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CATAPULT Offshore Renewable Energy

Net zero carbon fibre:

Drop-in decarbonisation solutions

Key findings

Prioritising the development and adoption of lower impact carbon fibres (CF) should be a central decarbonisation strategy for the wind industry and has the potential to reduce the global warming potential (GWP) of wind blades by up to 50%. To meet this ambitious target, the following interventions by CF producers are required to accelerate decarbonisation of the industry:

- **Bio-based feedstocks:** In the short-term, CF producers must prioritise switching to precursors produced via bio-based acrylonitrile feedstock, which would reduce CF GWP by 5 – 9 kg CO2e. per kg of CF.
- **Renewables electricity transition:** For CF producers already using electrified ovens, net zero electricity can cut GWP by nearly 50%, underscoring the importance of decarbonising power across the production chain.
- **Green fuels:** It is essential to implement lower-carbon solutions for the thermal energy used throughout the CF production value chain. CF producers should consider BioMethane as a temporary solution for the next decade (2025 – 2040), followed by the pursuit of eMethane as the long-term thermal energy source once electricity impact is sufficiently low (2035 – 2040 onwards).

This report summarises key findings from the wider SusWIND LCA study, available as an open-access resource. It also serves as a companion to lifecycle assessment, which explores the limitations of upstream supply-side interventions, the challenges of green hydrogen-based synthetic fuels, and highlights the vital role of production-side strategies—such as process electrification—in accelerating and de-risking carbon fibre decarbonisation.

Background

The demand for carbon fibre reinforced polymer composites (CFRP) is expected to surpass 180 kt per year by 2030[2]. While lightweighting using CFRP has played a critical role in reducing emissions from transportation, CFRP is now required for decarbonised energy generation and storage solutions. Many nations are reliant on rapid scale-up of wind energy generation to achieve net zero targets. Total electricity generated by wind increased by 273 TWh in 2021; the largest growth of all power generation technologies[3]. CFRP is unique in providing the stiffness needed to produce multi-megawatt wind turbine blades. As a result, the wind energy sector has surpassed aerospace as the largest consumer of CFRP[1].

CFs have high embodied energy due to the high temperatures required during carbonisation and graphitisation[4] 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. 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 study uses lifecycle assessment (LCA) to assess the impact of future material and energy scenarios on CF production. Multivariate analysis was used to rank solutions for CF decarbonisation up to the year 2050 and identify optimal timescales for their deployment. The impact of these strategies on reducing the carbon footprint of future wind blades was also assessed to generate data critical for informing long term decarbonisation for wind energy generation.

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[1] 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.

[2] J. Zhang, V. S. Chevali, H. Wang, and C. H. Wang, "Current status of carbon fibre and carbon fibre composites recycling," *Compos. Part B Eng.*, vol. 193, no. April, p. 108053, 2020, doi: 10.1016/j.compositesb.2020.108053.

[3] IEA, "Wind Electricity," 2022. [Online]. Available: https://www.iea.org/reports/wind-electricity.

[4] 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.

[5] 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.

Approach

SusWIND has created process models that generate lifecycle inventory data for each phase of CF production. This facilitates the assessment of the impact of the decarbonisation strategies. The GWP of CF products across different scenarios was incorporated into SusWIND's wind blade LCA tool[4] to further analyse the effects of low carbon CFs on the lifetime GWP of wind blades. The primary aim of the work was to evaluate the cradle-to-gate GWP of polyacrylonitrile (PAN) based carbon CF production, and to assess the potential of green energy solutions and alternative precursor materials to reduce the GWP of CF production. An initial screening identified numerous potential decarbonisation strategies for CF production, which are summarised in Figure 1. Given the wide range of proposed interventions, this study first focused on strategies that require minimal or no changes to existing CF production processes, ensuring the least disruption to manufacturers.

