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CATAPULT Offshore Renewable Energy

Net zero carbon fibre:

Practical pathways to net zero

Key findings

Developing and scaling low-impact carbon fibres (CF) should be a central decarbonisation priority for the wind energy sector, with the potential to reduce the global warming potential (GWP) of wind turbine blades by up to 50%. This report—designed as a companion to Net zero carbon fibre: Drop-In decarbonisation solutions—examines the limitations of upstream supply-side interventions, the challenges associated with green hydrogen-based synthetic fuels, and the critical role of production-side measures such as process electrification in accelerating and de-risking CF decarbonisation. A multi-horizon roadmap is presented, outlining strategic development pathways including solutions for "hard-to-decarbonise" areas of CF manufacturing.

- **Electrify to future-proof the net zero journey** – CF producers should avoid overreliance on green gases (such as hydrogen-based fuels) given uncertainties around their viability, scalability, and cost. Instead, CF producers should prioritise the electrification of oxidation and carbonisation ovens in both retrofitting existing infrastructure and new production facilities, as it offers a more reliable and faster pathway to advance and de-risk CF decarbonisation.
- **Target the toughest: Decarbonise exhaust treatment next** – Electrification can already address over 70% of energy demand in polyacrylonitrile (PAN) fibre and CF production. However, electrifying exhaust gas treatment remains a key challenge and should be prioritised to reduce reliance on future green gas solutions. In the interim, CF producers should purchase gas with Renewable Gas Guarantees of Origin (RGGOs) to support green gas growth and enable net zero gas consumption via market mechanisms.
- **Proactive energy strategy is essential to decarbonisation** – Passive reliance on electricity grid decarbonisation limits CF producers' control over their transition. To reduce uncertainty and accelerate progress, producers should secure Renewable Energy Guarantees of Origin (REGOs) backed electricity and invest in local renewables like onsite solar or wind. Pairing this with early energy-saving measures—such as heat recovery and low-power heating technologies—maximises emissions cuts before net zero electricity is fully realised.

Background & approach

CF have high embodied energy due to the high temperatures required during carbonisation and graphitisation[1], which is achieved with a combination of electrical power and thermal energy from natural gas. As a result, CFs used in the spar cap alone accounts for around 50% of the lifetime carbon footprint of a typical offshore wind blade, despite accounting for just 12% of the mass of the blade[2]. Therefore, developing solutions with lower environmental impacts for CF products represents a significant opportunity to decrease the carbon footprint associated with wind blade production and wind energy alike.

This report serves as a companion to SusWIND's publication, Net zero carbon fibre: Drop-In decarbonisation solutions, based on a lifecycle assessment (LCA) study evaluating the impact of future material and energy scenarios on CF production[3]. The study used multivariate analysis to rank decarbonisation strategies for CF production through to 2050 and to identify the optimal timelines for their implementation. Given the broad range of proposed interventions, the initial LCA study prioritised "drop-in" solutions—strategies requiring minimal or no modifications to existing CF production processes—ensuring minimal disruption to manufacturers. This approach focused on supply-side solutions for energy and material feedstocks, shifting the responsibility to suppliers to develop energy and material inputs compatible with current CF production infrastructure.

[1] Y. Cui, X. Hua, L. Z. Liu, S. Li, and Y. Shi, "Evaluating polyacrylonitrile precursor structure effects on carbon fiber production," Polym. Bull., vol. 80, pp. 8321–8338, 2023, doi: 10.1007/s00289-022-04451-4.

[2] K. Pender, "Deliverable 2.1.2 - NCC-TEC-3507 - Cradle-to-grave life cycle assessment of a state-of-the-art offshore wind turbine blade," 2022.

[3] K. Pender, F. Romoli, and J. Fuller, "Future strategies for decarbonisation of carbon fibre products: A roadmap to Net Zero 2050," J. Clean. Prod., vol. 486, p. 144525, 2025, doi: 10.1016/j.jclepro.2024.144525.

Figure 1 outlines a roadmap for decarbonising CF production using "drop-in" solutions, including bio-based acrylonitrile (Bio-ACN), synthetic methane (eMethane), and net zero grid electricity, as identified in the initial study. The analysis concluded that, among the thermal energy options assessed, eMethane would be necessary for both PAN fibre and CF production to achieve net zero CF products.

This report examines the limitations of relying solely on supply-side strategies for CF decarbonisation, the practical challenges and risks associated with synthetic, green hydrogen-based fuels (like eMethane), and the potential advantages of incorporating demand-side modifications in CF production. Specifically, it explores how electrification and process innovations could help de-risk and accelerate the transition to net zero CF production.

To support these kinds of developments, NCC and CPI are working together to strengthen innovation capabilities that are essential to the UK's supply and manufacture of advanced materials. Specifically, the focus is to develop sovereign capability for the production of novel carbon fibre formulations and processing techniques, which will, ultimately, support tangible advances in performance, cost and sustainability.

