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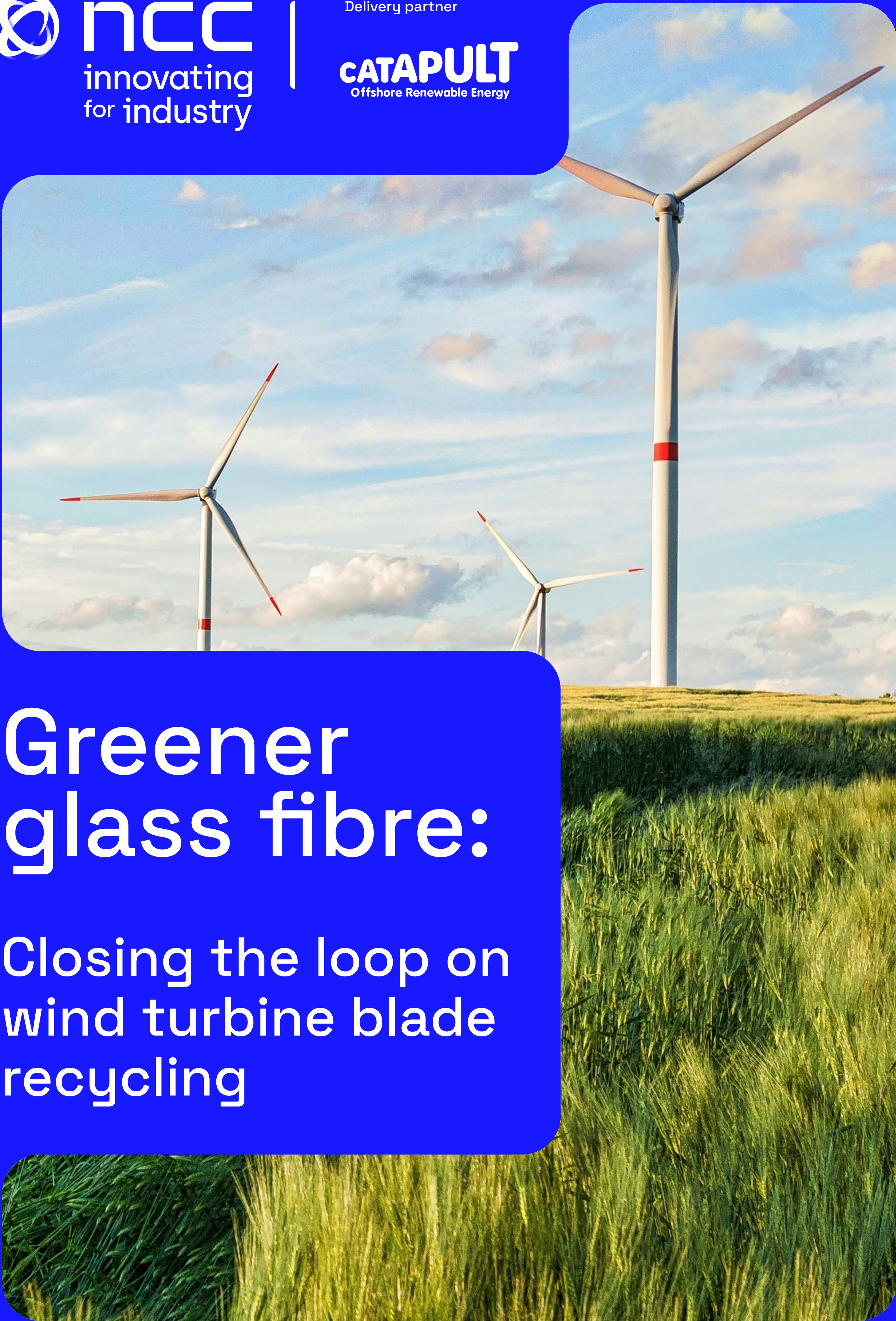

Greener glass fibre:

Closing the loop on wind turbine blade recycling

Key findings

Using lifecycle assessment, SusWIND has shown that, if certain conditions are met, making glass fibres with recycled content from wind turbine blades can have a carbon footprint similar to new glass fibres.
These conditions are:

- To make glass fibre with recycled content a viable closed-loop solution with a carbon footprint comparable to virgin glass fibre, commercial recyclers must reduce the greenhouse gas (GHG) emissions from wind blade recycling.
- The carbon footprint of glass fibre products containing recycled content could match that of virgin glass fibre if the processes used to produce clean glass fibre feedstock for melting achieve a total footprint of no more than 0.69 CO_2e / kg recovered glass fibre.
- For pyrolysis recycling of wind blades this is expected to be achieved through:

  1. Achieving energy self-sufficiency in the pyrolysis process when supply of fully renewable energy is not available.
  2. Recovering 75-80 wt% of the pyrolysis organics as secondary products.

