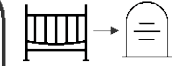
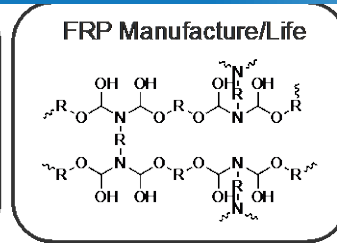
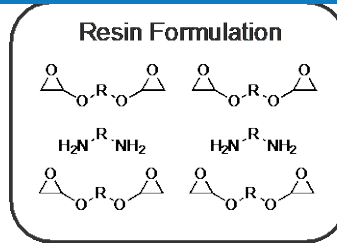


Developing a roadmap for bio-derivable and recyclable composites: Re-design and scale-up considerations

Nicholas A. Rorrer (He/Him), NREL

# Thermosets – Robust Materials, Heavily Carbonized



**ΔE**  
*Cradle-to-Grave*



**Thermosets have multiple energy relevant applications and are high in heteroatom content. Despite this, they are non-recyclable at the end of life**

# Thermosets – Robust Materials, Heavily Carbonized



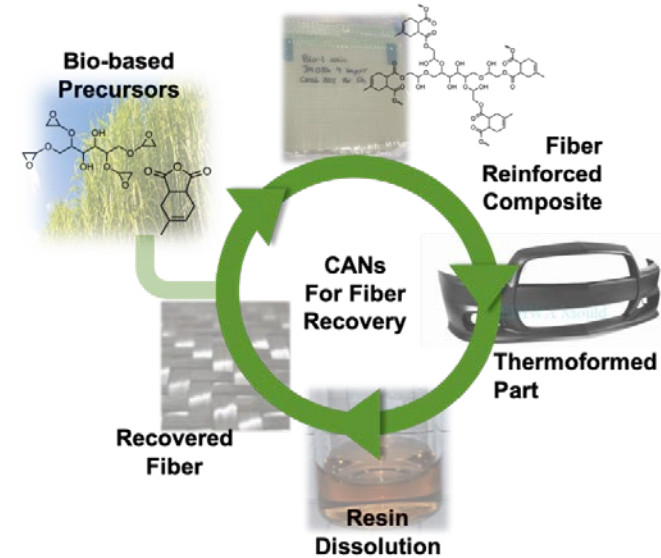
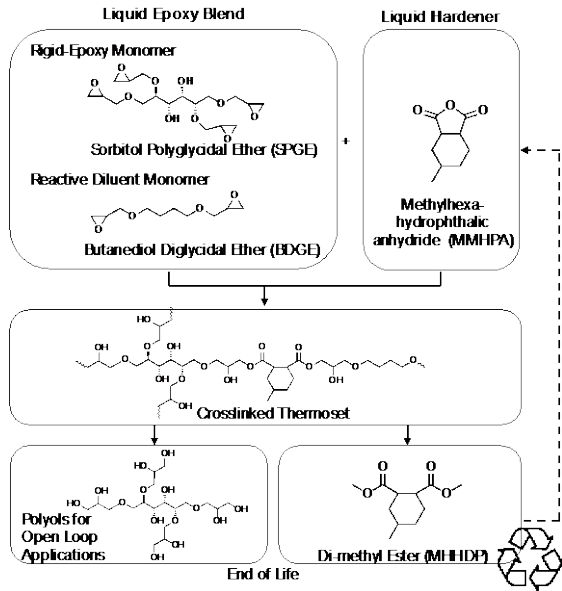
Resin Redesign



Wind Turbines



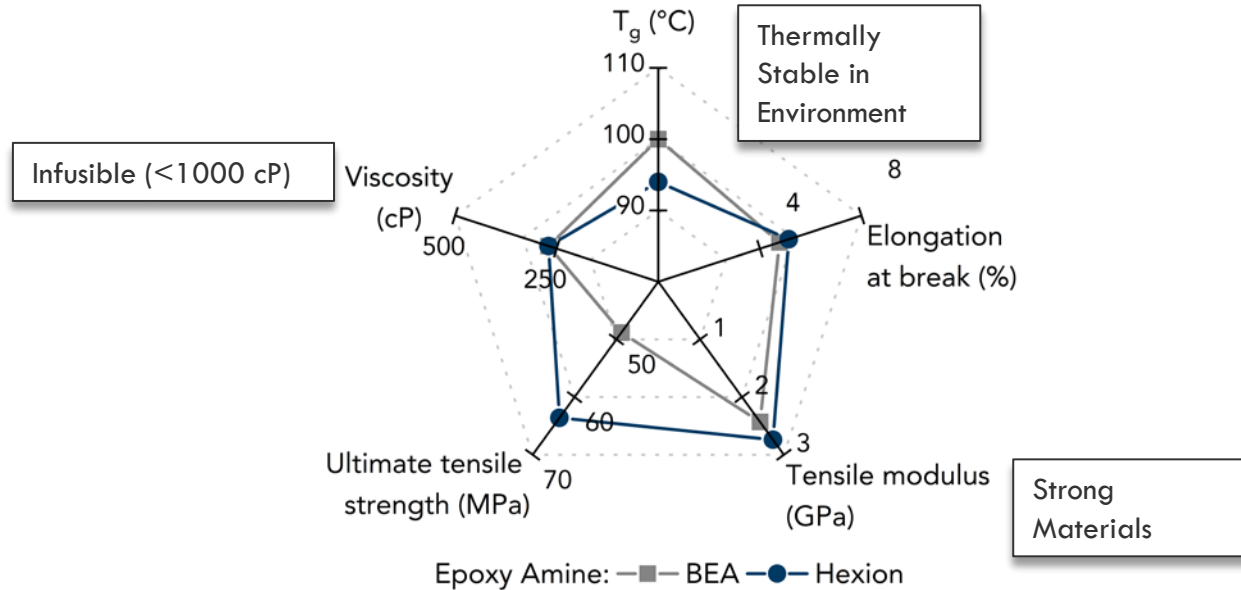
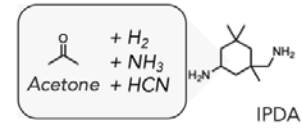
Vehicles



There are opportunities to redesign epoxy resins for multiple energy relevant applications

# Thermoset Redesign – The Need for A Proper Baseline

## Petrochemical Precursors



**Before selecting a redesigned chemistry, we must have a proper baseline for manufacturing and performance**

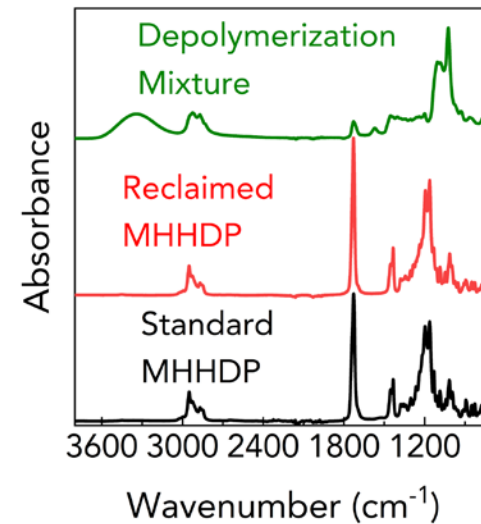
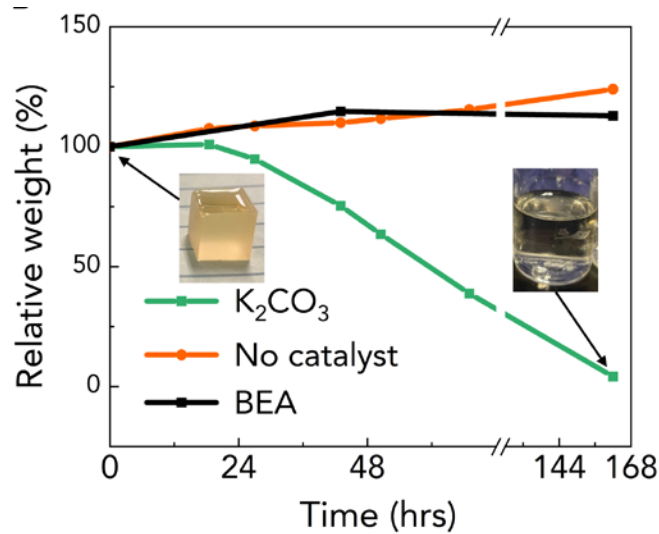
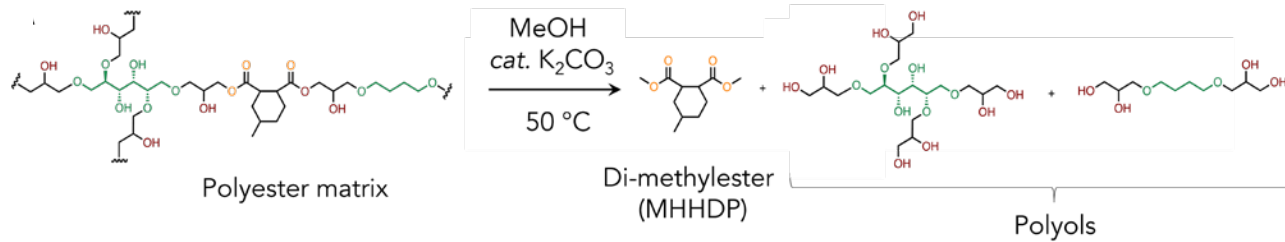








