CED within each product or unit process. For example, for the carbon fiber product (brown box plot), the lowest CED is 198 MJ per kg (excluding 7.56 MJ per kg, which was deemed unreasonable and treated as an outlier), while the highest is 1984 per kg (over one order of magnitude higher!), with a median value of 562 MJ per kg. For the carbonization process (purple box plot), the lowest CED is 720 MJ per kg of carbon fiber, while the highest is 1333 MJ per kg.

Second, variations in conversion rate (yield) could affect the CED. Take AN (orange box plot) as an example: the CED data collected for it range from 80 to 110 MJ per kg of AN (see SI Section 4). However, after the alignment of conversion rate (see Section 2.2), the CED distribution range expands to 156 to 346 MJ per kg of carbon fiber, with a median value of 194 MJ per kg of carbon fiber.

Third, the production scale is another factor that can influence the CED. When combining the product with the unit processes, such as by adding the values of PAN product (219–470 MJ/kg), stabilization (217–776 MJ/kg), carbonization (720–1333 MJ/kg), and other processes (31–112 MJ/kg), the resulting total gives a range of 1187–2691 MJ/kg, which is significantly higher than the CED range for carbon fiber alone (198–2000 MJ/kg). We speculate that this discrepancy may be due to two issues: first, the reported values do not specify the production scale, and second, data from pilot-scale operations may not be representative those of commercial-scale operations. Consequently, making direct comparisons between these data sets is challenging.

Fourth, the data in the literature or databases mainly focus on products (i.e., AN, PAN, and carbon fiber), with carbon fiber having the highest number of data sources at 30. However, there is less emphasis on the individual unit processes, with a lack of reported values for stretching, finishing, surface treatment, and sizing processes. As shown in Fig. 2, the processes indicated by dashed lines represent the absence of such data. We expect higher variability in these processes due to the limited number of available estimates.

Lastly, it is important to consider the different grades of carbon fiber. As mentioned in Section 3.1, the energy demand and environmental impact for manufacturing these grades can vary. However, most data sources do not clearly state the grades. Given the different grades of carbon fiber required for various applications, it becomes challenging to accurately compare energy demand.

3.2.3. Greenhouse gas emissions

Similar to the CED analysis, we examine the GHG emissions reported

Table 2
LCI data for PAN-to-carbon fiber manufacturing process. Each source is categorized as basic, intermediate, or detailed based on the LCI detail level, with the rubric provided in SI Section 6.

No.	Sources	LCI detail level	Carbon fiber grades	Production scale	Conversion rate	Notes
1	Duflou et al. (2009)	Intermediate	Standard	Not specified	53 %	The study mentions that the process generates NH_3, H_2O, H_2, CO, CO_2, HCN, and CH_4. After gas treatment, HCN, NH_3, CH_4, and CO are emitted. However, the study does not provide specific details on the emitted pollutants. It also mentions the use of standard high-tenacity fibers (1600 g/km).
2	Romaniw (2013)	Intermediate	Intermediate modulus	Not specified	58 %	This LCI was developed mainly for aerospace applications, specifically intermediate modulus fibers.
3	Meng et al. (2017)	Basic	Not specified	Not specified	57 %	This LCI is adapted from various literature sources and life cycle databases. The parameters were chosen through a consensus of literature, expert opinion, and a confidential industrial dataset. The study does not detail the outflows.
4	Khalil (2017)	Intermediate	Not specified	Not specified	55 %	This study compiled data from several sources to generate inventory data for carbon fiber but does not clarify the methodology used to derive this inventory data.
5	Pillain et al. (2019)	Intermediate	Not specified	Not specified	55 %	This study relies on LCI data from one report (Griffing and Overcash, 2009; Griffing and Overcash, 2009)
6	Groetsch et al. (2021a)	Intermediate	Standard, 24k, 277 Gpa modulus, 4.3 Gpa strength	120 tons / year	52 %	This LCI is based on data from a pilot production line.
7	Gopalraj et al. (2021)	Intermediate	Not specified	Not specified	53 %	This study compiled data from several sources to generate inventory data for carbon fiber but does not clarify the methodology used to derive this inventory data.
8	Benitez et al. (2021)	Detailed	Standard modulus (i.e., T700G)	1500 tons /year	36 %	This is the most detailed unit process-based LCI available. The production scale was confirmed through personal communication with the authors.
9	JCMA (2021)	Detailed	High strength, 12k to 24k, 230 to 250 Gpa modulus	Industrial scale, Not specified	Not specified	This LCI provides aggregated data (e.g., inflows are reported as natural sources), but it does not detail the process from PAN to carbon fiber. It is based on an industrial measurement of 6994 tons of carbon fiber production per year, although the production capacity per line is not mentioned. The location is Japan.
10	US LCI (2024)	Basic	Not specified	Not specified	48 %	The modeled system is representative only of key material and energy inputs required to produce carbon fiber.