Without primary data from pyrolysis recyclers, the above requirements provide a means to assess the feasibility of pyrolysis technology in producing recovered glass fibre with sufficiently low carbon footprint. SusWIND will use this approach to evaluate the viability of glass fibre products with recycled content while minimising reliance on sensitive operational data from recyclers.

Background

One of the primary challenges facing the composites industry today is the environmentally responsible management of composite products at the end of their lifecycle. The disposal of end-of-life (EoL) wind turbine blades (WTB), which are predominantly made from glass fibre reinforced polymer (GFRP), is expected to markedly increase the volume of global GFRP waste over the next few decades. Estimates suggest that by 2030, this waste could reach 0.5 million tons per year, growing to 1 million tons per year by 2040[1]. The market demand for recycled glass fibres (GF) from current recycling approaches is limited due to their discontinuous nature, significantly reduced strength compared to virgin GF, and challenges in handling and integration into established production lines.

An innovative approach has been explored; utilising GF recovered from composite WTB waste to displace raw materials in new GF production. This method blends waste GF in melt formulations to replicate the qualities of virgin GF, aiming to overcome existing performance and handling challenges, and facilitate integration into conventional manufacturing processes.

Approach

A lifecycle assessment was conducted to analyse the carbon footprint of producing GF with recycled content using waste WTB feedstocks. The proposed strategy involves two phases: 1) reclaiming GF from WTB waste and preparing them for melting, and 2) producing GF with 50 wt% recycled content by melting the recovered GF together with other raw materials in a melt furnace. This is illustrated in Figure 1. To align with both net zero and circular economy transition strategies and for this approach to be considered a preferable solution to produce new GF products, the carbon footprint of these two phases combined should be lower than that of virgin GF production.

