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Next-Generation Adhesives for Wind Turbine Blades

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As the global wind energy industry continues to evolve, how will adhesive bonding adapt? Adhesives are a critical contributor to the structural load-bearing performance of the final wind blade assembly. They are therefore subject to long qualifications at blade manufacturers. The current turbine blade bonding technology may be completely reshaped by three opportunities: raw material availability, blade recyclability, and the evolution of blade designs.

Jean-Luc Guillaume

The global wind energy industry consumed around $600 million of adhesives in 2022 for the manufacture of turbine blades. This amounts to 4 % of the global structural adhesives market in terms of value. China represented around 50 % of the global wind blade market, with a majority of the rest of the market being equally split between the Americas and Europe. Around 90 % of the world's wind blades have been produced using structural adhesives. Structural adhesives bond the two shell halves, as well as the shear webs that form the final structure of the wind turbine blades (see *Figure 1*). More than 80 % of the wind-related structural adhesive market is served with epoxy thermosetting adhesives for blade shells and shear webs made from epoxy-based systems. The remainder of the market is served with vinyl ester-based adhesives bonding polyester-based blade shells and shear webs. Additionally, some methyl methacrylate-based adhesives are used for non-structural applications such as shear web pre-positioning or add-on bonding, for example vortex generators.

The epoxy wind structural adhesive commercial offering is currently populated with two types of products – those that include glass fiber and those that do not. Glass fiber-filled adhesive represents the first generation of products, with 20 years of proven track record. Short glass fiber (10-100 mm) is used to control crack propagation, but it increases density and therefore blade weight. Glass fiber-free, toughened adhesives have been introduced over the past decade to the wind market as a second generation designed for longer blades. While these adhesives feature the benefits of lower density and higher elongation, their cost is higher than their glass-filled counterparts. *Table 1* shows a compilation of the typical properties described on technical data sheets for these two adhesive types.

Patented examples of adhesives compositions can be found in CN 101851481 B and EP3024908 B1. Wind bonding lines are relatively thick, with about 20-40 mm, to manage tolerances between the two blade halves to be bonded. Thus, wind adhesives need to feature a thixotropic behavior to prevent bond line sagging on vertical surfaces. Thixotropy is usually achieved through the addition of fumed silica in the adhesive formulation.

Adhesives are a critical contributor to the structural load-bearing performance of the final wind blade assembly and are therefore subject to long qualifications at blade manufacturers. For example, changes in adhesive compositions can have effects on adhesive processing conditions that are difficult to simulate at lab scale. This may generate unexpected defects in the bond line during blade assembly, potentially leading to blade failure in the field. Consequently, blade manufacturers have traditionally been extremely cautious in adopting changes in wind blade adhesive technology.

Evolving bonding technologies

Against this backdrop of cautious adoption for adhesive innovation, the current turbine blade bonding technology may be completely reshaped by three oppor-

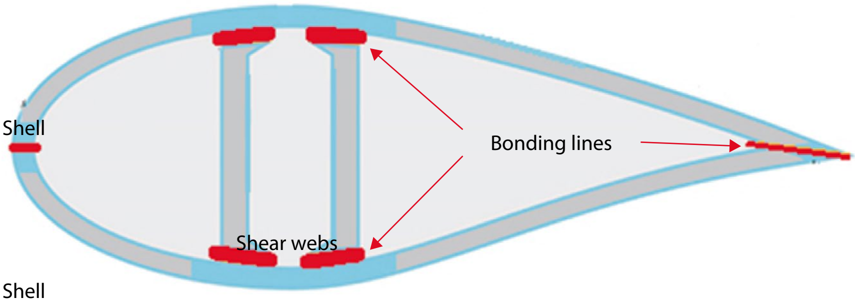

Figure 1 Structural wind blade bonding

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	Glass-Filled Adhesive	Toughened Adhesive	Test Method
Cured Adhesive Properties			
T_g (°C)	80	80	ISO 11357
Density (g/cm^3)	1,20-1,30	1,15-1,20	
Tensile Properties			
tensile modulus (Gpa)	4-5,5	2,8-3,2	ISO 527
tensile strength (Mpa)	65-75	45-60	ISO 527
tensile elongation (%)	2,5-3,2	3,5-8	ISO 527
Three-Point Bending Properties			
flexural modulus (Gpa)	4,7-5,3	3,2-3,6	ISO 178
flexural strength (Mpa)	110	90	ISO 178
flexural elongation (%)	2,7-3	5-6	ISO 178
SLSS (Mpa)	15-20	20-30	ISO 1465
K1C (Mpa.m1/2)	2,2	2,7-3,5	ISO 13586
Processing Properties			
Mixed Viscosity @10 1/s	200-300		
Mixed Viscosity @ 50 1/s	20-30		
Sag Resistance (mm)	30-35		
Open Time @ 30 °C (Hr)	1,5 -2		
Cure Time @ 70 °C (Hr)	5 -7		

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Table 1 Typical epoxy wind adhesives by type

tunities: raw material availability, blade recyclability, and the evolution of blade designs.

