Towards sustainable composites?

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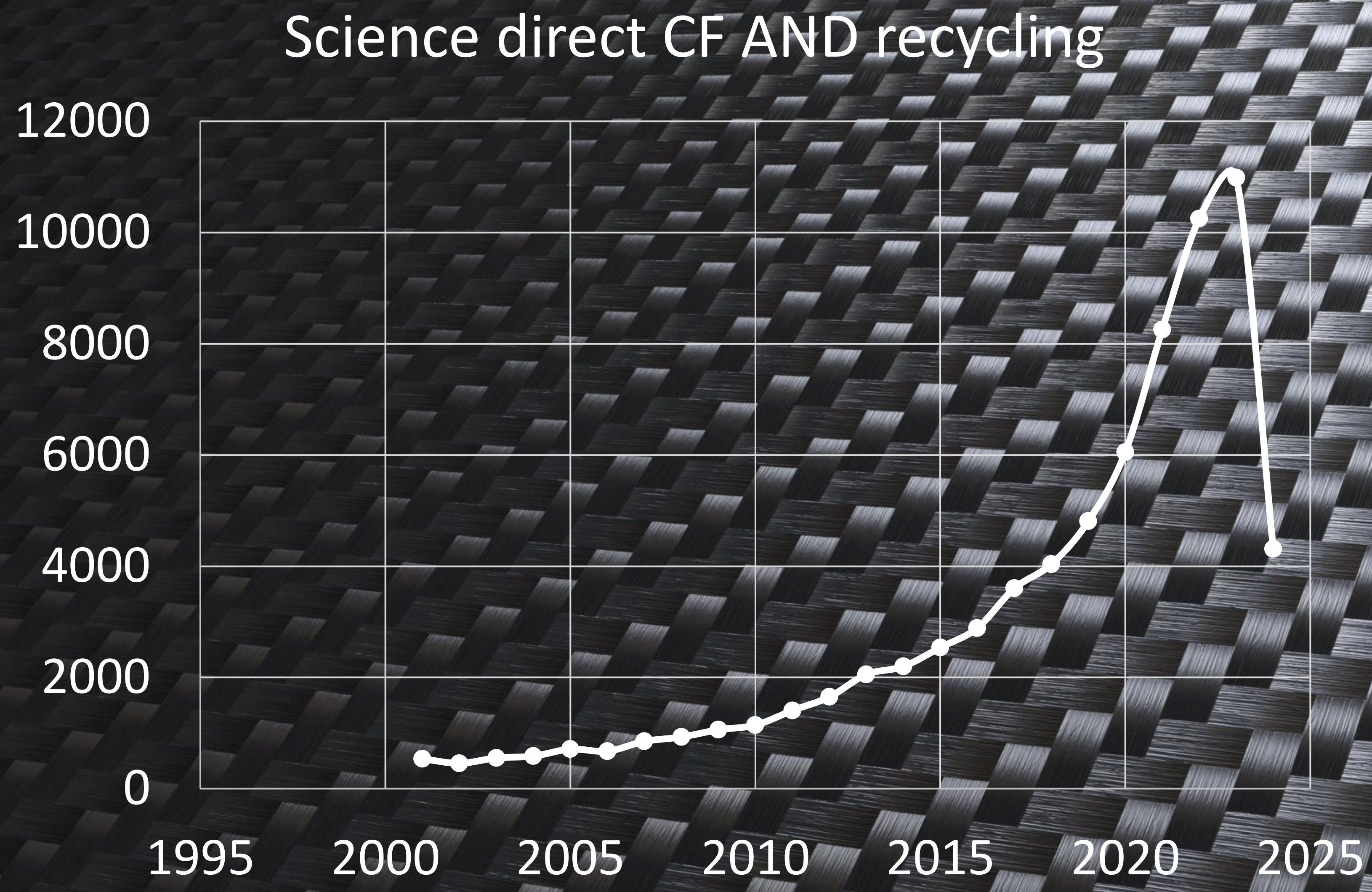
LPAC Laboratory for Processing of Advanced Composites

CF AND recycling: Science Direct



Question 1:
Does this correspond to an equivalent growth in CF recycling and recovery?

Question 2:
If NO, then why?

Question 3:
What is the degree of circularity of composites?

Question 4:
Can S&T solve this problem?

Overview - Towards sustainable composite solutions

- Policy
- End of life and recycling
- Bio-based / novel materials
- Circular composites
- Additive manufacturing
- Unmet challenges

Policy - Green deal

Commission adopted a set of proposals to make the EU's climate, energy, transport and taxation **policies fit for reducing net greenhouse gas emissions by at least 55% by 2030**, compared to 1990 levels.

Making transport sustainable for all

Our transition to greener mobility will offer clean, accessible and affordable transport even in the most remote areas.

Cleaning our energy system

Reducing greenhouse gas emissions by at least 55% by 2030 requires higher shares of renewable energy and greater energy efficiency.

The European Commission proposes more ambitious targets for reducing the CO_2 emissions of new cars and vans.

40%
new renewable energy target for 2030

36-39%
new 2030 energy efficiency targets for final and primary energy consumption

55%
reduction of emissions from cars by 2030

50%
reduction of emissions from vans by 2030

0
emissions from new cars by 2035

Transport emissions decrease by 90% by 2050 to meet GD objectives.

Policy - Reach (chemicals and their use, e.g. in polymers)

REACH: Registration, Evaluation, Authorization, and Restriction of Chemicals

EU legislation

- EL vehicle for automotive
- None for aerospace
- Landfill legislation
  - Current: Waste Framework Directive 2008/98/EC
  - Different EU state implementation; legal gaps
    - The need of harmonized EU provisions is highlighted by different approaches taken up by some EU Member States.
    - Belgium, Denmark and Austria allow landfilling in general
    - Germany & Netherlands established a ban on composite materials waste landfill
  - Future: Directive (EU) 2018/850: stronger limits

Policy - European ELV legislation

- "Polluter-pays"
  - Vehicle producers meet all or significant part of ELV treatments, collection & recycling network
- Component and material coding standards
  - Vehicle manufacturers must provide dismantling info for each new vehicle on the market
- Special mean values and prohibitions
  - Heavy metals - lead, cadmium, hexavalent chrome and mercury
- Design for recycling & recovery (conception phase)

Vehicles made (not designed) before 1 Jan 1990, recycling target of 75% (including max 5% to energy recovery)

From Jan 2015:

reuse & recovery: min. 95% wt./vehicle/yr

reuse & recycling: min. 85% wt./vehicle/yr

YESTERDAY:

Landfill: 25%
Re-use, materials recycling: 75%

Directive 2000/53/CE on the End of Life Vehicles

TOMORROW (2015):

Landfill: 5%
Re-use, materials recycling: 85%
Energy recovery: 10%

New design approach:
- design for recycling
- greenthinking

- Improve circular design of vehicles to facilitate removal of materials, parts and components for reuse and recycling
- **Ensure that at least 25% of plastic used to build a vehicle comes from recycling (of which 25% from recycled ELVs)**
- **"25 + 25"**

How much will these rules cost?

Less than 70€ per vehicle

Big issue for composite material systems (e.g. epoxy resin)

Aerospace end of life

- No equivalent EU legislation

In storage	2017-2030
• over 2’000 aircraft in storage world-wide • number of military aircraft in storage is considerably greater	• 6’000 to 8’000 commercial airlines reach end of life, 3kT CF/year • over next 20 years, ~5’000 commercial airliners are expected to be withdrawn or retired from service • ~250/year

1 (ox.ac.uk)

Overview - Towards sustainable composite solutions

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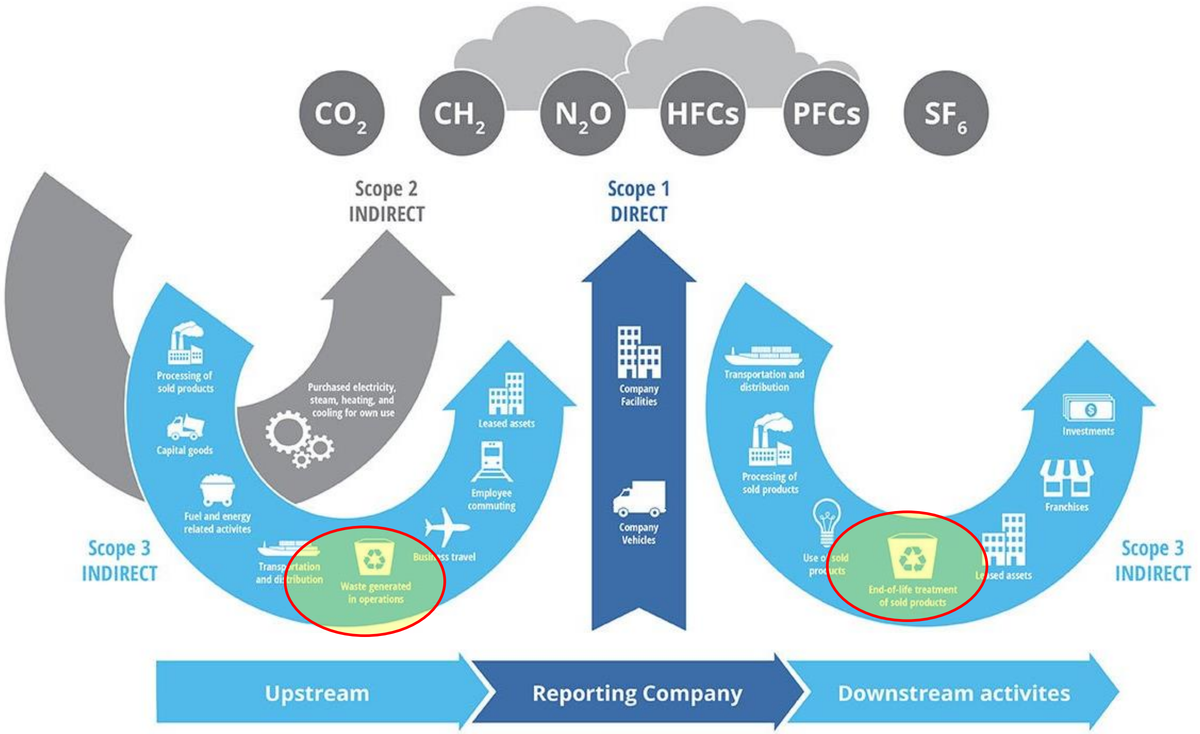


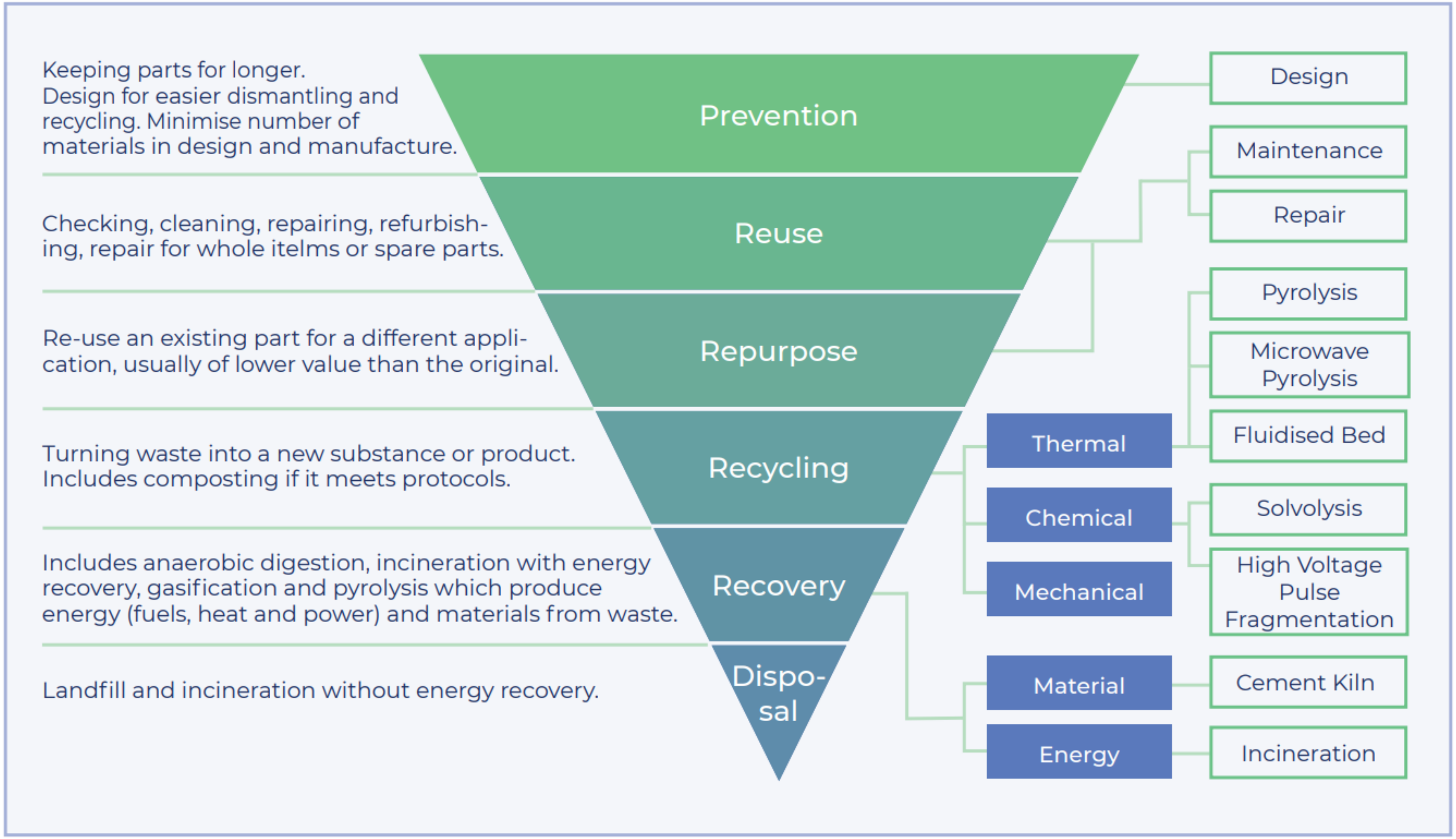
THE WORLD'S MOST ADVANCED MATERIAL HAS A DIRTY WASTE PROBLEM

- Over **90%** of carbon fibre ends up in landfill
- **20x** more CO_2 emitted than steel
- Expected **500,000,000 kg** of carbon fibre waste by 2035

15.5 Mt CO_2e

Composite waste management hierarchy

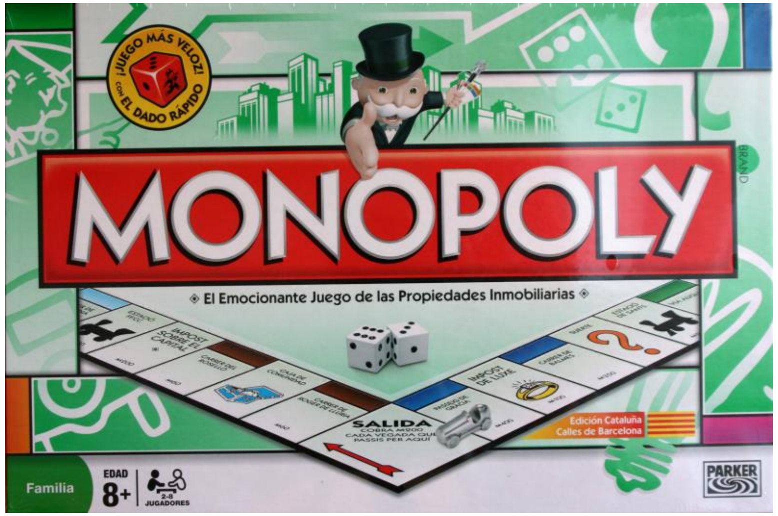
- Desirability is highest at the top of the diagram and decreases going down
  - Preventing a composite part from reaching its EoL is more desirable than recycling it
    - Recycling more desirable than disposing of it

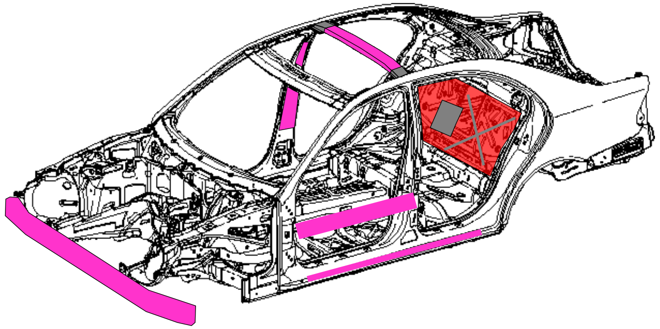


For each step, the processes identified as being most promising and desirable are given.

[Suschem_composites_circularity_pages.pdf (baxcompany.com)]

Post industrial CF waste = post industrial $ money






MONOPOLY
500
500
500

What is in our waste and EL streams?

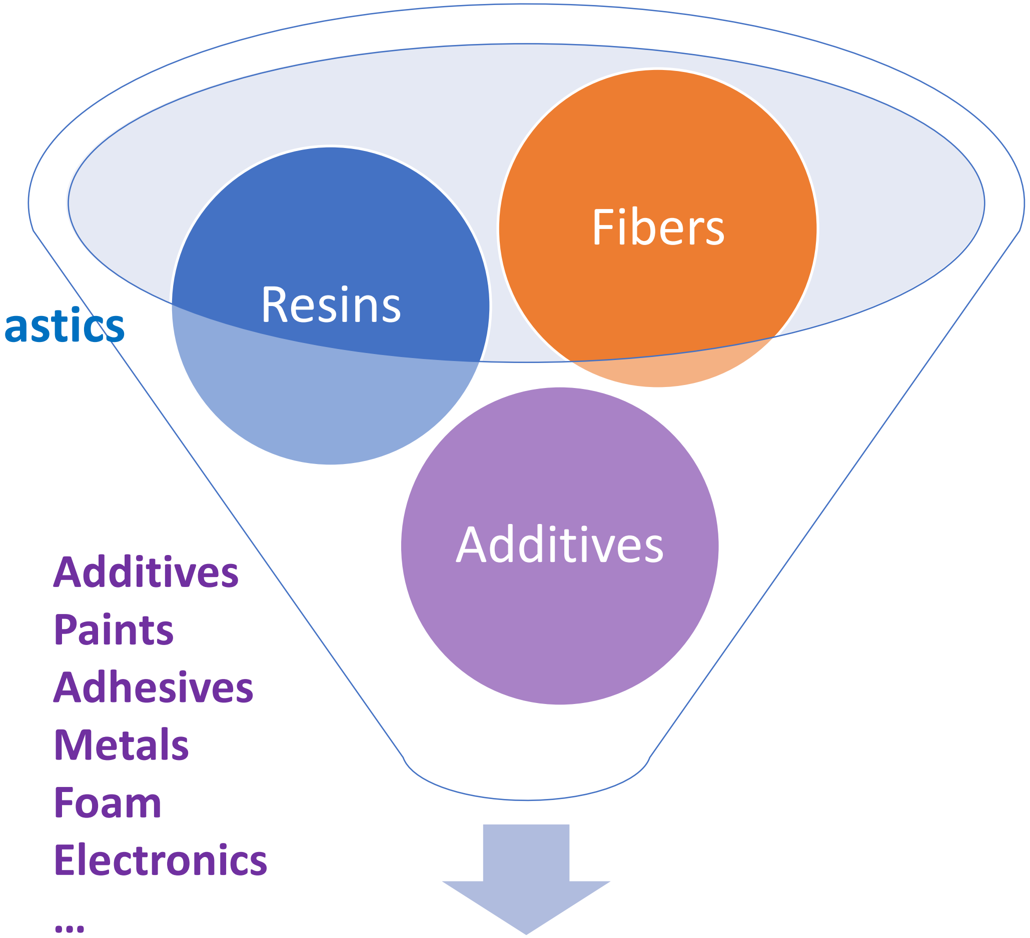
Thermosets
Cured / B-staged

- Polyester
- Polyurethane
- Vinyl-esters
- Epoxy
- Phenolic
- Cyanate Ester
- Bismaleimide and polyimide
- Benzoxazine
- Phthalonitriles
- …

Thermoplastics

- PE
- PP
- PET
- PA
- PPA
- PC
- PEI
- PPS
- PEAK
- PEEK
- …

Additives
Paints
Adhesives
Metals
Foam
Electronics
…



Our waste flow

- cm to 10's meters

- Different lengths
- Dry / impregnated
- Glass
  - S-Glass
  - E-Glass
  - C-Glass
  - XM-Glass
- CF PAN
  - Many different grades
- CF Pitch
- Kevlar (different grades)

Composites waste management?