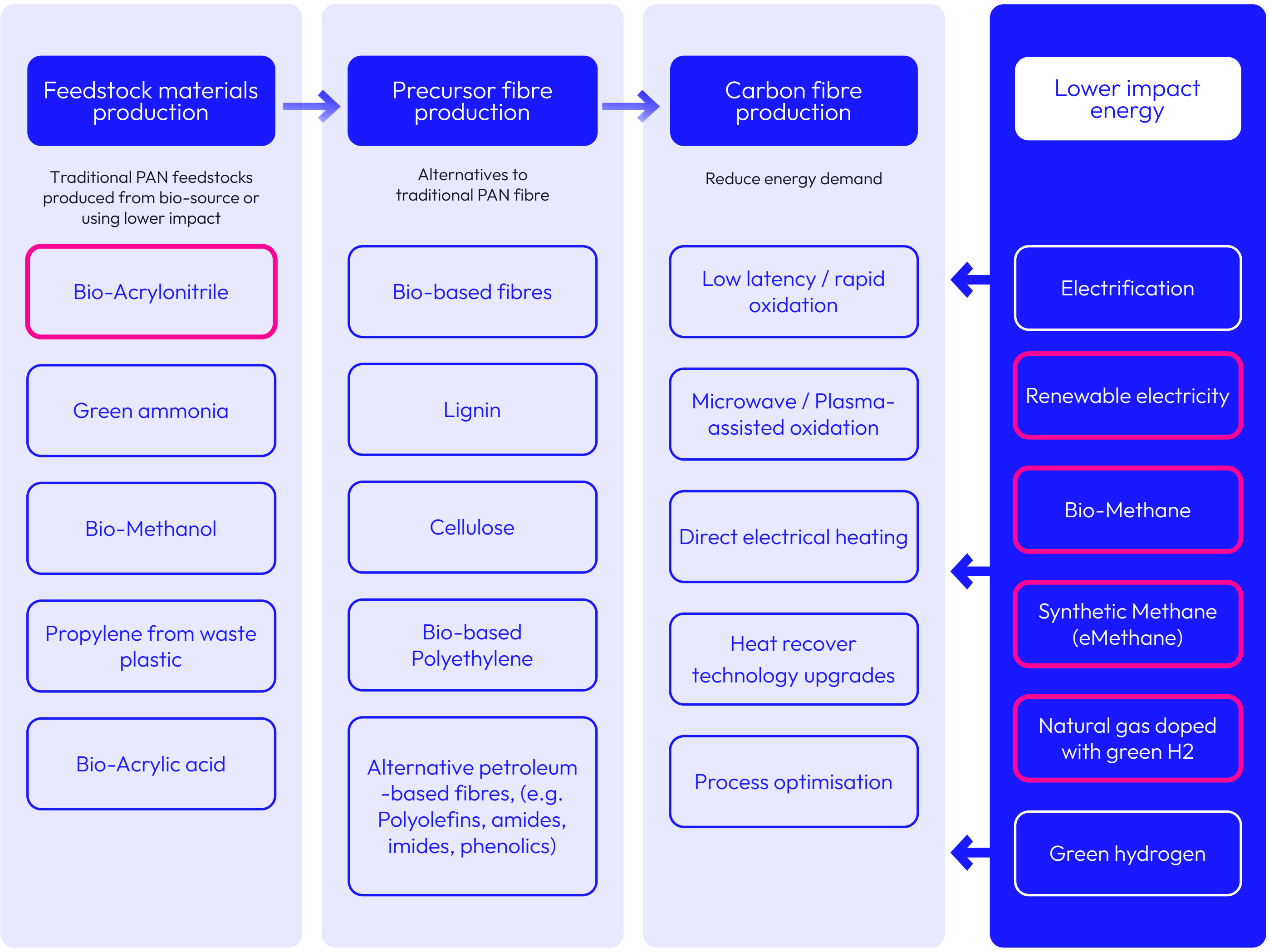

Figure 1 Summary of potential CF decarbonisation strategies, pink highlights the strategies assessed in the

The following areas were identified as priorities for assessment:

- **Bio-based feedstocks:** Using bio derived acrylonitrile (Bio-ACN) in place of standard petroleum-based acrylonitrile (ACN) feedstock during PAN fibre production[6,7].

- **Renewables electricity transition:** Future electricity grid mix used in the production of CF and raw materials ACN and PAN fibre according to projections made by UK National Grid ESO[8].

- **Green fuels:** Replacing thermal energy from natural gas with:

  1. Natural gas blended with 20 vol% green hydrogen gas with potential to reduce direct emissions by replacing combustion of fossil carbon with cleaner burning hydrogen gas.

  2. BioMethane made by upgrading biogas (renewable fuel produced from organic materials) to remove CO_2 and yield a calorific value on par with natural gas.

  3. eMethane produced through the electrochemical conversion of CO_2 and hydrogen, offering a sustainable energy carrier with potential applications in sectors such as transportation and industry.