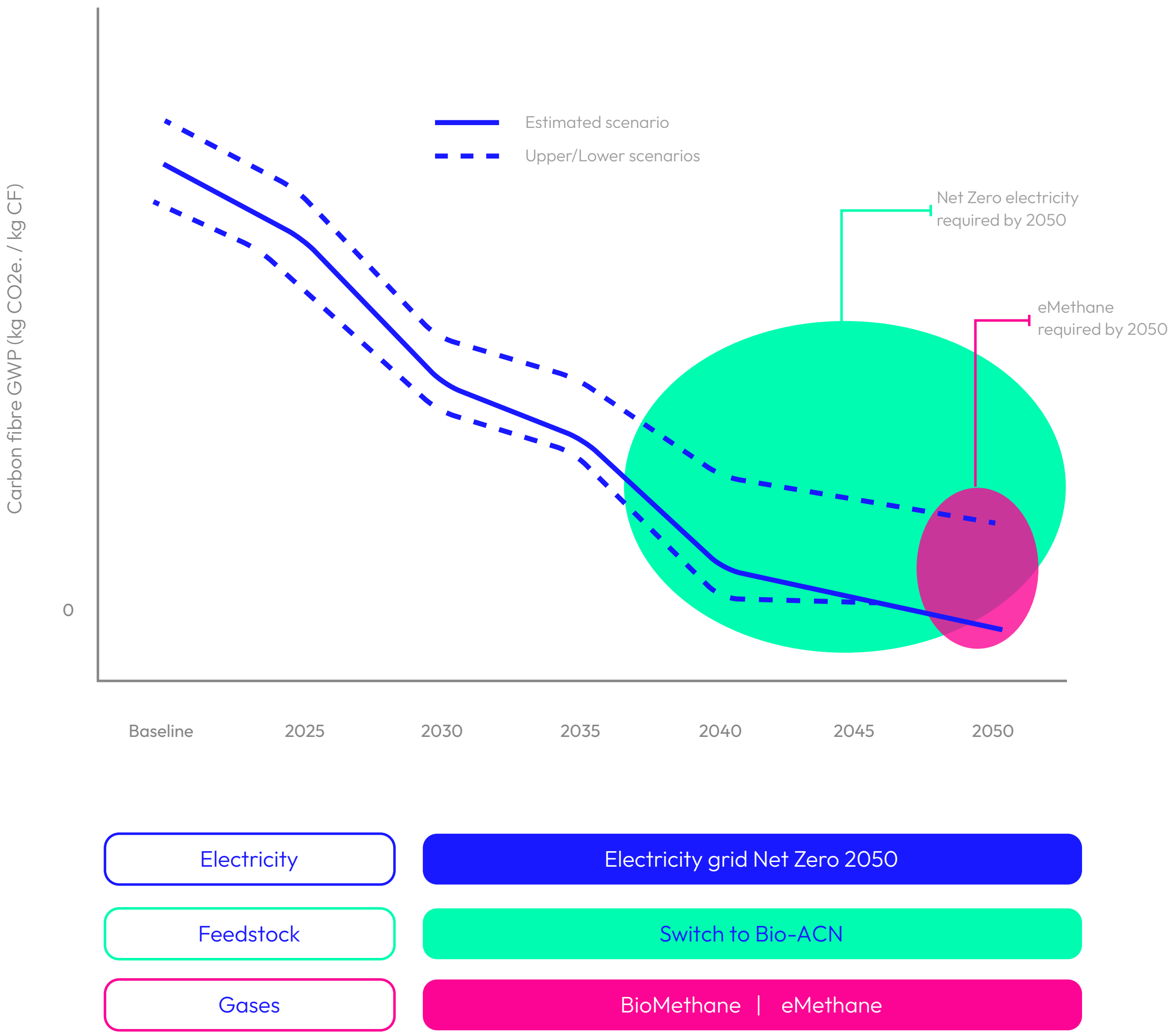


Figure 1 Summary of decarbonisation of CF production using "drop-in" solutions: Bio-ACN, eMethane, and net zero grid electricity

The risk of depending on green hydrogen-based fuels

Figure 1 illustrates that while "drop-in" energy solutions could decarbonise CF production, achieving net zero CF is only feasible with eMethane—a fuel that is currently not cost-competitive with natural gas. Commercially viable eMethane production depends on scaling up CO_2 capture technology, establishing a green H_2 economy, and integrating these with efficient methanation processes. Figure 2 provides an overview of the upstream industries and processes required for CF producers to access eMethane, along with the challenges these technologies still face. Given the uncertainty around the viability and timeline of eMethane deployment, it is risky for CF producers to rely solely on this pathway. Instead, they must also explore alternative strategies such as improving process efficiency, enhancing heat recovery, and increasing electrification to ensure a more resilient and sustainable transition to net zero CF production. The combustion of pure green hydrogen for heating could be considered as another pathway for decarbonising CF production. Unlike eMethane, hydrogen offers the significant advantage of bypassing the need to scale up CO_2 capture technology and infrastructure. However, the degree of modification required to adapt current CF production processes to hydrogen-based thermal energy remains uncertain.