in existing literature for products from AN to carbon fiber, with all values adjusted to a normalized output of 1 kg of carbon fiber following the procedure mentioned in Section 2.2, as shown in Fig. 6.

There is considerable variability in GHG emissions within each product, particularly carbon fiber. The lowest GHG emissions for carbon fiber are approximately 17 kg CO_2-eq per kg, while the highest are about 154 kg CO_2-eq per kg, with a median value of 31 kg CO_2-eq per kg. Additionally, most data sources do not clearly state the carbon fiber grades.

Another potential factor contributing to this variation is the use of different LCIA methodologies across existing literature, each based on a different version of the IPCC reports. Each updated version of the IPCC report revises certain characterization factors for GHG emissions. We recommend using the most up-to-date methodology for GHG emissions, which is the IPCC 2021.

4. Discussion

In this paper, we showed that the CED and environmental impact results associated with carbon fiber manufacturing vary widely across the existing literature. We identified several underlining factors that may contribute to these variations, including carbon fiber grades, production parameters, production scale, conversion rate, and geographic location. One key observation is that carbon fiber is not a homogeneous commodity; rather, it is a carefully designed and engineered material that varies substantially in mechanical properties, end-use markets, and applications. Different grades of carbon fiber likely have different energy demands and environmental impacts. However, due to limited data, our current assessment can only be qualitative, not quantitative. To build on this understanding, we hypothesize that higher modulus carbon fibers have a higher CED and GWP on a unit mass basis due to the higher temperatures required in production. In contrast, heavy tow carbon fibers have a lower CED and GWP on a unit mass basis compared to low tow fibers because of their higher throughput for the same level of energy demand or emissions in the production line. Yet, this advantage comes with the trade-off of sacrificing certain mechanical properties (e.g., strength or stiffness). Unfortunately, detailed data on the relationship between energy demand, environmental impacts, and carbon fiber grades is often not clearly disclosed, so further data would be required to corroborate our hypothesis.

Our meta-analysis found that existing literature provides LCI data with detailed information on CED and GHG emissions (e.g., electricity, natural gas, CO_2 emissions flows), or reports results specifically for these two metrics. However, other material flows, such as chemicals used in the carbon fiber manufacturing process, may not be disclosed. This lack of transparency will almost certainly affect the accuracy of other environmental metrics. For example, the ozone depletion potential is notably higher when polydimethylsiloxane (PDMS) is included in LCIs for PAN production. If such material flows are not disclosed, this adverse impact may be hidden, resulting in an underestimation of the actual environmental burden. Therefore, recommendations on the results for impact categories other than CED and GHG emissions need to consider uncertainties related to cutoff or system boundaries to draw robust and comprehensive environmental conclusions, including preventing unfavorable burden shifts between impacts.

LCA is heavily data-driven; however, data are often limited. To simplify the model —for example, for a specific input or output—it is common practice to use a single data source or to determine a representative value by averaging or using the median from multiple similar sources. However, the significant variations in carbon fiber data within the existing literature, combined with the lack of detailed information on factors such as carbon fiber grades, production scale, operational parameters, and geographic location, suggest that the quality of these data may be inadequate. In Section 3.1, we qualitatively discussed how