# Thermoset Redesign – Facile Recyclability



**The polyesters yield depolymerizability alongside a recoverable hardener**

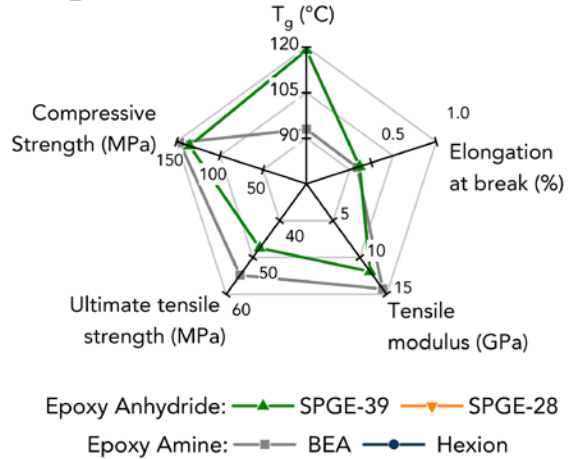




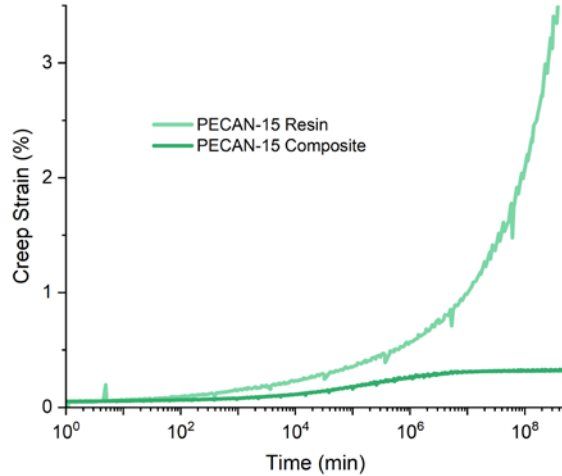


# Wind Blade Redesign – Considerations

Tunable



Creep Resistant



Multiscale

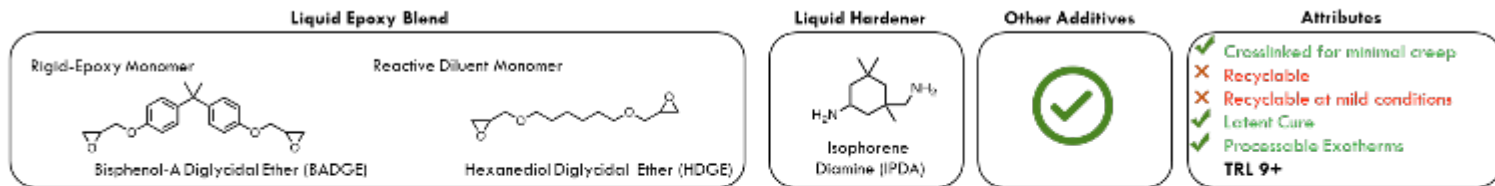


Wind turbine manufacturing will have different considerations from other FRPs

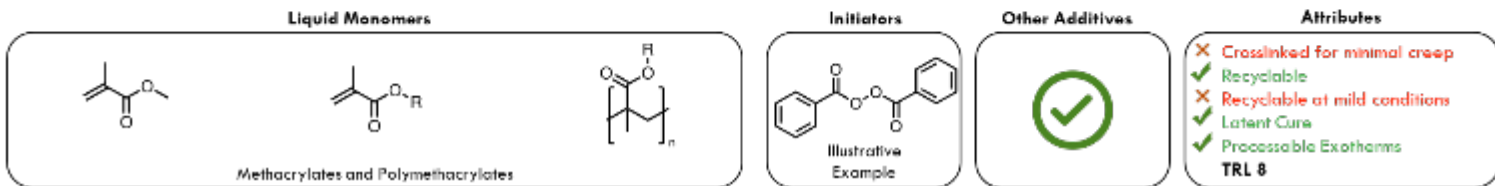
# Wind Blade Redesign – Considerations



## Epoxy-Amine Resins (Baseline – 'Industry Standard')



## Thermoplastic Resins (Baseline – 'Recyclable Standard')



### Materials for FRP must:

Be infusible at room temperature

Have an adequate working time

Have realistic exotherm.

Not Creep/Be compatible with fiber sizing

Have a latent cure

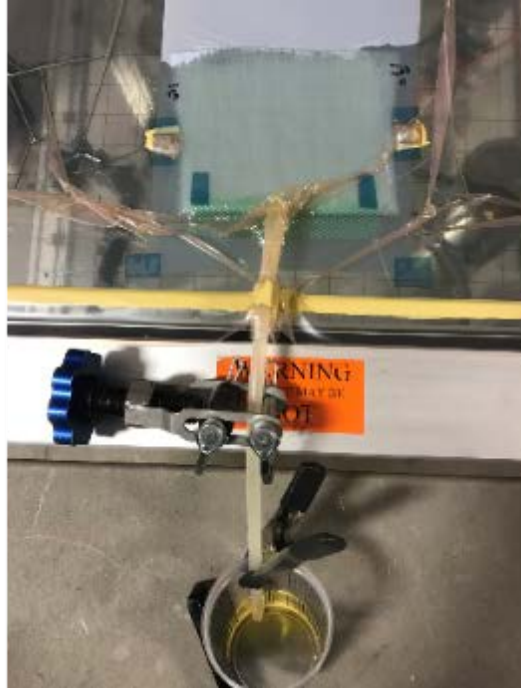
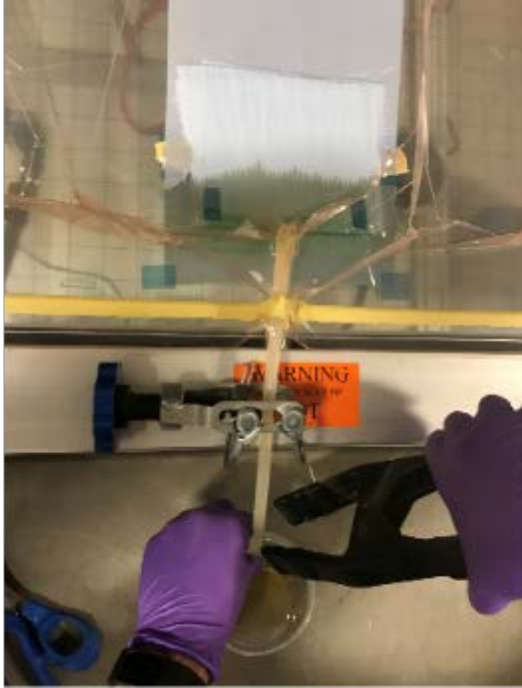
### Materials for FRP Ideally Would:

Be recyclable under mild conditions (think at a wind site)