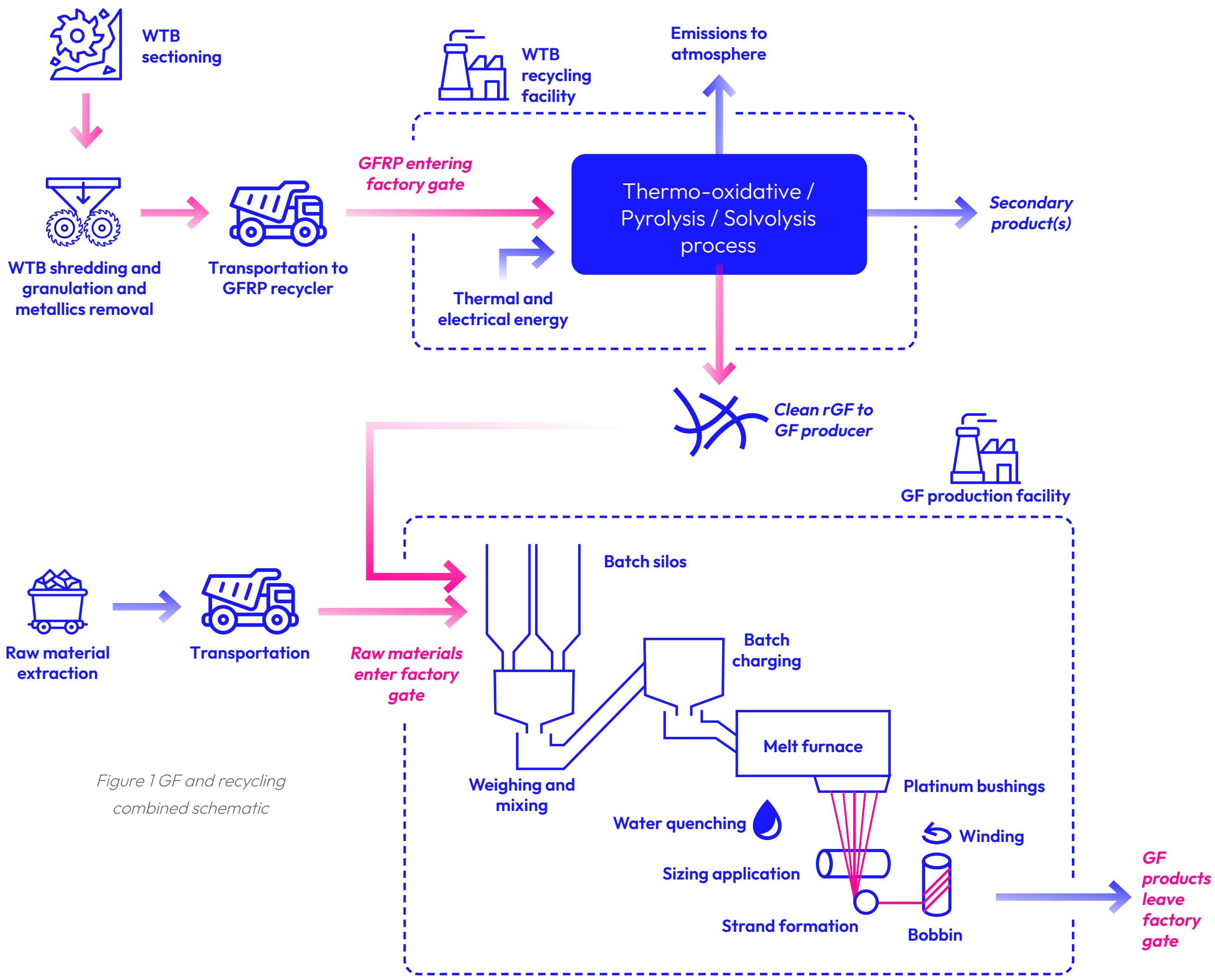

Figure 1 GF and recycling combined schematic

Three WTB recycling technologies for recovering GF were considered based on their capability to recover clean GFs from legacy WTBs: thermo-oxidative, pyrolysis, and solvolysis recycling*. Descriptions of these recycling technologies and the assumptions used in calculating lifecycle inventory data are reported in [2]. Various pyrolysis recycling iterations were also assessed to establish requirements for producing GF with recycled content with carbon footprint comparable to virgin GF (reported in detail in [3]). Pyrolysis in particular was selected for further analysis because of the greater adoption of this technology by commercial recyclers and previous work by SusWIND showing the potential for pyrolysis decarbonisation[4]. Lifecycle inventory (LCI) data for the GF melting phase were provided by Owens Corning which is described in [5]. For results across different impact categories, recycled content, and melt energy scenarios see [3], [3], and [5] respectively.

* SusWIND has also investigated GF products with recycled content from WTB produced using recyclable resin systems and recycled using other chemical and thermal based recycling technologies which are reported in [5] and [6].

Results and recommendations

Impact of GF with recycled content using reported recycling technologies

Figure 2 gives the total carbon footprint, expressed as global warming potential (GWP) to produce GF with recycled content across the three WTB recycling scenarios using publicly available LCI data. The sources of GWP have been grouped across:

- **WTB preprocessing:** Waste WTB shredding and transport to recycler.
- **GF recovery:** WTB recycling to extract clean GFs for melting.
- **Raw material and melting:** The production of supplementary raw materials and processes involved in production of GF with recycled content using GFs recovered from WTB waste.

The GWP to produce the GFs with recycled content are compared to virgin GF counterpart (cyan column in Figure 2). Figure 2 shows that, using publicly available data on the WTB recycling technologies assessed, GFs with recycled content consistently have a GWP greater than virgin GF counterparts. Critically however, the GWP of the melting phase to produce GF products with recycled content remains lower than the GWP of virgin GF products, due to 1) the partial mitigation of raw material inputs and 2) less energy intensive operating conditions during the melt phase.

The results depicted in Figure 2 therefore indicate that for GFs with recycled content to be a viable closed-loop solution with a GWP comparable to that of virgin GF, commercial recyclers must reduce the GHG emissions associated with the WTB recycling itself ("GF recovery" phase in Figure 2). This reduction is necessary when compared to the existing publicly available data on lower Technology Readiness Level (TRL), smaller scale, or under-optimised recycling technologies in Figure 2. The technology developments required for pyrolysis recycling to facilitate the production of GF with recycled content with GWP on par with virgin GF are evaluated below.