Wind energy needs a circular approach

- by 2050, 43 million tonnes of decommissioned turbine blades will reach their end of life and need to be managed through the global waste stream
- Current practice in US and EU is landfill

Circular economy theory of wind turbine blades

Source: GWEC Market Intelligence, March 2021

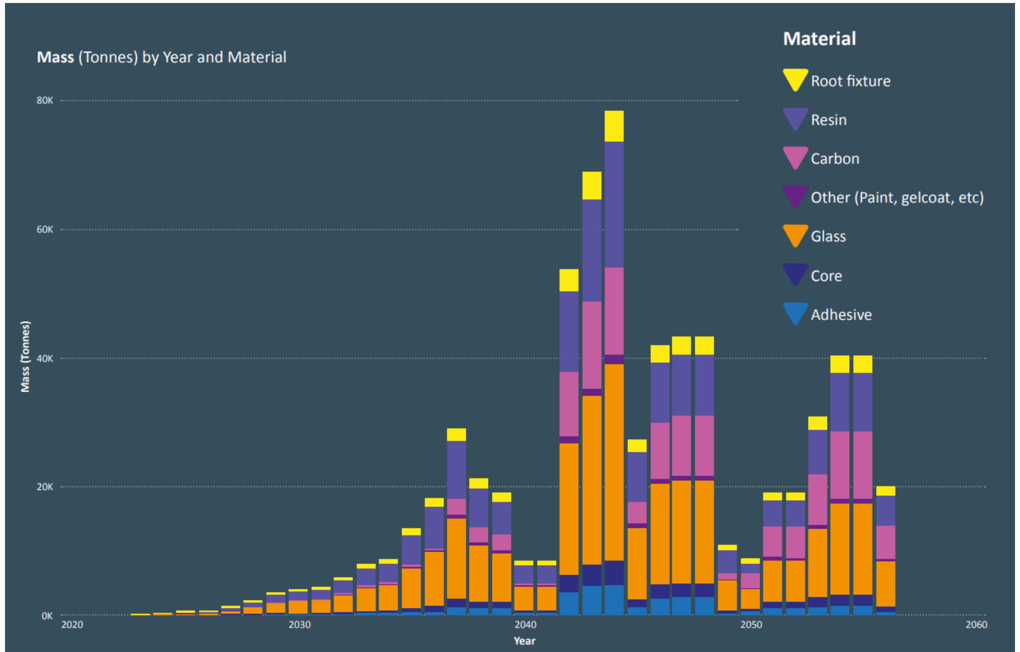


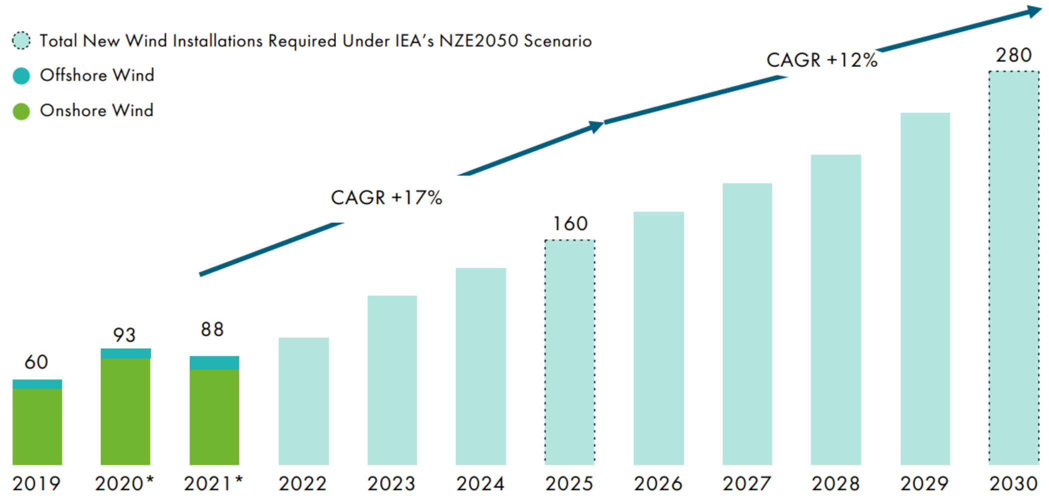
Figure 4 Offshore blade masses by material

Offshore UK wind waste stream by material to 2055

suswind-annual-review-2022-final.pdf (nccuk.com)

Annual wind installations must increase dramatically to reach net zero by 2050

New global wind installations (GW)



Source: GWEC Market Intelligence; IEA World Energy Outlook (2020), volume in 2022-2024 and 2026-2029 are estimates

EPFL

Energies | Free Full-Text | How to Repair the Next Generation of Wind Turbine Blades (mdpi.com)

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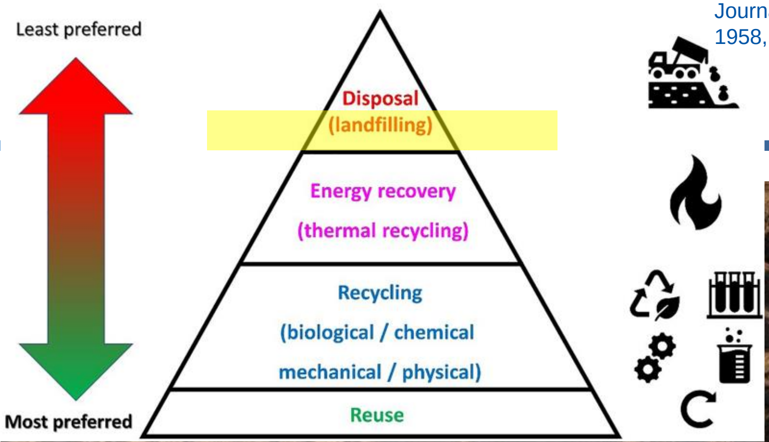
Issues with landfill

Journal of Polymer Science, Volume: 61, Issue: 17, Pages: 1937-1958, First published: 19 May 2023, DOI: (10.1002/pol.20230154)

Wyoming's Wind Turbine Graveyard
CASPER, WYOMING, USA - January 9, 2020: Pieces of wind turbine blades are buried in the Casper Regional Landfill in Casper, Wyoming. Around 8,000 wind turbine blades will need to be removed and disposed of a year in the United States alone. Because of the conditions they are built to withstand, the blades cannot be easily recycled. This leads many of them to be buried in landfills like Casper's, where 870 blades stacked into holes 30 feet deep. (Photo by Benjamin Rasmussen/Getty Images)



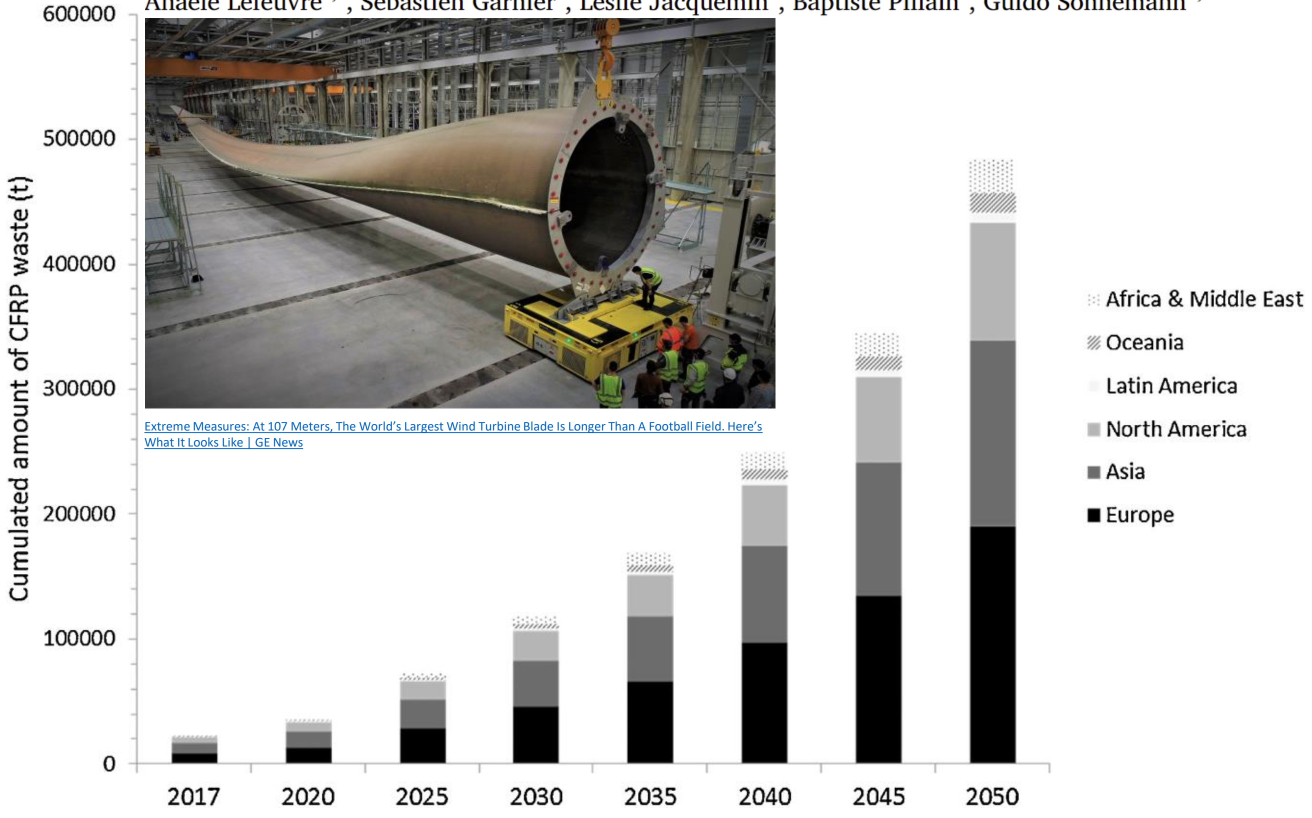
Bisphenol-A-Pollution-Wind-Turbines.pdf (wind-watch.org)
Abandoned Wells Can Provide Use for Pulverized Wind-Turbine Blades | Journal of Petroleum Technology | OnePetro
ACP_MicroplasticsFactSheet_March-2023.pdf (cleanpower.org)

Start by not throwing it away …

Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050

600kT

Anaële Lefeuvre[a,*], Sébastien Garnier[a], Leslie Jacquemin[a], Baptiste Pillain[a], Guido Sonnemann[b,c]

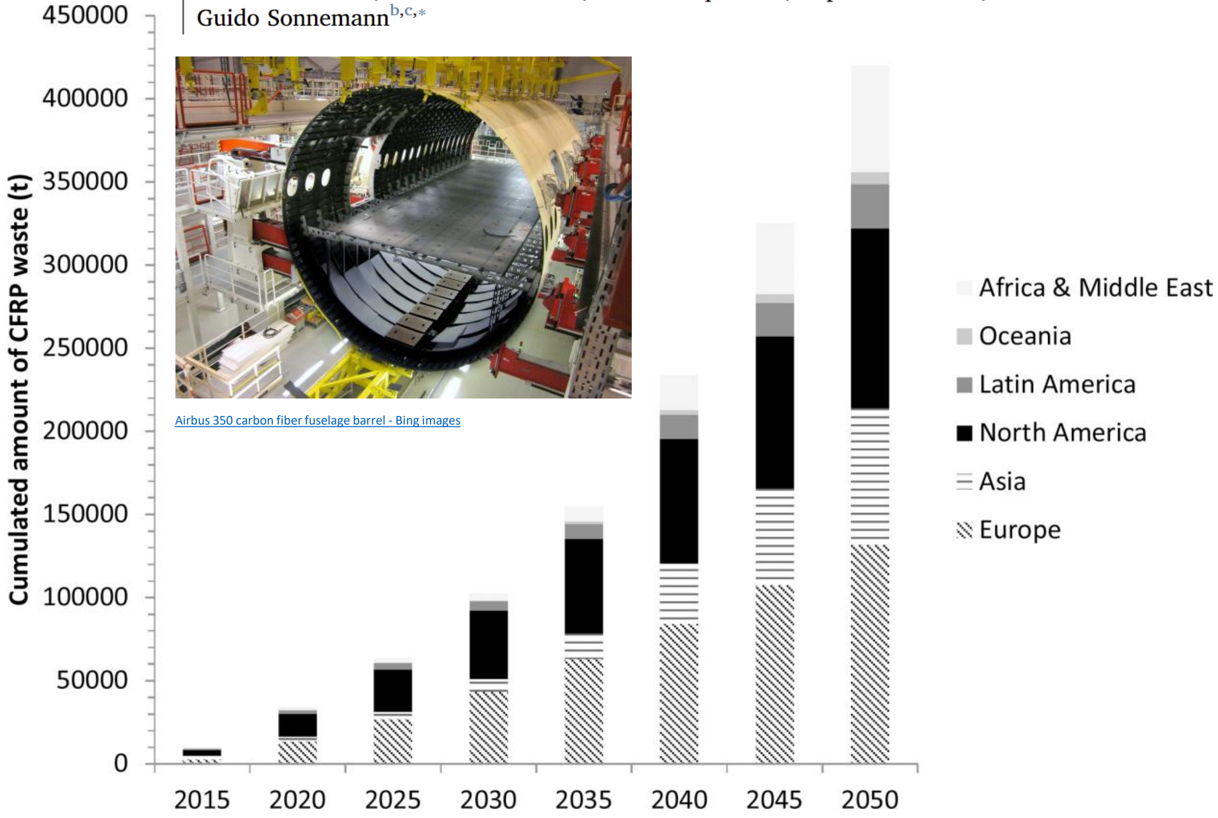


[Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050 - ScienceDirect]

Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050

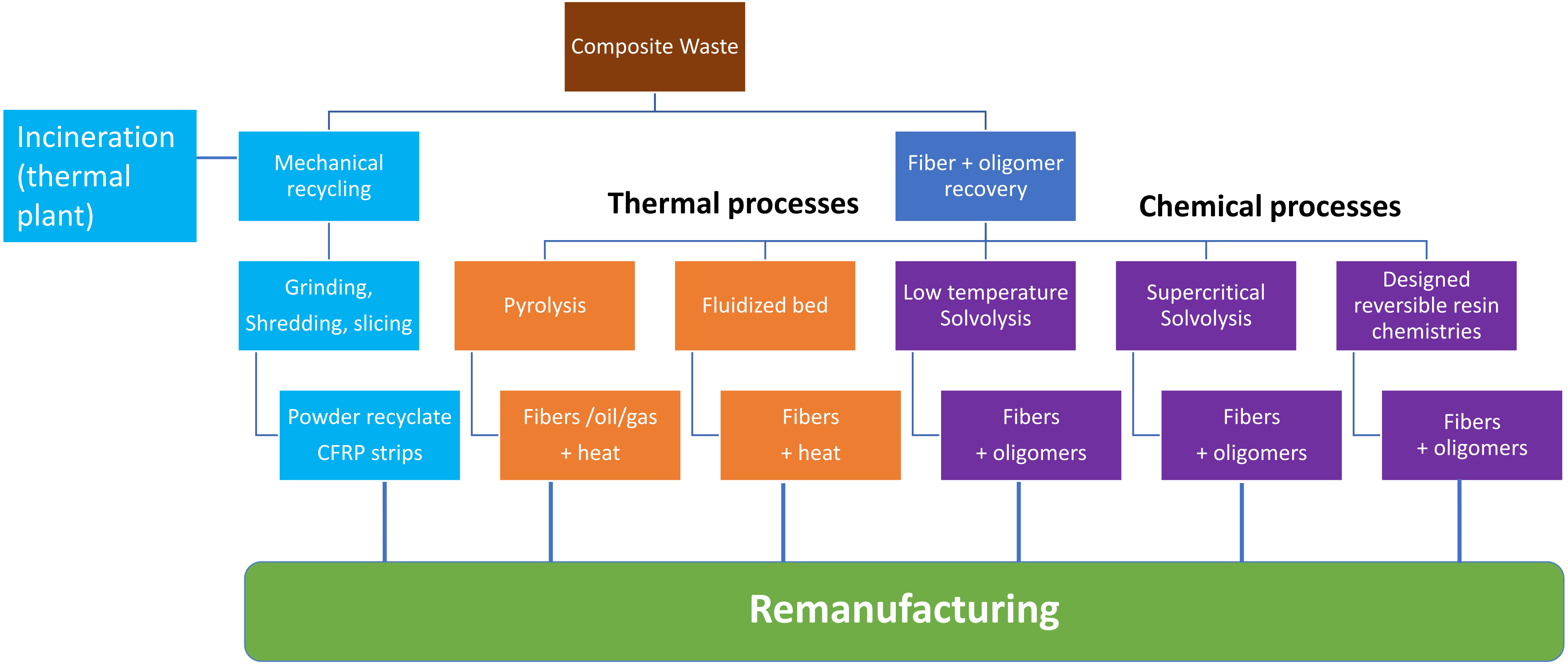
450kT

Anaële Lefeuvre[a], Sébastien Garnier[a], Leslie Jacquemin[a], Baptiste Pillain[b,c], Guido Sonnemann[b,c,*]