Be low carbon intensity

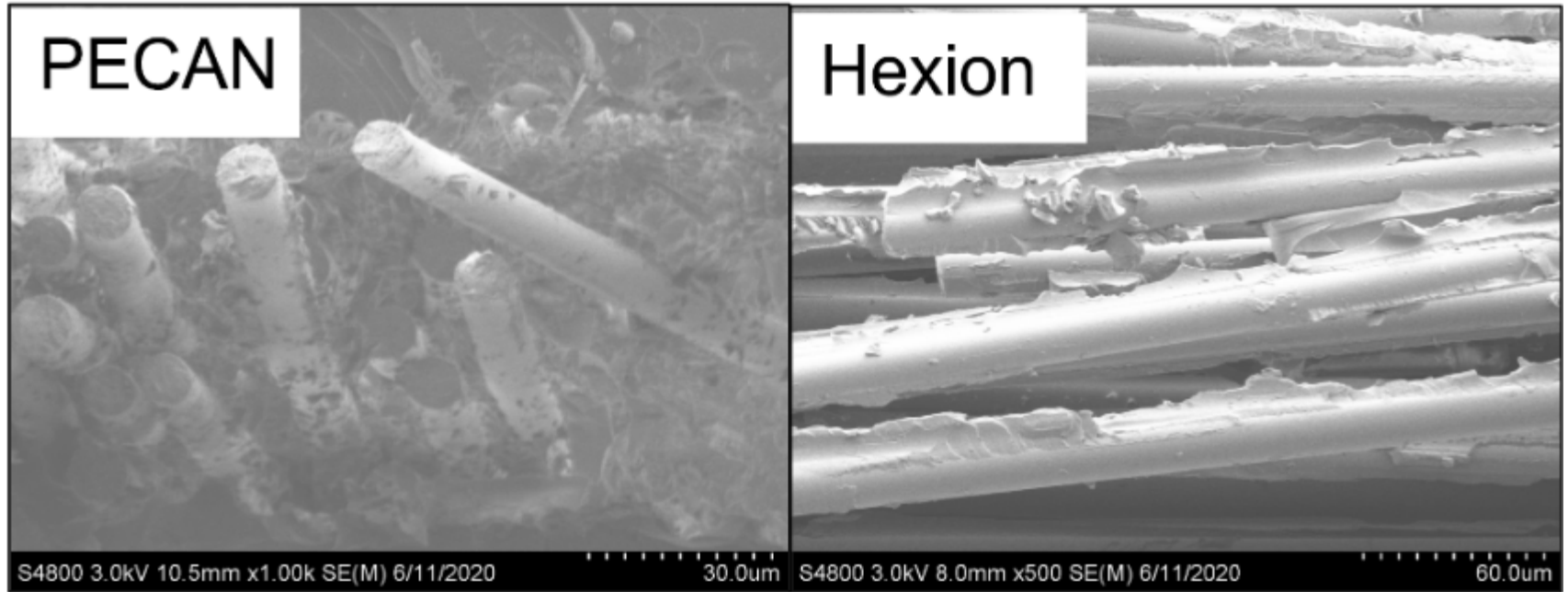
Possess lower energy cures

# Wind Blade Redesign – Scalable



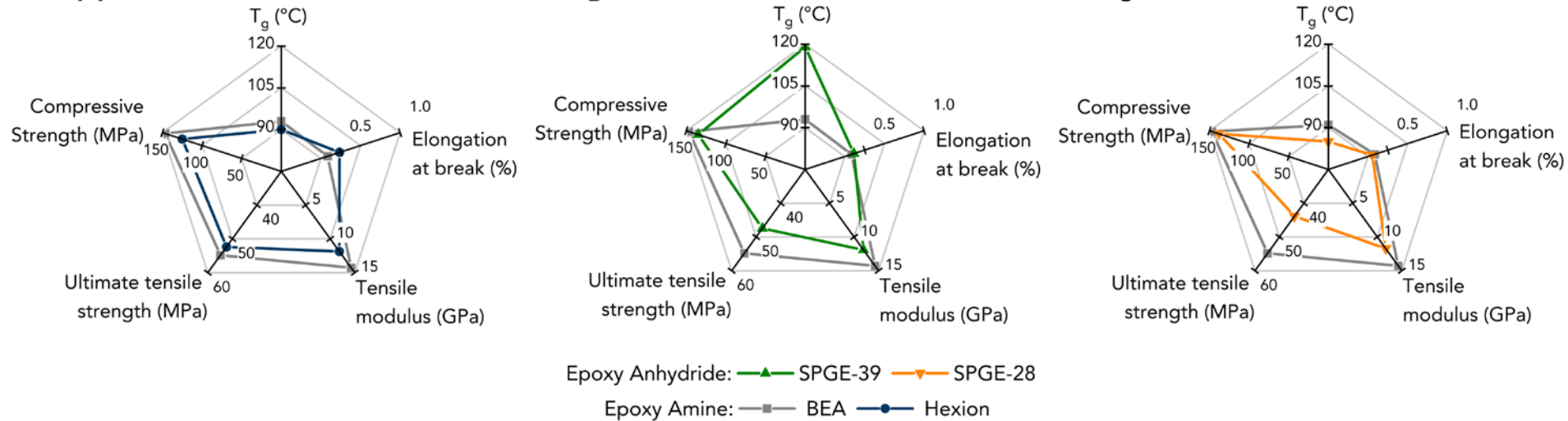
As noted before, the resin is infusible and can be cured to make a part

# Wind Blade Redesign – Compatible



**The interfacial reaction with the sizing is still favorable**

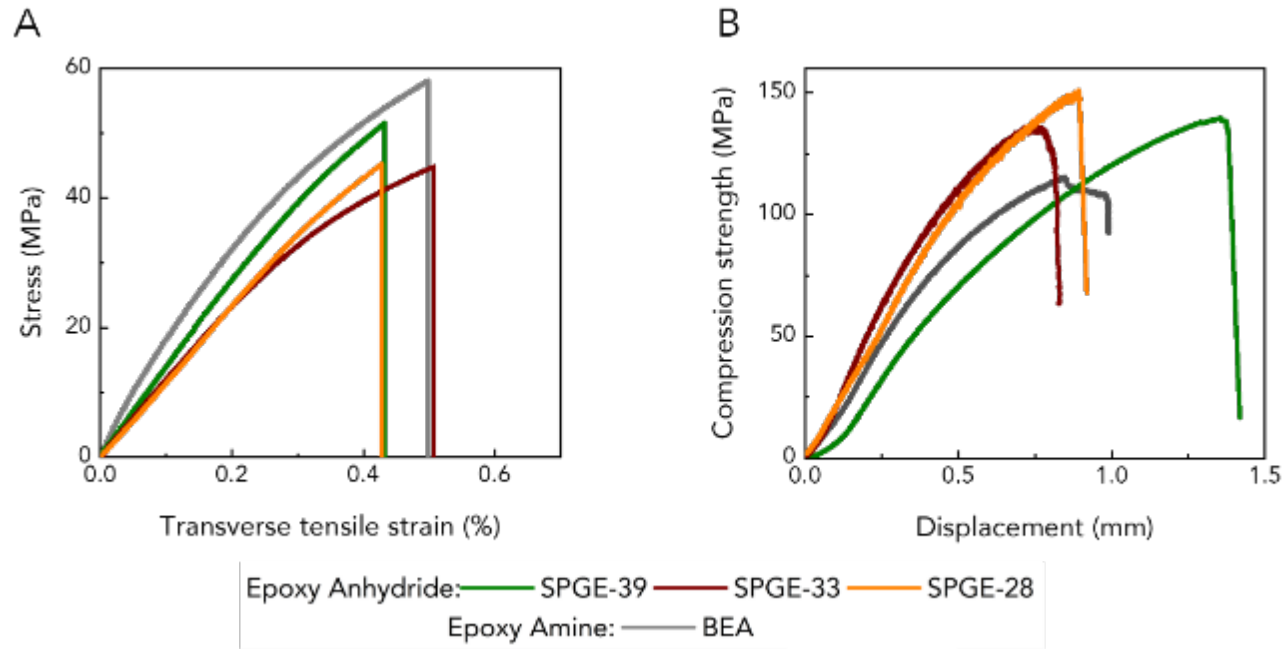
# Wind Blade Redesign – Tunable



**Baseline thermomechanical properties are tunable and meet epoxy amine properties**



# Wind Blade Redesign – Performance



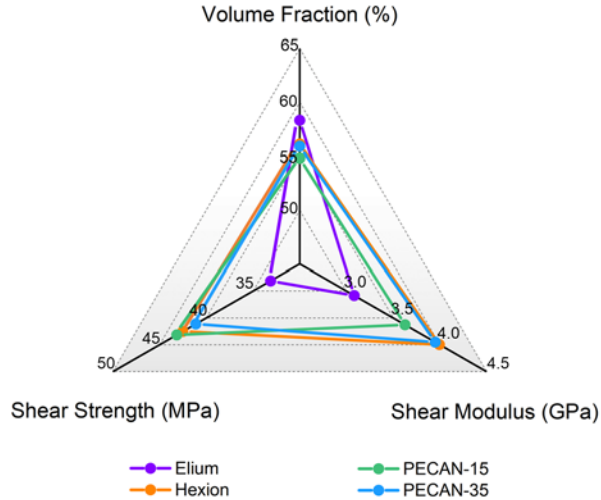
**Tensile properties, which matter for wind blades, are still aligned**