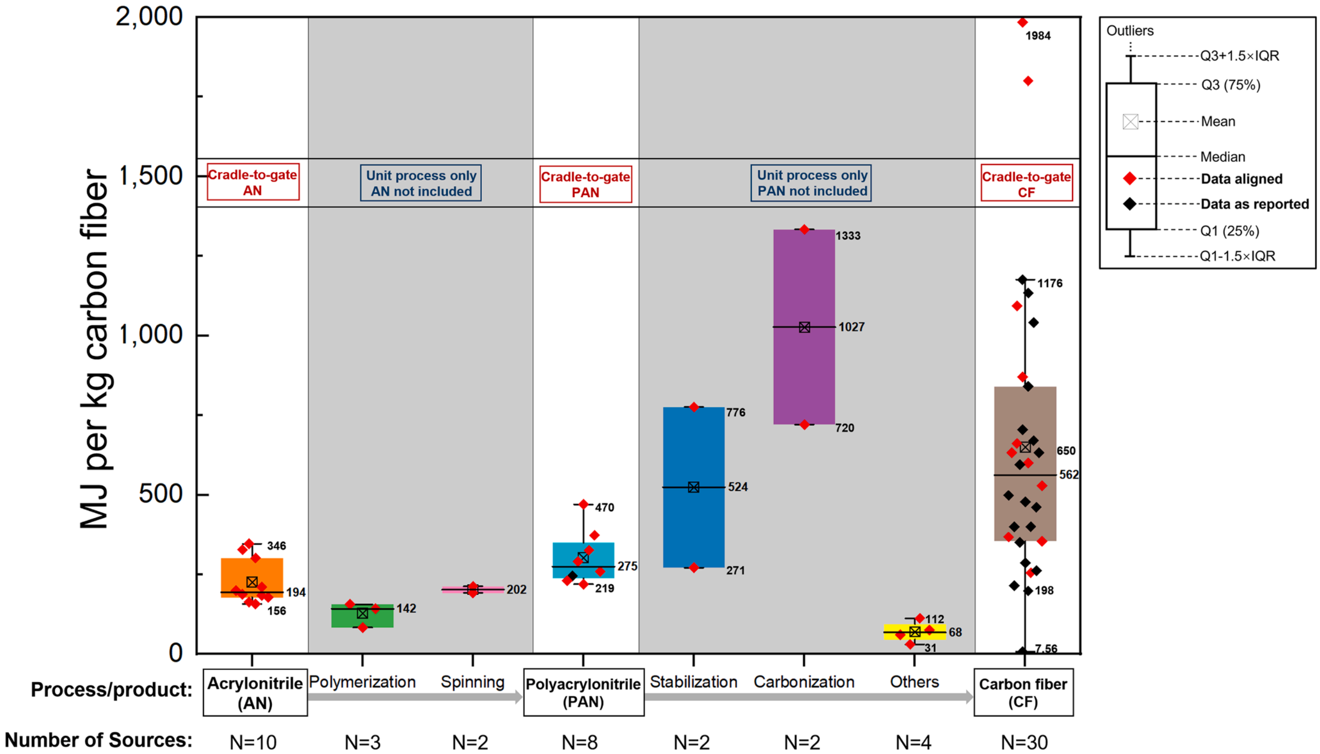

Fig. 5. Cumulative energy demand (CED) for the conversion of AN to PAN to carbon fiber (all values in units of MJ per kg of finished carbon fiber). In each column, the box plot represents the distribution of CED for the unit operation indicated, with each point representing one data source reporting energy demand for that operation, all adjusted to a normalized output of 1 kg of carbon fiber. The grey-shaded areas indicate gate-to-gate CED data for individual unit processes, excluding upstream impacts of other operations. ("Others" means the process of surface treatment, sizing, drying and winding). The white-shaded areas represent the cradle-to-gate CED for finished or semi-finished products; these data are cradle-to-gate and include all upstream impacts. Data points shown as black diamonds are as-reported (no post-processing). Data points shown as red diamonds involved some post-processing by the authors to align units and normalize based on process conversion rates. The value of N below the graph indicates the number of data sources for each column.