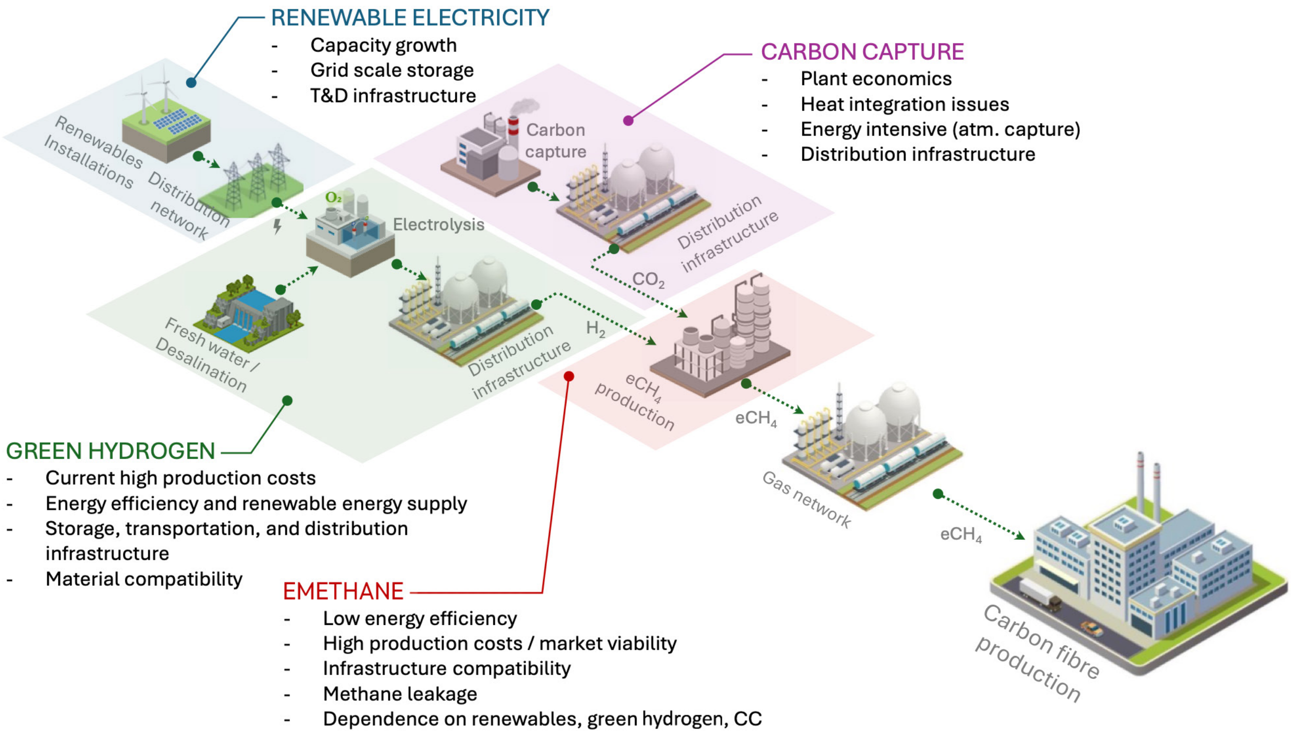


Figure 2 Overview of upstream industries / processes required for CF producers to get access to synthetic methane and green hydrogen

Even by 2050, eMethane is expected to remain significantly more expensive than natural gas, largely due to the high electricity demand of green hydrogen production, with carbon capture adding additional cost. These inefficiencies increase the need for upstream renewable energy, straining capacity expansion. While synthetic fuels offer a flexible, renewable alternative to fossil fuels without requiring major process changes, their high cost and uncertain scalability make sole reliance risky. A balanced approach should support synthetic fuel development while prioritising demand-side solutions like electrification. Figure 3 illustrates the advantages and disadvantages of CF producers switching to synthetic green hydrogen-based fuels as a means of achieving net zero production.

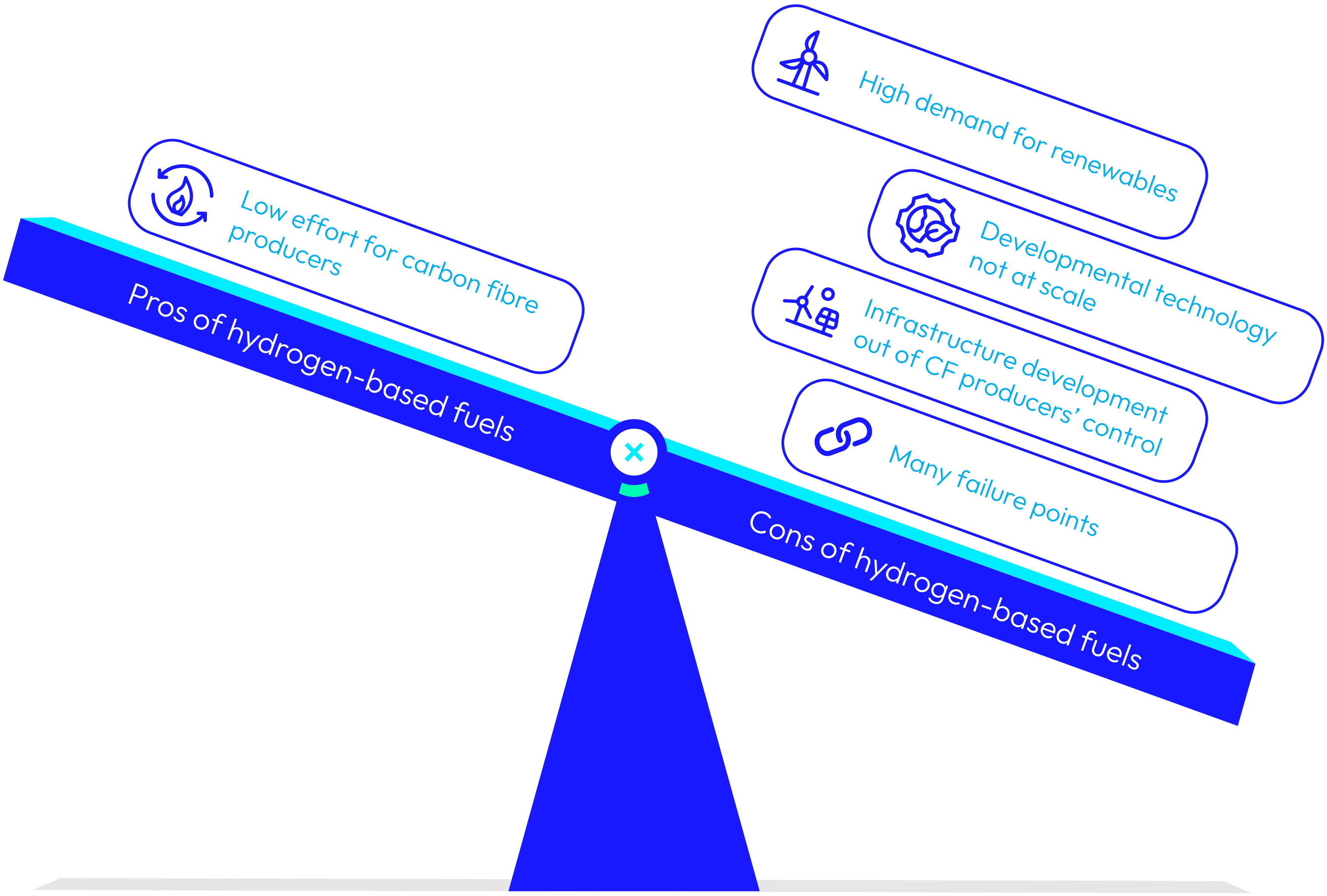


Figure 3 Illustration of pros and cons of CF producers switching to synthetic green hydrogen-based fuels as a means of achieving net zero production

Electrification as a strategic decarbonisation pathway for CF production

While green hydrogen-based synthetic fuels hold potential for the future of CF production, electrification of the process represents a promising and lower-risk decarbonisation pathway. When coupled with renewable energy sources, electrification leverages existing infrastructure, ensures greater cost stability, and enhances energy efficiency in CF production. Electrification of heating processes already exists and avoids the conversion losses inherent in producing, transporting, and utilising green hydrogen or synthetic fuels. Figure 4 illustrates the advantages and disadvantages of electrification of CF production as a means of achieving net zero production.