It's important to note that the LCA was based on a representative CF production line already using electrically heated oxidation and carbonisation ovens. Consequently, natural gas use is largely limited to the exhaust gas cleaning system, making it the primary target for green fuel deployment in the assessed scenarios.

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[6] M. O. Guerrero-Pérez and M. A. Bañares, "Metrics of acrylonitrile: From biomass vs. petrochemical route," *Catal. Today*, vol. 239, pp. 25–30, 2015, doi: 10.1016/j.cattod.2013.12.046.

[7] E. M. Karp *et al.*, "Renewable acrylonitrile production," *Science*, vol. 358, pp. 1307–1310, 2017, doi: 10.1126/science.aan1059.

[8] "Future Energy Scenarios 2023." National Grid ESO, 2023, [Online]. Available: https://www.nationalgrideso.com/document/283101/download.

Carbon fibre decarbonisation strategies

Renewable energy solutions for carbon fibre decarbonisation.

Impact of renewables on carbon fibre GWP

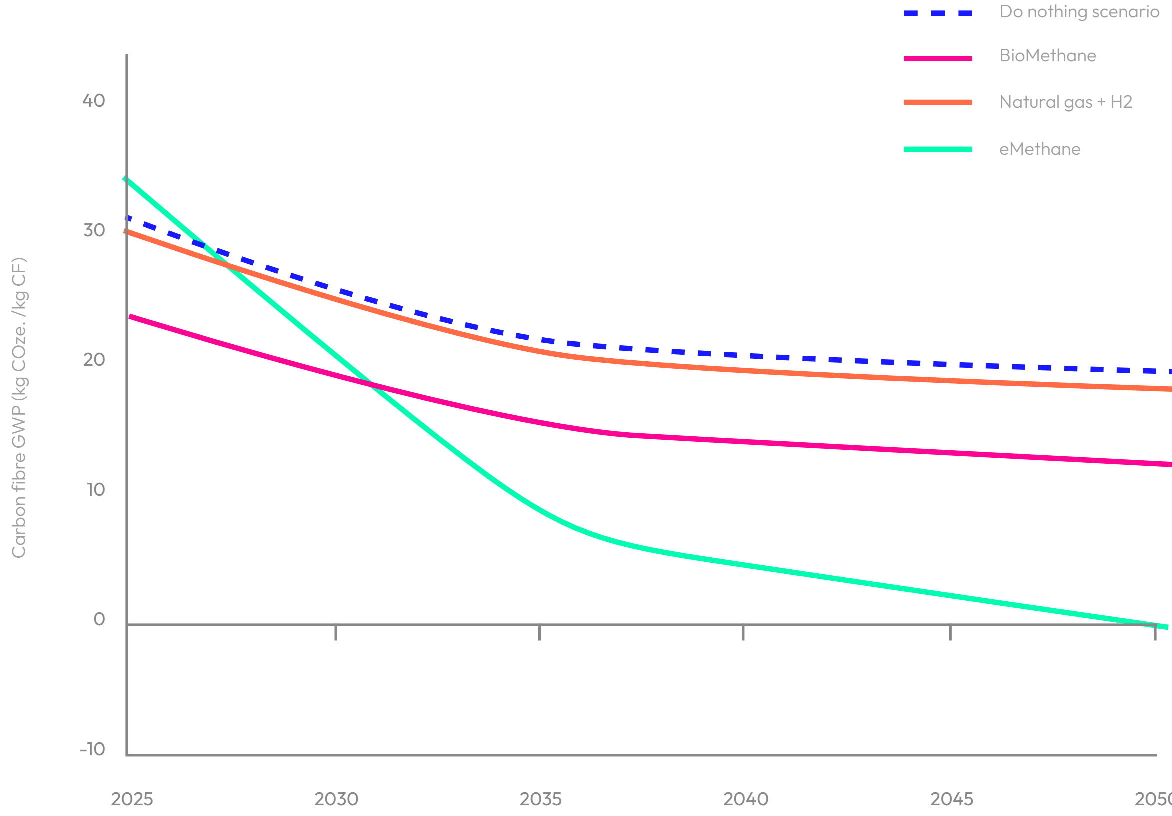


Figure 2 Projected GWP of carbon fibre production up to 2050 for each energy scenario

Figure 2 presents the projected GWP of CF production up to 2050 for each energy scenario. The “Do nothing scenario” (dashed line) represents the case where CF producers continue to use natural gas, with reductions in GWP only coming passively from the adoption of renewables in the electricity grid mix. Figure 2 shows that achieving net zero electricity generation by 2050 alone can result in an almost 50% reduction in the GWP of CF. This underscores the critical importance of decarbonising electricity throughout the entire CF production value chain, a passive development expected to occur irrespective of additional sustainable initiatives by CF producers. The rate of grid electricity decarbonisation is highly dependent on the geographic location of CF production and upstream processes for raw material production. While the transition to green electricity will be critical to CF decarbonisation, Figure 2 underscores the imperative for lower-carbon solutions in the thermal energy used across the CF production value chain.