Raw material availability

It is estimated that the wind industry would have to accelerate from its historical CAGR of approximately 6 % to a CAGR of 16 % (starting from 2023) to help meet the global 2050 zero-emission target. As a result, the industry and its raw material suppliers would be required to supply 2-3 times the current annual tonnage of epoxies or polyester and vinyl esters going into the wind industry.

The Chinese epoxy industry has announced a doubling of its nameplate epoxy capacity over the 2023-2026 time period, while much more modest capacity increases were announced in the rest of the world. However, the current global economic slow-down depletes the demand for epoxy resins. Epoxy prices have now massively fallen in Q3 2023, putting the profitability of potential future capacity expansion under question.

Hypothesising different new capacity build-up scenarios indicates that the epoxy resin price/availability balance could become an issue as soon as 2028, should the wind industry CAGR accelerate from 6-16 % while only 25 % of the announced world epoxy capacity expansion projects are actually completed (see *Figure 2*). Given the time needed to qualify novel adhesives in the wind industry, this potential situation creates an immediate incentive to formulate wind blade adhesives with alternative chemistries to epoxies.

Blade recyclability

While decommissioned blades are mostly landfilled today, the wind industry has committed to implementing end-of-life technologies that generate blades with zero waste by 2030-2040. Structural adhesives represent less than 5 % of a blade weight, so the industry has thus far focused on developing a circular value chain for the blade's bulky composite components, which comprises of shells, spar caps, and shear webs, made with epoxy or an unsaturated polyester matrix reinforced with continuous fibers.

Typically, after removal of the metallic parts, such as the lightning protection or root inserts, the blades are sawn and shredded into pieces in the cm range without separating the adhesives from the composite material that forms the struc-

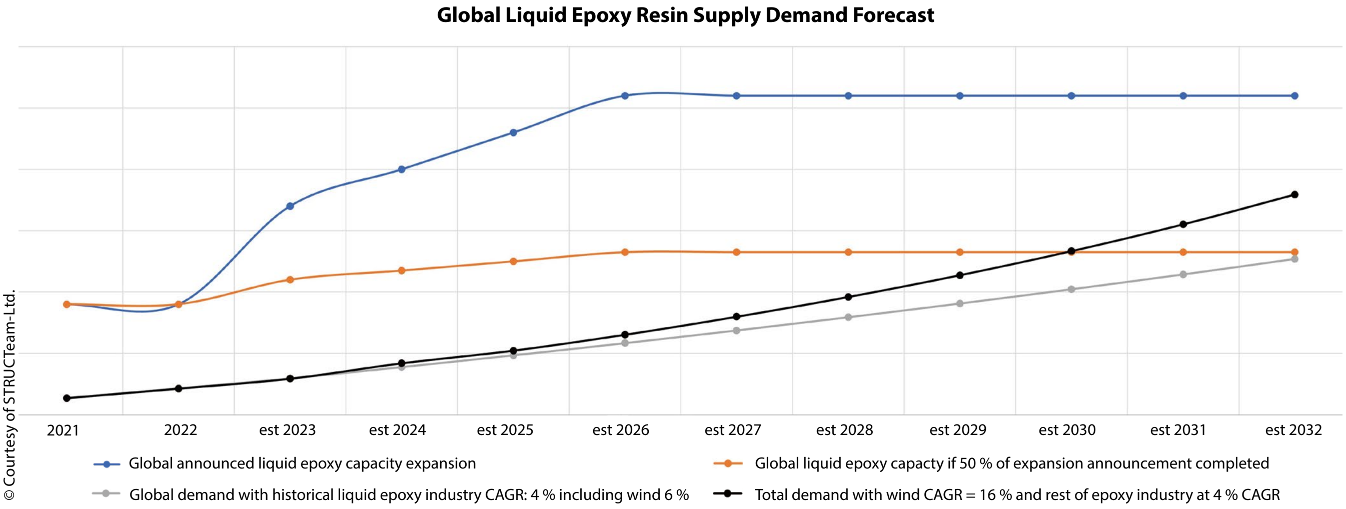

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Figure 2 Balance of global epoxy resin supply and demand (in million T)