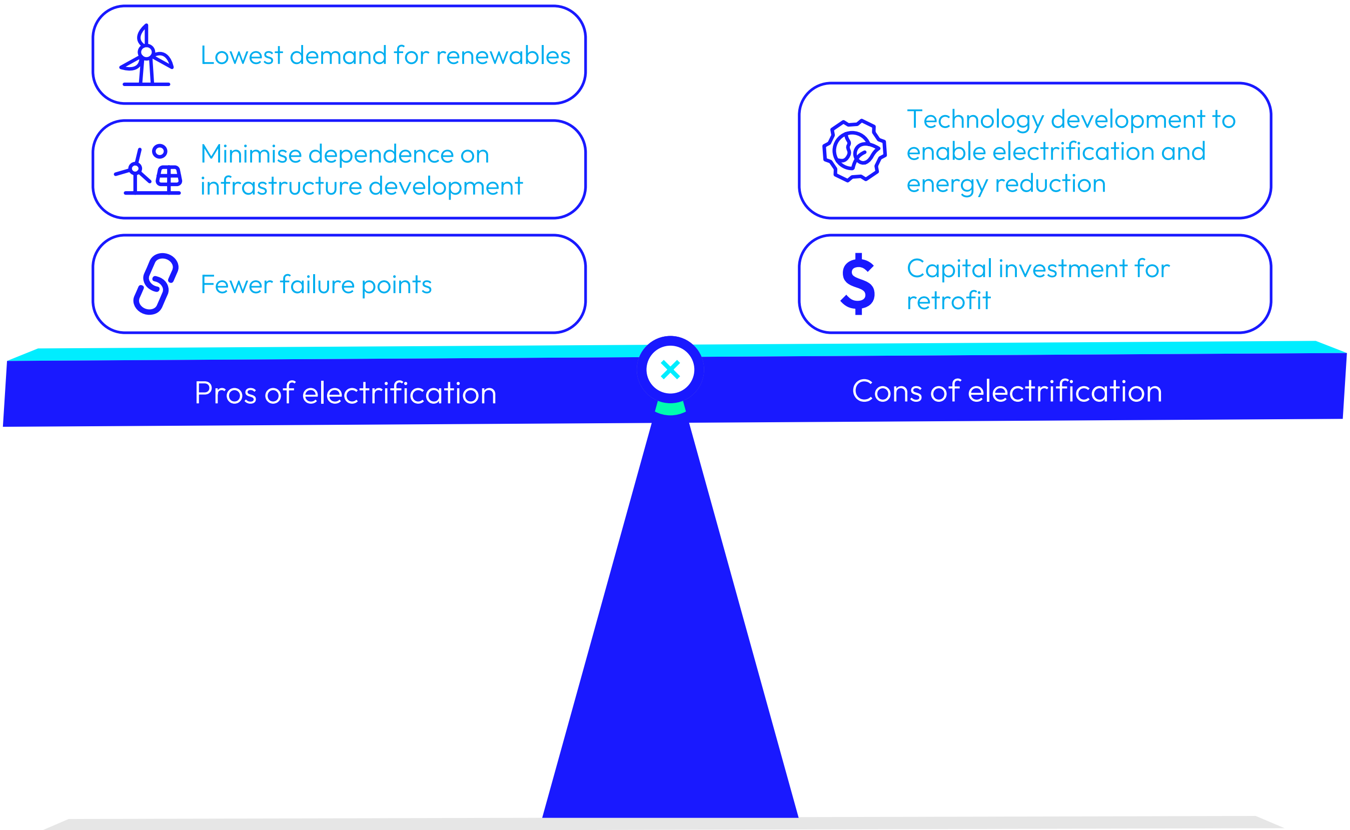


Figure 4 Illustration of pros and cons of electrification of CF production as a means of achieving net zero production

Figure 5 shows a representative energy consumption breakdown for PAN fibre and CF production, based on the use of electrified oxidation and carbonisation ovens in CF manufacturing. The percentages reflect the share of total energy demand per unit mass of CF produced, including both PAN fibre and CF production stages. Natural gas use in PAN fibre production—mainly for solvent recovery at temperatures below 200 °C—and for CF drying, can be readily electrified.

A key barrier to full electrification lies in the abatement systems used to treat emissions from the oxidation and carbonisation ovens. For example, hydrogen cyanide (HCN), a hazardous byproduct, requires treatment at temperatures up to 1000 °C to ensure complete combustion, leading to high natural gas consumption. This accounts for approximately 28% of the total energy demand across PAN and CF production, representing the critical "hard-to-decarbonise" energy source.

Energy efficiency gains in abatement systems could be achieved by reducing airflow and integrating regenerative thermal oxidizers (RTOs) for oxidation oven exhaust, which are effective for high-airflow, moderate-VOC streams and can recover up to 95% of heat. However, while these approaches lower natural gas use, they do not fully eliminate the resulting GHG emissions and must be combined with broader decarbonisation strategies. Potentially more challenging to decarbonise is the use of direct-fired thermal oxidizers (DFTOs) for low-flow, high-VOC exhaust streams, such as those from the carbonisation furnace. While DFTOs effectively treat tar-rich and HCN-laden emissions, they lack heat recovery and consume more fuel, contributing significantly to the remaining natural gas demand in CF production.