# Wind Blade Redesign – Performance



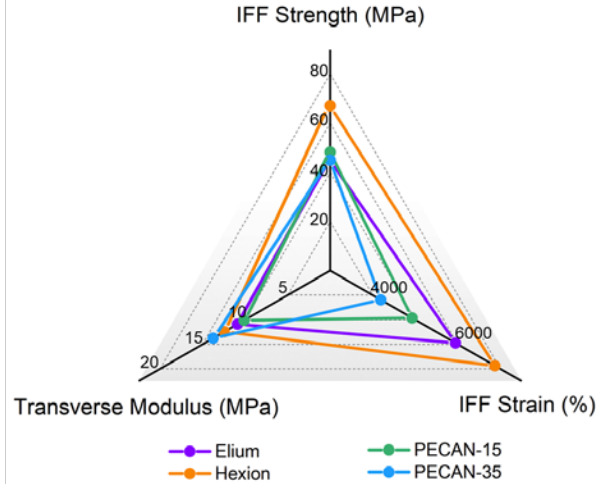
## Composites

Shear Testing (ASTM-D3518)



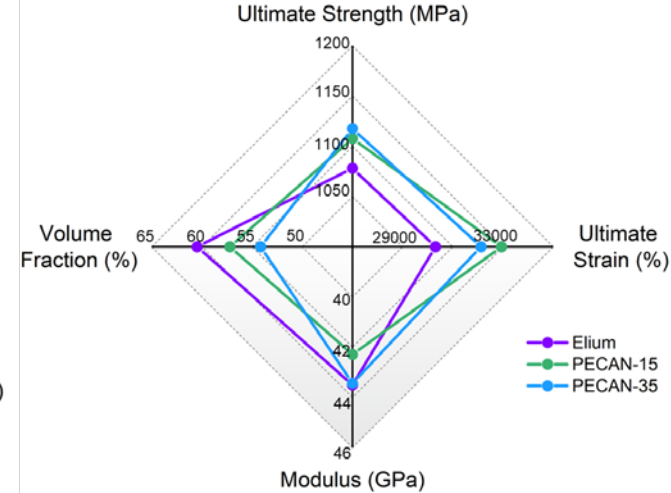
## Composites

Transverse Tensile (ASTM-D3039)



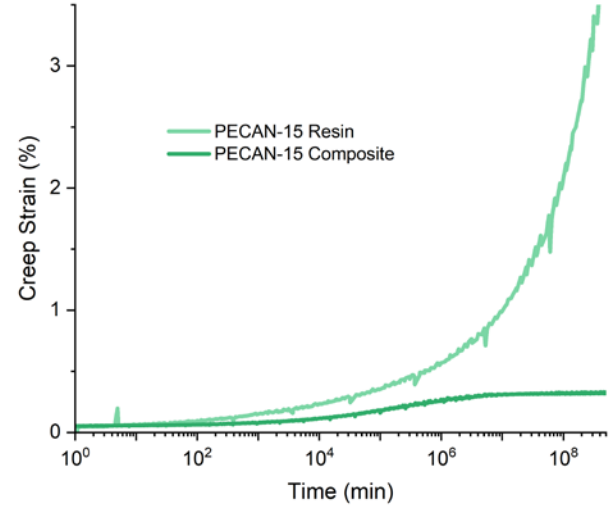
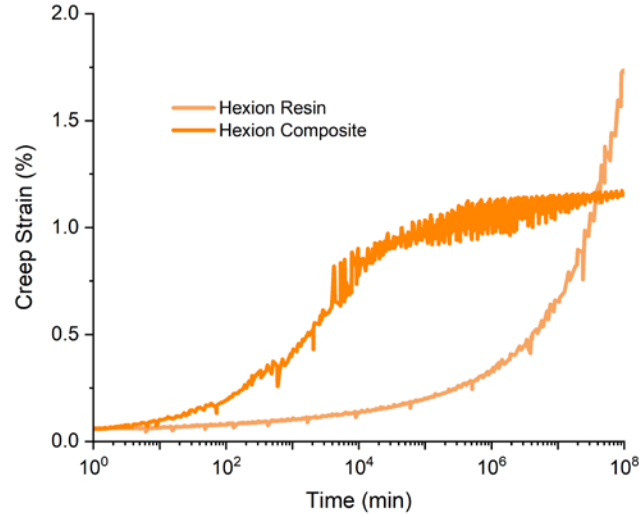
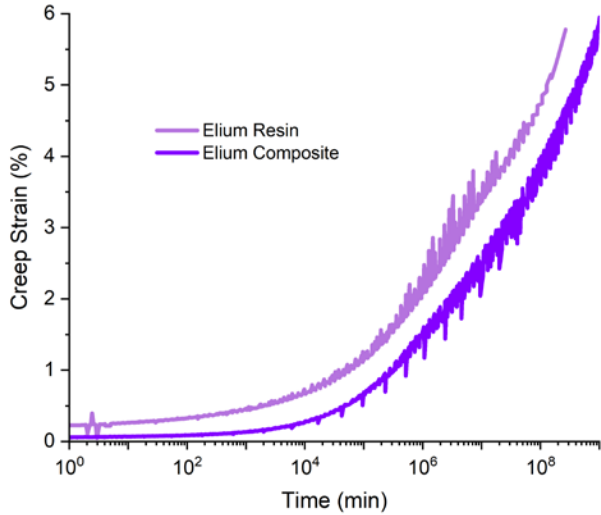
## Composites

Longitudinal Tensile Testing (ASTM-D3039)



**Epoxy anhydrides exceed PMMA performance while matching hexion**

# Wind Blade Redesign – Performance



**Epoxy anhydride do not creep. Importantly, creep is suppressed in FRPs**

# CFRC Redesign – Considerations

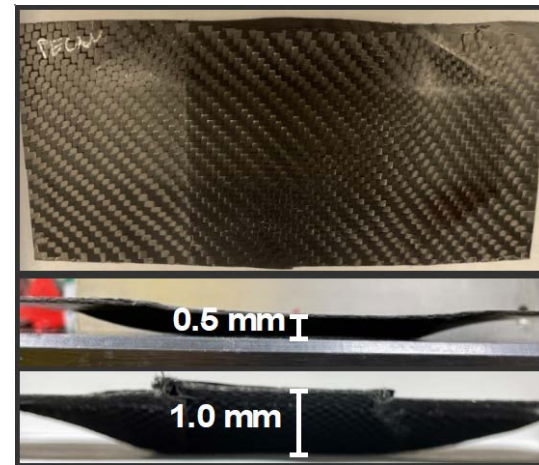
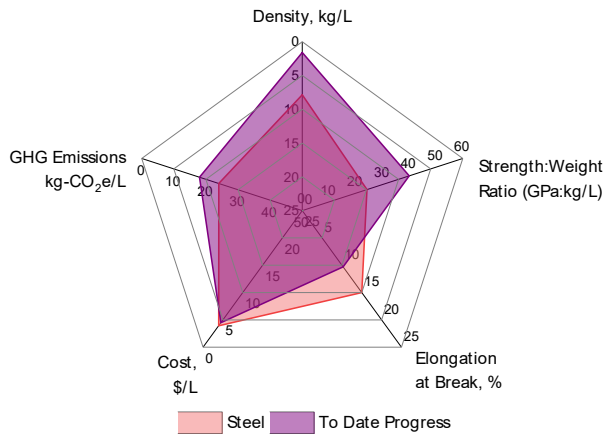
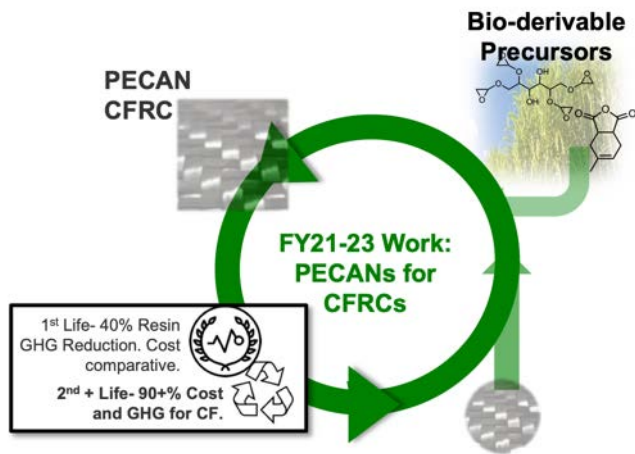