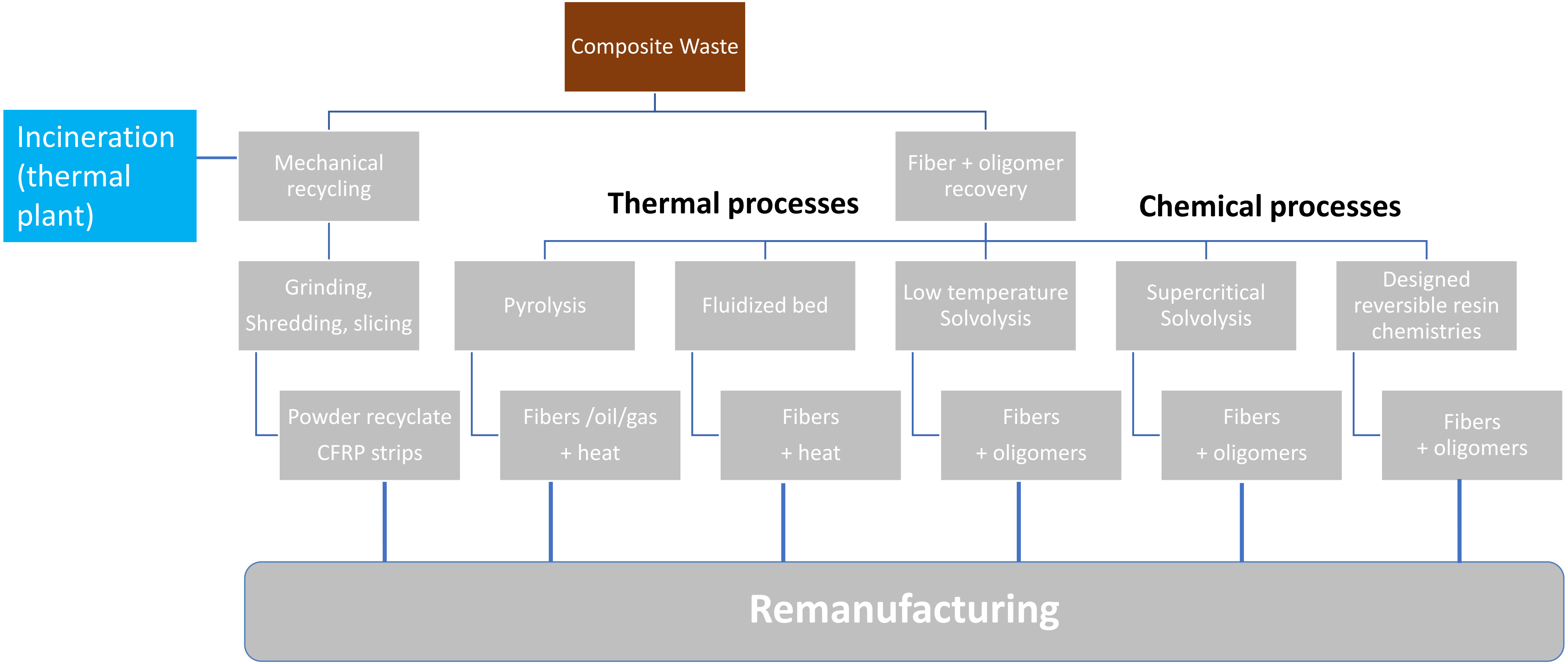
Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050 - ScienceDirect

Recycling Routes



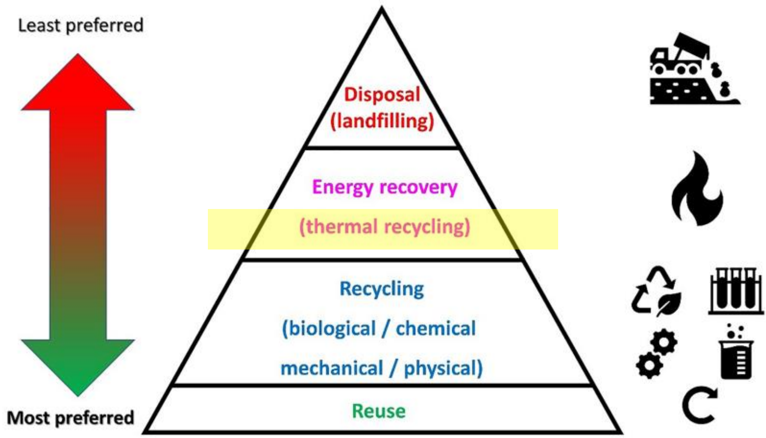
Adapted from Pickering, Composites Part A (2006)

Recycling Routes



Adapted from Pickering, Composites Part A (2006)

How the EU sees composites recycling



EuPC EUROPEAN PLASTICS CONVERTERS

EuCIA

European Composite Recycling Services Company

Glass fibre reinforced thermosets: recyclable and compliant with the EU legislation

June 2011

The European Plastics Converters (EuPC), the European Composites Industry Association (EuCIA) and the European Composite Recycling Service Company (ECRC) welcome the End-of-Life of Vehicles Directive (2000/53/EC) and the Waste Framework Directive (2008/98/EC): **glass fibre reinforced thermosets are both material and energy recyclable through the cement kiln route and compliant with the EU legislation.**

[EuCIA-position-paper-52816.pdf (csmres.co.uk)]

GF composites: Thermal plant feedstock

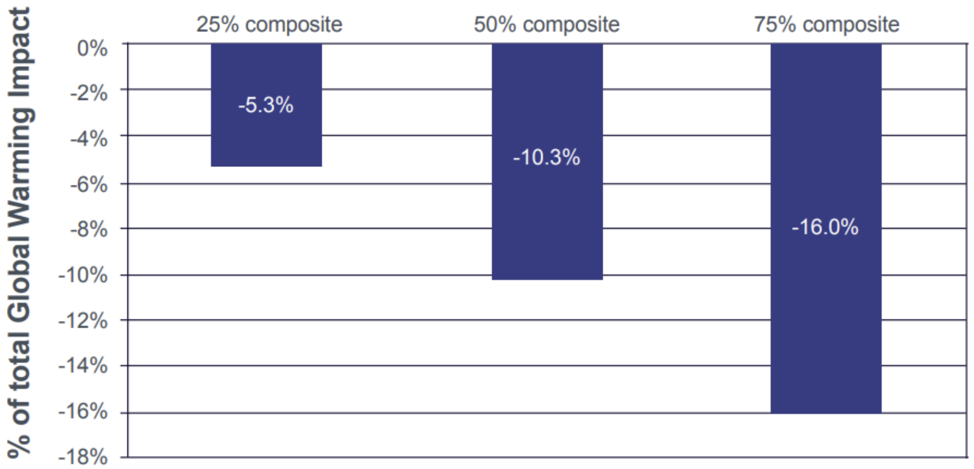
- Co-processing of End of Life/ composites used in cement manufacturing
  - highly effective source of energy
  - calorific values of~30,000 kJ/kg
- Glass fiber in oxide form, replacing hydrated or carbonated minerals in Portland cement
- Replacement of fossil fuels by non-recyclable & biomass waste, and use of alternative raw materials
  - 15% CO_2 emissions reduction in cement industry by 2050
- Co-processing plants (such as cement or lime kilns, steel plants, etc.) that produce material products, waste used as a fuel and/or raw material that otherwise would be subject to disposal.

Fig.1 : Unloading of windmill blades at processing site
Courtesy: Zajons, Melbeck

Fig.2 : Part storage prior to mechanical treatment
Courtesy: Zajons, Melbeck

Fig.3 : Mobile sawing equip-ment to reduce transport costs
Courtesy: Zajons, Melbeck

Fig.4 : Typical composite regrind, made from ground windmill blade
Courtesy: Zajons, Melbeck



Recycling Routes

©René Notenbomer #491287131 source: stock.adobe.com 2023

[Bringing circular economy practices to glass and carbon fibre composites | Research and Innovation (europa.eu)](#)

Composite Waste

Incineration (thermal plant)

Mechanical recycling

Grinding, Shredding, slicing

Powder recyclate CFRP strips

Fiber + oligomer recovery

Thermal processes

Pyrolysis

Fibers /oil/gas + heat

Fluidized bed

Fibers + heat

Chemical processes

Low temperature Solvolysis

Fibers + oligomers

Supercritical Solvolysis

Fibers + oligomers

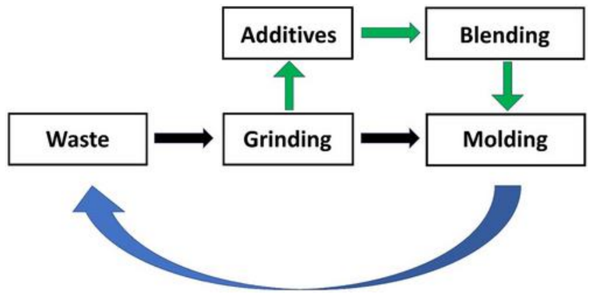
Designed reversible resin chemistries

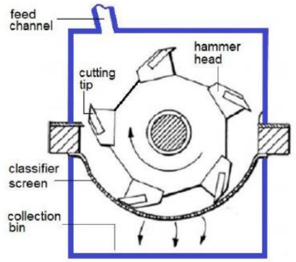
Fibers + oligomers

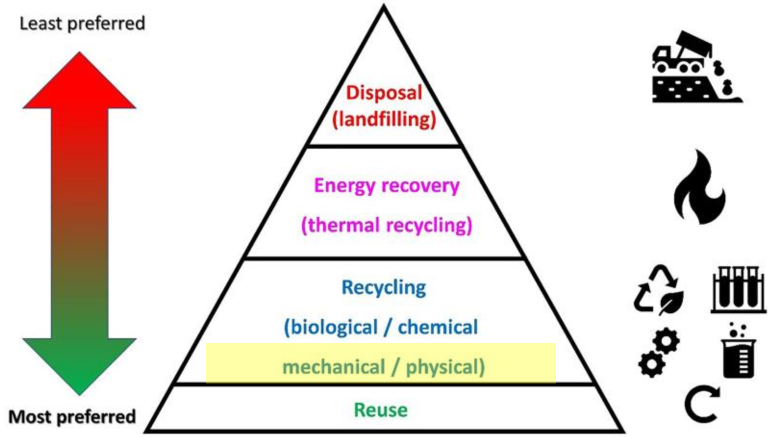
Remanufacturing

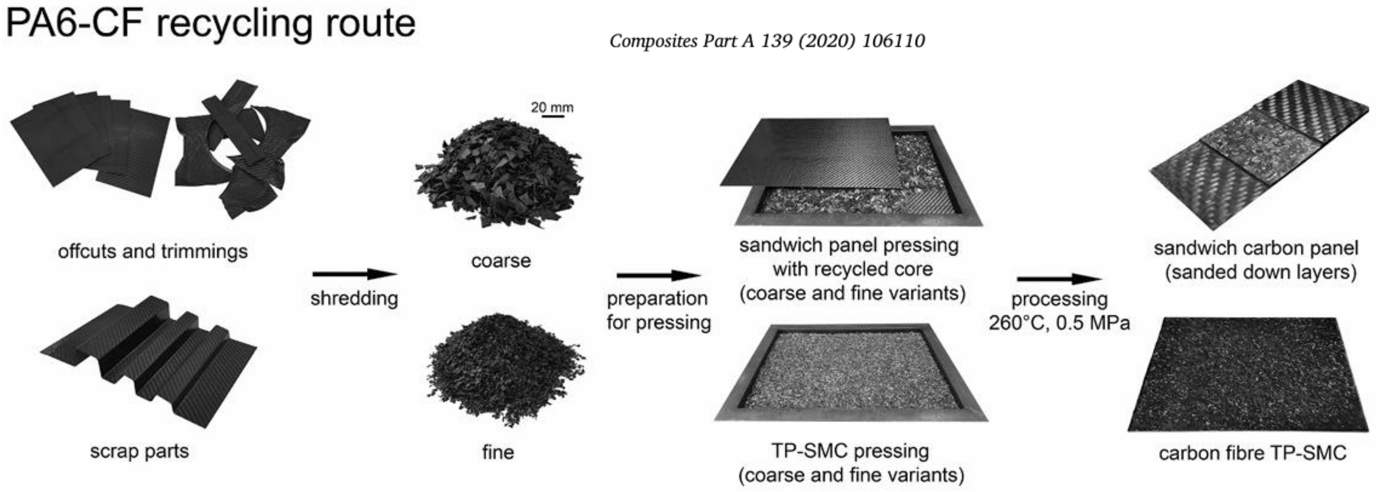
Mechanical recycling (thermoplastic composites)

- Post industrial waste
- Shredded
- Used for injection molding
- Higher fiber lengths vs. short glass injection







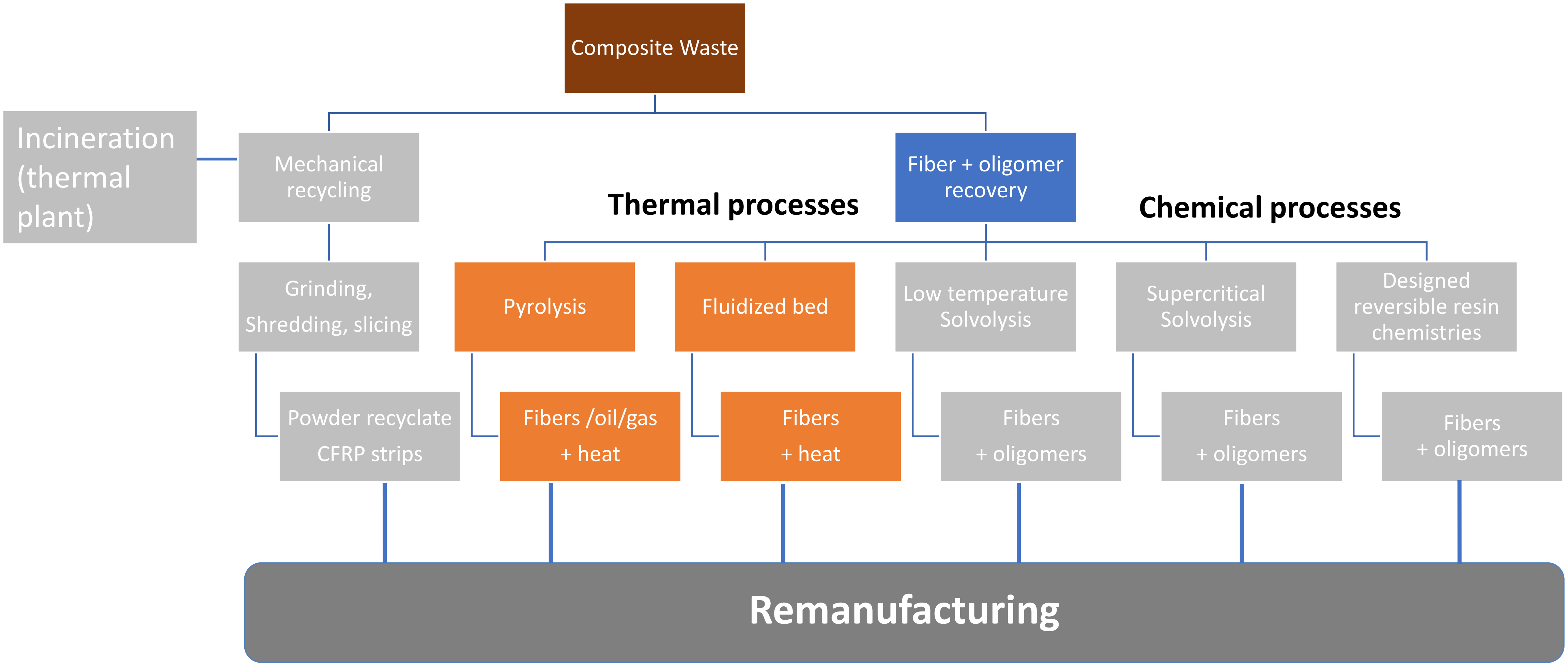


Journal of Polymer Science, Volume: 61, Issue: 17, Pages: 1937-1958, First published: 19 May 2023, DOI: (10.1002/pol.20230154)

Fig. 1. Recycling routes for PP-GF and PA6-CF based TPCLs.

[In-house recycling of carbon- and glass fibre-reinforced thermoplastic composite laminate waste into high-performance sheet materials - ScienceDirect]

Recycling Routes

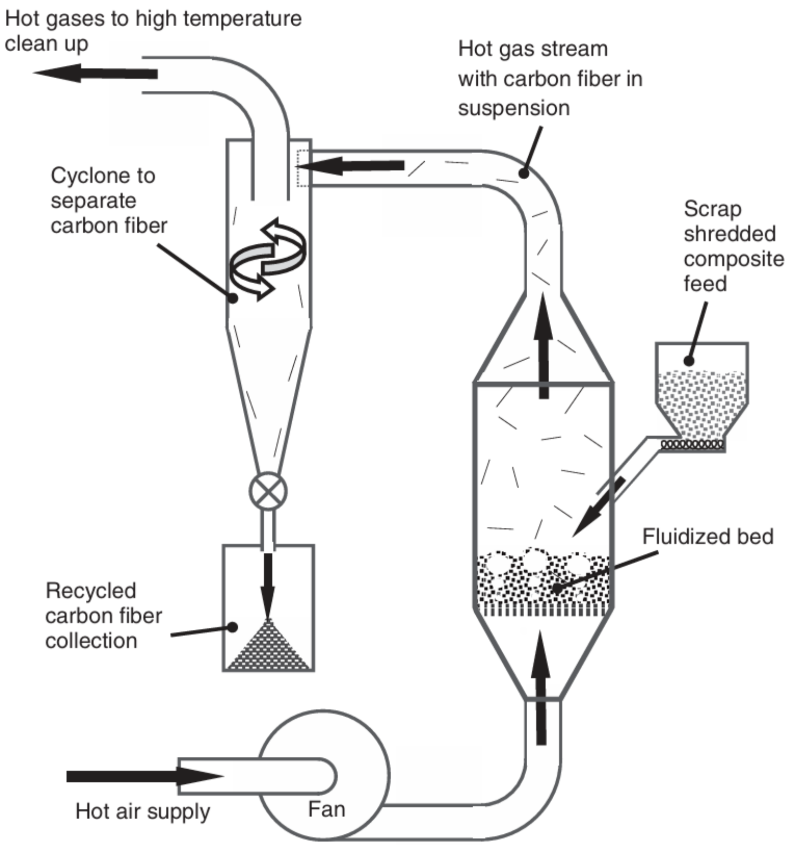


Adapted from Pickering, Composites Part A (2006)

Fluidized bed recovery

- Waste composite material shredded 25mm in size
- Silica and (0.85mm) is fluidized by hot air.
- 450◦C for glass / polyester; 550◦C for carbon fiber epoxy composites
- Fibers separate from one another, carried out of fluidized bed in the hot air stream
- Cyclone is used to separate the fiber from the gases which then pass to a high temperature combustion chamber for full oxidation.
- Energy recovery possible from high temperature gases leaving combustion chamber
- Tolerant of contaminated and mixed materials, suitable for end-of-life components

CF strength retention 46-62%
Modulus not affected



Boeing funds carbon fibre recycling research – Research, The University of Nottingham

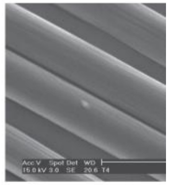
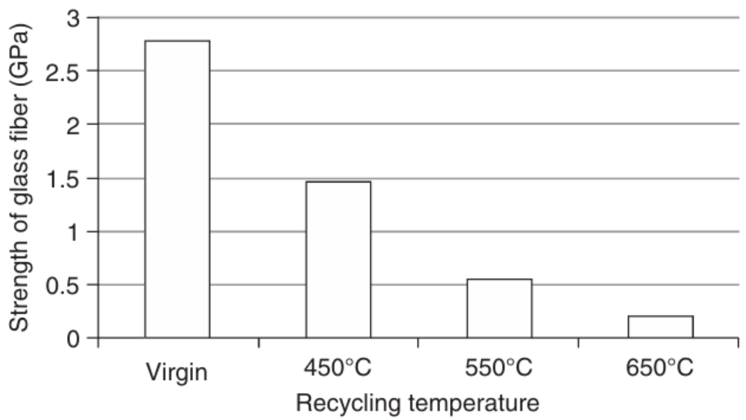


Figure 4. Recycled carbon fiber in a fluffy form.