Figure 2 shows that blending green hydrogen gas with natural gas does not substantially reduce CF GWP, even though hydrogen gas combustion generates no direct GHG emissions. Pure hydrogen for heating should not be dismissed as a potential avenue for CF decarbonisation. However, the extent of modifications needed to integrate hydrogen thermal energy into current CF production processes remains uncertain, while the feasibility of using pure hydrogen gas in existing gas pipelines remains questionable.

Using BioMethane for thermal energy can reduce the current GWP of CF products by around 20%. Therefore, as a short-term mitigation strategy, CF producers should consider purchasing Renewable Gas Guarantees of Origin (RGGOs) to support the green gas market and achieve net zero gas consumption through market-based mechanisms.

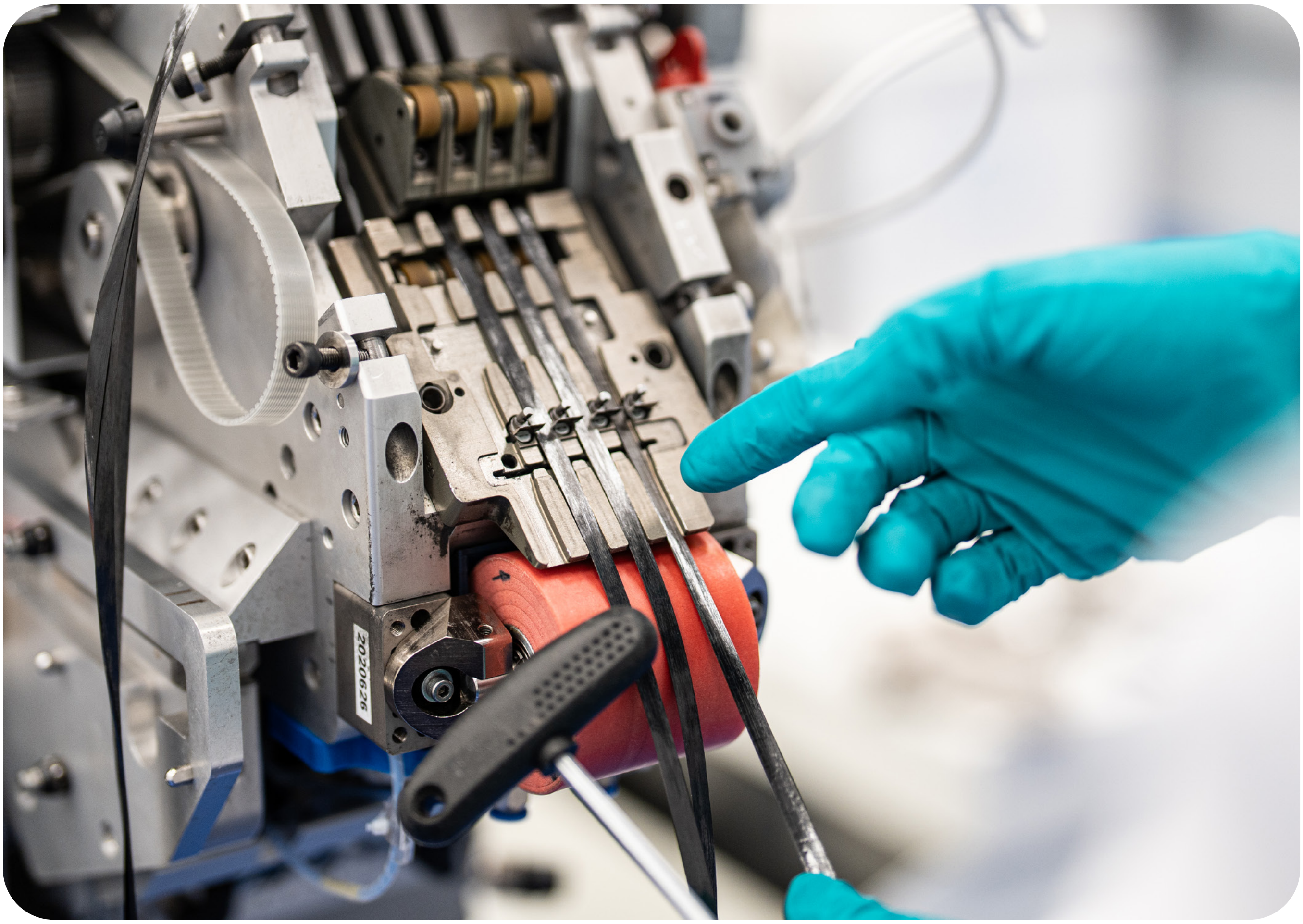
Among the thermal energy solutions examined, Figure 2 shows that eMethane exhibits the greatest long-term potential for decarbonising CF products when used in conjunction with net zero electricity. By 2050, the projected GWP of CF produced using eMethane is approximately 0 kg CO2e. / kg CF, reflecting a 100% reduction in GWP compared to current estimates utilising natural gas.