Recyclable



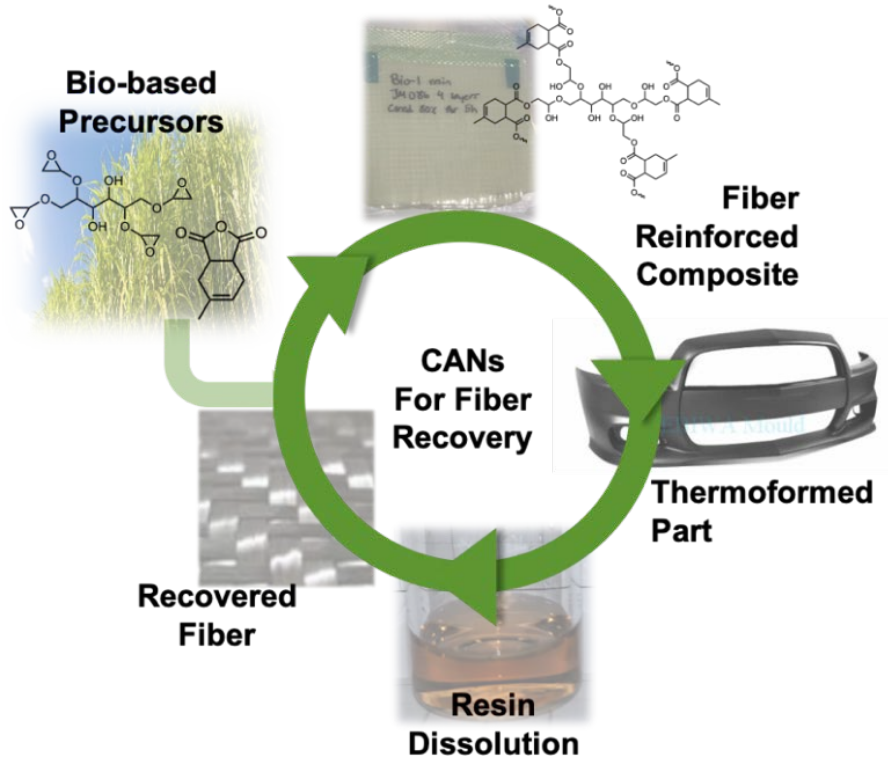
Tunable

Thermoformable



When redesigning CFRCs, we aren't replacing epoxy amines. We are replacing metal

# CFRC Redesign – Considerations



## Materials for CFRCs Ideally Would:

Be recyclable under mild conditions

Be thermoformable

Be cheap

Be ductile

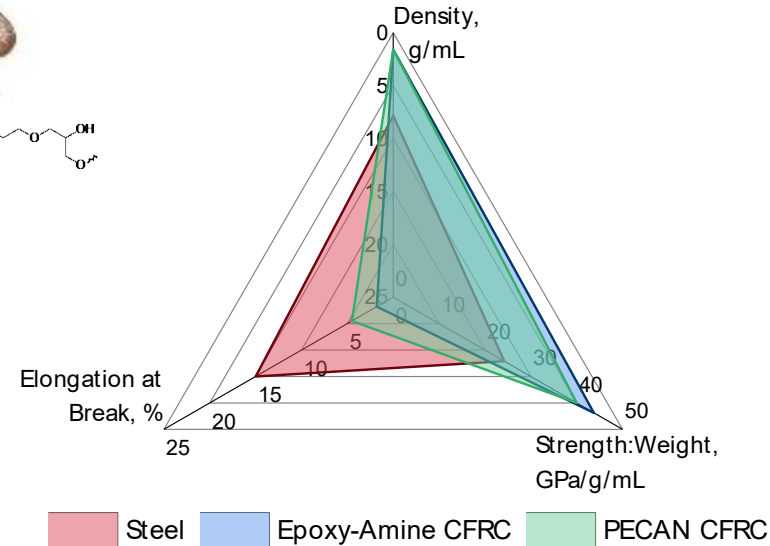
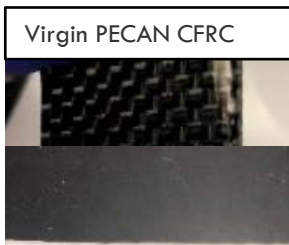
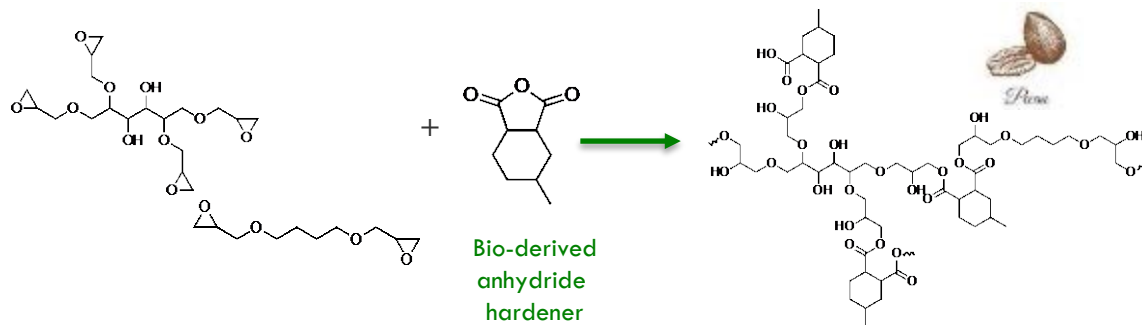
Have minimal associated GHG emissions with their manufacture

Have a robust supply chain

**Be lightweight to enhance fuel economy**

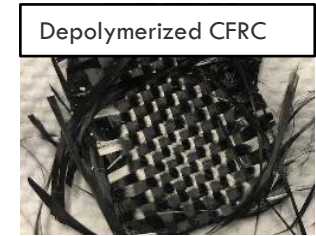
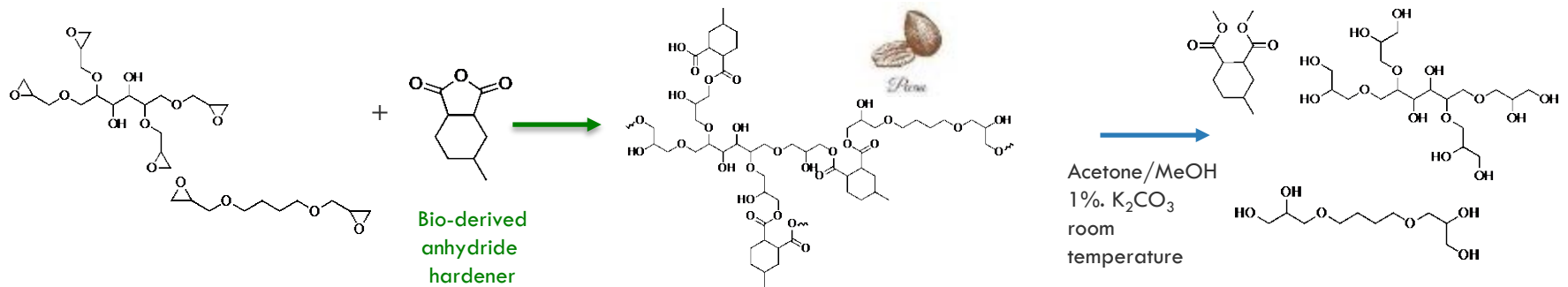
CFRCs are expensive, GHG intensive, brittle materials. Recycling can help two of those issues