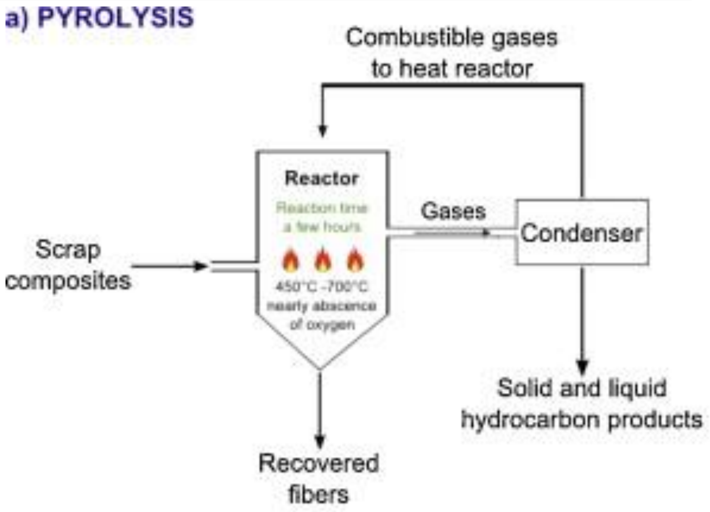


Pyrolysis

- Thermal degradation of resin / polymeric additives (absence of oxygen / nitrogen atmosphere)
- 400-500°C
- Calcification step in air to remove char on fiber surface
- 1 or 2 step process
- Fibers recovered
- Gas / oil / char

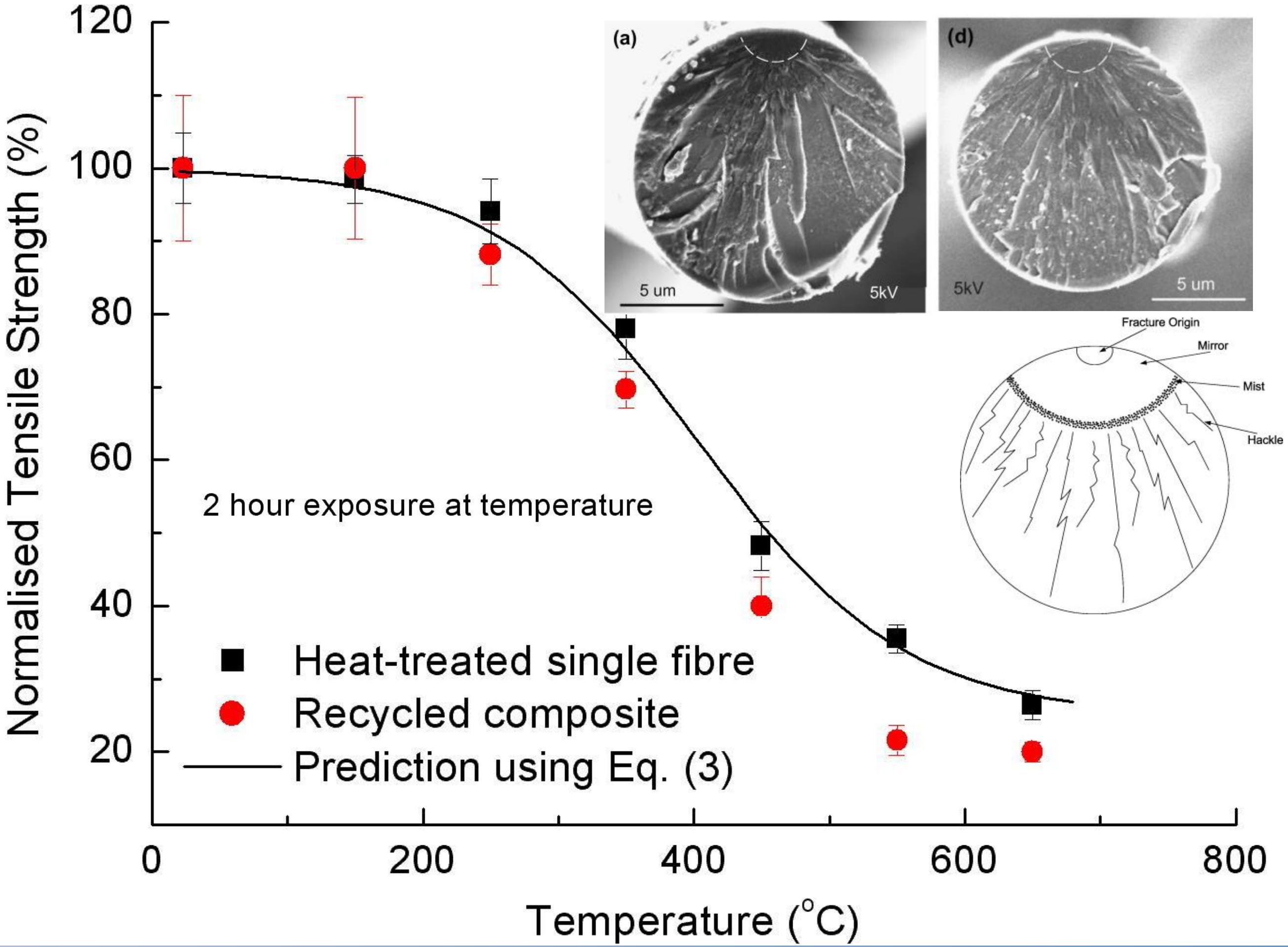
Recycling of carbon fibre-reinforced plastics (youtube.com) 1:45s – 6:11

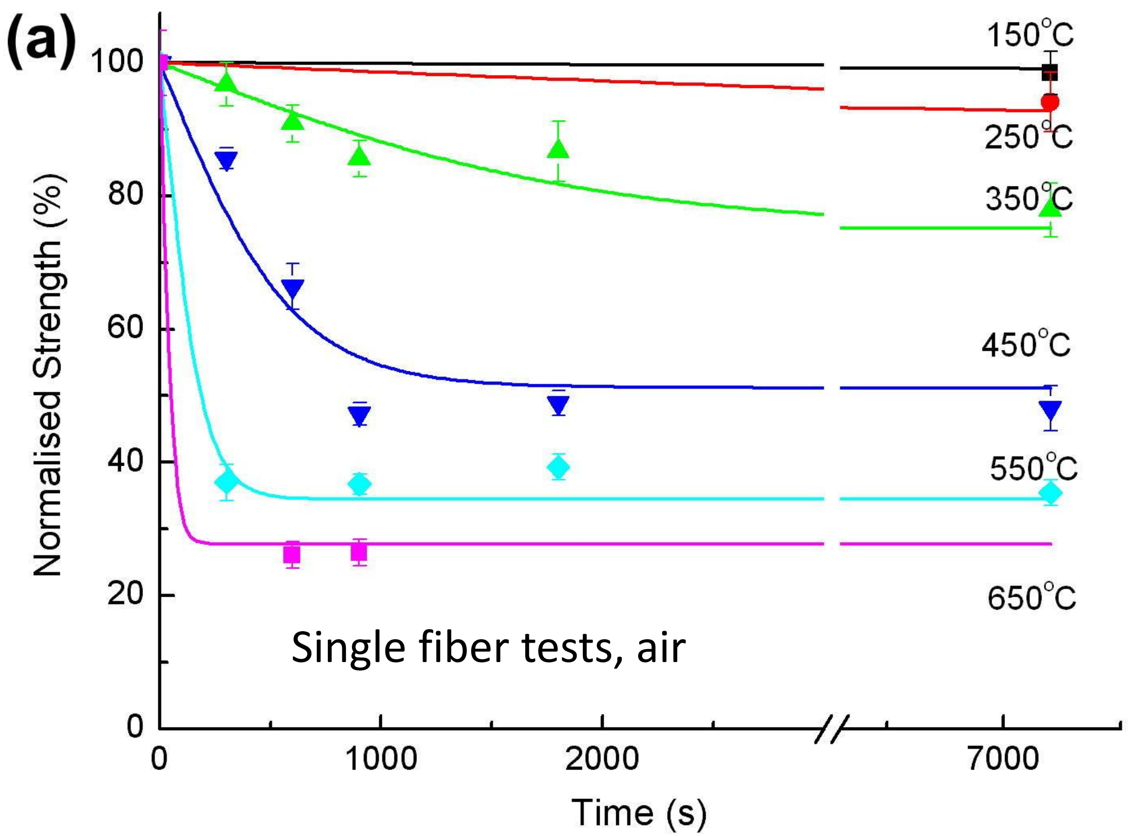
500°C in Nitrogen



Effect of pyrolysis on glass fiber properties

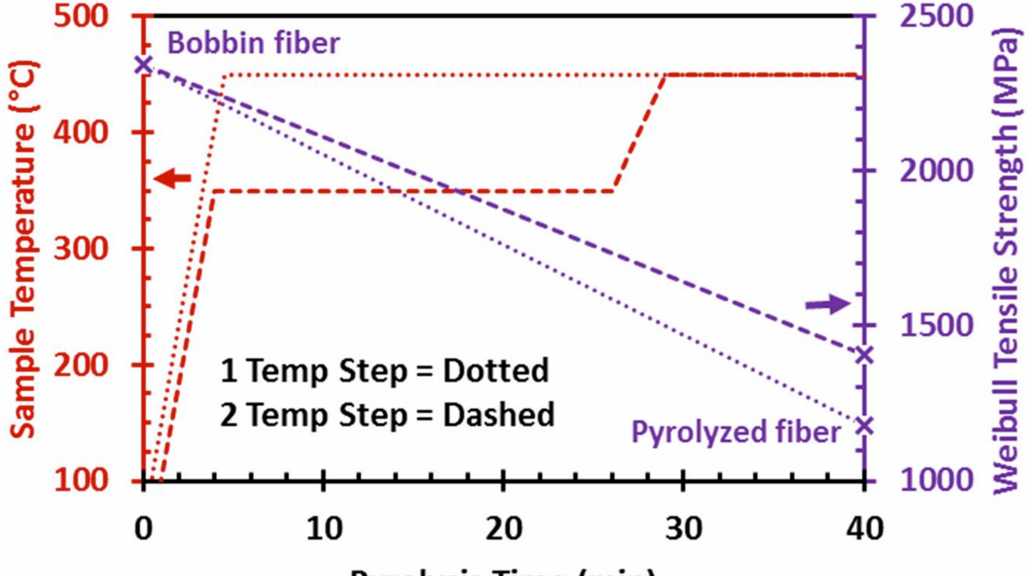
- Modulus not affected
- Strength loss after heating due to surface defects, annealing/stress relaxation, chemical diffusion





Two step pyrolysis

- Two step
  - 350°C for 22minutes
  - 450°C for 11 minutes
- Glass fiber structural changes

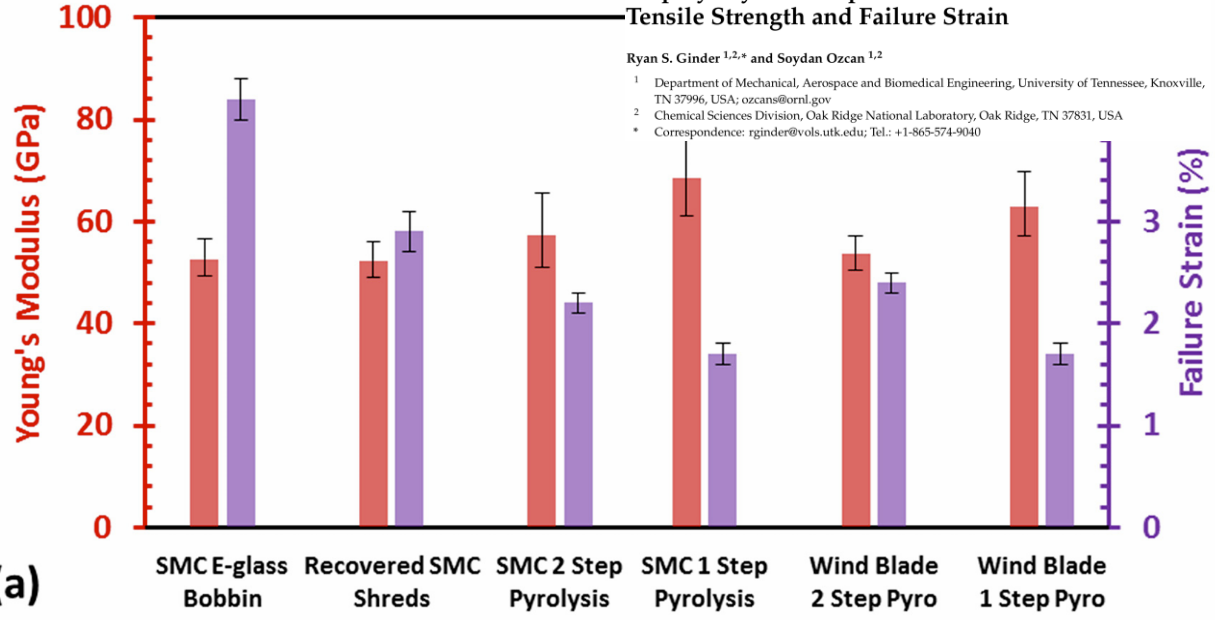


(a)

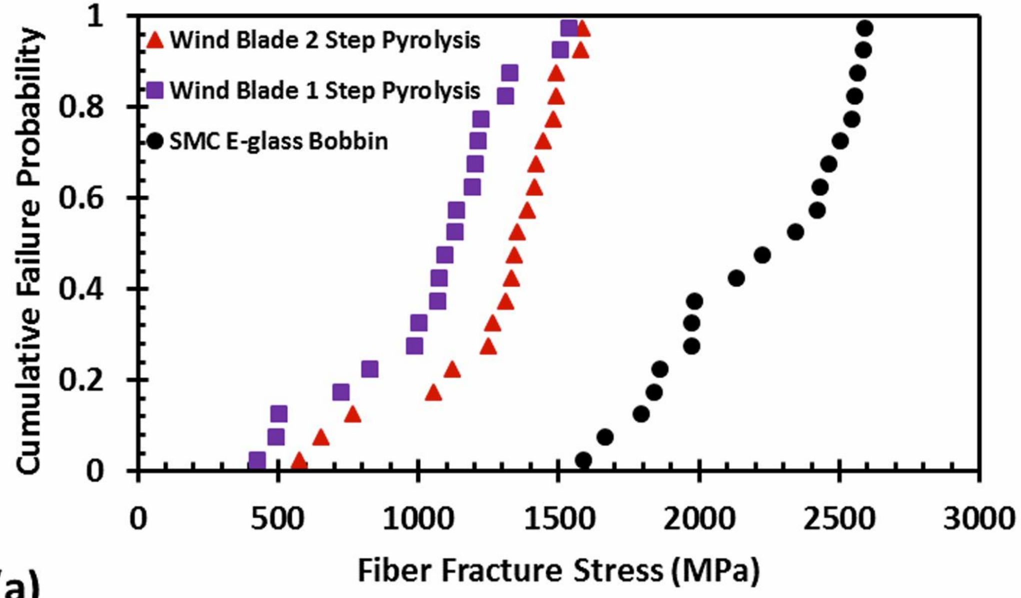
Recycling of Commercial E-glass Reinforced Thermoset Composites via Two Temperature Step Pyrolysis to Improve Recovered Fiber Tensile Strength and Failure Strain

Ryan S. Ginder [1,2,*] and Soydan Ozcan [1,2]

1 Department of Mechanical, Aerospace and Biomedical Engineering, University of Tennessee, Knoxville, TN 37996, USA; ozcans@ornl.gov
2 Chemical Sciences Division, Oak Ridge National Laboratory, Oak Ridge, TN 37831, USA
* Correspondence: rginder@vols.utk.edu; Tel.: +1-865-574-9040



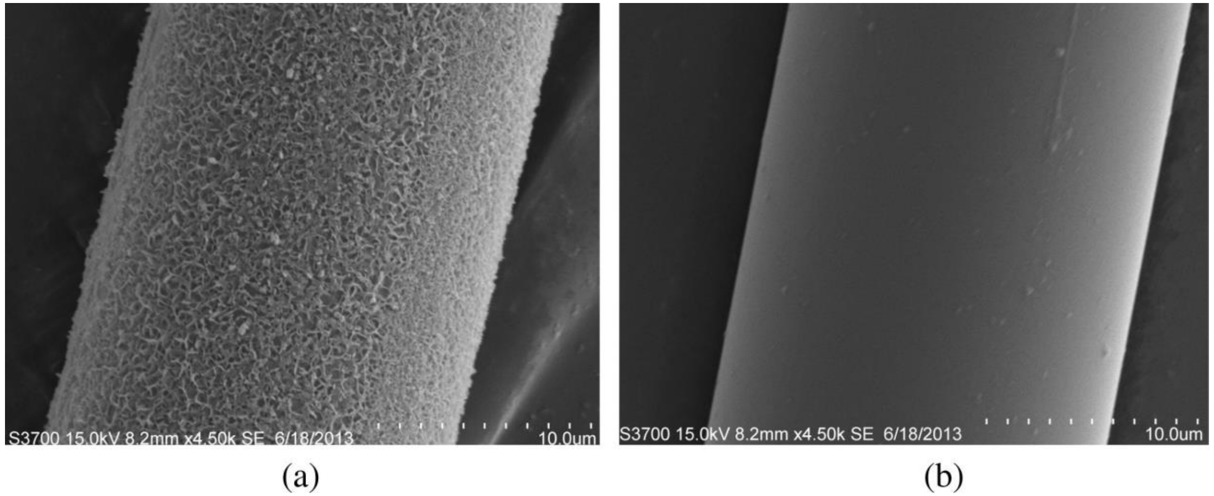
(a)



