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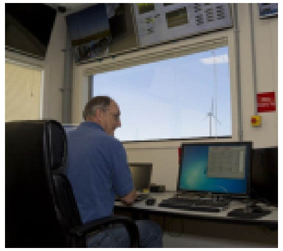
Second Life Opportunities for Wind Turbine Materials in Future Designs



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Wind Blade Recycling Project

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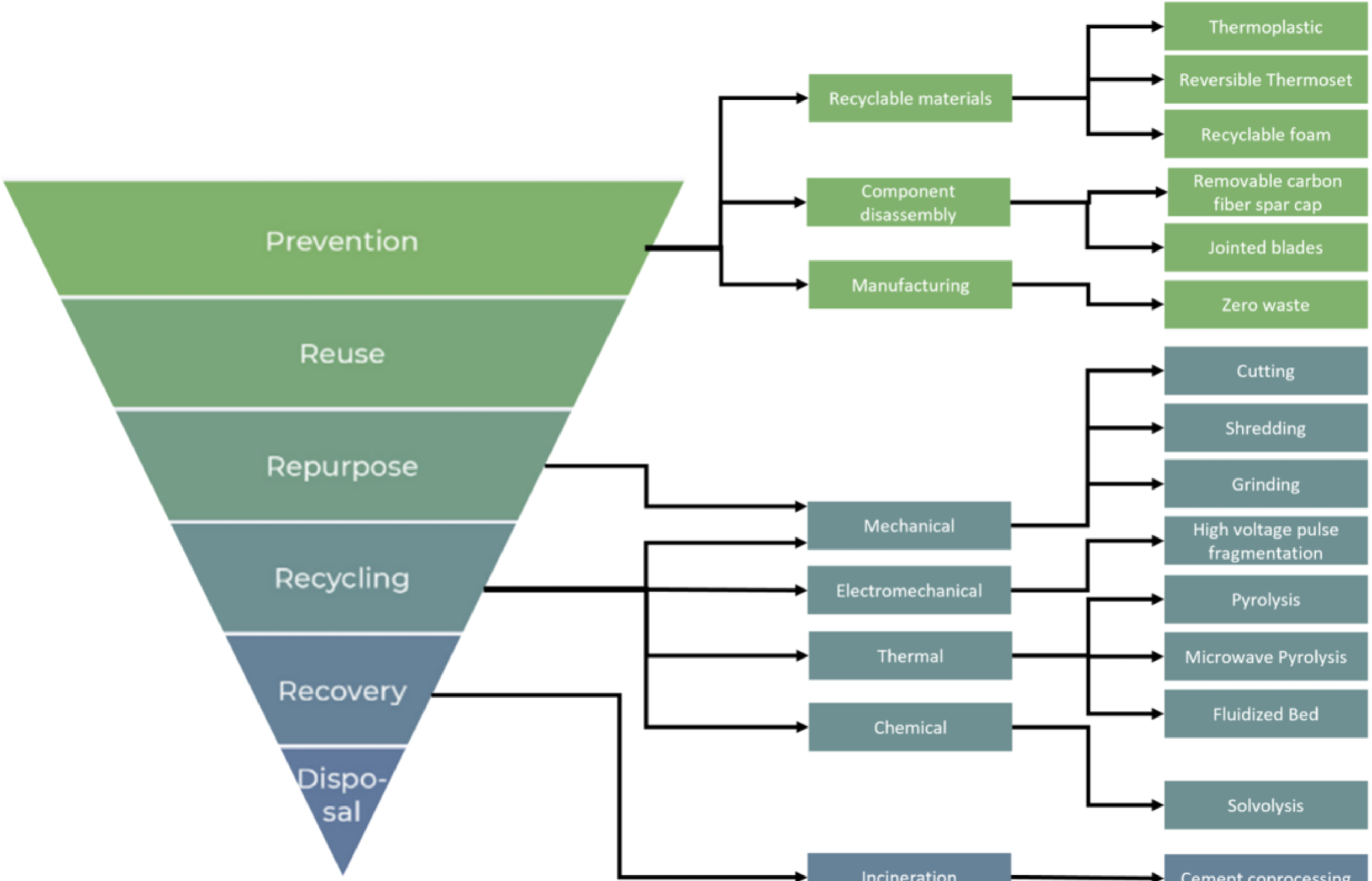
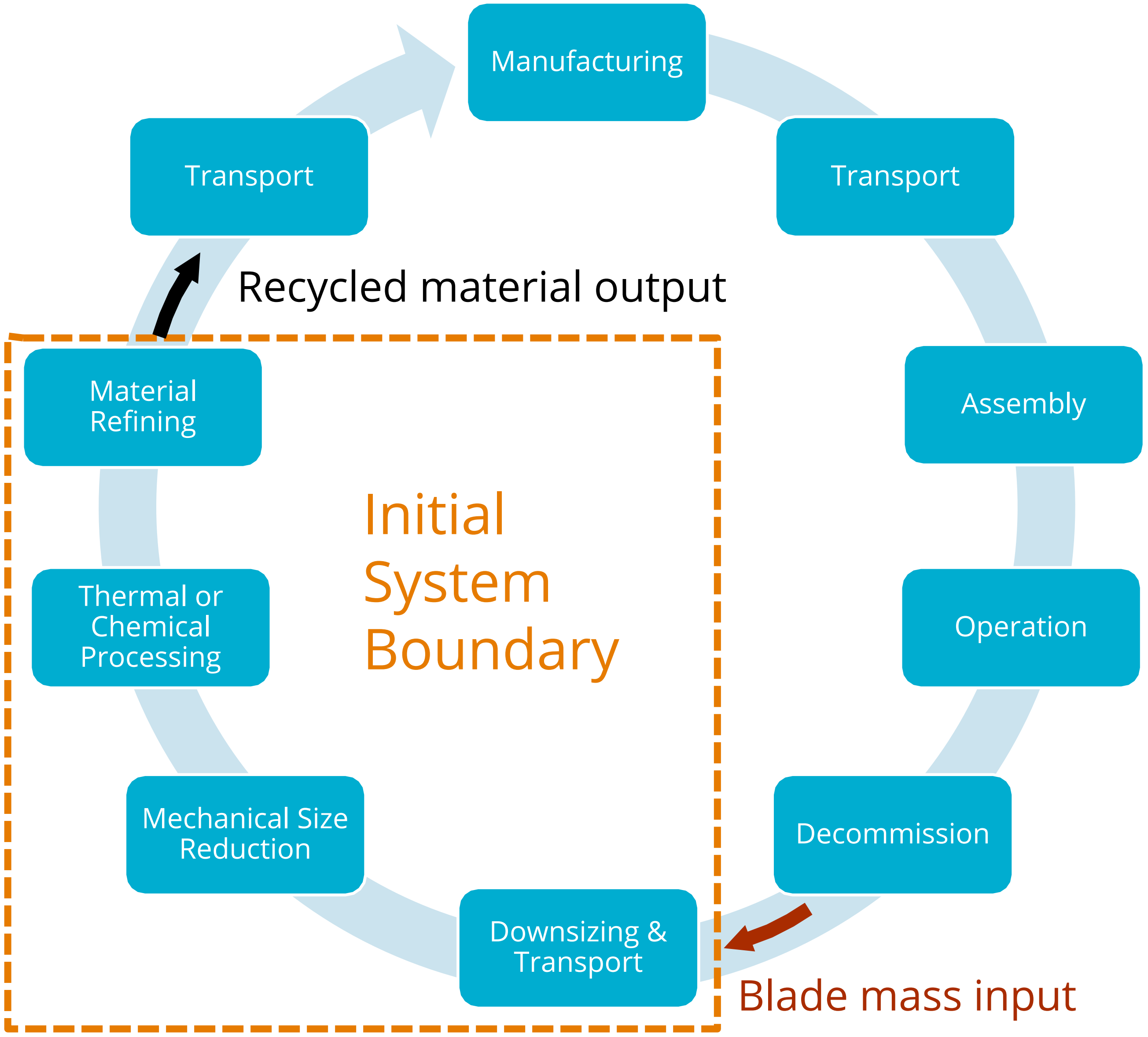
The primary goal of this assessment is to understand how different design and end-of-life approaches can enable **more efficient, cost-effective, and environmentally responsible disassembly and resource recovery** from wind turbine blade systems.