# CFRC Redesign – Fiber Maintenance



Epoxy anhydride outperform the epoxy amine materials

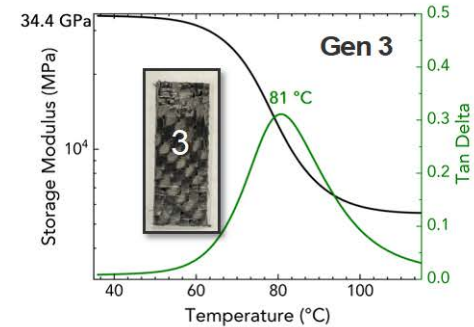
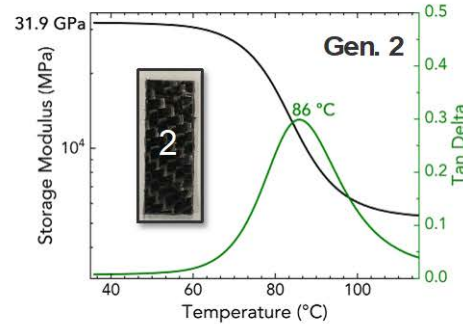
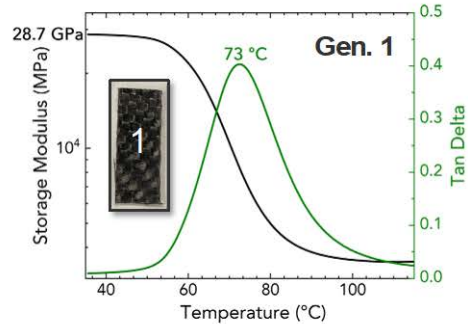
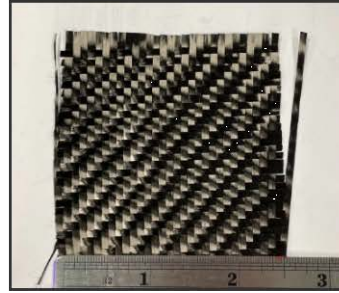
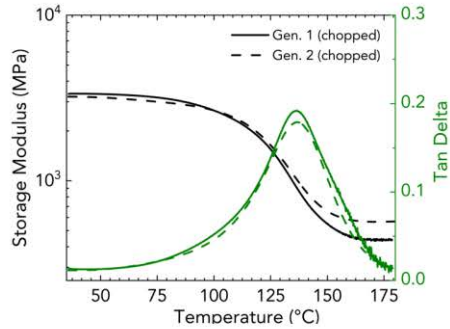
# CFRC Redesign – Fiber Maintenance



**Our mild recycling can maintain fiber alignment, which is important for maintaining properties**

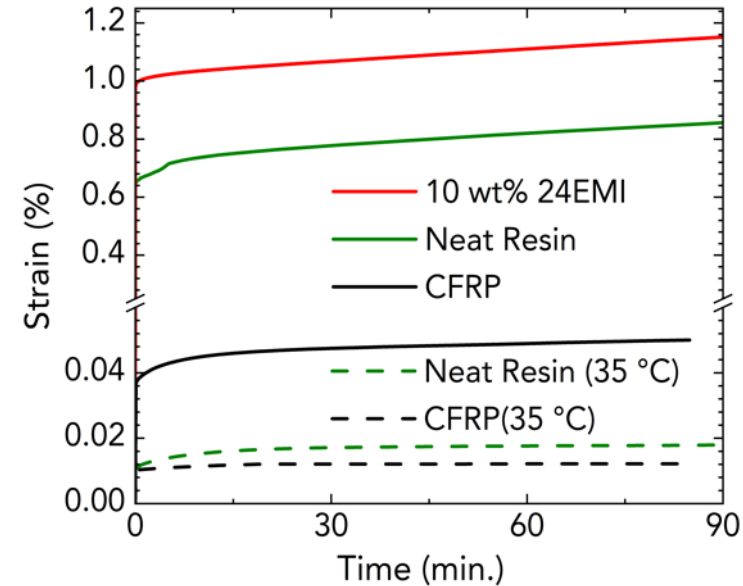
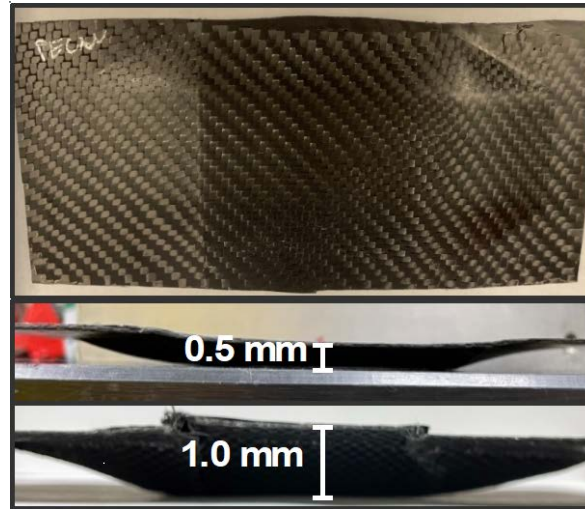
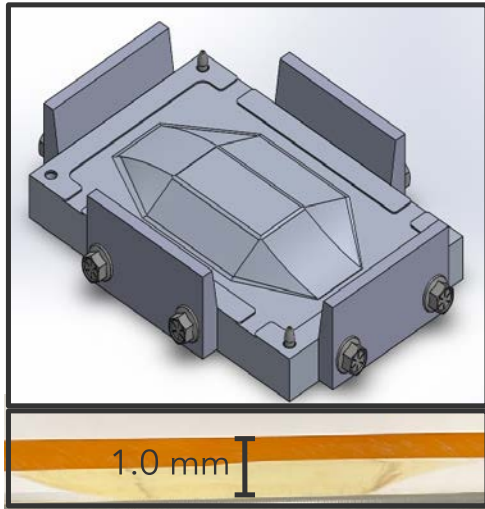


# CFRC Redesign – Performance Across Lives



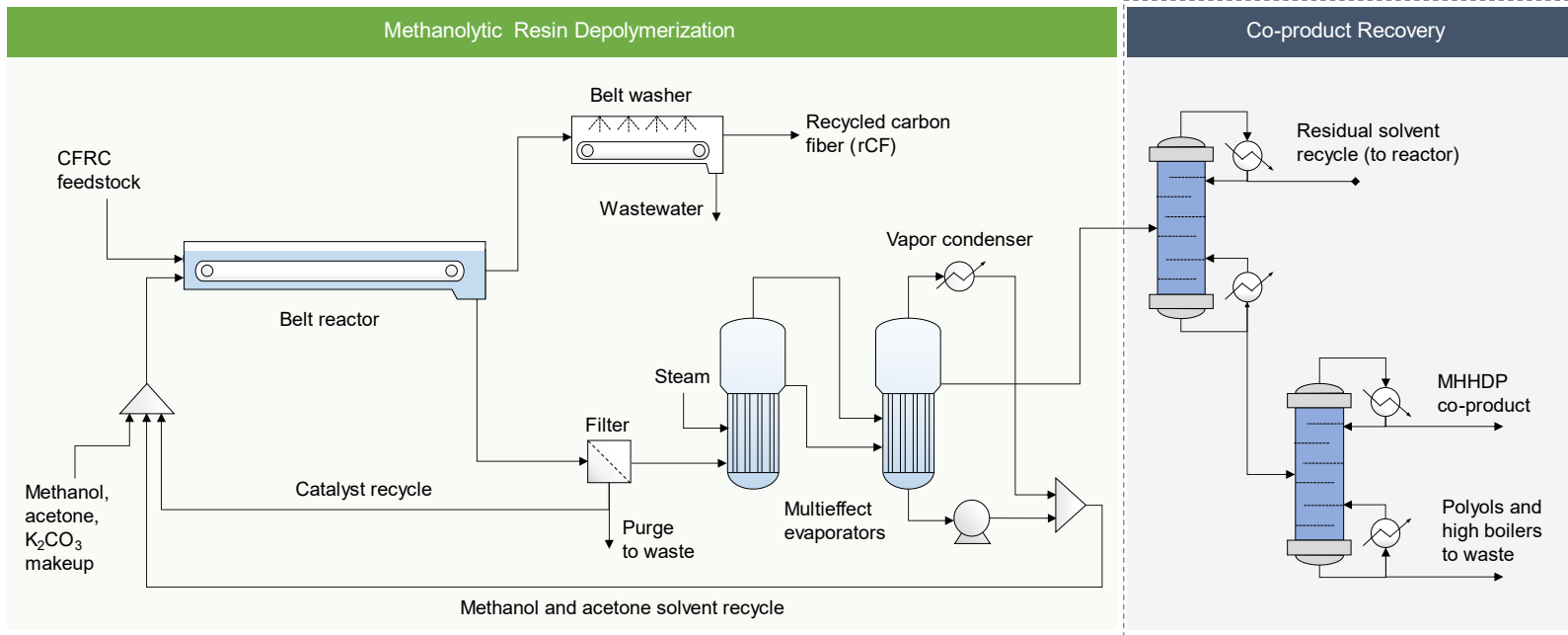
**Maintaining fiber alignment maintains performance**