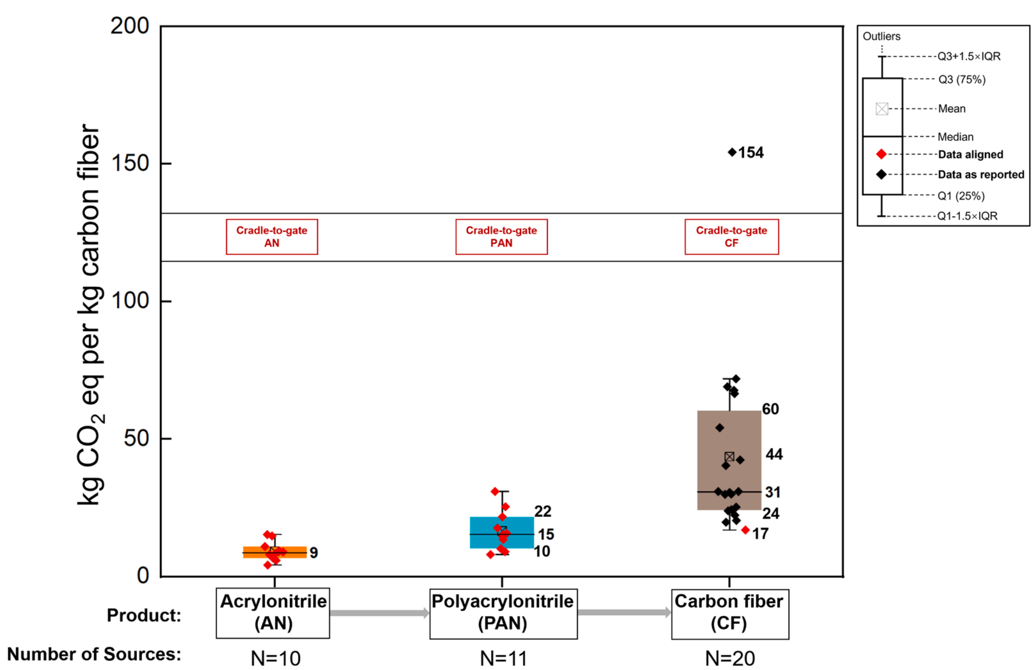

Fig. 6. Greenhouse gas emissions (GHG) emissions (kg CO_2-eq per kg of finished carbon fiber). The columns, from left to right, show the products from acrylonitrile to carbon fiber. In each column, the box plot represents the distribution of GHG emissions, with each point representing a data source, all adjusted to a normalized output of 1 kg of carbon fiber. Each data point includes cradle-to-gate GHG emissions. Data points shown as black diamonds are as reported (no post-processing). Data points shown as red diamonds involved some post-processing by the authors to align units and normalize based on process conversion rates. The value of N below the graph indicates the number of data sources for each column.

the environmental impact of carbon fiber is influenced by these factors. As a result, relying on this common practice may not lead to robust conclusions.

Consequently, we suggest that undertaking LCA studies involving carbon fiber should be approached with caution, including careful attention to the goal and scope of the study. Before making LCA results available to inform design and engineering decisions regarding the use of carbon fiber, it is advisable to conduct a robust sensitivity analysis, particularly if only secondary data (e.g., from literature or technical reports) are available. Better yet would be establishing supply chain relationships and obtaining environmental impact data specifically relevant to the project's needs. To support this, we provide a checklist that outlines key factors for stakeholders to consider in eco-informed decision-making (see Appendix A), ensuring that the choice of carbon fiber data is suitable and that the conclusions are well-supported by reliable information. However, environmental product declarations (EPDs) for carbon fibers and related products are extremely sparse. For example, a search of the EPD International EPD Portal turned up only a single EPD document match for the search term "carbon fiber," versus 446 for "aluminum," 568 for "cement," and 722 for "steel" (ECO Portal - Eco Platform en, 2024).

Carbon fiber was once mainly used in specialized, high-end industries, where data sharing and disclosure were often restricted, and energy use or environmental impact was not a priority. However, in recent years, its use has spread to many other sectors. As the carbon fiber market expands and sustainability becomes more important, it is necessary to improve environmental performance. Carbon fiber cannot be treated as a single homogeneous commodity, particularly since the energy demand and environmental impacts of manufacturing various grades of carbon fiber are likely to vary substantially. Therefore, it is essential to obtain detailed LCIs or EPDs to establish a baseline for carbon fiber manufacturing. This baseline, with specific energy demand and environmental impact data, should be categorized by grade (e.g., high modulus, standard modulus), application (e.g., wind energy, automotive), tow sizes, or precursor type (e.g., bio-based source such as lignin). Without this detailed information, evaluating the feasibility of using carbon fiber in other sectors becomes challenging. Future carbon fiber data should be as transparent as possible, including details on system boundaries, production scale, conversion rate, emissions, chemicals used, and carbon fiber grades. Such transparency will help fill gaps in life cycle inventory data, enhancing its value to the scientific and manufacturing community.

A comprehensive approach to research and innovation can enhance the understanding of carbon fiber manufacturing and promote its sustainability. Currently, there is limited analysis of sub-processes involved in carbon fiber manufacturing and how operational parameters change when producing different grades of carbon fiber (e.g., different modulus or tow sizes). We recommend that future research focus on a bottom-up analysis of carbon fiber manufacturing to better understand the environmental hotspots in the process. Developing an effective upscaling model from lab or pilot scale to full production scale for carbon fiber manufacturing is also highly recommended.