The assessment will also identify **opportunities for reuse of recycled wind blade materials within second life applications**, including future wind blade designs and alternative end-use markets.



Wind Blade Recycling Project – Life Cycle Assessment



High Priority Metrics	Units
Recycled Material Output	kg
Energy Consumption	MJ
Greenhouse Gas Emissions	kg CO_2 eq
Cost	U.S. Dollars
Recycled Material Value	qualitative

Metric

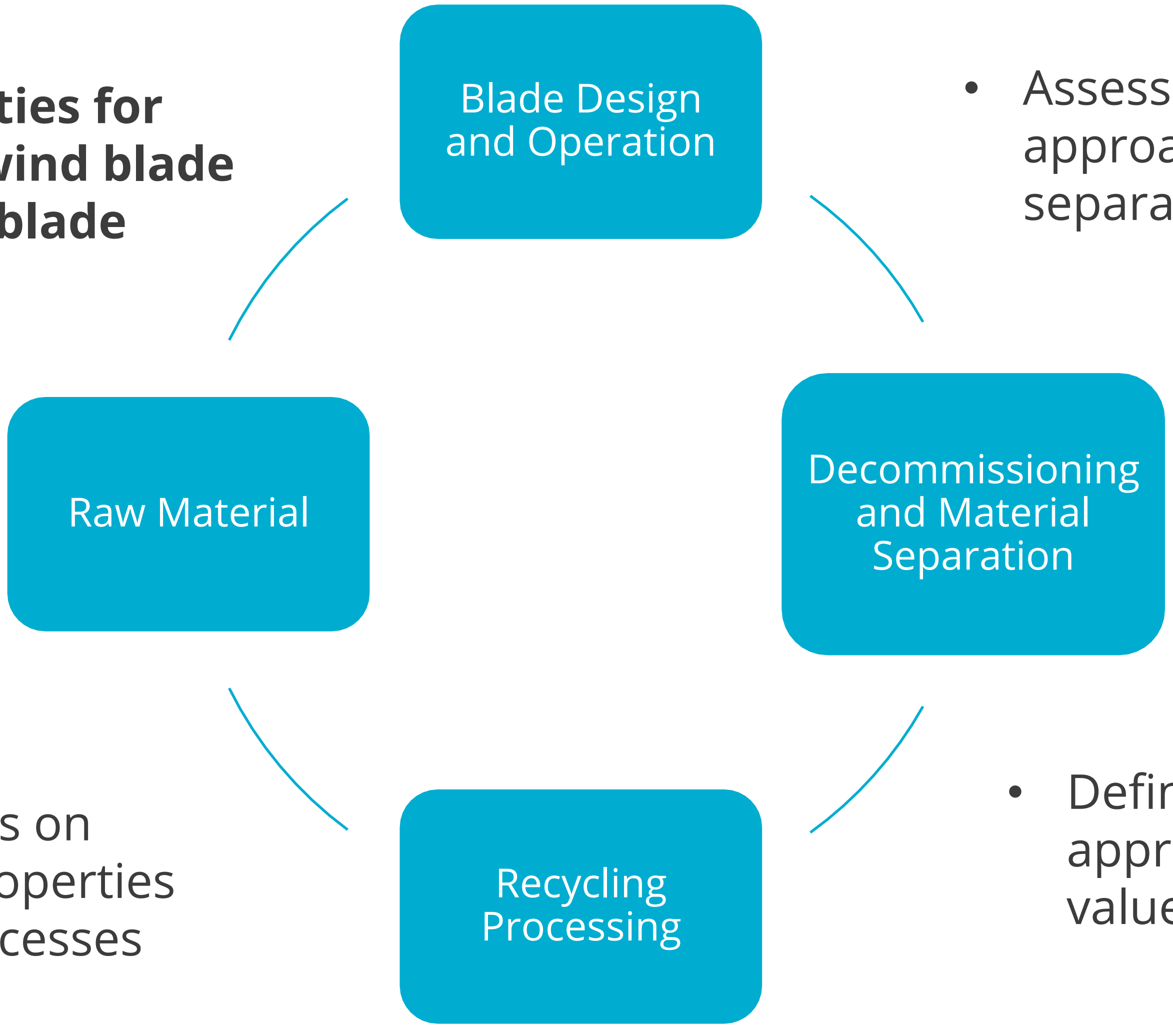
$$\frac{kg\ of\ CO_2eq}{kg\ of\ blade\ mass\ input}$$