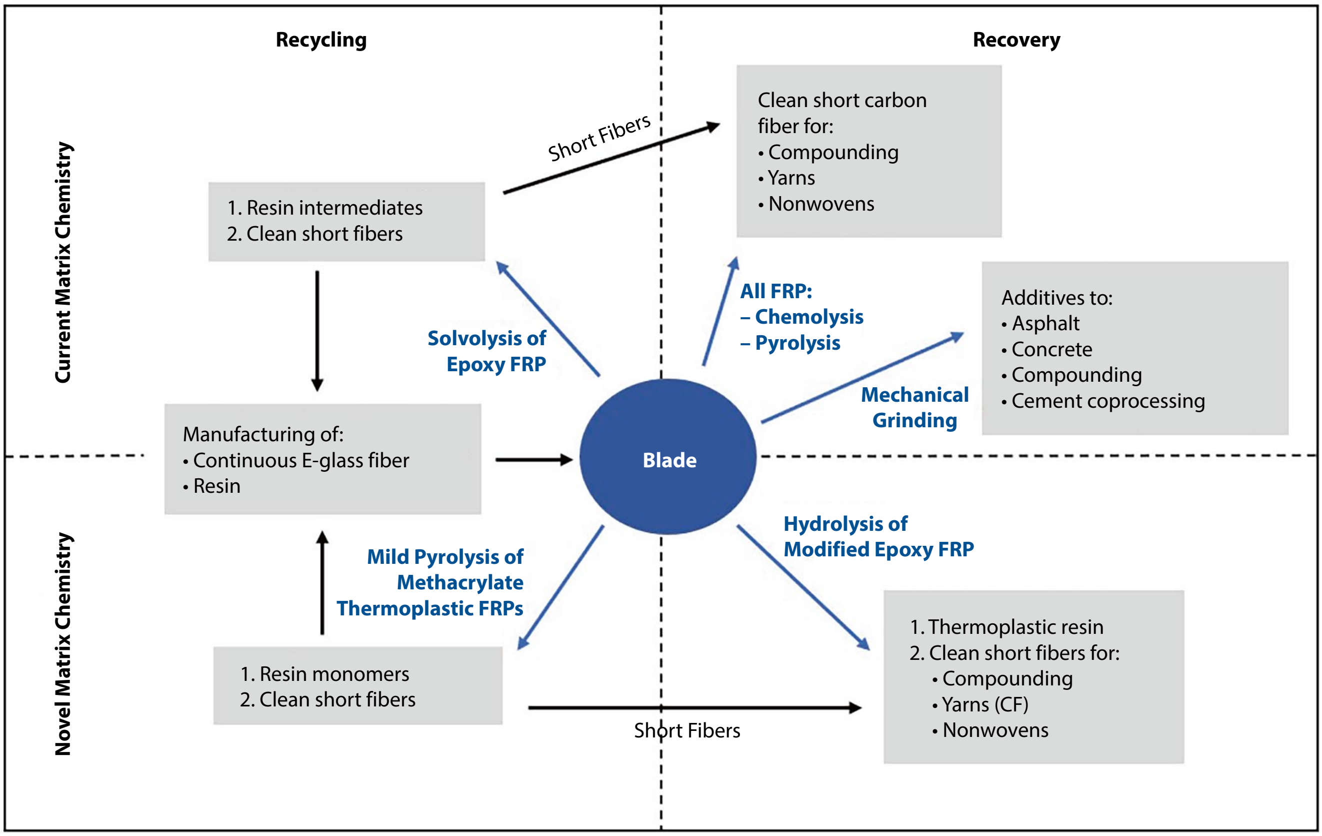

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Figure 3 Blade circular end-of-life options (The recycling method and type of composite [FRP] recycled is shown in blue, recyclate type is in black)

ture of the blade. The adhesive therefore becomes an integral part of materials entering into the blade recycling process. Several blade end-of-life options are currently being explored and are summarized in *Figure 3* as a function of the type of resin matrix chemistry involved versus the ranking in the circularity hierarchy. *Table 2* details the current status of the options shown in *Figure 3*.

Figure 4 shows the tonnage per annum of waste composite material to be generated from blades expected to go in retirement through 2030. Both *Table 2* and *Figure 4* focus on North America and Europe.

Several conclusions can be drawn from this. Contrary to options enabling blade raw material recycling, options leading to recovery, mostly focused on fiber recovery, have advanced to industrial scale and can offer an immediate alternative to landfilling. However, the field experts for the mechanical grinding-based options report that such a step would currently be more costly than landfilling.