We acknowledge that this study examines only the cradle-to-gate energy demand and environmental impacts of carbon fiber manufacturing, without focusing on the use phase and end-of-life. The lightweighting benefits of carbon fibers have been explored extensively (e.g., Atescan-Yuksek et al., 2024; Khalil, 2017; Wegmann et al., 2022). Similarly, while recycling technologies are not yet in broad commercial use for carbon fiber composites, they could potentially reduce the demand for primary materials, promote the circular economy, and enhance sustainability (Oliveux et al., 2015). CFRP recycling technologies can be broadly categorized into mechanical, thermal, and chemical recycling (Hecker et al., 2023). Several studies have explored the energy demand and environmental impacts of these recycling methods, generally showing lower energy demand and reduced environmental impacts compared to virgin carbon fiber production, primarily due to the assumption that recycled carbon fiber can directly replace virgin fiber (for detailed data, please refer to the SI Section 7). Despite these promising advancements, recycled carbon fiber suffers from degraded mechanical properties (particularly due to random fiber orientation and shorter fiber length) and reduced bonding effectiveness with the polymer matrix compared to virgin fibers (Baley et al., 2024) and may not be cost-effective. Consequently, recycled carbon fiber cannot replace virgin fiber on a one-to-one basis or through a simple substitution ratio. Future research is recommended to explore integrated recycling and remanufacturing pathways and identify (re)use applications/markets that can accept material property limitations. This also re-emphasizes the importance of establishing a baseline for the energy demand and environmental impact of current virgin carbon fiber manufacturing. Using this baseline, we aim to provide effective guidance on adopting carbon fiber in appropriate applications to maximize its environmental and economic benefits, support sustainability efforts in overcoming material constraints while meeting industry needs, and ultimately advance a truly circular economy rather than a theoretical one.

While this study focuses on energy demand and environmental impacts, it's important to note that cost is a critical driver in carbon fiber applications (Gill et al., 2016; Nunna et al., 2019). Energy consumption directly influences manufacturing costs, and environmental emissions can shape policy decisions, such as taxation and financial incentives, which further affect costs. Therefore, a comprehensive analysis is recommended to explore the intricate relationships between energy demand, environmental impact, and economic factors.

5. Conclusions

In this study, we conducted a critical literature review and meta-analysis, revealing the considerable variations in reported cumulative energy demand, greenhouse gas emissions, and other environmental impacts of carbon fiber manufacturing. We analyzed and discussed key underlying factors contributing to these variations. A key takeaway is that carbon fiber is not a homogeneous product but varies significantly across grades in terms of mechanical properties, end-use applications, and energy intensity, as well as external factors such as geographic production location and manufacturing scale—all of which ultimately influence its environmental footprint. However, these factors and related knowledge are often not effectively communicated to the LCA community or consciously shared. To address this gap, we provide a checklist that incorporates these factors to support stakeholders—including LCA practitioners, engineers and policymakers—in making more informed decisions (see Appendix A).

Another key takeaway is that publicly available data on carbon fiber production is inadequate. This data limitation, coupled with limited awareness of carbon fiber heterogeneity, often leads researchers and practitioners to assume that all carbon fiber is the same, resulting in the selection of unrepresentative data and, consequently, misleading conclusions in energy and environmental analyses. If only secondary data are available, it is advisable to conduct a robust data quality assessment and sensitivity analysis using our checklist. This underscores the urgent need for new life cycle inventory datasets that accurately capture the inherent heterogeneity of carbon fiber to support more precise and sustainable decision-making. We strongly recommend establishing a granular cradle-to-gate carbon fiber dataset that captures this heterogeneity by incorporating key factors outlined in our checklist, such as production country, manufacturing scale, grades (e.g., tow size and modulus), and applications (e.g., aerospace, automotive, and wind energy).

However, these challenges are fundamentally linked to a broader issue: the lack of transparency. The carbon fiber industry remains somewhat of a "black box" when it comes to environmental data, with limited transparency preventing stakeholders from fully understanding its heterogeneity and accessing high-quality data. As the market expands and regulatory pressures to meet stringent environmental standards increase, improving data transparency will be critical to ensuring the long-term viability and market competitiveness of carbon fiber and its products (CFRPs) in the transition toward a low-carbon and sustainable future.