Functional Unit

Wind Blade Recycling Project – Task Overview

- **Identify opportunities for reuse of recycled wind blade material in future blade designs**

- Assess design for disassembly approaches that enable material separation

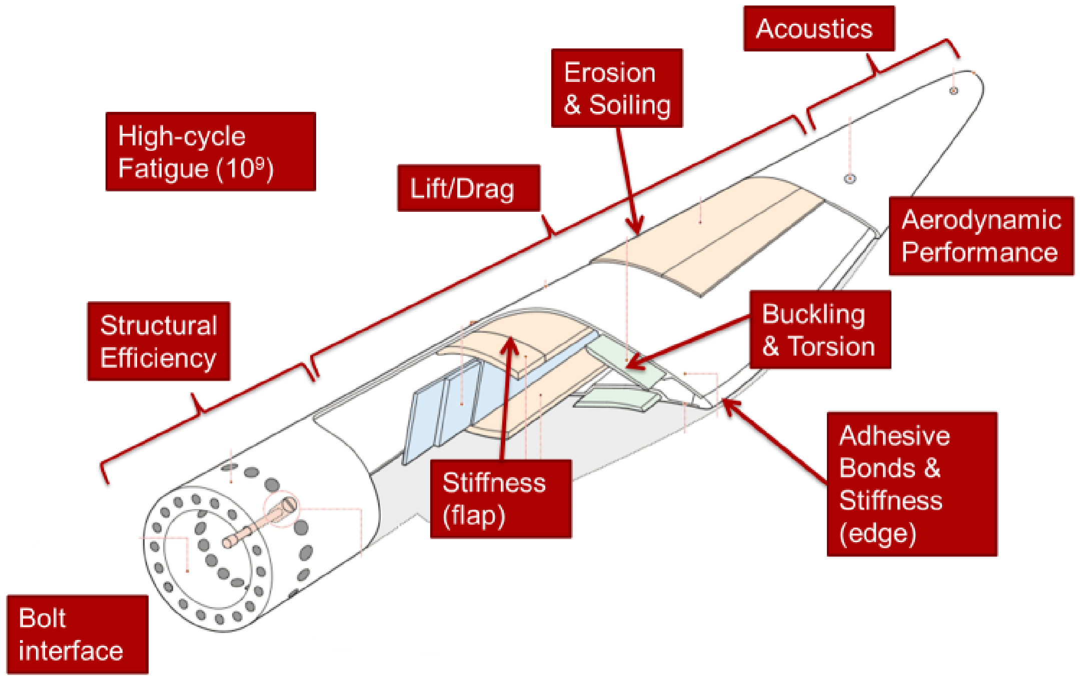


- Characterize impacts on material physical properties versus recycling processes

- Define intelligent separation approaches to yield higher value recycled products

Wind Turbine Blade Material Considerations

- Wind blades are optimized to reduce mass and cost while satisfying design constraints:
  - Deflection limits
  - Ultimate strength
  - Fatigue
  - Buckling
- An optimized design balances these constraints, but the various constraints are controlling in different sections of the blade