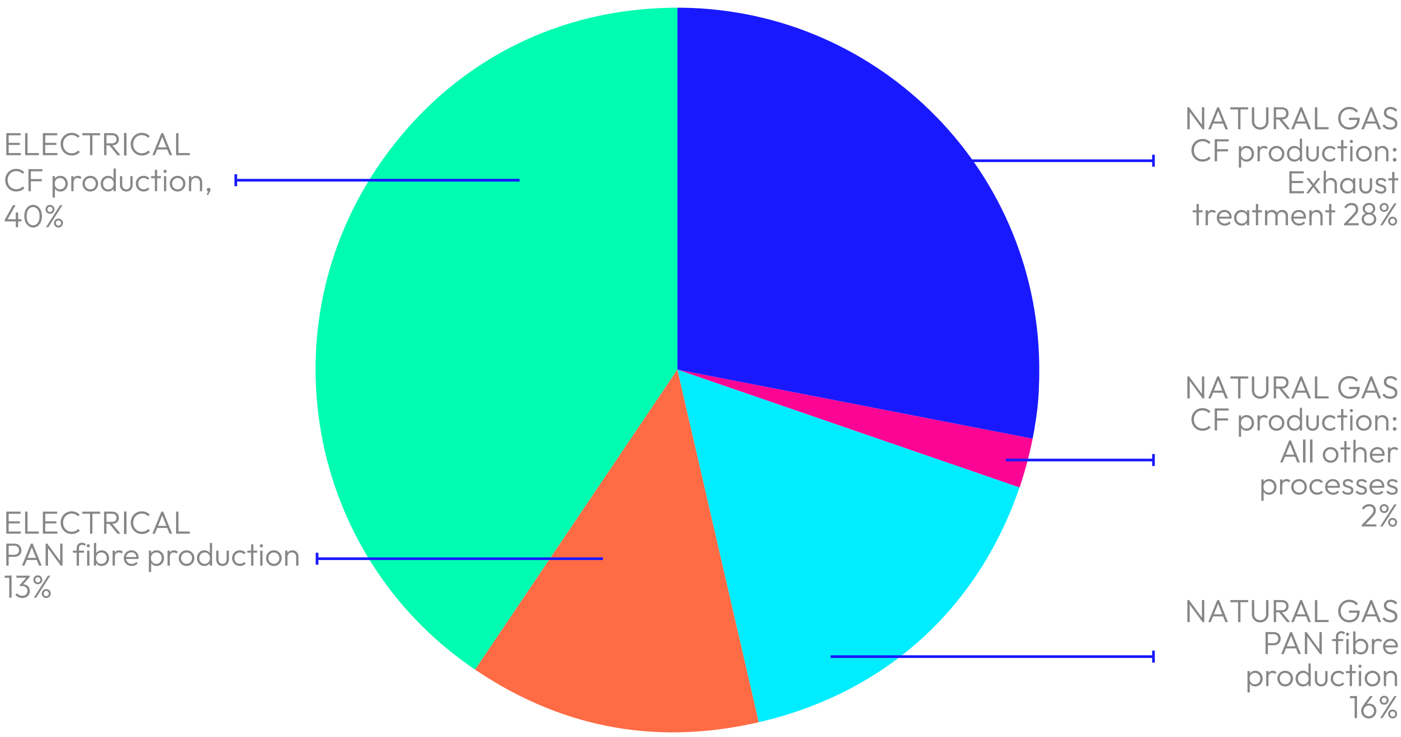


Figure 5 Representative energy consumption breakdown for CF production using electrified oxidation and carbonisation ovens

Electrified thermal oxidisers present a potential pathway to decarbonise high-temperature exhaust gas treatment in CF production by eliminating the need for natural gas or synthetic fuels in current abatement systems. When powered by low-carbon electricity, these systems could mitigate GHG emissions associated with thermal energy used for gas cleaning. Electrified RTOs (eRTO) are commercially available and may be suited for oxidation oven exhaust treatment. Electrically powered flameless thermal oxidisers (eTO) may also replace DFTOs currently used for high-temperature, high-VOC exhaust streams from carbonisation ovens. While promising, these technologies have not yet been deployed in CF production, and their ability to safely and reliably process hazardous emissions such as oxidisers and tar-laden streams remains unproven. Further research, pilot-scale trials, and performance validation of eRTO and eTOs under CF production conditions are required to determine their technical feasibility and facilitate industry uptake. Key barriers to implementation include likely higher upfront capital costs compared to conventional gas-fired systems, the potential need for complete system redesigns when retrofitting existing infrastructure, and grid constraints that may necessitate upgrades or energy storage solutions to manage peak electricity demand.

Accelerating emissions reduction through electrification

Figure 6 presents a comparison of various CF decarbonisation pathways, including electrification, BioMethane, and E-Methane strategies, building on previous studies[4]. The assessment assumes the UK National Grid ESO projection for decarbonising electricity to net zero by 2050. In each scenario, natural gas is replaced on an energy-equivalent basis by the respective alternative energy source. The use of Bio-Methane-based acrylonitrile is also assumed, as it (or other lower impact precursor alternatives) is essential for achieving fully net zero CF products.

Figure 6 shows that electrification offers the fastest route to net zero CF production and should be prioritised by manufacturers. While electrification may necessitate substantial modifications to existing equipment currently reliant on natural gas, these upgrades are within the control of CF producers and do not depend on the future scalability of emerging technologies, such as green hydrogen-based synthetic fuels. Although initial retrofit costs may be significant, electrification offers the potential for long-term cost savings through more efficient use of renewable electricity and can deliver considerable emissions reductions, positioning it as a viable and strategic decarbonisation pathway as technology and renewable energy infrastructure continue to advance.