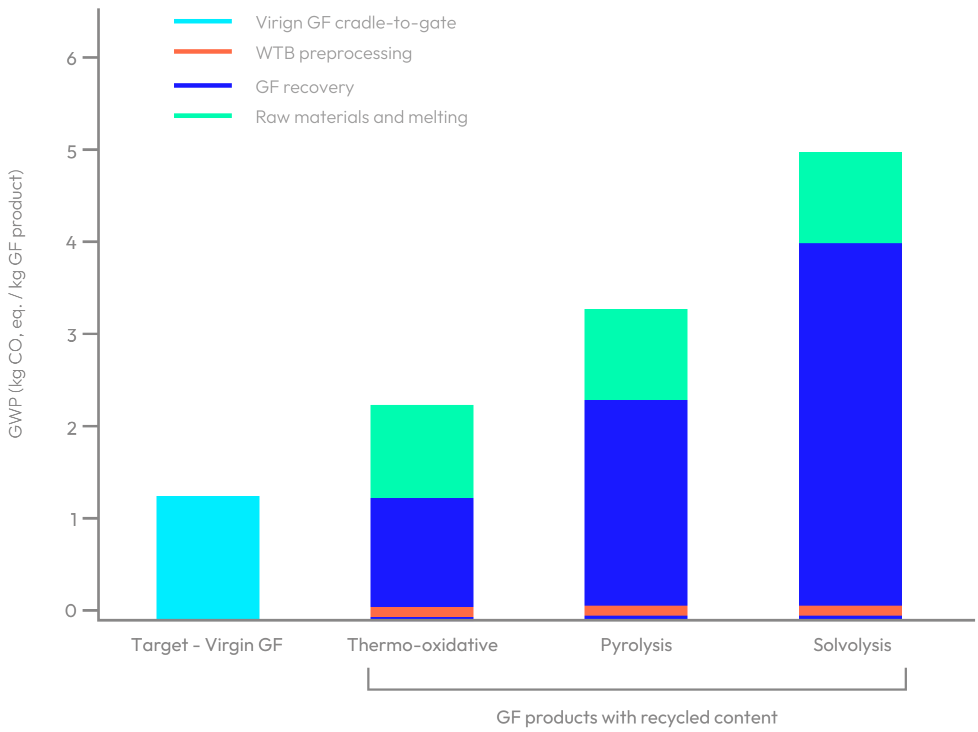

Figure 2 GWP of GF with recycled content across several WTB recycling using publicly available data

Decarbonisation of GF with recycled content

Pyrolysis recycling faces challenges due to high energy requirements and direct GHG emissions from the incineration of polymer by-products. Advancements in pyrolysis technology could enable 1) self-sustaining processing by recirculating and combusting pyrolysis gases to power the system, and 2) condensing, collecting, and reprocessing pyrolysis oils to produce chemical industry feedstocks. These solutions have the potential to reduce energy consumption and direct emissions while redistributing some of the environmental burden to secondary petrochemical products. Three stages of pyrolysis technology development were assessed to evaluate their impact on producing GF with recycled content. The pyrolysis recycling scenarios were based on progressive technology developments established in [4]:

- **Current data:** Pyrolysis energy consumption based on current publicly available data.
- **Energy efficient:** Pyrolysis is thermally self-sustaining, and no additional energy is added to the system.
- **Polymer recycling:** A majority of the polymer in WTB waste is recycled during pyrolysis.

Figure 3 shows that increasing energy efficiency and recovering and utilising polymer products are strategies that can significantly reduce the GWP of WTB recycling using pyrolysis technology. When both strategies are applied, the GWP of GF products with recycled content are on par with virgin GF counterparts. As an approximate target for technology developers, for GF products with recycled content to remain a lower GWP solution compared to virgin GF, the processes required to produce clean GF feedstock for melting must have a total GWP of no more than 0.69 CO2 eq. / kg recovered GF (this is dependent on energy source used during melting which is explored further in [3]). For pyrolysis recycling this is expected to be achieved through:

1. Enabling self-sustained energy operation, in the absence of full renewable supply (e.g. not requiring additional heat energy input from electricity or natural gas produced outside of the process).
2. Recovering 75-80 wt% of the pyrolysis organics that must be recovered as secondary products (e.g. 20-25 wt% of the organic fraction in the WTB waste should be combusted within the pyrolysis system boundary).