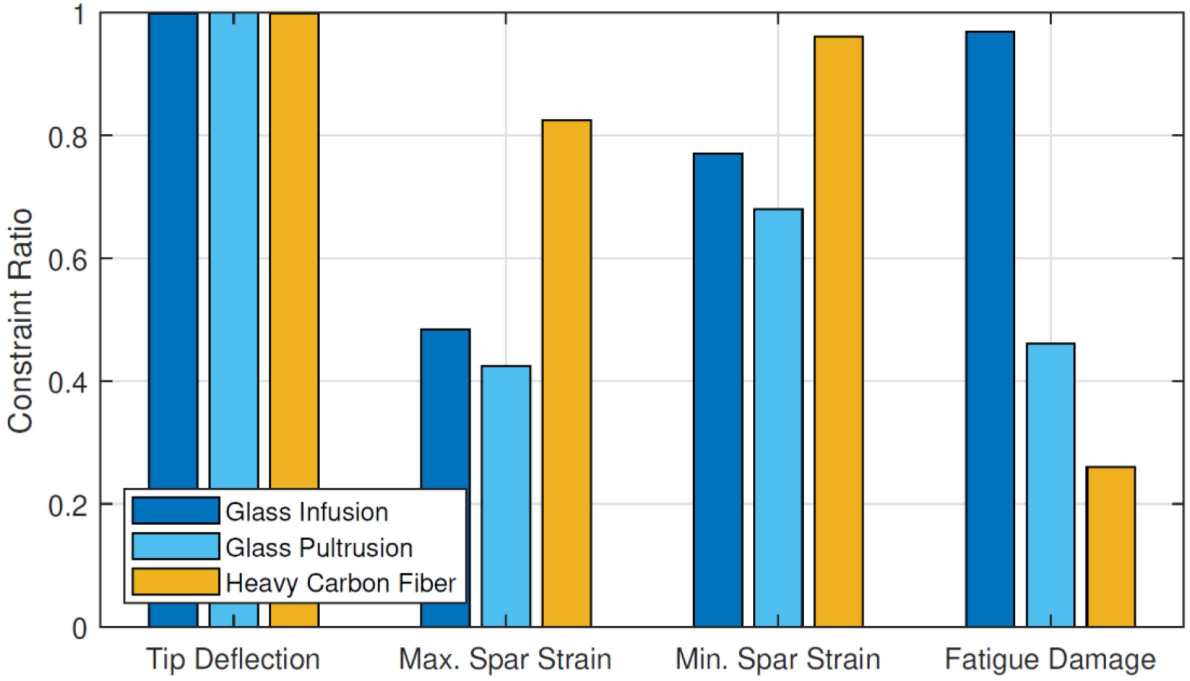
Blade mass breakdown

Carbon Fiber Spar Cap	12%
Root buildup	15%
TE/LE reinforcement	8%
Shell panel	51%
Shear webs	10%
Gelcoat, adhesive	4%

Wind Turbine Blade Material Considerations

- A majority of the wind blade material is stiffness-driven, not strength-driven
- A blade at the end of its design life means that a portion of the blade has no predicted remaining useful life, this is a small portion of the total mass
- There may be opportunities to utilize recycled blade material in future wind blade designs
- Recycled reinforcement fibers have degraded mechanical performance
  - Characterization of mechanical properties as a function of separation and recycling processes

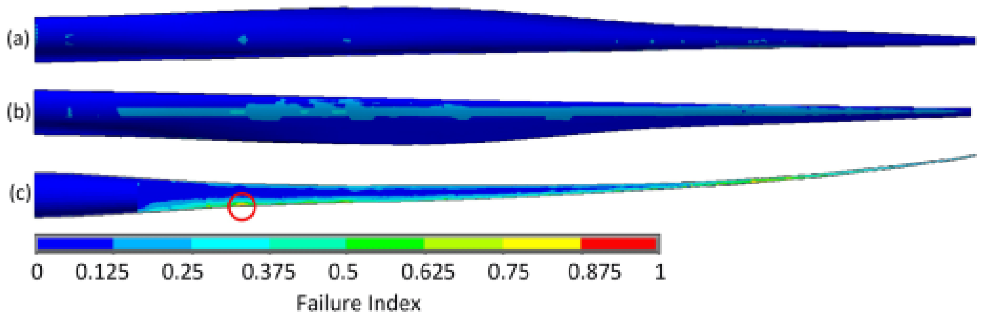
Wind turbine spar cap material design constraints for a 72m blade (IEC Class 3A)



Wind Blade Material Strength Characterization

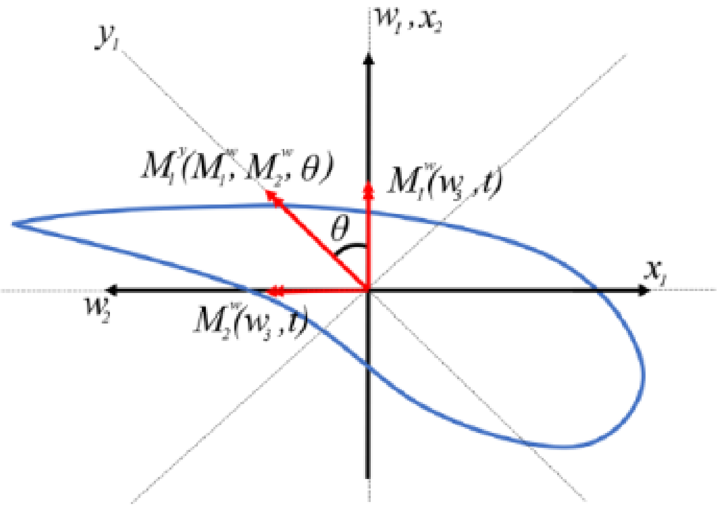
Reference Blade (Big Adaptive Rotor, BAR-URC):

- 100 meter blade, 5 MW land-based design
  - Carbon fiber spar cap
  - Upwind, rail transport
- Low wind resource classification