Net zero GWP in CF production could be achieved through future grid scenarios that include bioenergy with carbon capture and storage (BECCS), potentially resulting in negative GWP electricity[7]. However, since BECCS has yet to be deployed at scale, it remains a significant uncertainty in reaching below-net-zero electricity. Depending on how the future grid mix evolves over time, CF producers should consider BioMethane as a temporary solution (2025 – 2040). Once electricity-related emissions are sufficiently reduced (post-2035), eMethane should be adopted as the long-term thermal energy solution in applications where direct natural gas replacement is necessary.

Roadmap to net zero carbon fibres

Figure 3 Projected carbon fibre decarbonisation roadmap up to 2050

Figure 3 presents an optimised CF decarbonisation roadmap based on findings from the energy scenarios analysed (discussed above) and the Bio-ACN production analysis. The analysis found that switching to precursors produced via Bio-ACN feedstock could immediately reduce CF GWP by 5 – 9 kg CO2e. per kg of CF. For the UK case study, this road map therefore prioritises a switch to Bio-ACN precursor in 2025, followed by successive transitions to BioMethane and eMethane in 2030 and 2040 respectively.



Accelerating CF production decarbonisation—particularly in regions with fossil-heavy electricity grids—will require strategies to reduce energy consumption within production processes. This will likely necessitate the replacement or modification of existing infrastructure, a consideration beyond the scope of this study. It is crucial to acknowledge, however, that global CF production capacity is projected to increase to meet rising demand for CF products. Consequently, the industry should prioritise improving the energy efficiency of new production facilities, as reducing energy consumption holds greater short-term potential for mitigating CF GWP, given the high impact currently associated with energy consumption. In the long term, as decarbonised energy is realised, efficiency improvement may no longer be a primary driver for CF decarbonisation but will likely still be pursued for economic reasons regardless. Siting new CF plants in regions with ongoing or assured grid decarbonisation is key. However, as illustrated in Figure 3, uncertainties in large-scale grid decarbonisation complicate long-term planning. To reduce reliance on grid electricity, CF producers could accelerate decarbonisation by investing in local or onsite renewable energy generation.

Green gas solutions, if scaled, may gradually replace natural gas. Still, without clear roadmaps, reliance on BioMethane or eMethane introduces uncertainty, as producers have limited control over deployment timelines. Onsite eMethane production offers greater certainty and stronger decarbonisation potential, though its feasibility depends on advancements in carbon capture, electrolysis, and methanation, as well as improved efficiency and supportive regulation. Due to the uncertainty around green fuel availability, CF producers should pursue strategies such as improving process efficiency, utilising lower power heating solutions (such as microwave or plasma heating), enhancing heat recovery, and electrifying readily electrifiable systems like oxidation and carbonisation ovens. At the same time, they should support the development of "hard-to-electrify" systems, such as exhaust gas cleaning, to enable future natural gas replacement and reduce reliance on green gases. This is explored in more detail in the companion report Net Zero Carbon Fibres: Practical pathways to net zero[9].