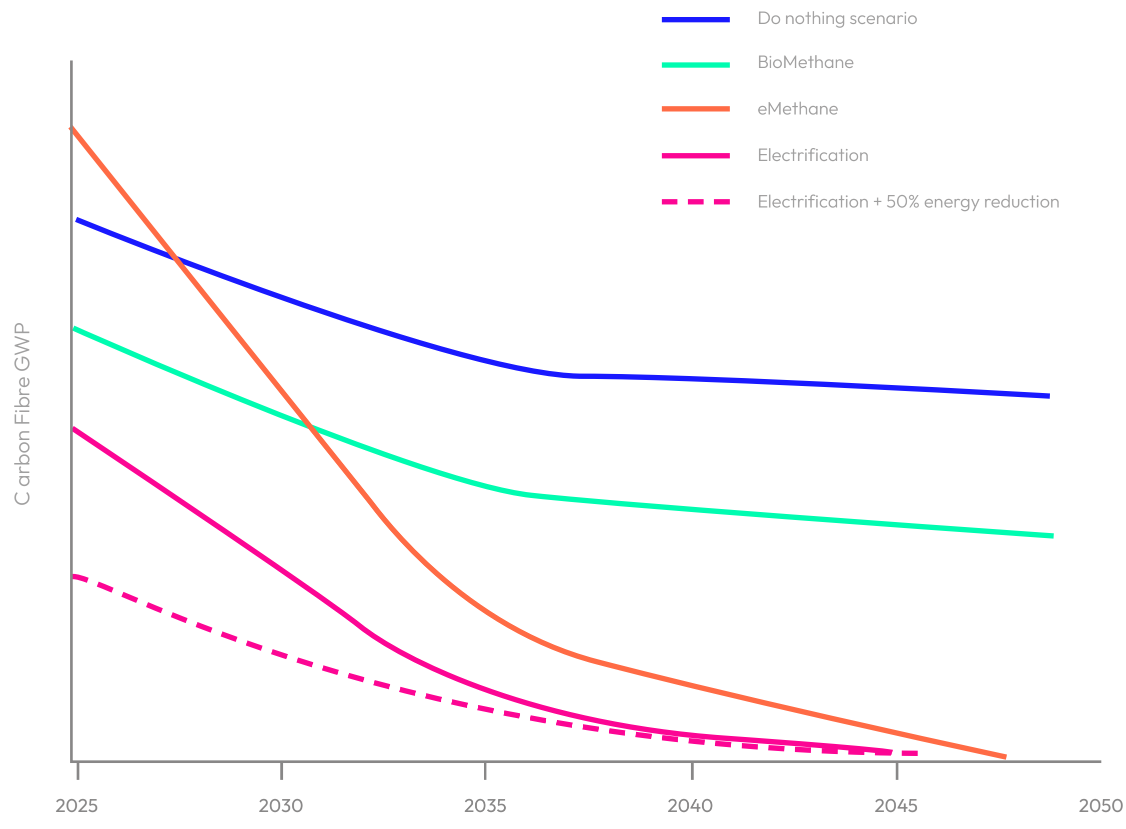


Figure 6 Comparison of electrification and green gas solutions on CF production decarbonisation (assumes electrification of heat from natural gas in PAN and CF production processes on an equal calorie basis)

[4] K. Pender, F. Romoli, and J. Fuller, "Future strategies for decarbonisation of carbon fibre products: A roadmap to Net Zero 2050," J. Clean. Prod., vol. 486, p. 144525, 2025, doi: 10.1016/j.jclepro.2024.144525.

[5] M. A. Stróżyk et al., "Decreasing the environmental impact of carbon fibre production via microwave carbonisation enabled by self - assembled nanostructured coatings," Adv. Compos. Hybrid Mater., vol. 7:39, 2024, doi: 10.1007/s42114-024-00853-2

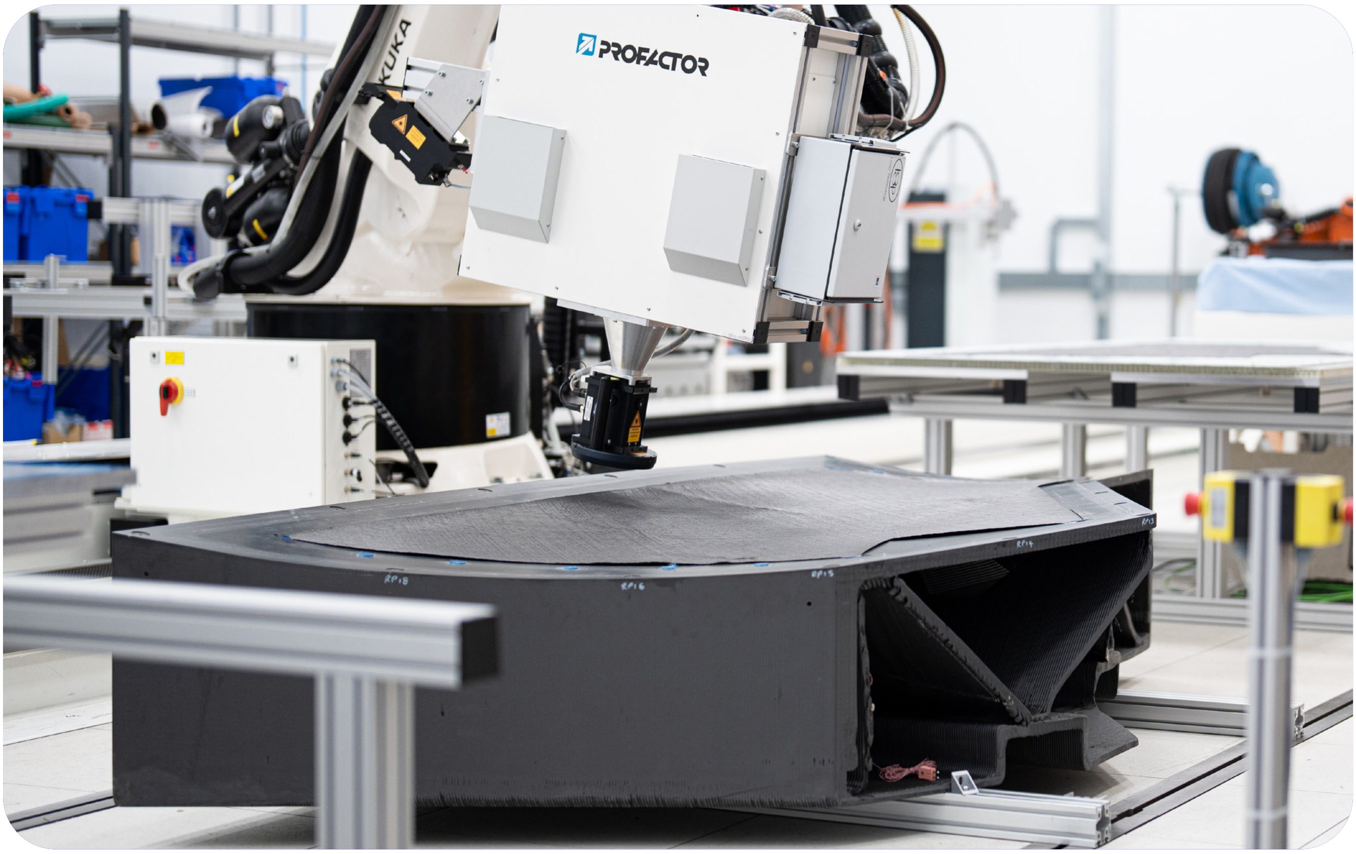
[6] J. Sloan, "LeMond Carbon audits rapid-oxidation carbon fiber technology," Composites World, 2019. https://www.compositesworld.com/news/lemond-carbon-audits-rapid-oxidation-carbon-fiber-technology- (