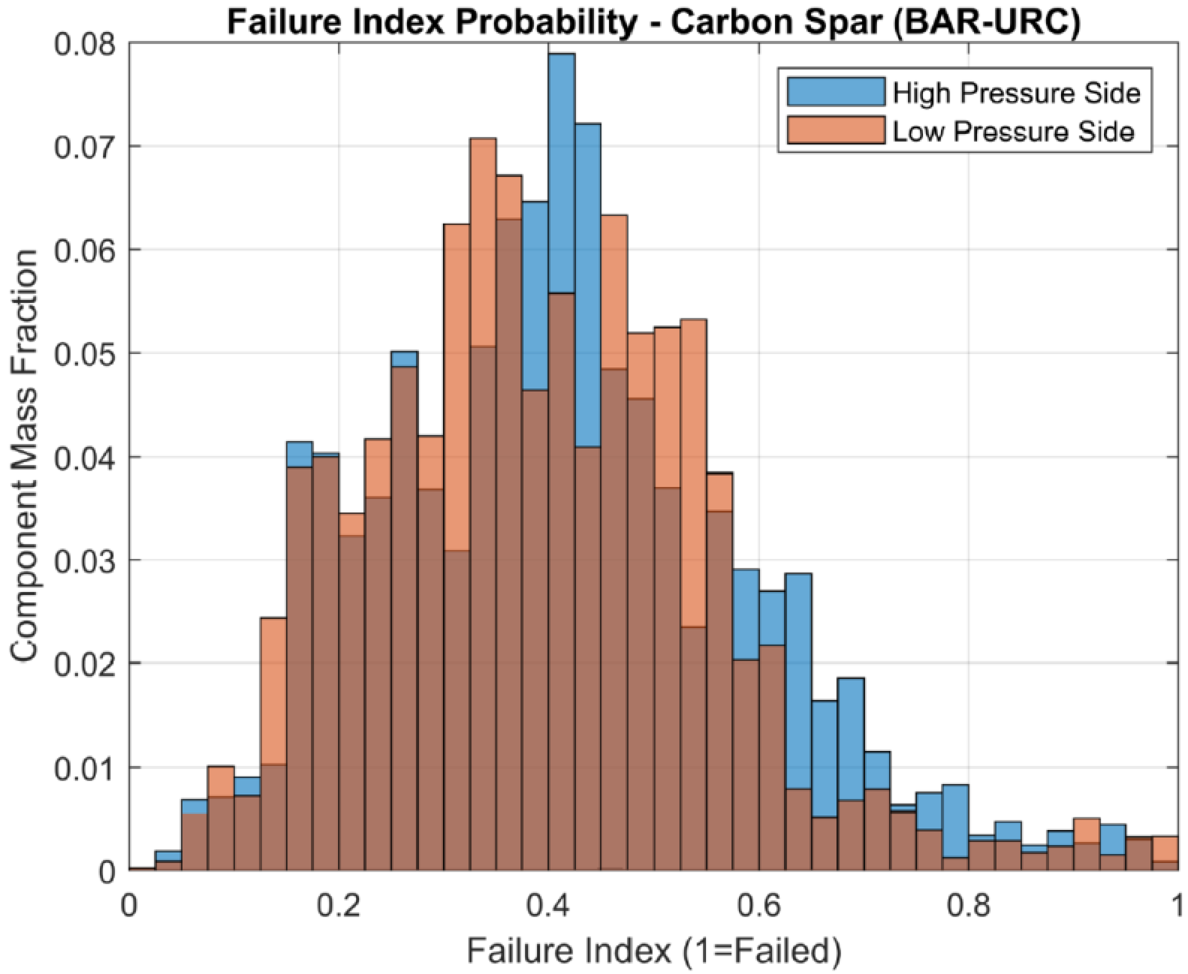
Material Characterization Approach:

- Treat material modulus as that of virgin material
  - Deflection and buckling are stiffness-driven and therefore unaffected
- Loads from aeroelastic design simulations
- Assess the ultimate and fatigue strength margins within the entire blade using ANSYS
  - Peak moment profile aggregated along the blade span in 8 rotational directions
  - Composite failure criterion