To address this, we recommend proactive efforts from both industry and policymakers, including strengthening collaboration between manufacturers, policymakers, and academia to enhance representative data sharing and disclosure, and accelerate the development and commercialization of emerging technologies (e.g., bio-based precursors and high-energy-efficiency heating technologies). These efforts will not only reduce the energy demand, environmental footprint and cost of carbon fiber and fiber-reinforced composites but also strengthen the industry's leadership in sustainable materials innovation, aligning with the Sustainable Development Goals (SDGs).

CRediT authorship contribution statement

Hao Chen: Writing – original draft, Visualization, Investigation, Formal analysis, Data curation, Conceptualization. **Heather P.H. Liddell:** Writing – review & editing, Writing – original draft, Data curation. **Amod A. Ogale:** Writing – review & editing. **Zoe Chunyu Miao:** Writing – review & editing, Visualization. **Muzan Williams Ijeoma:** Writing – review & editing. **Michael Carbajales-Dale:** Writing – review & editing, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2025.108302.

Appendix A. Carbon fiber data collection checklist for stakeholders

This checklist for stakeholders lists factors that could affect the energy demand and environmental impact of carbon fibers. It is intended as a framework to provide, collect, and interpret information about carbon fiber products to support eco-informed decision-making.

Carbon Fiber Data Collection Checklist for Stakeholders
Internal factors
Tow size
It represents the number of filaments per bundle of continuous filament in the material. Tow size ranges from 1000 to 320,000 filaments, with common tow sizes being 1 K, 3 K, 12 K, and 24 K.
Heavy tow carbon fibers have a lower CED and GWP on a unit mass basis compared to low tow fibers because of their higher throughput for the same level of energy demand or emissions in the production line. Yet, this advantage comes with the trade-off of sacrificing certain mechanical properties (e.g., strength or stiffness).
Grade (mechanical properties)
Carbon fiber can be broadly categorized into standard modulus, intermediate modulus (high tensile strength), and high modulus.
Higher modulus carbon fibers have a higher CED and GWP on a unit mass basis due to the higher temperatures required in production.
Precursor
Polyacrylonitrile (PAN) precursors currently dominate commercial carbon fiber production, accounting for >90 % of output, followed by petroleum pitch. Several alternative precursors are currently under investigation, including lignin, asphaltene, polyolefin, and polyethylene.
Carbon fiber production from other precursors involves different manufacturing processes as compared to PAN-based carbon fibers. Pitch is better suited for processing at high temperatures (e.g., 3000 °C) and can achieve a higher modulus than PAN.
Form
Continuous or chopped fibers. Virgin carbon fiber production typically produces continuous fibers.
Chopped fibers may originate from virgin carbon fiber waste or result from cutting continuous virgin fibers to meet specific application needs.
Production scale
The typical nameplate capacity for a single carbon fiber production line currently ranges from 1500 to 2500 tons per year, depending on the tow size and grade of carbon fiber being produced. Data from lab-scale or pilot plant capacities cannot accurately represent industrial production lines.
As production scale increases, the energy demand and environmental footprint per unit weight of carbon fiber tend to decrease.
External factors
Applications
Different applications (e.g., aerospace, automotive, wind energy and pressure vessel) require different types of carbon fiber. Aerospace applications primarily use low tow sizes (< 12 K), wind energy typically use heavy tow sizes (≥48 K).
Geographic location of the plant(s)
The generation mix greatly affects the emissions associated with unit operations involved in carbon fiber production, which are electricity-intensive. Grid generation mixes are also rapidly shifting in many regions. Additionally, check if there are export restrictions.
Scope
The scope and goal of the LCA study should be documented, especially the boundaries and unit operation inclusion.
Cradle-to-gate: it should include all upstream burdens, such as acrylonitrile monomer production.

(*continued on next page*)

(*continued*)

Carbon Fiber Data Collection Checklist for Stakeholders
Gate-to-gate: it considers only the processes involved in processing the acrylonitrile monomer into PAN precursor, and PAN precursor into carbon fiber. Analysts should confirm that cradle-to-gate and gate-to-gate studies include all of the key carbon fiber production processes, such as stabilization, carbonization, gas abatement (if relevant), surface treatment, and sizing.

Data availability

I have provided data in Supplementary information file.

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