# CFRC Redesign – Thermof ormable



Due to the 'recyclable'/vitrimeric nature of the polyester resins, they can be formed to shape

# CFRC Redesign – TEA/LCA of Recycling



**Due to the properties of this material, we can model recycling three different ways**

# CFRC Redesign – TEA/LCA of Recycling



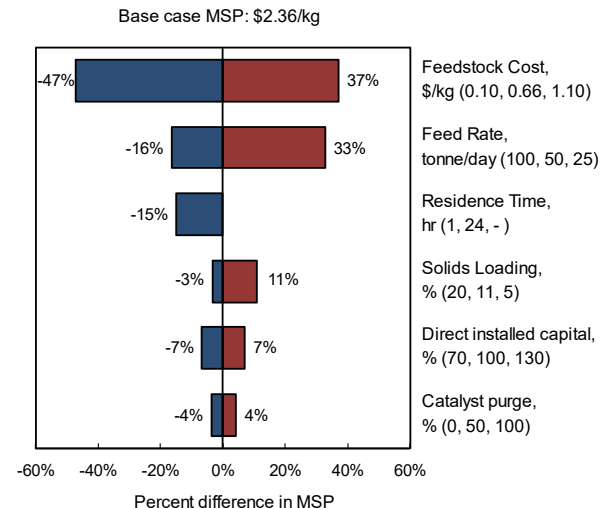
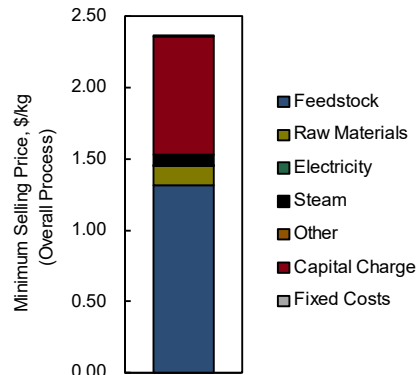
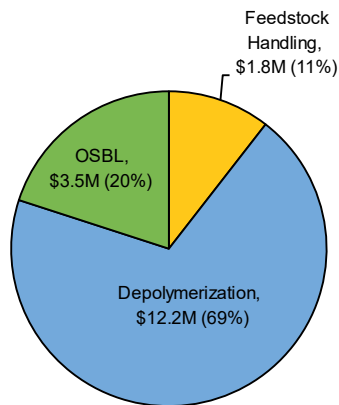
Fiber estimate price:  
**\$21.5/kg (variable)**



Hexion estimate price: **≥ \$2.03/kg**

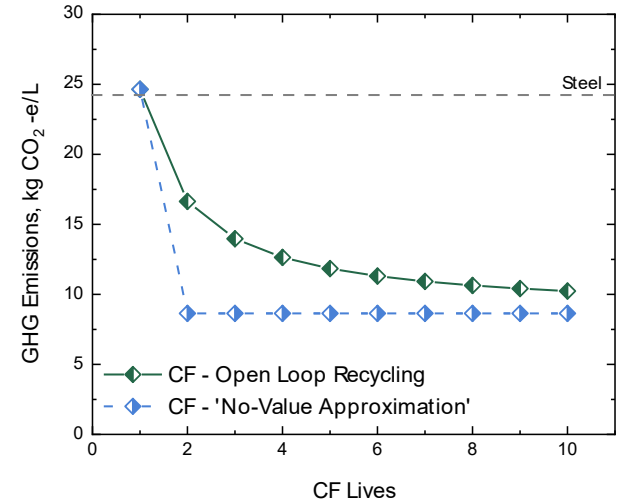
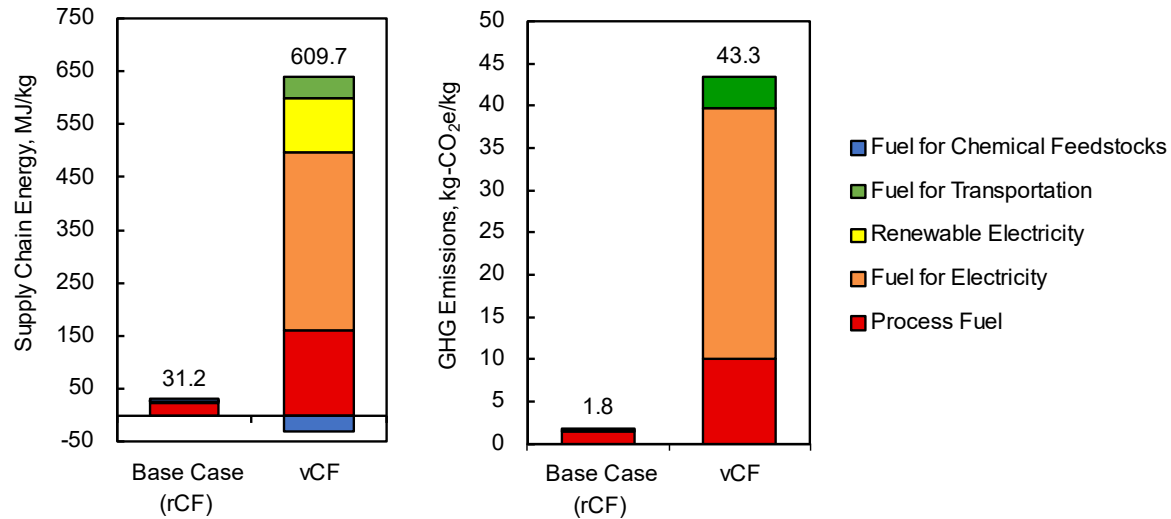


Estimate initial selling price: **≥ \$2.17/kg**



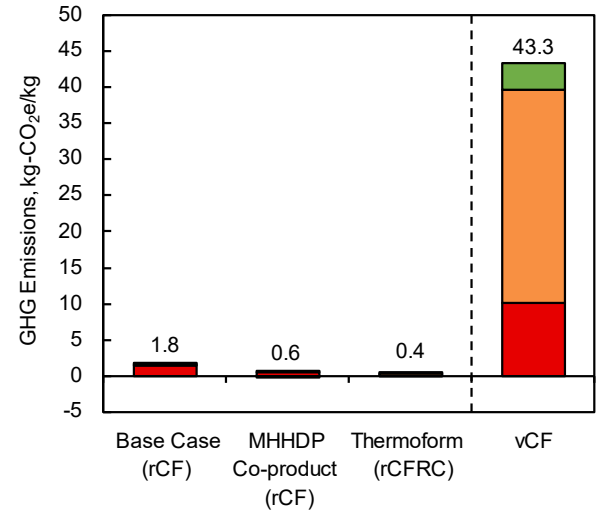
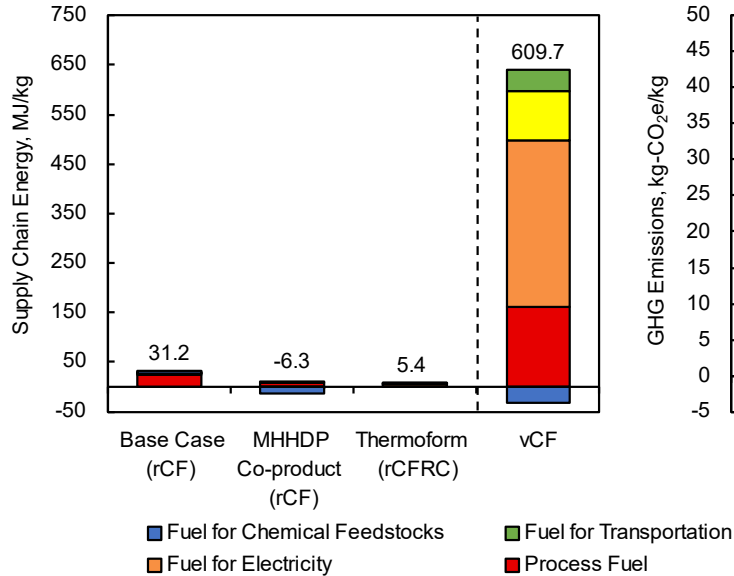
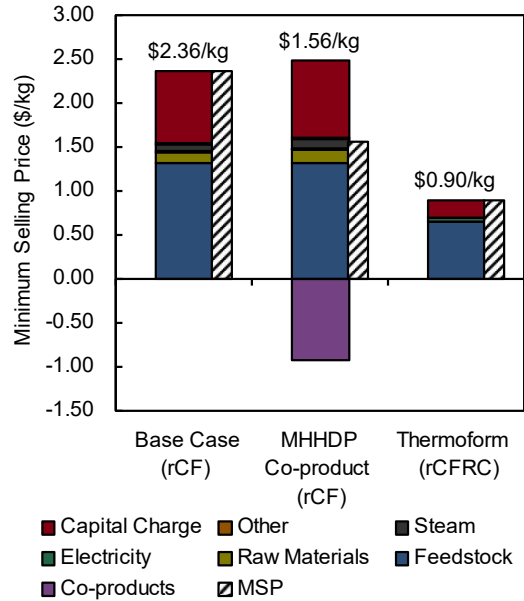
**The second life of the carbon fiber can cost 90% less than the first life, with more reductions possible**