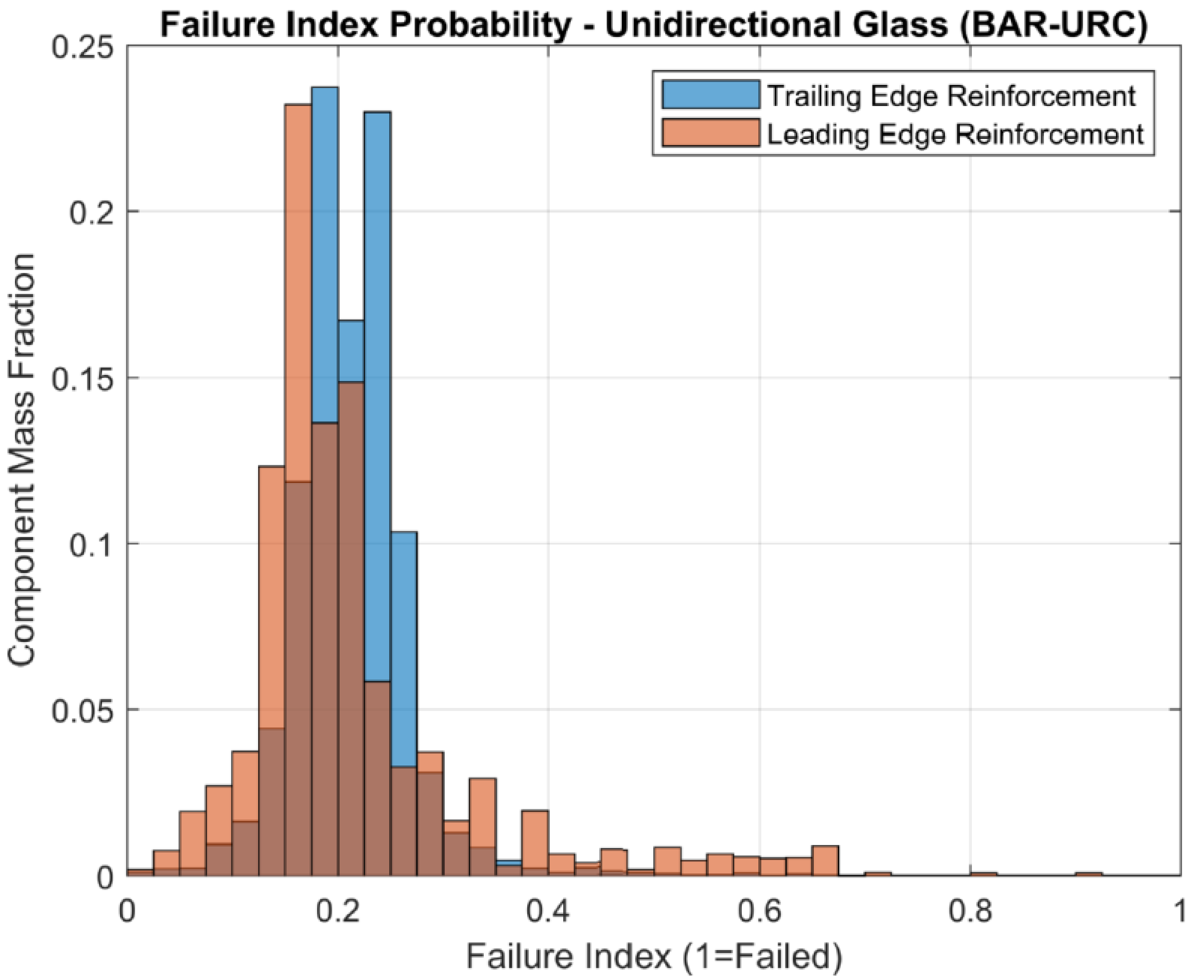
Failure Probability – Carbon Fiber Spar Cap

- Carbon fiber spar caps are typically strength-driven, due to their high modulus and relatively low failure strain
- However, carbon fiber spar caps are not fatigue driven
- Due to the high costs of carbon fiber and low damage levels, separation of the carbon fiber spar cap will be studied where the pultruded planks are reused without shredding



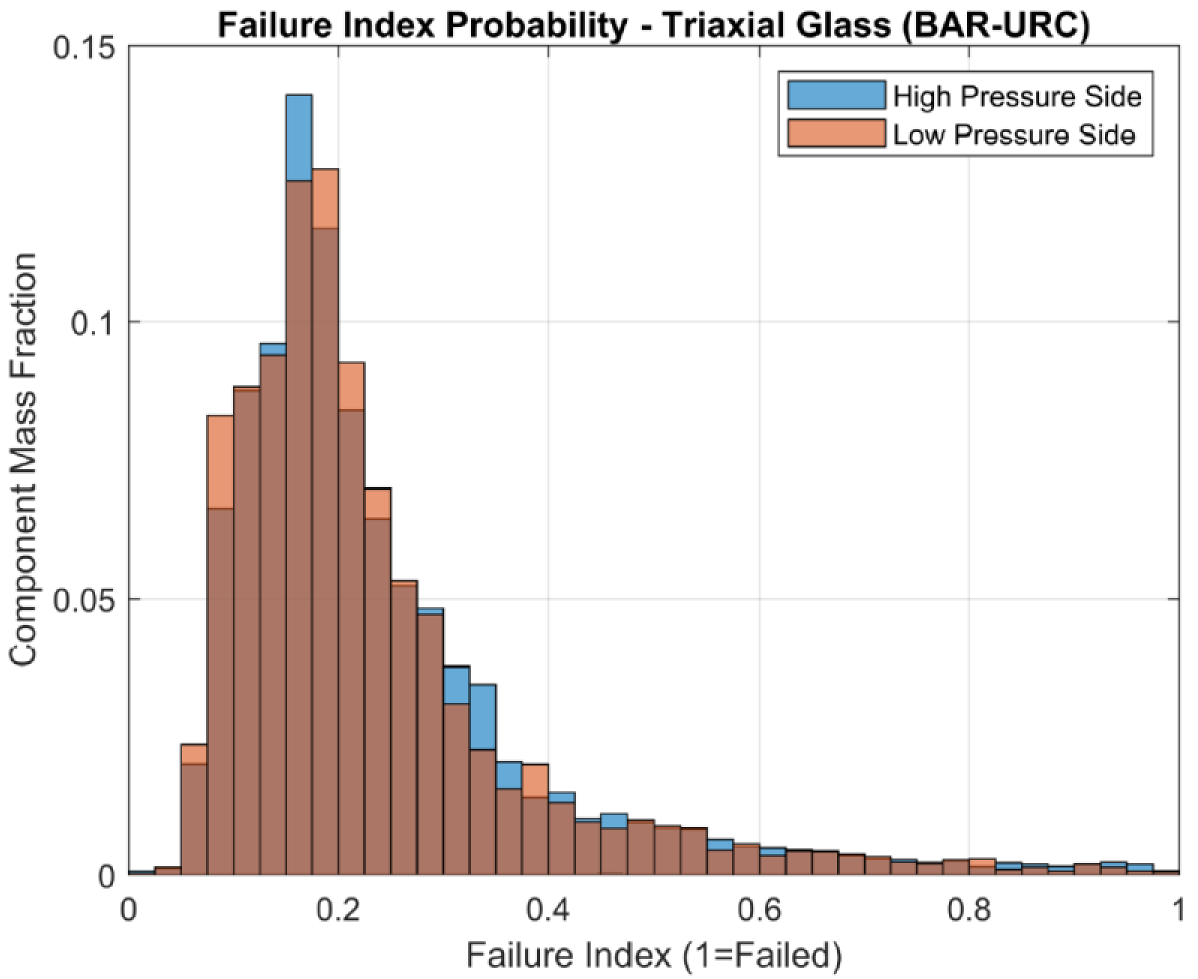
Failure Probability – Edgewise Reinforcement