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[9] K. Penderand J. Fuller, Net Zero Carbon Fibres: The Big Picture & Practical Solutions, 2025

The role in wind blade decarbonisation

Wind blade GWP with decarbonised carbon fibre

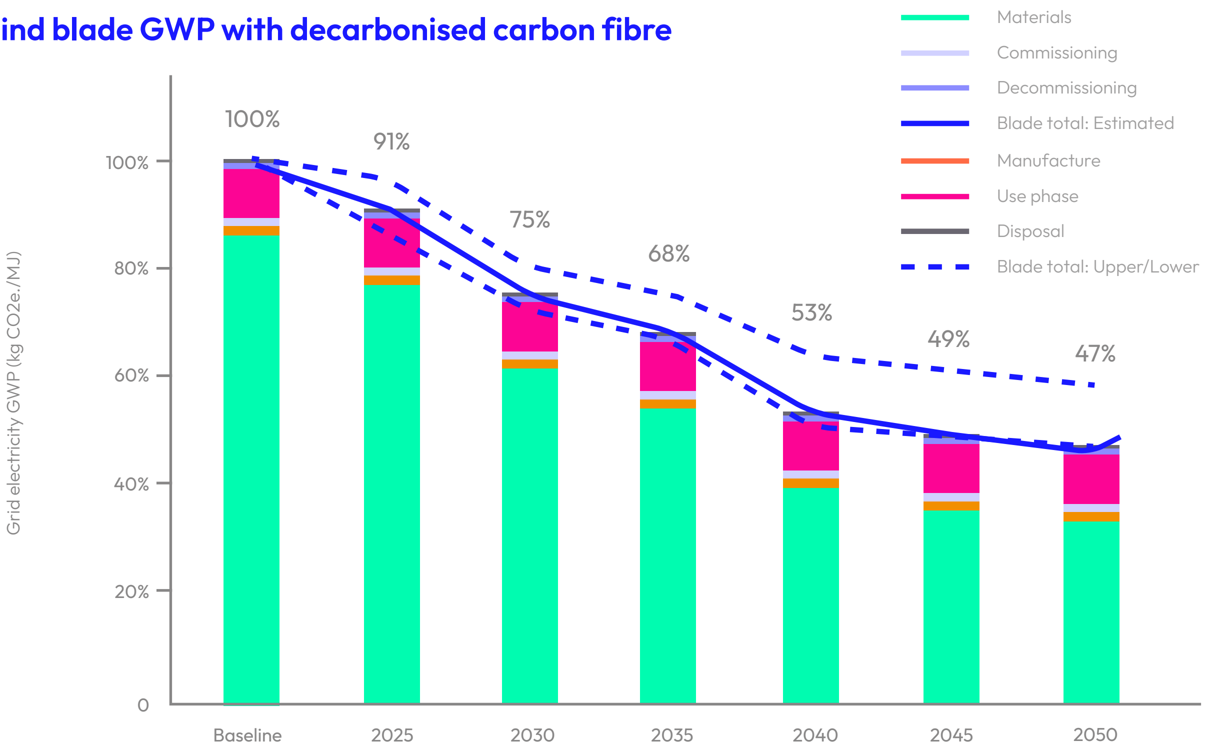

Figure 4 Projected lifetime GWP of representative wind turbine blade using decarbonised CF according to the roadmap in Figure 3

Figure 4 illustrates the projected lifetime GWP of a representative offshore wind turbine blade manufactured using decarbonised CF, as outlined in the roadmap shown in Figure 3. Figure 4 underscores the substantial potential of CF decarbonisation to reduce the GWP of wind blades. The use of CFs produced from 2040 onwards have the potential to reduce the GWP of wind blades by more than 50%, therefore, prioritising the development and adoption of lower impact CFs should be a central decarbonisation strategy for the wind industry. While the impacts of decarbonising transport, use phase, and disposal are comparatively limited, these strategies still contribute to reducing wind blade GWP[10], and advancements in these areas can be applied to existing infrastructure. Conversely, the impacts related to materials and manufacturing are fixed once the blades are manufactured. This underscores the importance of prioritising the use of lower impact materials in wind blade production, with CF presenting the most significant opportunity for reduction. Therefore, the wind industry should actively promote initiatives to develop bio-based feedstocks, ensure net-zero electricity generation, and, in parallel, accelerate electrification, along with scaling up green fuels to de-risk “hard-to-decarbonise” processes.

To support these 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.

Terms

Term	Definition
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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[10] K. Pender, F. Romoli, and J. Fuller, “Evaluating priority strategies for decarbonising offshore wind turbine blades through lifecycle assessment [Under review],” 2024.

Find out more: nccuk.com/suswind