The cumulative treatment capacity of these end-of-life options having reached industrial scale seems to be large enough to absorb the flux of blades to be decommissioned to 2030, leaving time for the wind industry to prepare the implementation of higher value recycling options. However, many of these options are pro-

End of Life Technology	Technology Promoter	Sponsoring Blade Manufacturer	Capacity (kT/a) by 2024/25
Mechanical Grinding			
cement coprocessing	Veolia, Zajon	GE Wind	~ 25
compounding	Global Fiber Solution, REGENfiber, Continuum		~ 80
Pyrolysis	Carbon River	TPI	~ 50
Chemolysis	Vcarbon		prototyping
Hydrolysis	Aditya Birla (Recyclamine) Swancor (EzCYclo)	SGRE	25 (resin system) prototyping
Pyrolysis of Thermoplastics	Arkema	LM GE (project ZEBRA)	prototyping
Solvolysis	Vestas (project CETEC)	Vestas	prototyping

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Table 2 Commercialization readiness of blade end-of-life options

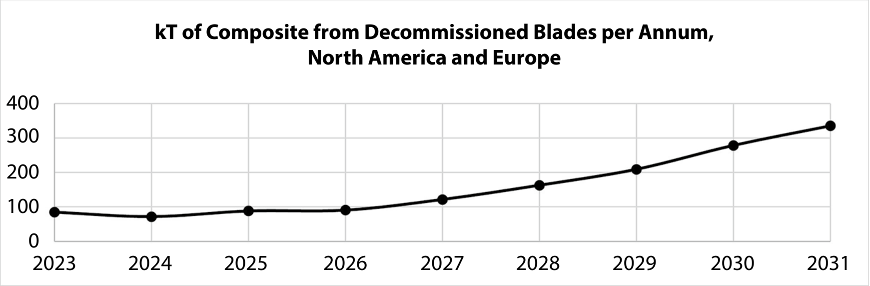

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Figure 4 Tonnage of waste composite material from retired blades in North America and Europe

moted by companies starting businesses that still need to optimize their economic sustainability.

Options involving current matrix chemistries, for example epoxy and polyester, can be applied to blades currently in service. These options do not move blade designers and process engineers out of their current technology comfort zone when designing novel blades.

Further options involving novel matrix chemistries can only apply to future blade designs and do not enable the recycling of blades in service made with the current chemistries. They also require a complete material qualification cycle, in addition to moving blades designers and process engineers out of their current technology comfort zone.

Whatever the pros and cons of each of the options shown in *Figure 3*, a systematic comparison of their economics and life cycle analysis (LCA) is not yet available. It is therefore not currently possible to predict which end-of-life option or options may emerge as a winner and therefore what preferable type of resin next-generation wind adhesives should be based upon.

This situation currently hinders the development of recyclable wind adhesives. To date, just one wind adhesive designed for circularity, using recyclamine technology, is commercially available, from Aditya Birla.

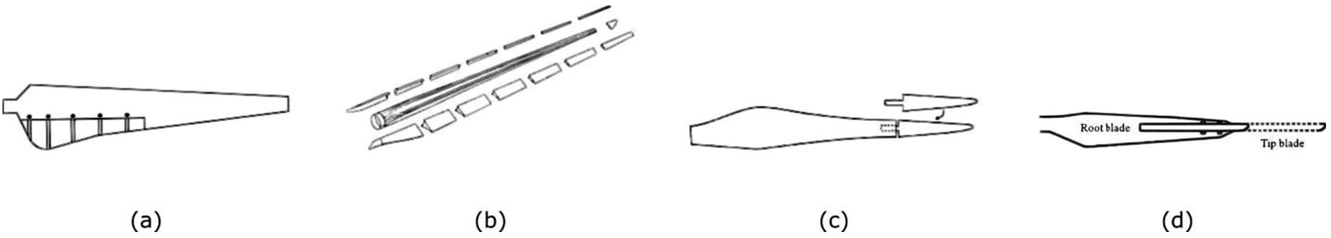
Evolution of blade designs

Wind turbine power generation efficacy and economics are improving with increasing blade length. A typical onshore workhorse blade currently reaches a length of 70-80 m, routinely placing today's onshore wind power cost below the cost of power generated from fossil fuels. Against this background, blade designs and their associated raw material selection have historically been characterized by two facts:

The power generation efficacy of a blade increases with the area swept by the blade, that is with the blade diameter to the second power. However, the blade weight and costs both increase faster than the power generation efficacy because they are a function of the volume of material used in the blade, that is a function of the blade diameter to the third power. Over the past 20 years, the optimization of the balance between power generation efficacy and costs was predominantly achieved through design innovations, for example slender blades and/or blade prebend, all based on proven existing wind raw materials rather than through the selection of new raw materials. This illustrates another signal of the wind industry's caution regarding the adoption of novel raw materials.