- Edgewise reinforcement (leading edge and trailing edge) for large blades is often fatigue-driven
- 97% of the material requires less than 50% of the controlling strength
- Depending on the fatigue characteristics, edgewise reinforcement could utilize lower strength recycled material



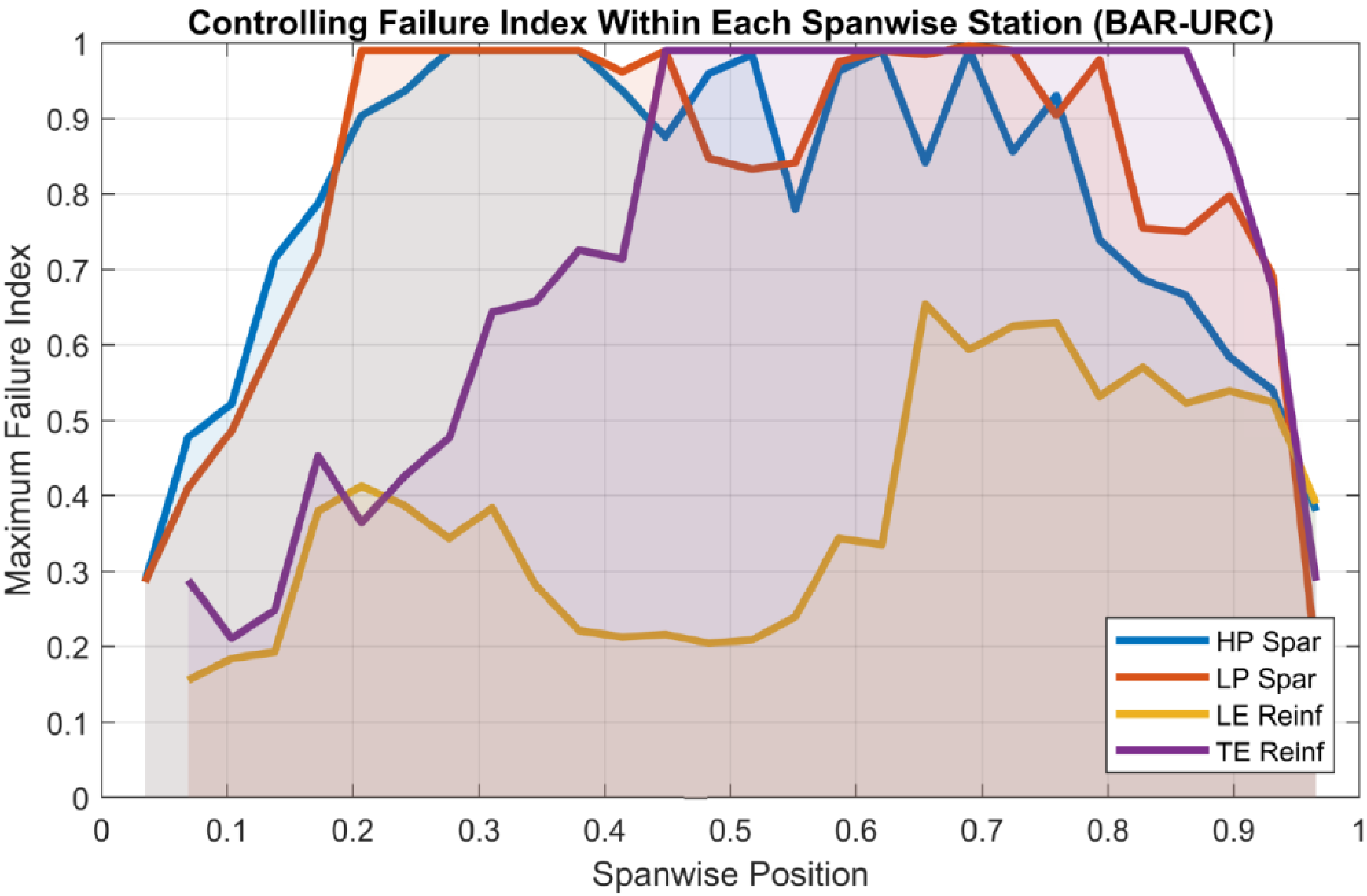
Failure Probability – Blade Root and Shell

- Fiberglass shell and root buildup are mostly stiffness-driven
- 93% of the material requires less than 50% of the controlling strength
- The shell and root components represent the greatest opportunity for use of recycled fibers in future blade designs
    - Glass reinforcement fibers in these two components represents ~40% of the total blade weight