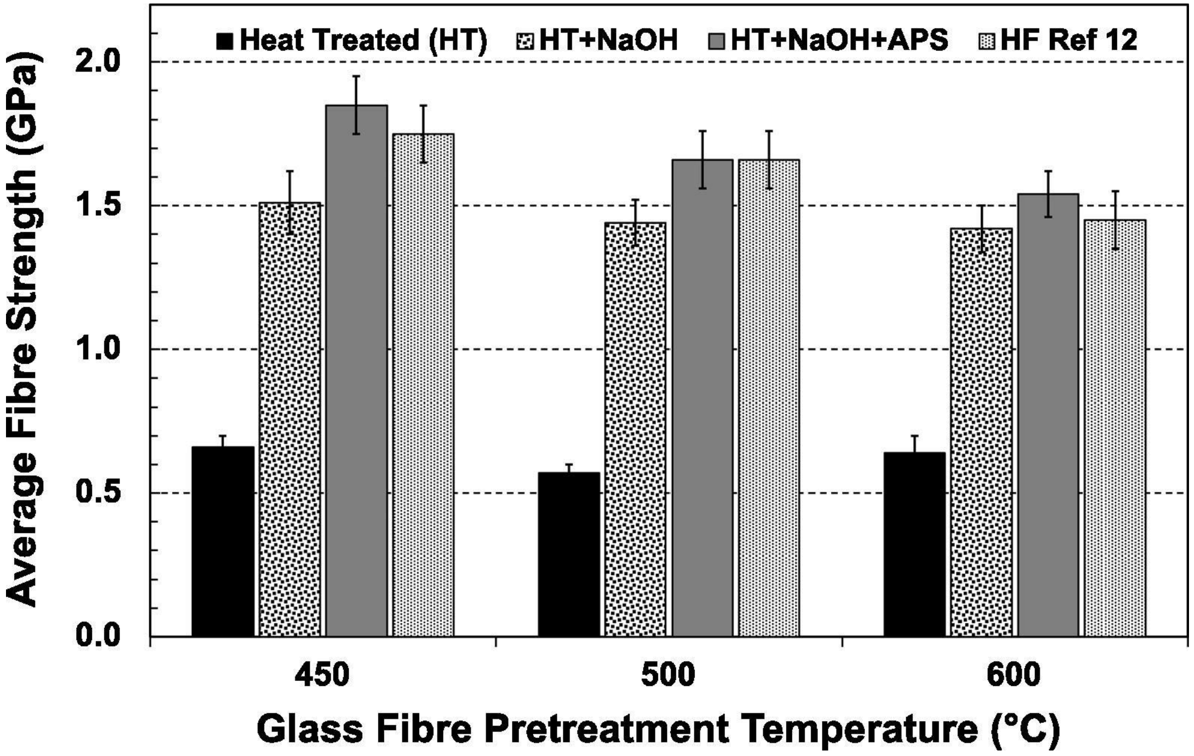
(a)

Glass fiber post treatment after pyrolysis

- Immersed in a sodium hydroxide solution (NaOH) for 10 min at 90 °C
- Fibrers drained & rinsed in hydrochloric acid (HCl) to neutralize, followed by silane sizing treatment
- Recover compatibility of fiber to resin and interfacial stress transfer

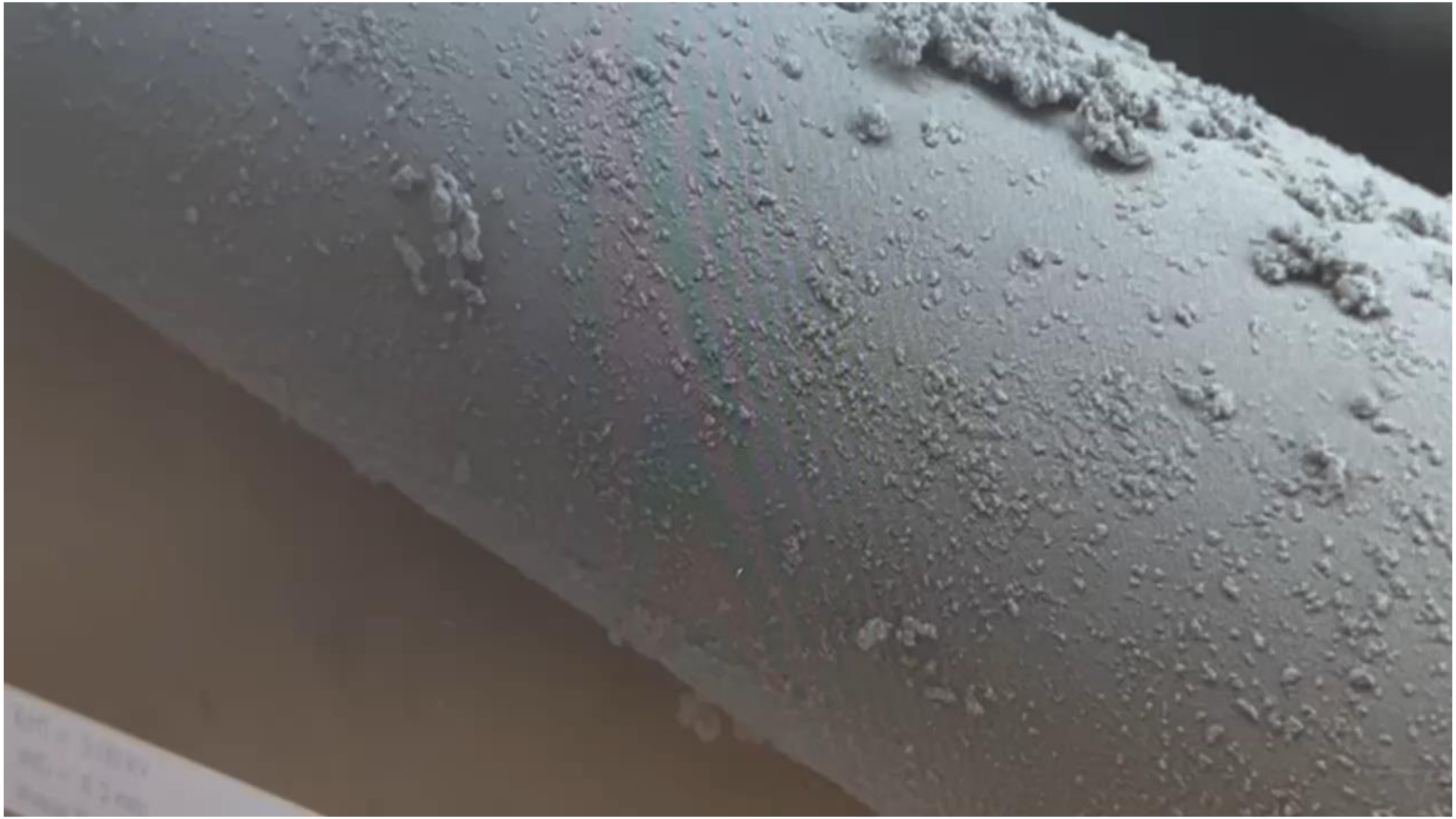


SEM images of heat conditioned fibre after (a) NaOH treatment, (b) NaOH treatment + HCl rinse + Silane coating.



Influence of heat treatment temperature and ReCoVeR chemical treatments on the average glass fibre strength at 20 mm gauge length.

Dr. Nour Halawani



Effect of pyrolysis on carbon fiber

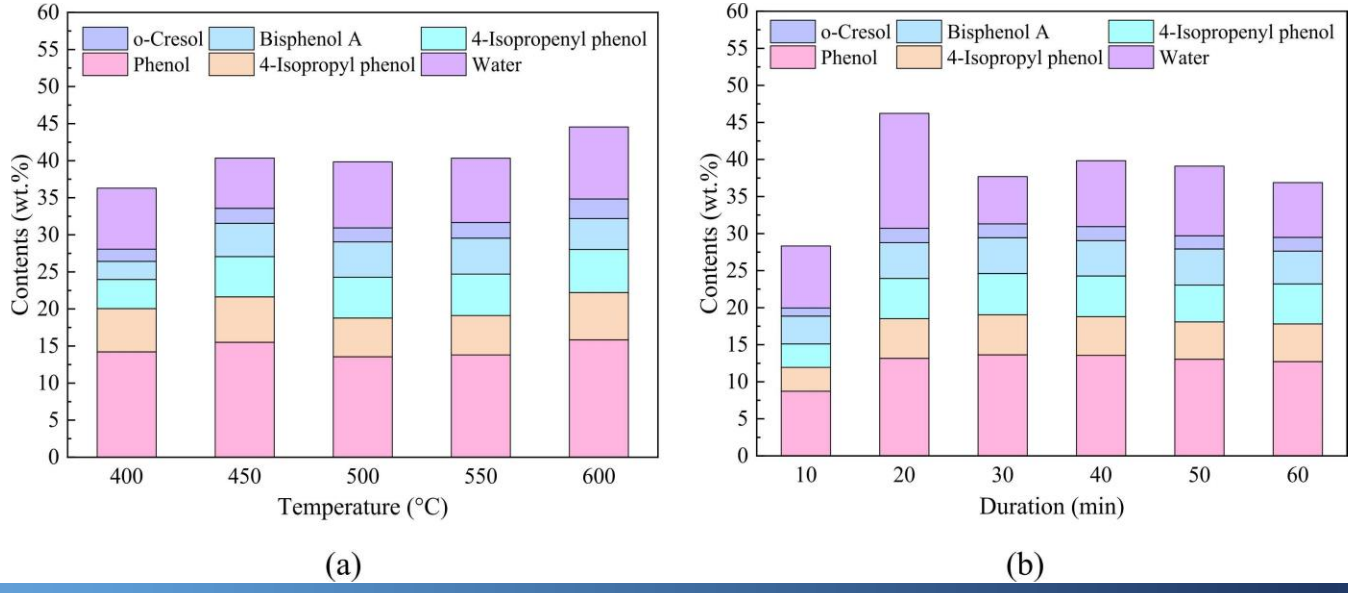
- Modulus generally maintained
- Strength reduction, process and parameter dependent
  - Lower end: SM 80%, IM as much as 55%
  - Upper end: pyrolysis temperature of 500ºC / 20 mins, 94%.
- Surface chemistry similar to virgin CF
- Some post heat in air/oxygen at 500-600ºC to remove pyrolytic char from CF surface
- Microwave heating can reduce avoid char formation on fiber surface or gasification, heated in oxygen to 600ºC

Table S1 The tensile strength retention of carbon fibers recovered by different methods.

Method	Tensile strength retention* (%)	Sources
Mechanical method	50-65	Zhu, et al [1]
Fluidized bed method	80.00	E. Pakdel, et al [2]
Pyrolysis method #1	92.00	O. Zabihi, et al [3]
Pyrolysis method #2	75.86	Lopez, et al [4]
Chemical method #1	93.55	Pei, et al [5]
Chemical method #2	Almost 100	Jiang, et al [6]

* Tensile strength retention was the ratio of tensile strength between recovered and virgin carbon fibers [7].

Pyrolysis oil candidate for re-synthesis into epoxy



[Evolution of pyrolysis char during the recovery of carbon fiber reinforced polymer composite and its effects on the recovered carbon fiber - ScienceDirect]

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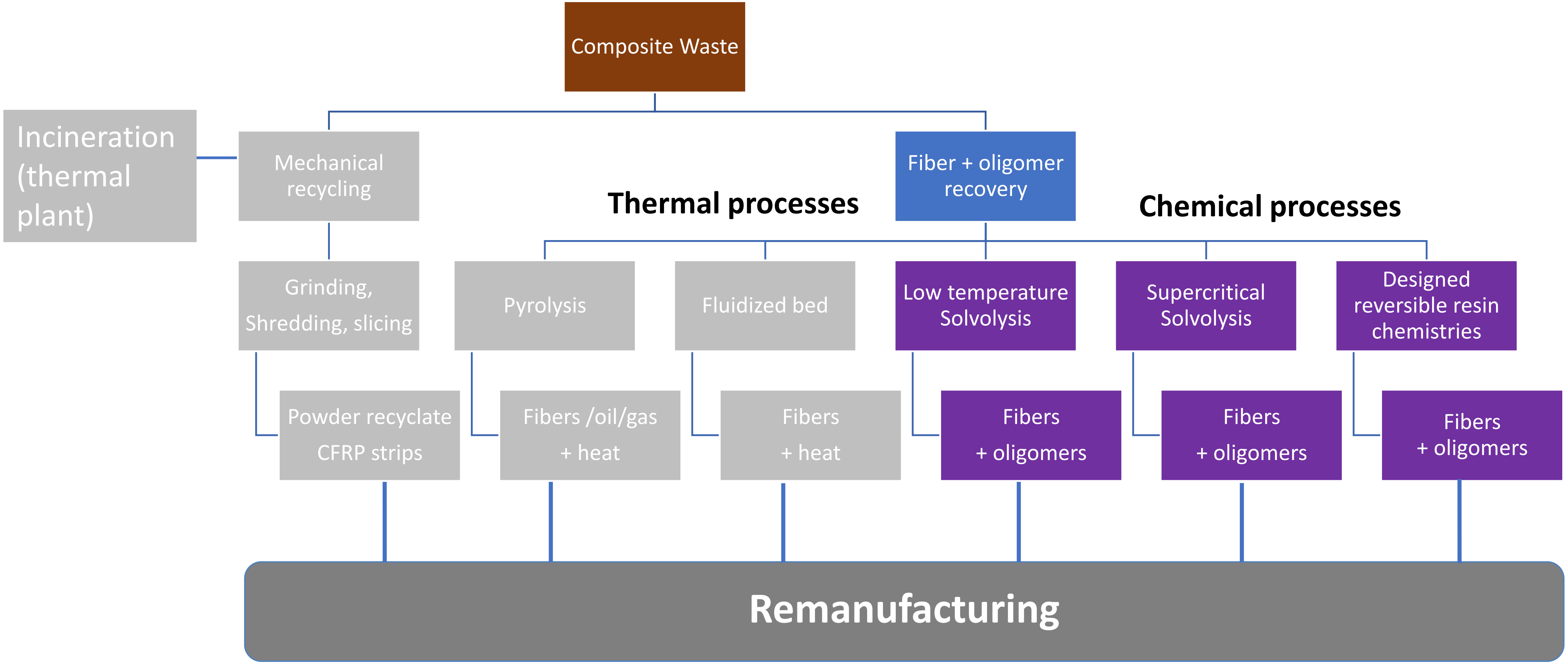
Recycling Routes



Adapted from Pickering, Composites Part A (2006)

CF tensile strength retention by process

Table S1 The tensile strength retention of carbon fibers recovered by different methods.

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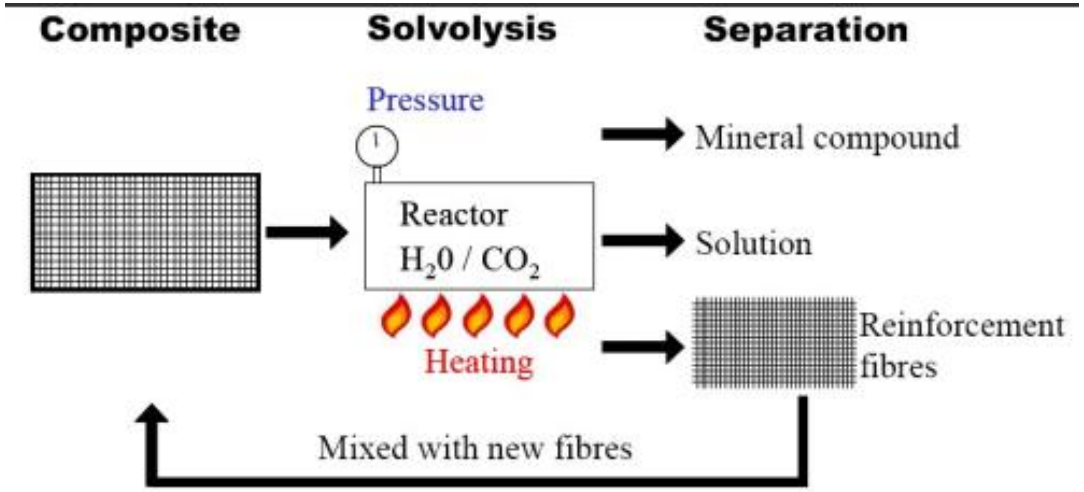
Thermo-chemical depolymerization: solvolysis

EURECOMP: EU-FP7 partially financed project (2009 for 3 years)

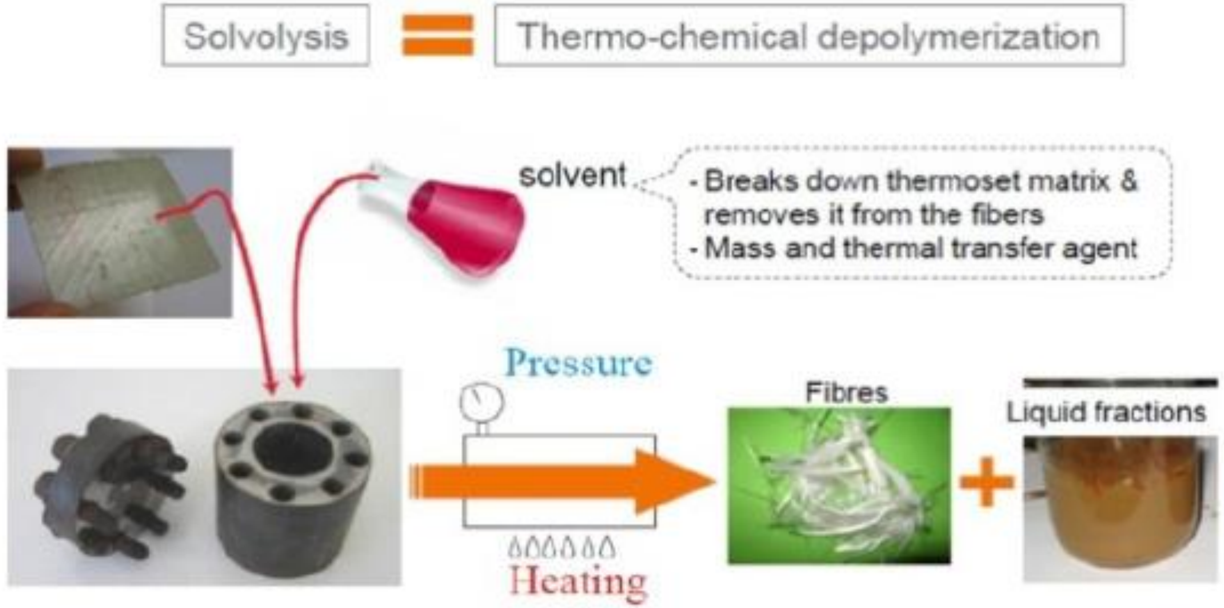
1. Mechanical recycling: insufficient separation of the components
2. Incineration: gain only in terms of energy recovery.