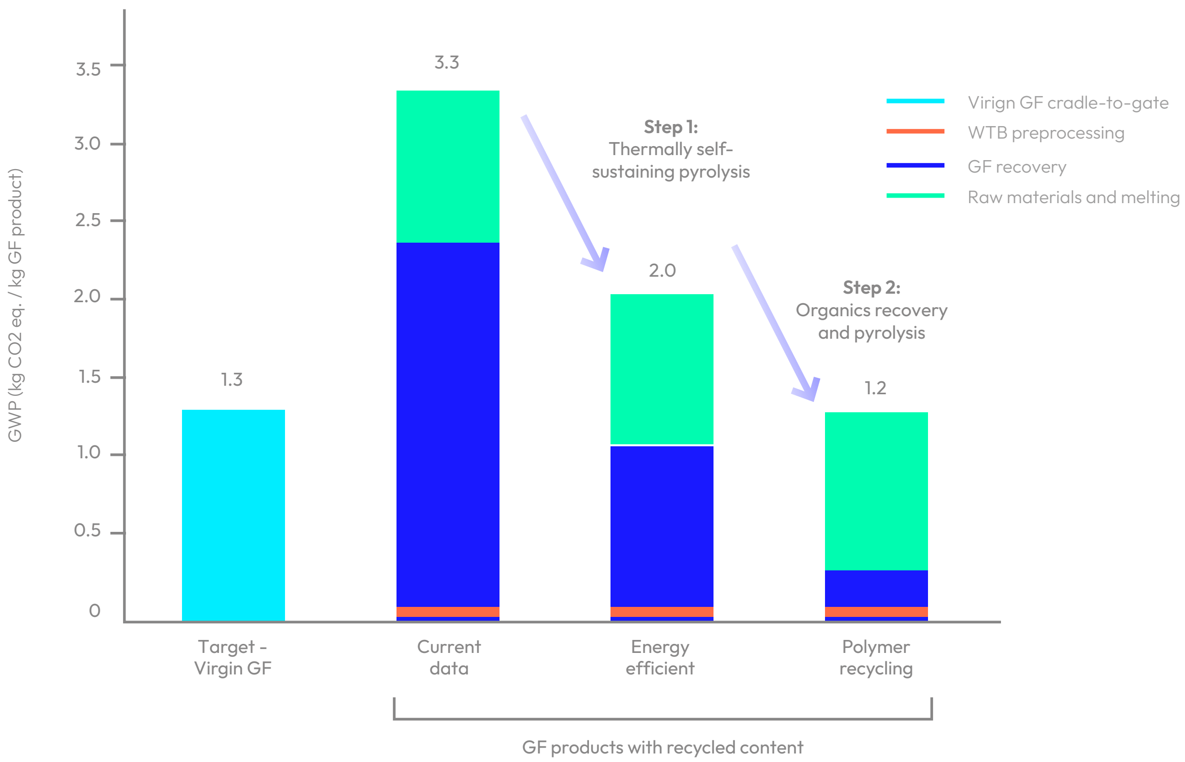

Figure 3 GWP of GF with recycling content on par with virgin GF

In the short term, it is recommended to develop low-value petrochemical applications for pyrolysed polymers. Long-term research should focus on maximising the value and reducing the environmental burden of more refined products. Priority should be given to advancing separation and purification techniques to improve the quality and purity of recycled polymers. Additionally, investigating innovative methods for modifying and functionalising recycled polymers could broaden their use across various industries.

With the requirements for GF recovery now defined—ensuring that recycled feedstock can be used in GF production with a GWP comparable to virgin GF—the next phase of our work focuses on scaling up this approach for large-scale demonstration. This effort will be supported by comprehensive process data collection, enabling us to refine and update the lifecycle assesment to provide a more accurate representation of the environmental feasibility of advanced composite recycling technologies. By validating the process at scale, we aim to support the development of recycling that can reliably supply high-quality feedstock for GF production, further advancing the transition toward a circular economy in wind blade manufacturing.

Terms

CO2e
Carbon Dioxide Equivalent

GF
Glass Fibres

GFRP
Glass Fibre Reinforced Polymer

GWP
Global Warming Potential

LCI
Life Cycle Inventory

TRL
Technology Readiness Level

vGF
Virgin Glass Fibres

Wt%
Weight Percentage

WTB
Wind Turbine Blade

References

[1] P. Liu and C. Y. Barlow, "Wind turbine blade waste in 2050," Waste Manag., vol. 62, pp. 229–240, 2017, doi: 10.1016/j.wasman.2017.02.007.

[2] SusWIND, "NCC-TEC-4111 Environmental Impact of Wind Turbine Blade Recycling Technologies with Recycled Glass Fibre Remelt," 2024.

[3] K. Pender, F. Romoli, and J. Fuller, "Environmental impact of glass fibre products with recycled content: A closed-loop recycling solution for legacy composite wind blade waste [under review]," 2024.

[4] K. Pender, F. Romoli, and J. Fuller, "Lifecycle assessment of strategies for decarbonising wind blade recycling toward Net Zero 2050," Energies, vol. 17, p. 3008, 2024, doi: 10.3390/en17123008.

[5] SusWIND, "NCC-TEC-4110 Cradle-to-Gate Environmental Impact of Secondary Glass Fibre Products using Wind Blade Recyclate and Remelt Strategies," 2024.

[6] K. Pender, F. Romoli, and J. Fuller, "Multi-lifecycle assessment of close-loop recyclable wind turbine blades [under review]," 2024.

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