The roadmap also evaluates a 50% reduction in electricity demand, reflecting the potential of technologies such as microwave heating and rapid oxidation, which have demonstrated energy savings of up to 67%[5] and 70%[6], respectively. Early adoption of these energy efficiency measures is key, as they offer the most impact while the electricity grid is still carbon intensive. Beyond 2040, as the grid approaches net zero emissions, the primary motivation for further energy reductions will shift from carbon savings to economic benefits.

For processes where electrification faces technical challenges—such as exhaust gas treatment in abatement systems—green gas options may offer viable alternatives. In the near term (5–10 years), BioMethane is favoured over eMethane due to its independence from net zero electricity. However, in the long term, eMethane may offer greater emissions reductions as low-carbon electricity becomes more accessible. In the near term, particularly within the UK, CF producers can support decarbonisation by purchasing gas backed by Renewable Gas Guarantees of Origin (RGGOs), facilitating market-based allocation of BioMethane, which currently comprises a small share of the national gas supply.

It is important to note that the effectiveness of electrification in reducing CF GWP depends heavily on the regional energy mix. In the UK, where the electricity grid already contains a high share of renewables, electrification leads to lower GWP. In contrast, in regions with fossil fuel-dominant grids, direct natural gas use for heat may result in lower GWP than electricity-based alternatives. This highlights the need for region-specific assessments and decarbonisation roadmaps that reflect local energy infrastructure and grid composition.

Moreover, the future electricity grid compositions remain uncertain, and the projections in Figure 6 are based on average grid mix scenarios. Even when considering the UK as a sole case study, there are large uncertainties in the timeline for grid scale renewable deployment which poses challenges in precisely mapping out the decarbonisation trajectory for CF. Relying passively on network level transition leaves CF producers with little control over the timing of net zero energy generation, introducing uncertainty into decarbonisation roadmaps. To address this uncertainty and actively expedite the decarbonisation of their electricity consumption, CF producers could incorporate local or onsite renewable electricity generation technologies, such as solar or wind power, to displace some or all the grid electricity used. An example being SGL Carbon Fibers Ltd.'s Moses Lake site, which purchases renewable energy from local hydropower plants[7].



[7] SGL Carbon Fibers, "The climate-friendly carbon fiber from SGL Carbon - up to 50% less CO2 emissions, " 2024. https://www.sglcarbon.com/en/newsroom/news/press-report/the-climate-friendly-carbon-fiber-from-sgl-carbon-up-to-50-less-co2-emissions/

Multi-horizon CF decarbonisation strategy

Figure 7 presents a multi-horizon strategy for CF production decarbonisation, encompassing energy sourcing, technology development, and deployment timelines. This roadmap is designed to provide high-level guidance and actionable steps for CF producers aiming to transition towards net zero carbon fibre products. It integrates the carbon footprints of the various decarbonisation strategies assessed in this study alongside pragmatic considerations of the current and emerging technology landscape, market readiness, and infrastructure requirements. By aligning near-, mid-, and long-term actions with both impact potential and feasibility, the strategy supports informed decision-making and prioritisation of interventions that can accelerate progress toward net zero CF production.

Energy strategy

- Ahead of the UK grid reaching net zero emissions, CF producers should procure electricity backed by Renewable Energy Guarantees of Origin (REGOs) to both support the growth of renewable energy and achieve net zero electricity consumption through market-based allocation. Additionally, producers should explore opportunities for on-site renewable energy generation at existing facilities or consider siting new developments in regions with access to local renewable resources to further accelerate decarbonisation.

- While electrified solutions for hard-to-decarbonise processes—such as exhaust gas treatment—are under development, CF producers should purchase gas backed by Renewable Gas Guarantees of Origin (RGGOs) to support the expansion of green gas production and achieve net zero gas consumption through market-based mechanisms.

Technology deployment

- CF producers should transition to PAN fibre suppliers utilising bio-based acrylonitrile (or other low impact alternative) feedstocks. This advanced technology is anticipated to reach commercial availability by the end of the decade and should be implemented independently of other process modifications, allowing for adoption as soon as market access becomes feasible.

- Electrification of currently viable technologies—particularly oxidation and carbonisation ovens—should be prioritised. This includes retrofitting existing infrastructure where feasible and ensuring that all electrifiable processes are implemented in new CF production facilities.