# CFRC Redesign – TEA/LCA of Recycling



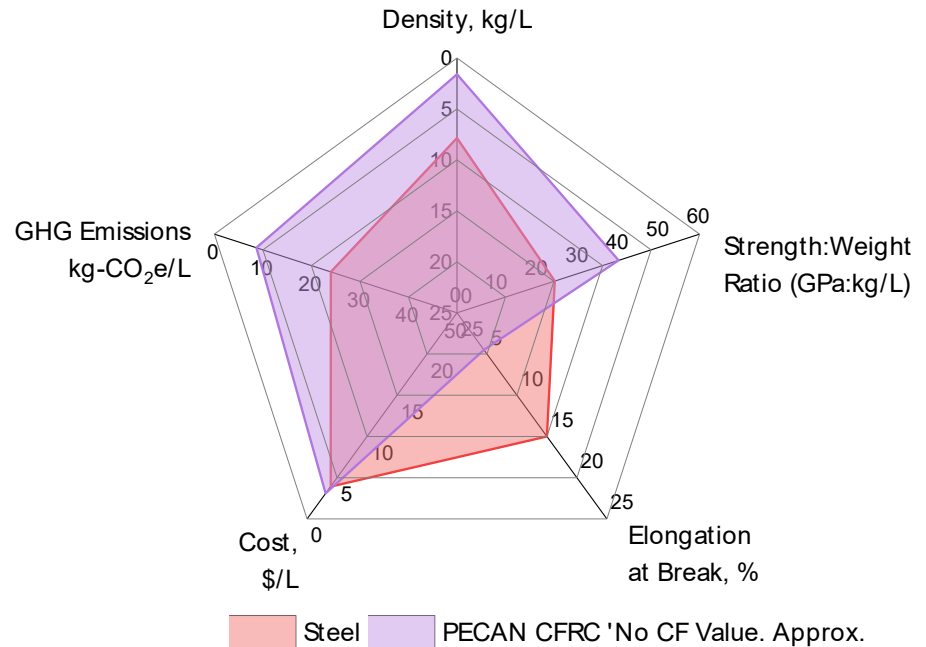
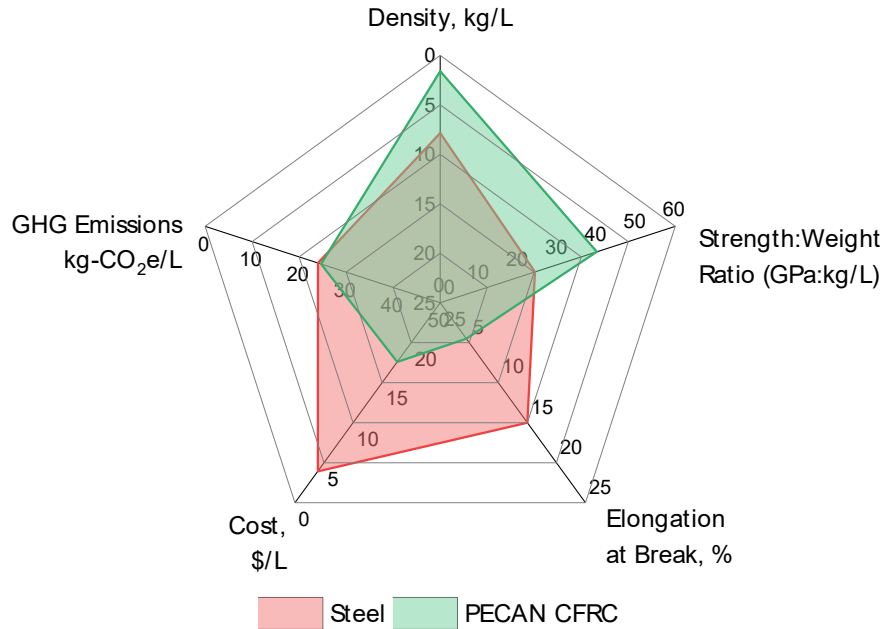
**GHG emissions are also reduced by >95%**

# CFRC Redesign – TEA/LCA of Recycling



**Hardener recovery, or implementing thermoforming for re-use, results in greater reductions**

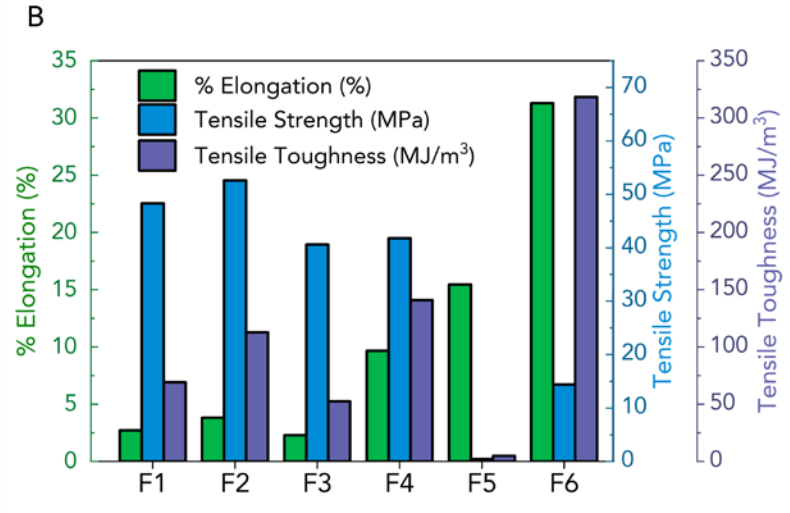
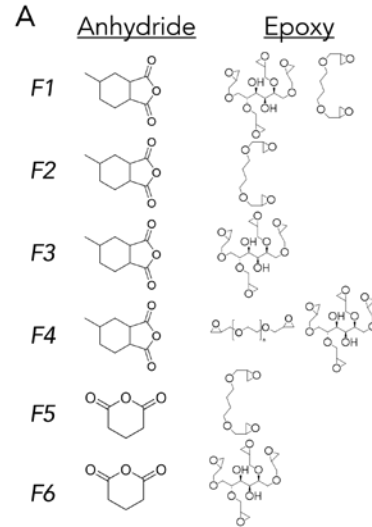
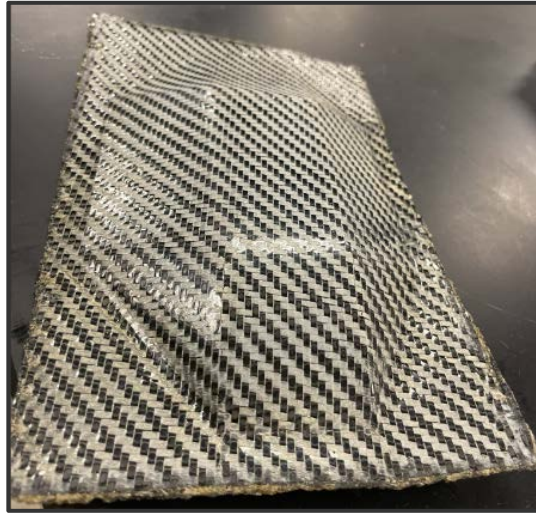
# CFRC Redesign – TEA/LCA of Recycling



**The second+ life CFRCs become cost and GHG competitive with steel**



# CFRC Redesign – Further Property Enhancement



**Formulation of the entire composite can achieve better properties for the first life as a steel replacement**



# Thank You!

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[www.nrel.gov](http://www.nrel.gov)

NREL/PR-2800-87186

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