EURECOMP: full material recovery through solvolysis

Further aim: collating information on upstream and downstream markets, economic efficiency and LCA



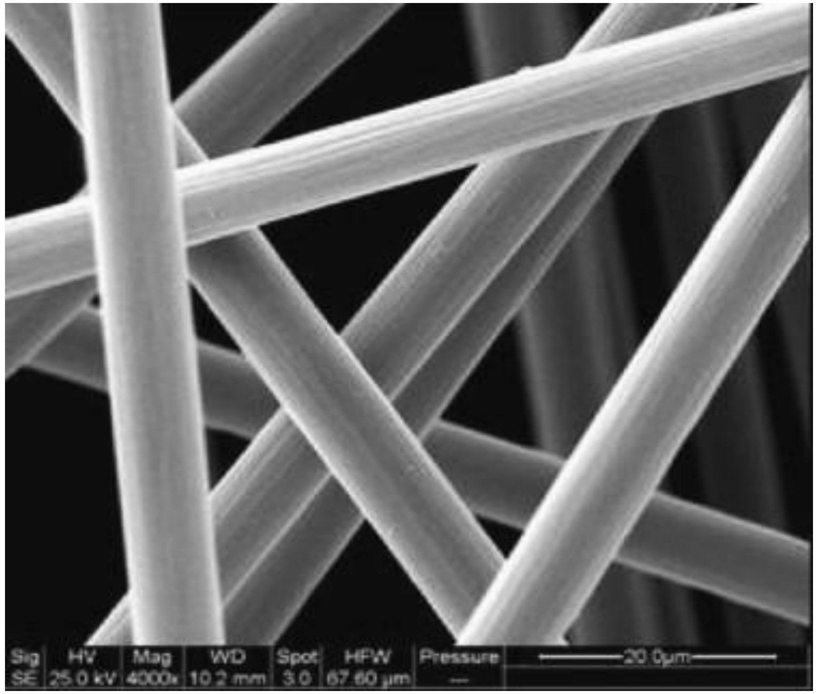
Solvolysis: Physico-chemical separation



Chemical treatments

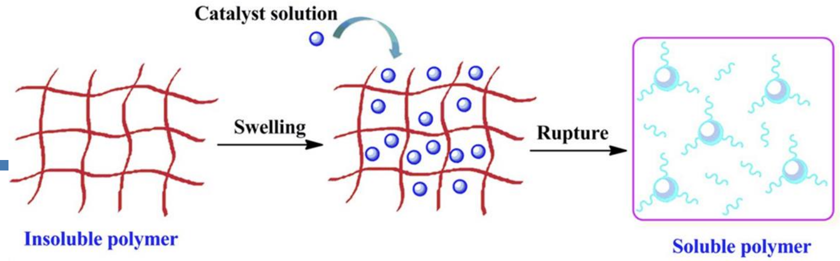
- Break down of polymer matrix in high-value oligomers in a reactive medium at low temperature (< 350°C)
  - e.g. Benzyl Alcohol
  - Supercritical fluid (water, acetone, propanol…)
  - Catalytic solution
- But
  - Loss of fiber surface treatment
    - Reduced adhesion
  - In some case hazardous solvents
- Different chemicals for different polymers
    - Treatment is dependent on matrix composition
    - Sensible to mixed composite waste

Recycled carbon fibers treated with supercritical 1-propanol at 350°C

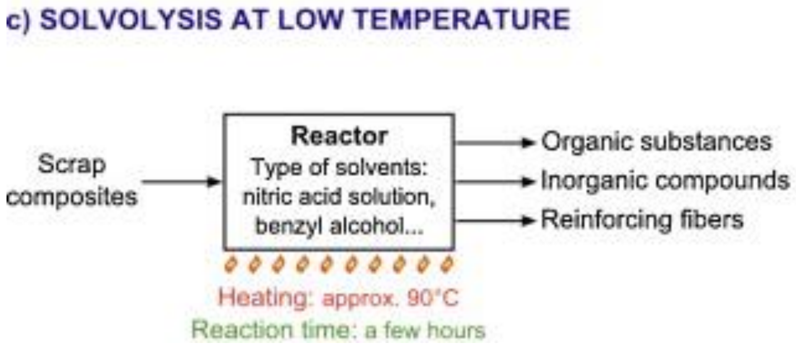


Pickering et al., Journal of Supercritical Fluids (2008)

Low-Temperature Solvolysis



- Uses reactive solvents such as alcohol, ammonia, phenolic, or glycol
- Break down the chemical bonds of the epoxy or phenolic matrix
- Solvents can be toxic
- Yields fibers and organic liquid (mixture of monomers and excess reactive solvent)
- e.g. Hitachi Chemical
  - 180°C, benzyl alcohol solvent and tri-potassium phosphate catalyst, 5-20hrs
  - Used for tennis rackets
  - 63 MJ/kg vs 286 MJ/kg virgin CF



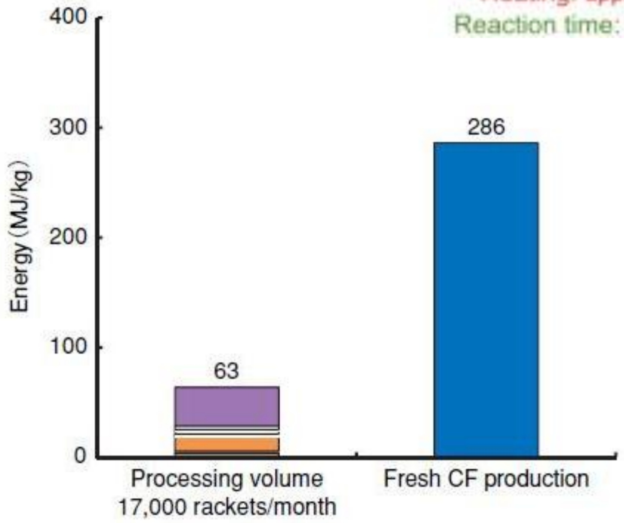
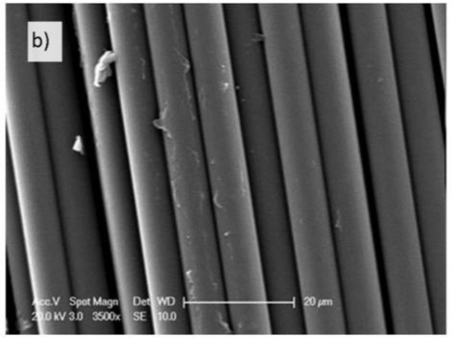


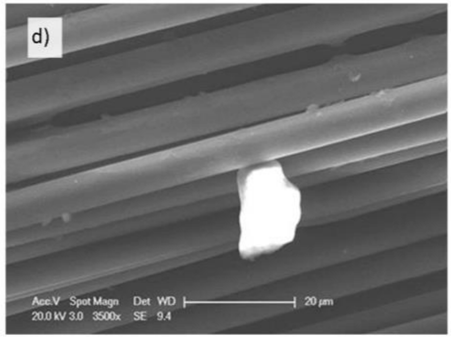
Figure 13 A comparison of energy of a recovered CF by dissolving method under ordinary pressure with a fresh CF on the market

Item	Depolymerization under ordinary pressure
Organization	Hitachi Chemical
Temperature	200 ℃
Pressure	Ordinary pressure
Solvent	Benzyl alcohol
Catalyst	Alkali metal salt
Preprocessing	None
Processing capacity	12 tons/year (200 L x 2 baths)

Supercritical solvolysis

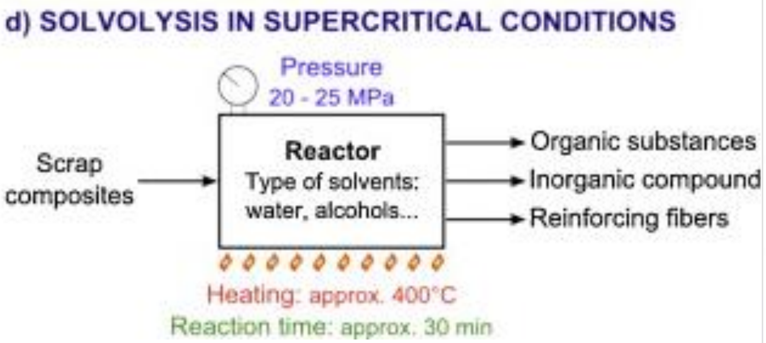
- Supercritical fluid
  - *Any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist, but below the pressure required to compress it into a solid*
  - e.g. water 373ºC, 220bar, alcohols, used as alternatives to organic solvents, and catalysts.
- Non toxic / low cost solvents
- 310-440ºC, 15-30 MPa
- Excellent fiber property retention
- CF, GF, TP, TS materials
- End products: fibers, monomers, gas emissions (CO2, CO)

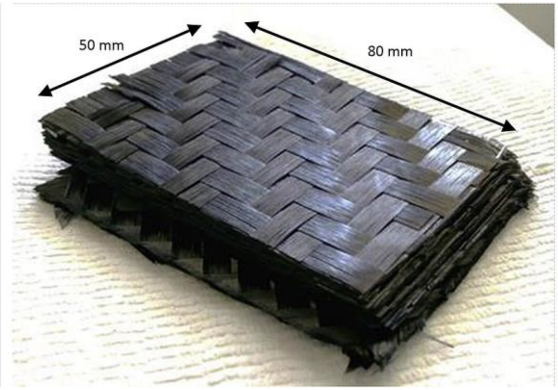


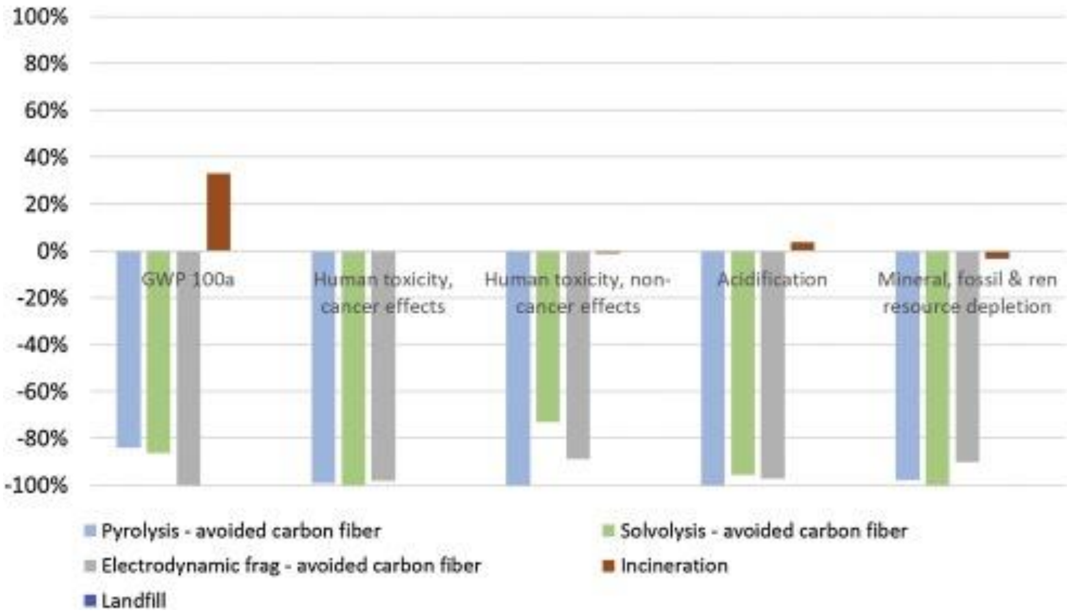


b) unwashed carbon fibres recovered after solvolysis; d) solid particle of partially degraded resin on slightly washed carbon fibres.

Recovery and reuse of discontinuous carbon fibres by solvolysis: Realignment and properties of remanufactured materials - ScienceDirect







Recycling of thermoplastics

Target products are substances that can be reintegrated into existing process chains in the chemical industry

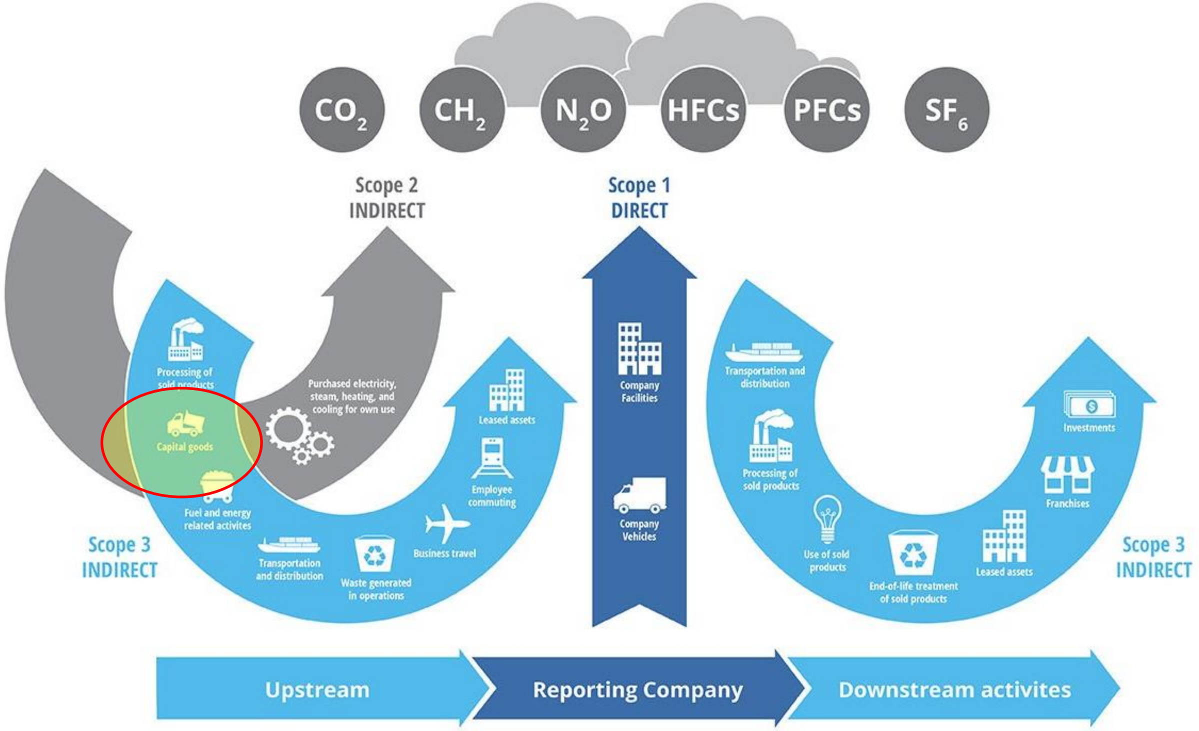
Solvolysis	Pyrolysis	Gasification
• Waste decomposed using solvents into monomeric components	• Decomposed in inert atmosphere at high temperature • Gives solid/ liquid/gas products to replace hydrocarbons in monomer production	• Partial oxidation to give synthesis gas carbon monoxide and hydrogen • Feedstock for chemical products

What kind of waste is used in the ChemCycling™ project?

We focus on post-consumer plastic waste that is not recycled mechanically for technological, economic, or ecological reason. Examples are plastics with residues and mixed plastic waste fractions consisting of different plastic types, such as polyethylene (PE), polypropylene (PP) and polystyrene (PS), which are not further sorted. In addition, it includes used tires.

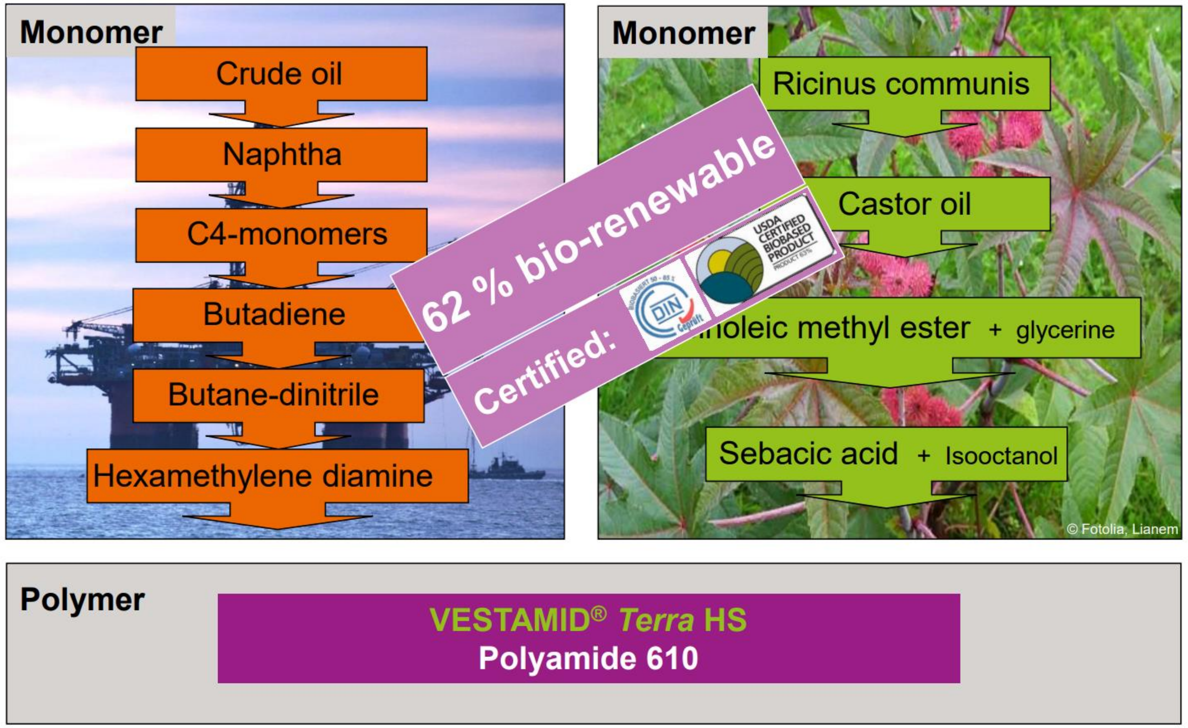
Overview - Towards sustainable composite solutions