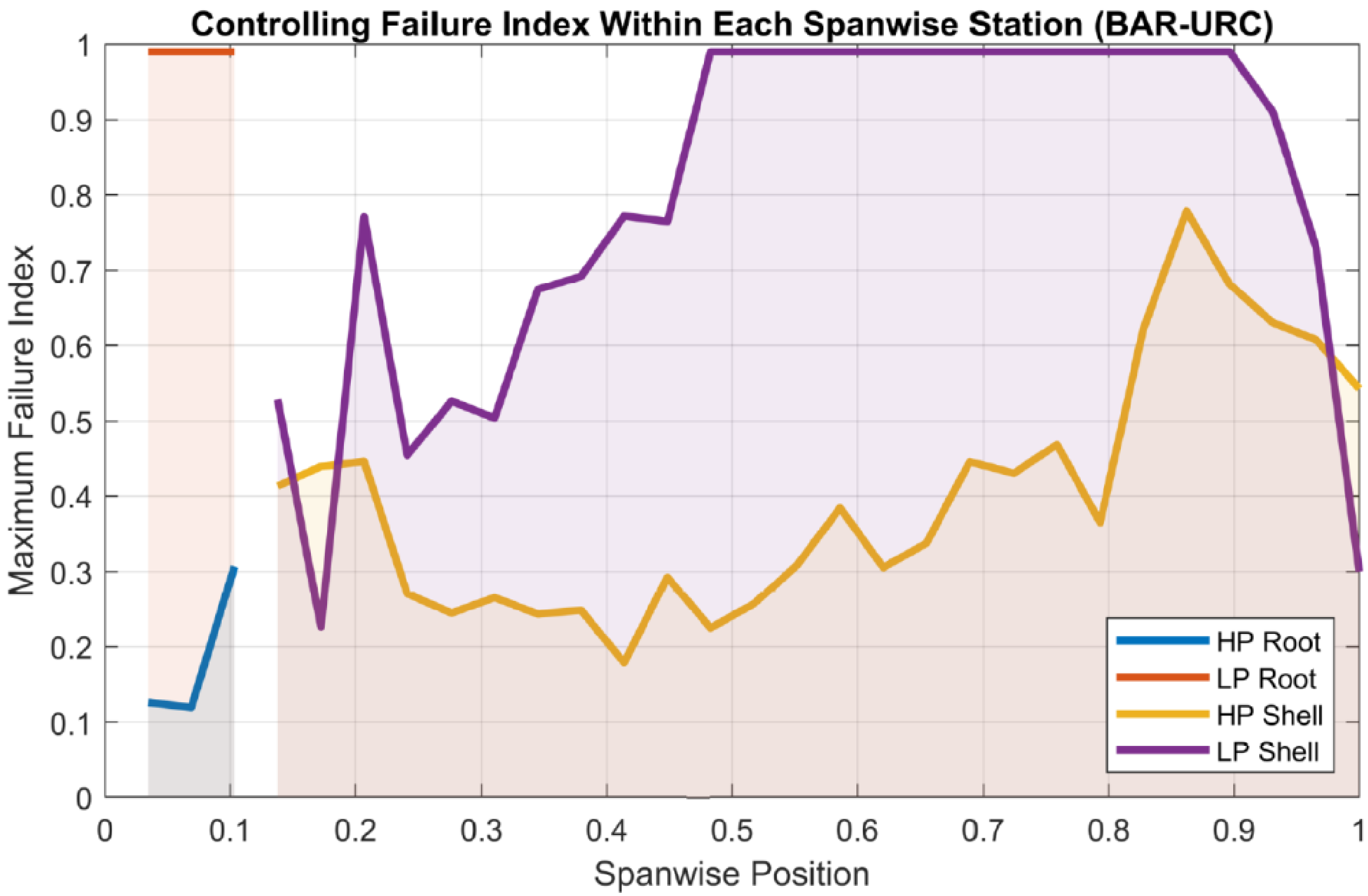
Spanwise Failure Index – Unidirectional Reinforcements

- A spanwise assessment is shown based on functional groupings that represent manufactured plies
- The maximum failure index at each spanwise station is plotted as the controlling element within the ply
- The spar cap (HP and LP) is optimized to the controlling strength along the span
- Edgewise reinforcement has strength margins inboard; Leading Edge has higher margins



Spanwise Failure Index – Triaxial Glass Fiber

- The tensile, HP surfaces have more margin than the compressive LP surfaces
- The HP blade root has a large strength margin
- The shell material has margin inboard that diminishes after midspan
- The HP shell has margin along the entire span



Conclusions and Next Steps

- Wind turbine blade recycling is not cost-competitive in the US for current approaches
- Enabling higher value end product can help to close this technology gap
  - There are opportunities to coordinate intelligent separation methods for higher value product recycling, enabling favorable material properties
- Some wind turbine components are likely best suited for direct reuse:
  - Carbon fiber spar caps
  - Shear web panels
- Recycled reinforcement fibers can be used in future wind turbine blade designs:
  - Shell and root materials are primarily stiffness-driven
  - Edgewise reinforcement has the lowest average failure index, fatigue analysis needed
  - Glass spar caps are typically fatigue-driven for low wind resource sites
- Mechanical properties of recycled reinforcement fibers are typically degraded
  - Modulus, compressive strength, and fatigue characteristics need better characterization