- Established energy recovery technologies should be implemented to improve the energy efficiency of CF production and reduce overall energy consumption. This could include deploying high-efficiency RTOs for oxidation ovens and incorporating heat recovery systems for high-temperature DFTOs. Prioritising these measures is critical, as energy-saving strategies offer the greatest benefits in the near term while energy-related impacts remain significant.

Technology development*

- Lower-power electric heating technologies should be developed to further enhance the benefits of electrifying oxidation and carbonisation ovens. While their near-term emissions reduction potential is high, commercial readiness may limit their contribution to decarbonisation. Nonetheless, development should continue given their potential for long-term cost savings and efficiency gains in future CF infrastructure.

- Electrifying exhaust gas cleaning systems is anticipated to be the most technically challenging aspect of CF production decarbonisation. These systems currently account for approximately 25–30% of the total energy demand across PAN fibre and CF manufacturing. Therefore, their electrification is essential. To achieve this, CF producers must actively support the development and integration of electric gas cleaning technologies, which would enable the sector to reduce emissions without depending on the uncertain future availability of green gases (such as BioMethane and synthetic fuels).

** Note that there are many other proposed technology developments for CF production that could support decarbonisation; their exclusion from this proposed strategy is not indicative of a lack of potential but rather reflects current limitations in data availability, technology readiness, or alignment with the near- and mid-term priorities outlined in this roadmap.*

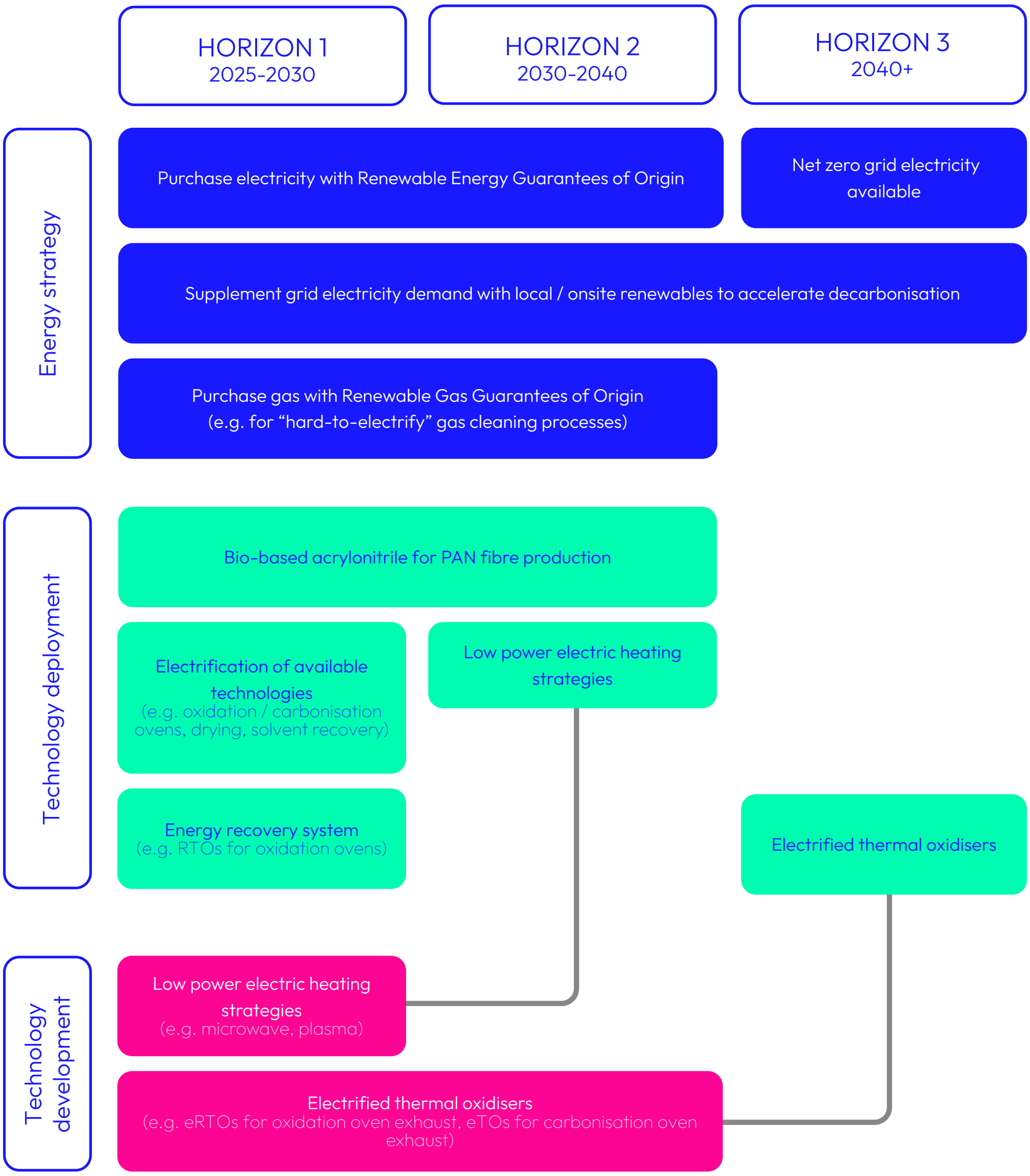


Figure 7 Multi-horizon strategy for CF production decarbonisation

Terms

Bio-ACN
Bio-based Acrylonitrile

CF
Carbon Fibre

eRTO
Electrified Regenerative Thermal Oxidiser

eTO
Electrically powered flameless thermal oxidisers

DFTOs
Direct-fired Thermal Oxidisers

GWP
Global Warming Potential

HCN
Hydrogen Cyanide

PAN
Polyacrylonitrile

REGO
Renewable Energy Guarantees of Origin

RGGO
Renewable Gas Guarantees of Origin

VOC
Volatile Organic Compounds

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