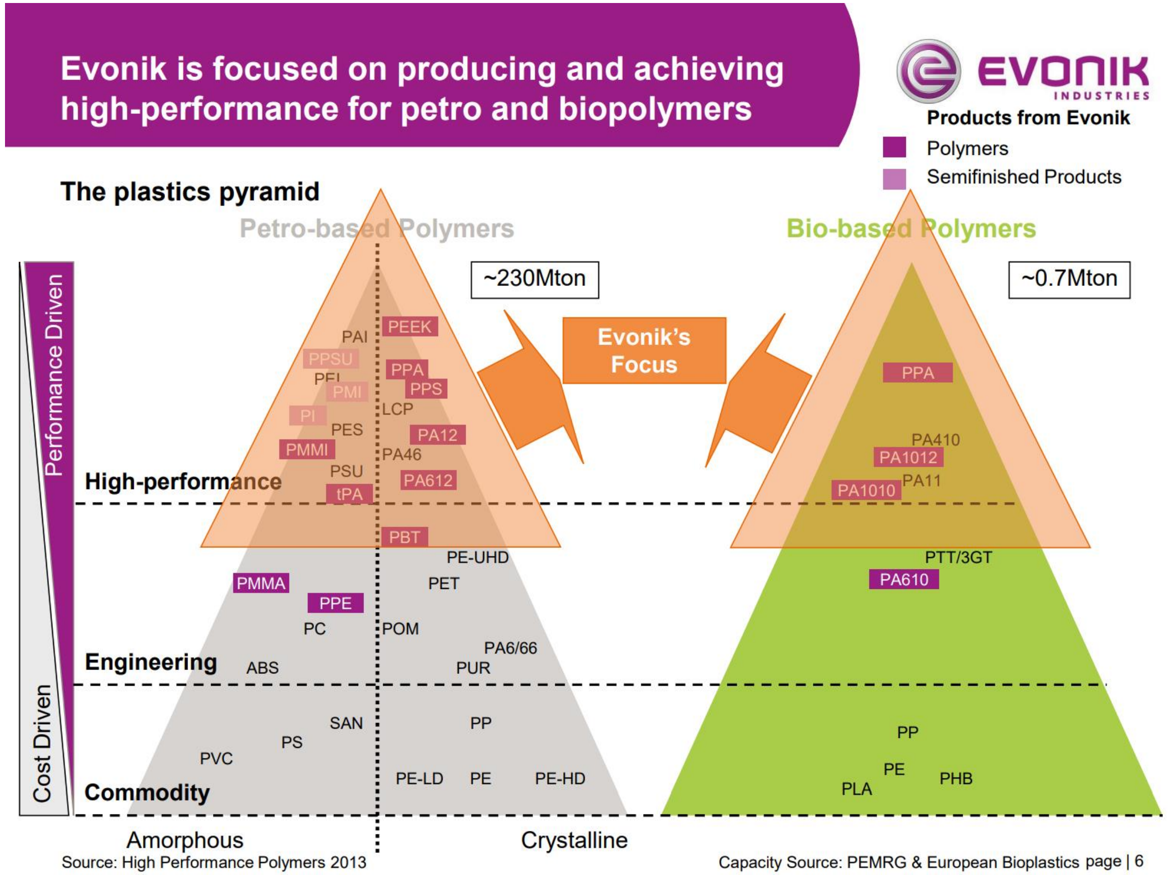
- Policy
- End of life and recycling
- Bio-based / novel materials
- Circular composites
- Additive manufacturing
- Unmet challenges



Castor bean products for bio-based PAs

- Bio-based polymers from non-food stock sources polymerized via renewable energy
- Bio-based does not mean biodegradable
- Bio-polymers are not recycled polymers





Bio-based epoxy

- Bio-based epichlorohydrin (ECH) from vegetable glycerol derived from biodiesel and oleochemical production
- Bio diesel made from many types of plant oil
- Chemical intermediate for epoxy resin

Epicerol® is 100% bio-based epichlorohydrin (ECH) produced by an innovative technology from Solvay. Based on renewable glycerol, Epicerol® is the most sustainable ECH in terms of CO2 emis-sions and process environmental performance. It is a chemical intermediate for a wide range of industries, including epoxy resins for coatings and composites.

Epicerol® earns Sustainability Certification | Solvay

www.solvay.com/en/press-release/solvay-epicerol-earns-roundtable-sustainable...

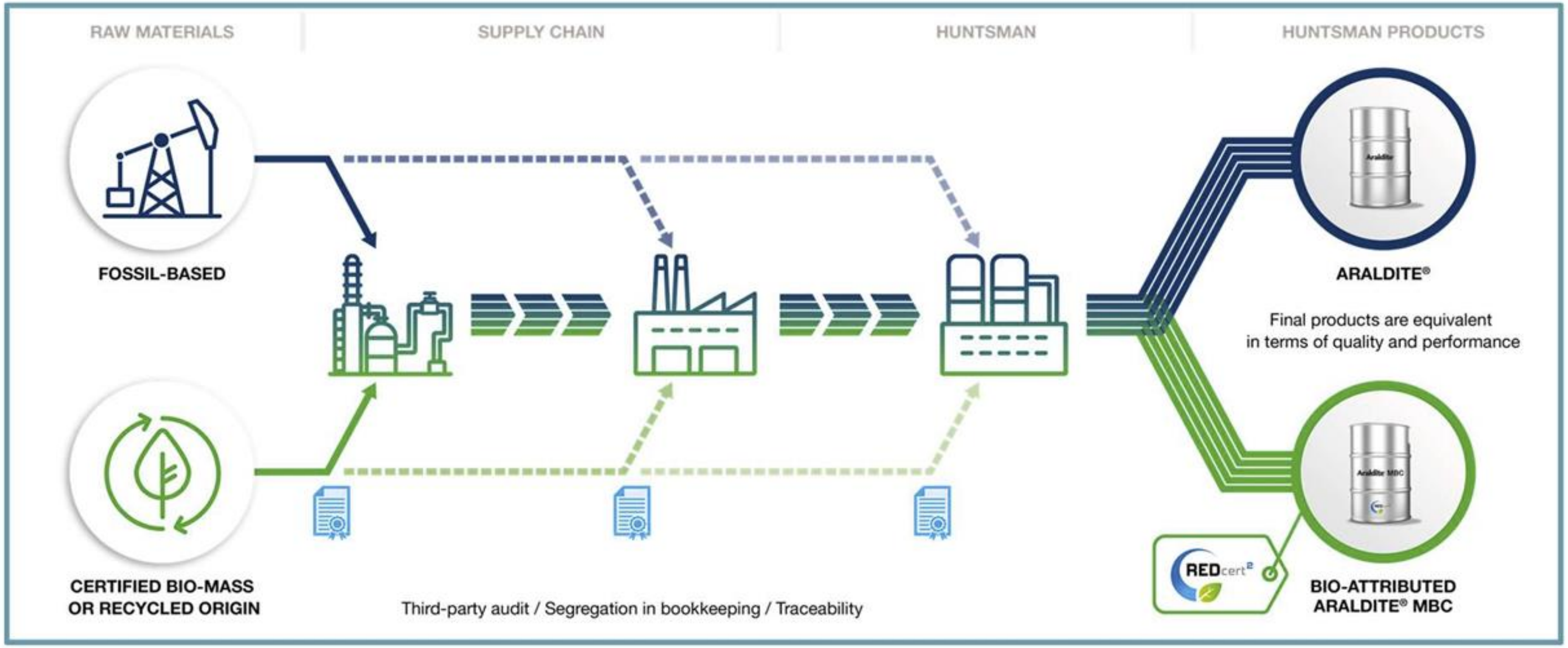
Green resins: Closer to maturity | CompositesWorld

Epicerol® earns Sustainability Certification | Solvay

Glycerol from biodiesel production: Technological paths for sustainability - ScienceDirect

HUNTSMAN
Enriching lives through innovation

Verified substitution of fossil raw materials by sustainably certified biomass



Mixing

Tracking

Verifiying

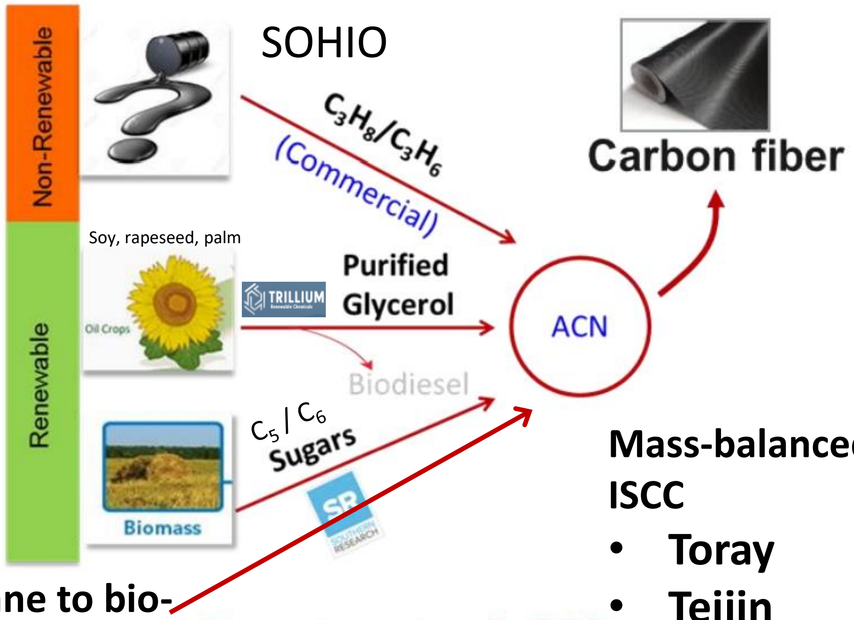
Mixing renewable and fossil raw materials,
Tracking the quantities in the books,
Verifiying through an independent certification

Carbon fiber manufacture

Block A
- Stage 1: AN precursor (propylene & ammonia)

Block B
- Stage 2: PAN polymerization
- Stage 3: Solution spinning

Block C
- Stage 4: Stabilization / oxidation
- Stage 5: Carbonization

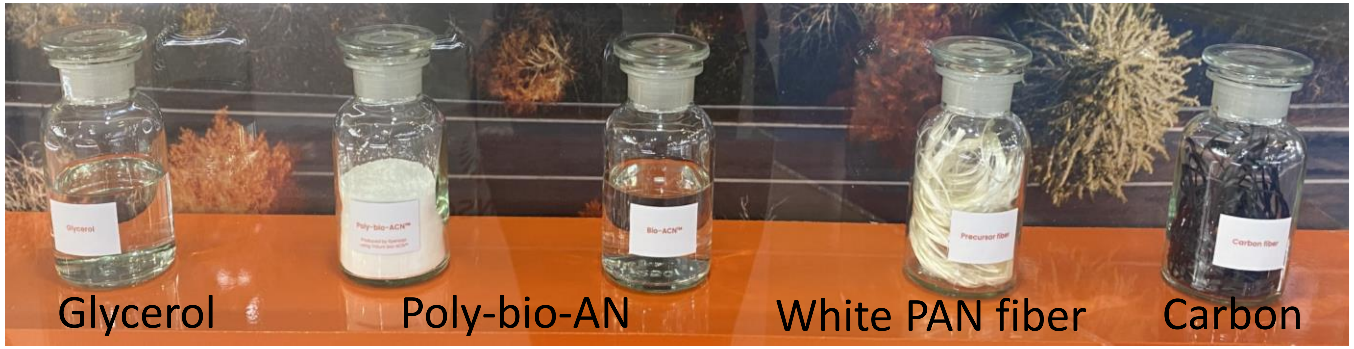


Bio-methane to bio-attributed propylene

Routes to ACN

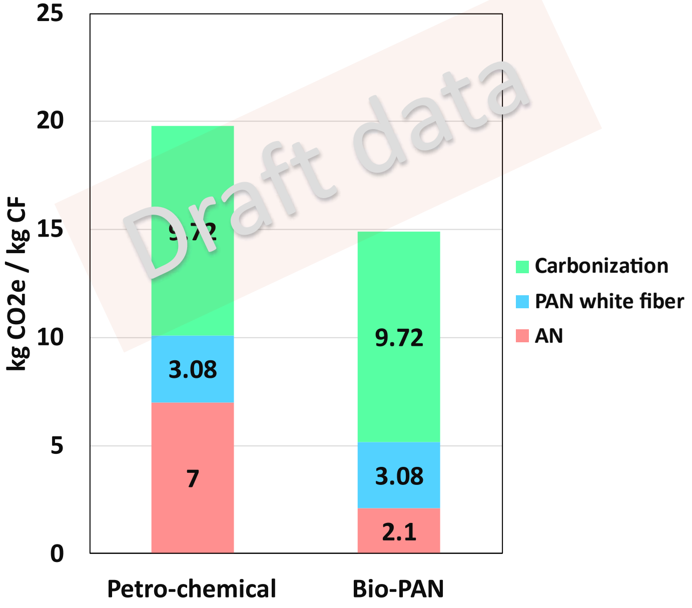
Mass-balanced ISCC
- Toray
- Teijin
- Ineos

SYENSQO

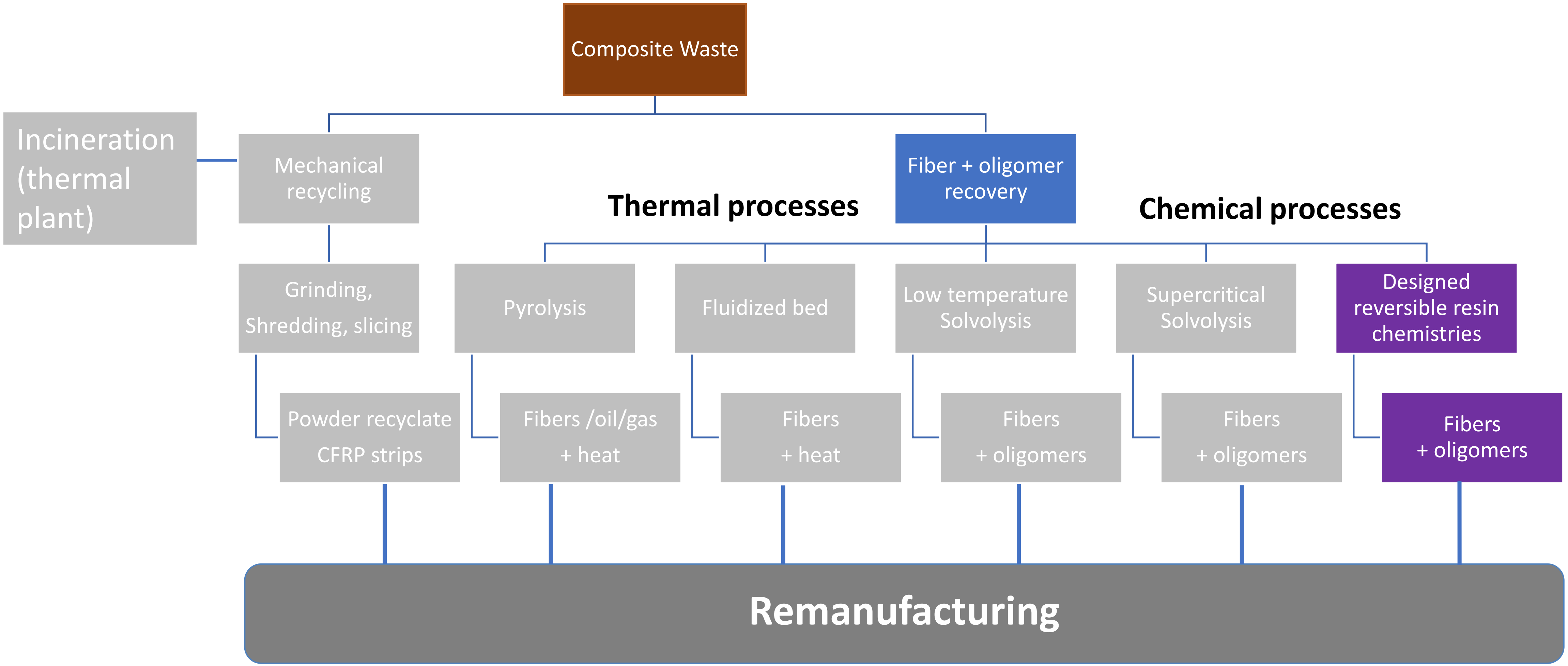


"Syensqo to Showcase Sustainable Mobility and Technology Collaborations at JEC 2024." Accessed: May 14, 2024. [Online]. Available: https://polymer-additives.specialchem.com/news/product-news/syensqo-jec-world-2024-carbon-fiber-applications-000233226

JCMA 19.8 $kgCO_2e/kg$ CF [4]



Recycling Routes

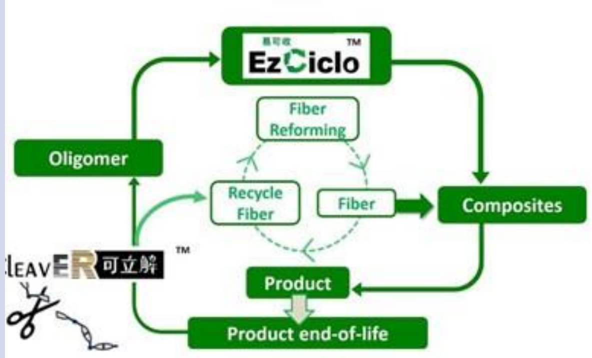


Adapted from Pickering, Composites Part A (2006)

Wind energy: recyclable blades

- Siemen's RecycleableBlades (81m long) [Cleaver]

Novel resin	End of life	Recovery
• Chemical structure • Ketal diamines (recyclamine) in hardner • Can efficiently separate the resin from the other components	• Blade immersed into a heated mild acidic solution (solvolysis) • 140ºC , 4-5hrs	• Separates resin from the fiber glass, plastic, wood and metals • Oligomer recovered, directly re-used



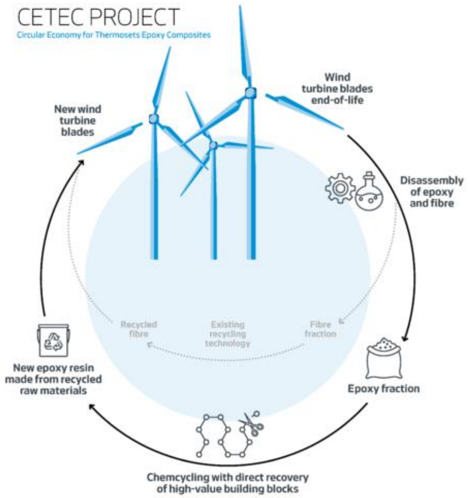
[Swancor, Siemens Gamesa solidify recyclable wind blade partnership | CompositesWorld]
[Swancor launches recyclable thermosetting epoxy resin | CompositesWorld]