Designers prefer to strictly match adhesive resin type with the composite component matrix, that is epoxy adhesive with epoxy shells or vinyl ester with unsaturated polyester, to avoid issues with compatibility, adhesion, and coefficient of thermal expansion.

The latest blade design trends are challenging these traditions, however. The continuing race for longer blades implies



© [1]

Figure 5 Modular blade segmentation strategies: a) blade with a separate TE segment to reduce blade width; b) blade with separate LE and TE panel segments to reduce blade width; c) blade divided to reduce the length of the components; and d) telescopic wind turbine blade. [1]

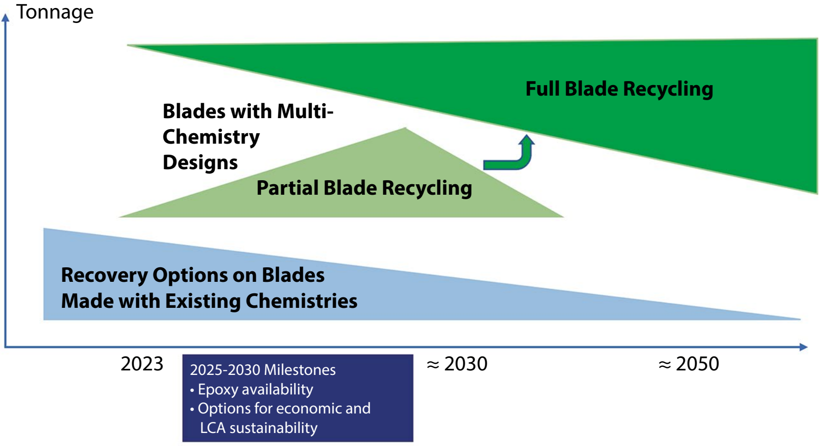


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Figure 6 Wind blade circularity scenario

ever-stricter control on blade quality. Toward that end, the blade manufacturing industry is likely to accelerate the move from a "full-blade molding process" to a better controlled "assembly of pre-manufactured modules process".

A good example of this evolution is the emergence of modular blades (*Figure 5*). Commercially available since 2020, the Cypress wind turbine family from GE Wind Energy is based on this concept. Assembling modular blades on site also enables a reduction in the cost of transportation to the wind farms under construction.

Interestingly, the next generation of modules researched by GE Wind Energy incorporates thermoplastics and 3D printing [2]. This indicates in our opinion that design innovation can now be successfully combined with the adoption of new raw materials in multi-chemistry blades.

Next-generation adhesive features

In summary, ChemQuest and Structeam hypothesize that a potential epoxy resin availability issue in the next 5-6 years could lead wind adhesive formulators to consider alternative resins at a time when multiple chemistry blades begin to be considered by blade designers [3]. This opens an opportunity for the stepwise insertion of circular resin chemistries until fully recyclable blades are commercialized in 2030.

A possible timeline for such a scenario is described in *Figure 6*, with the partial adoption of recyclable resins being in a first step likely focused on blade components that offer lower manufacturing risks, for example shear webs. The scenario also considers that several blade end-of-life options will coexist until at least 2050, offering time for the industry to decommission blades made through 2030 with non-recyclable chemistries.

In this framework, next-generation wind blade adhesives should provide two novel key features over the current state of the art to ensure successful adoption:

1. **The ability to bond substrates with different chemistries and minimized surface preparation.** This would allow blade designers to create blades from pre-manufactured components with multiple chemistries, enabling designers to generate the best recyclable component performance for the safest raw material availability at the lowest cost.
2. **No interference with the shell and other blade components recycling process.** In line with today's practice, the adhesive would deconstruct under the same conditions as the rest of the blade. ChemQuest and Structeam hypothesize that an isolation step of the adhesives from the rest of the blade prior to recycling would add too much cost to the overall process for a relatively small volume of pure adhesive recyclate.

Additional features may further accelerate the adoption of these next-generation adhesives: An improved mechanical performance can better manage the weight and therefore the bill of material of longer blades. Furthermore, a faster cure at lower cure temperature without reduction of open time, ideally cure on demand, can reduce the blade mold occupancy time and minimize production costs. The blade bonding represents 50 % of the mold occupancy time, and a significant reduction (> 50 %) should be targeted to maximize savings on blade production costs.

Conclusions

Next-generation adhesives should generate a total blade cost of ownership equal to or ideally lower than the current state of the art while meeting all the health and safety requirements in place around the globe. The adhesive formulations providing the best balance between all these sometimes contradictory requirements will win the race. //

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