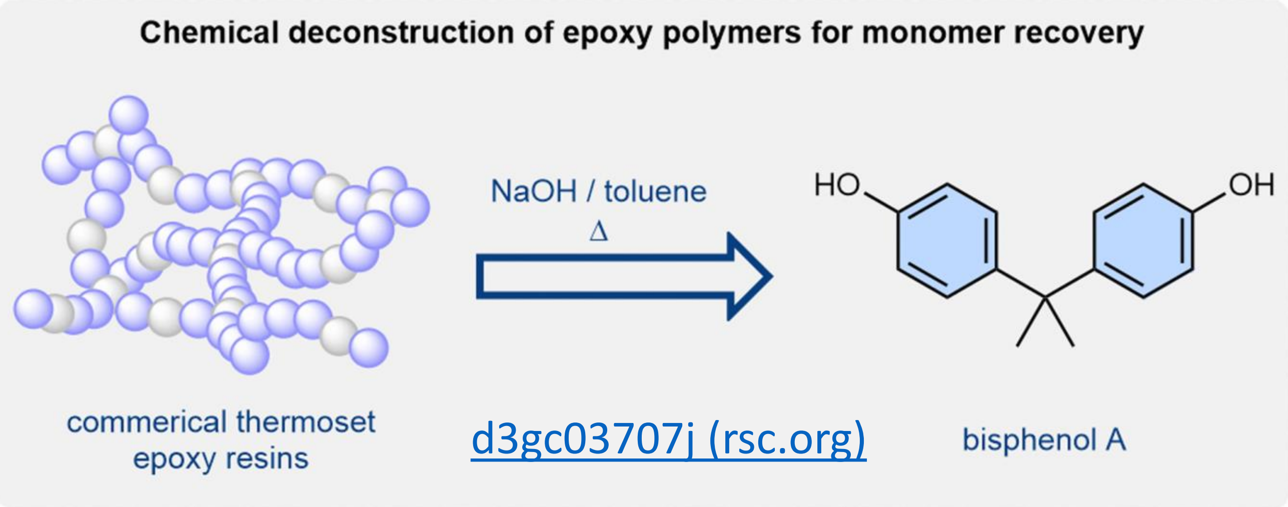
[SWANCOR: Leading into the Zero-Carbon Era: Recyclable Thermosetting Resin System EzCiclo and CleaVER (youtube.com)]

[World's first "fully recyclable" wind turbine blades roll off production line | RenewEconomy]

Vestas (legacy & current)

- Recover BPA using solvent base mismatch (alkaline base with apolar solvent)
- 190°C, 2hrs





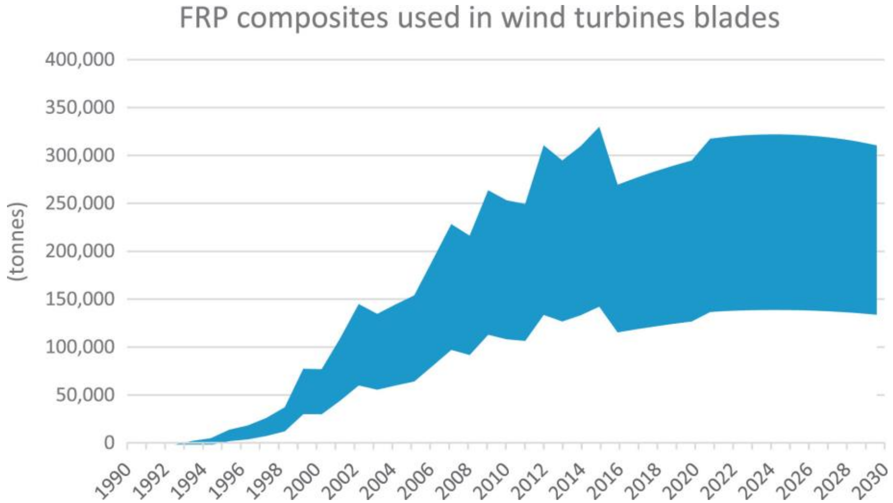
[d3gc03707j (rsc.org)](https://pubs.rsc.org)

Renewables

Vestas hails breakthrough for recyclable wind turbines

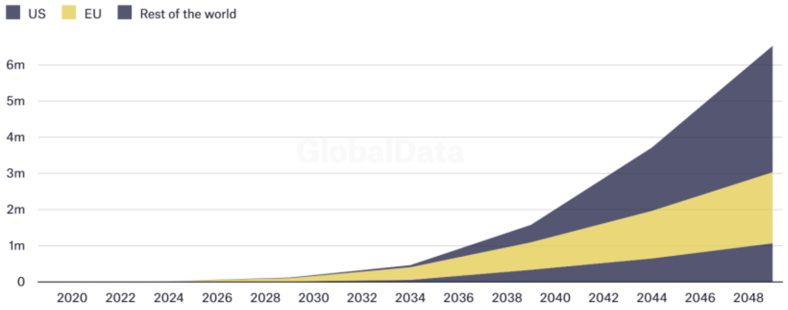
A new chemical recycling process can break down the epoxy resin in wind turbine blades into virgin-grade materials.

Oliver Gordon | February 21, 2023



Already-operating wind turbine blades will produce millions of tonnes of material

Estimated cumulative blade material produced by existing wind turbines coming to the end of their lives, in tonnes



Modelling is based on scenario where turbines produce ten tonnes of waste per MW, and have a 30-year lifespan
Source: Emma Delaney, Re-Wind Network

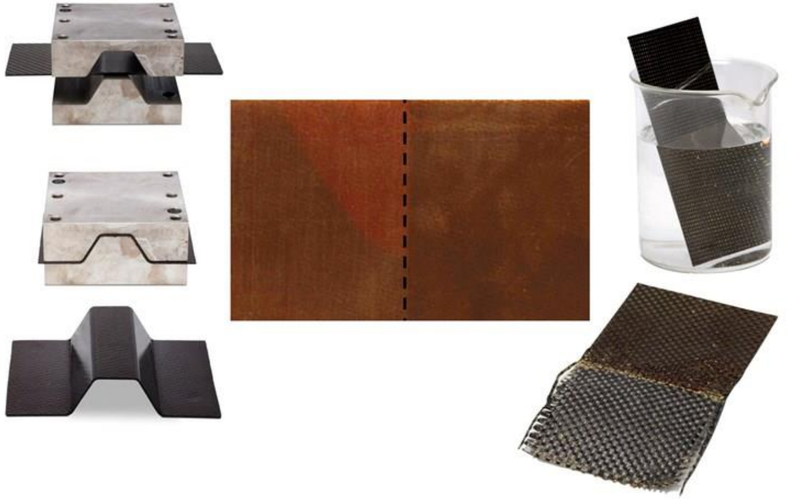
Chemical recovery of epoxy resins

Dissociative chemistry (the crosslinks are broken)

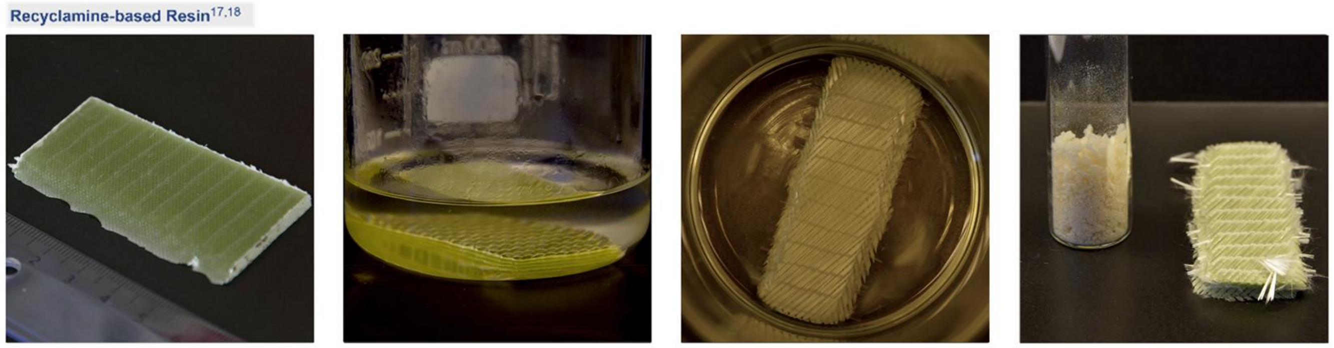
- Recyclamine
  - Low-pH solvent 25% vol acetic acid at elevated temperature converts resin to a thermoplastic epoxy while freeing the continuous fiber reinforcement
  - Both resin and fiber can be reused
- Epotec recyclable epoxy resins
- Thermoreversible Crosslinkable Thermoplast-Thermoset Hybrid (Evonik)

Associative chemistry (cross-links never broken)

- Epoxy vitrimer resins
- Provide cure cycles and properties comparable to conventional aerospace epoxies
  but also allow a range of behaviors more akin to thermoplastics
- thermoset properties below T_g, yet behave like a *thermoplastic* at elevated temperatures, such as 80°C above T_g



reprocessing via thermoforming (left), joining via welding, repair of delaminations using heat and pressure (center) and recycling by solvolysis (right) as well as by remolding ground up scraps



Composite Sample | Submerged in 75% Acetic Acid | After Fragmentation | Polymer Fraction and Glass Fibres

Natural fibers

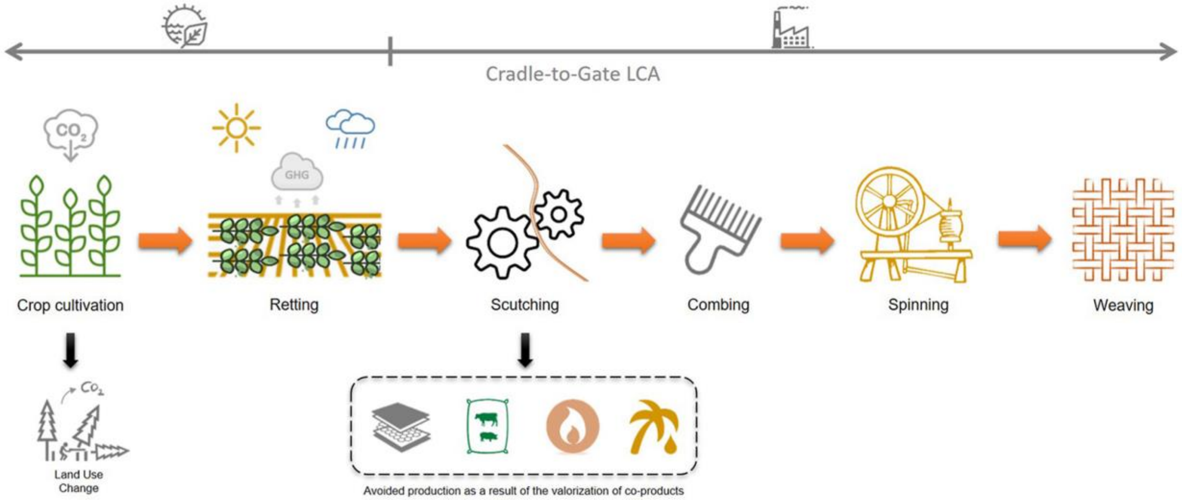
- Flax (42 GPa), hemp, sisal, bamboo, rice husk …



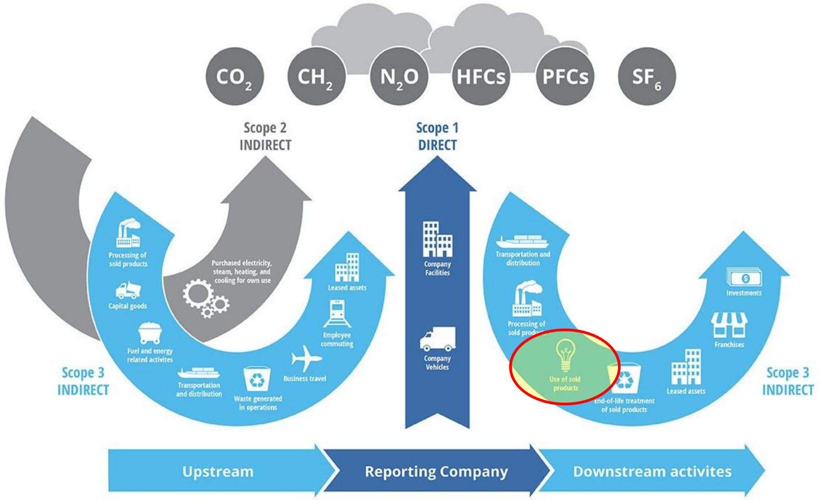
Energy Intensity ~ 3-6 MJ/kg

- Bcomp, EPFL spinoff
  - European flax for TS and TP composites
  - Improved safety with non-catastrophic crash behaviour
  - High vibration damping, specific bending stiffness and fatigue resistance
  - Novel design options – colouring and natural translucency
  - Radio transparency

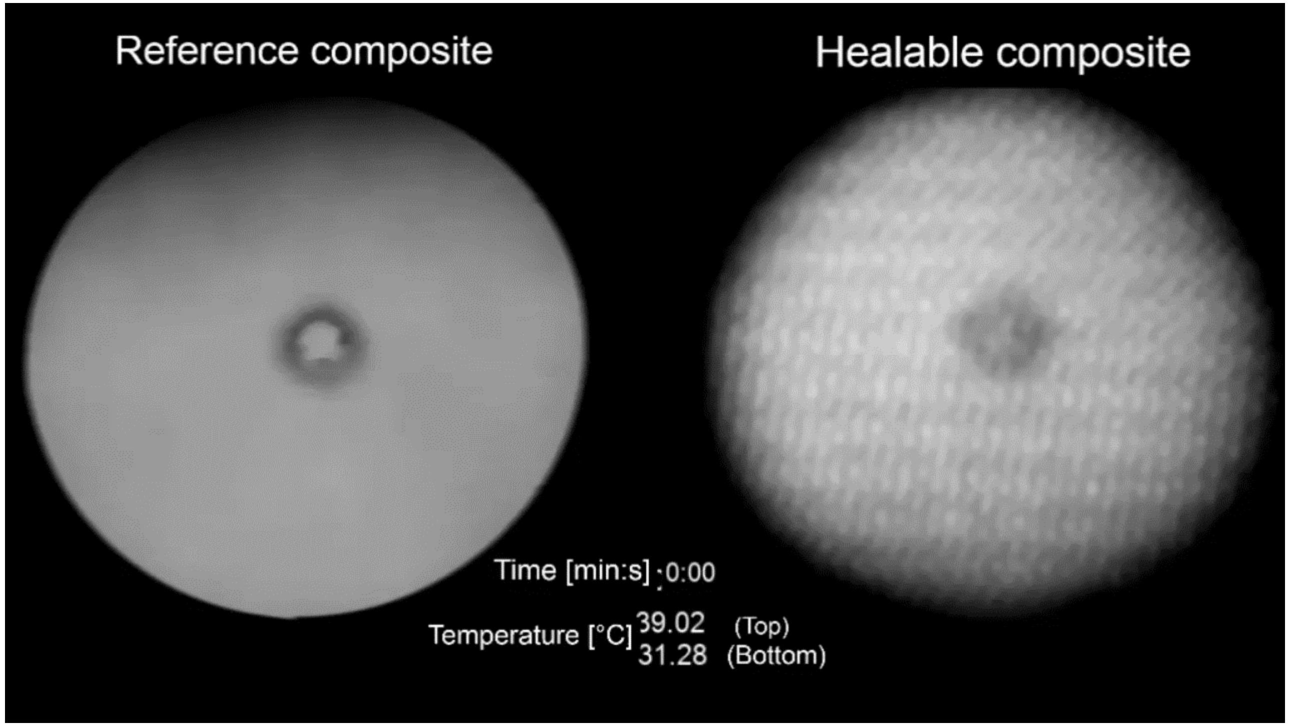
[Recycling of natural fiber composites: Challenges and opportunities - ScienceDirect]



Durability: Self-healing composites



- Self-healing technology to
  - reduce maintenance cost,
  - reduce manufacturing defects
  - extend the lifetime of composites.
- 12 years of research at EPFL
- HealTech™ is a new type of resin giving composite materials the ability to heal resin micro cracks and de-laminations in a few minutes.
- Composite structures (resin damage) can be fully repaired on site as the parts stay structural during healing.



Overview - Towards sustainable composite solutions

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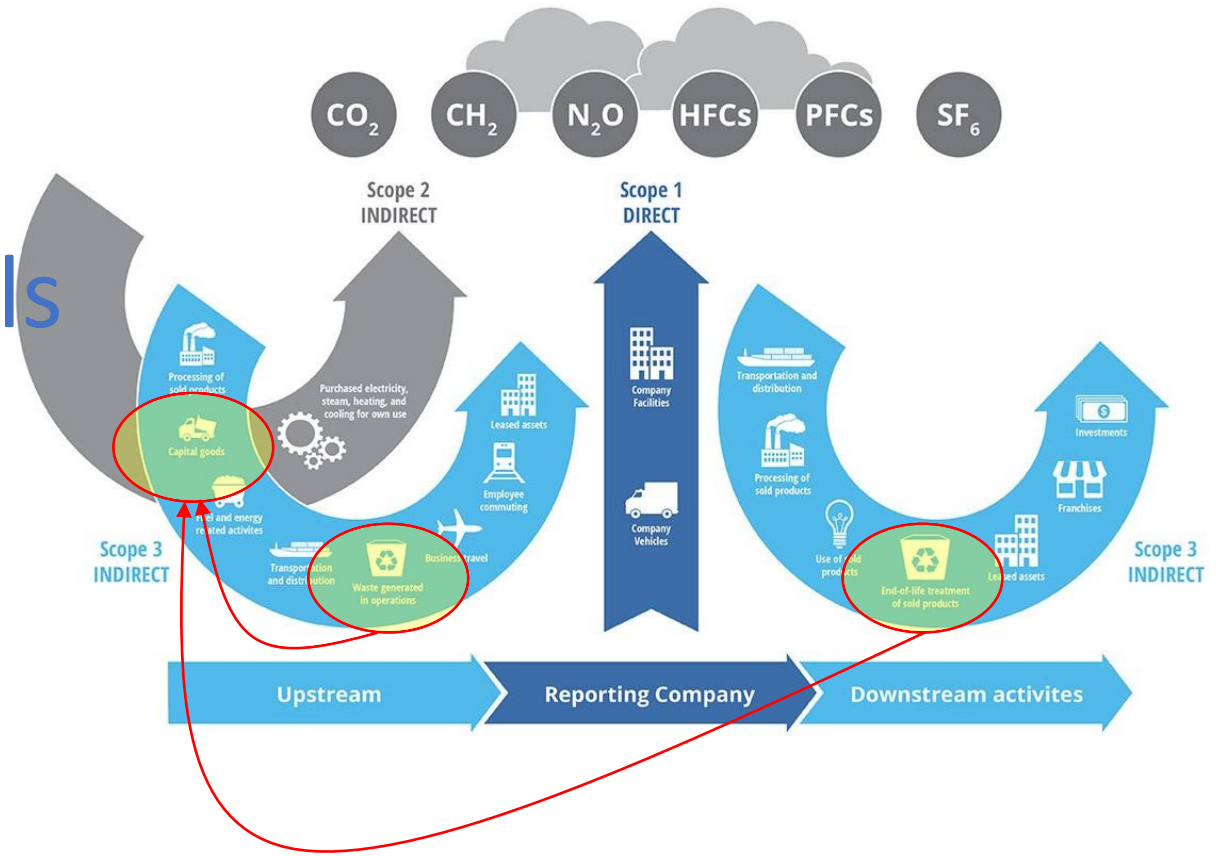
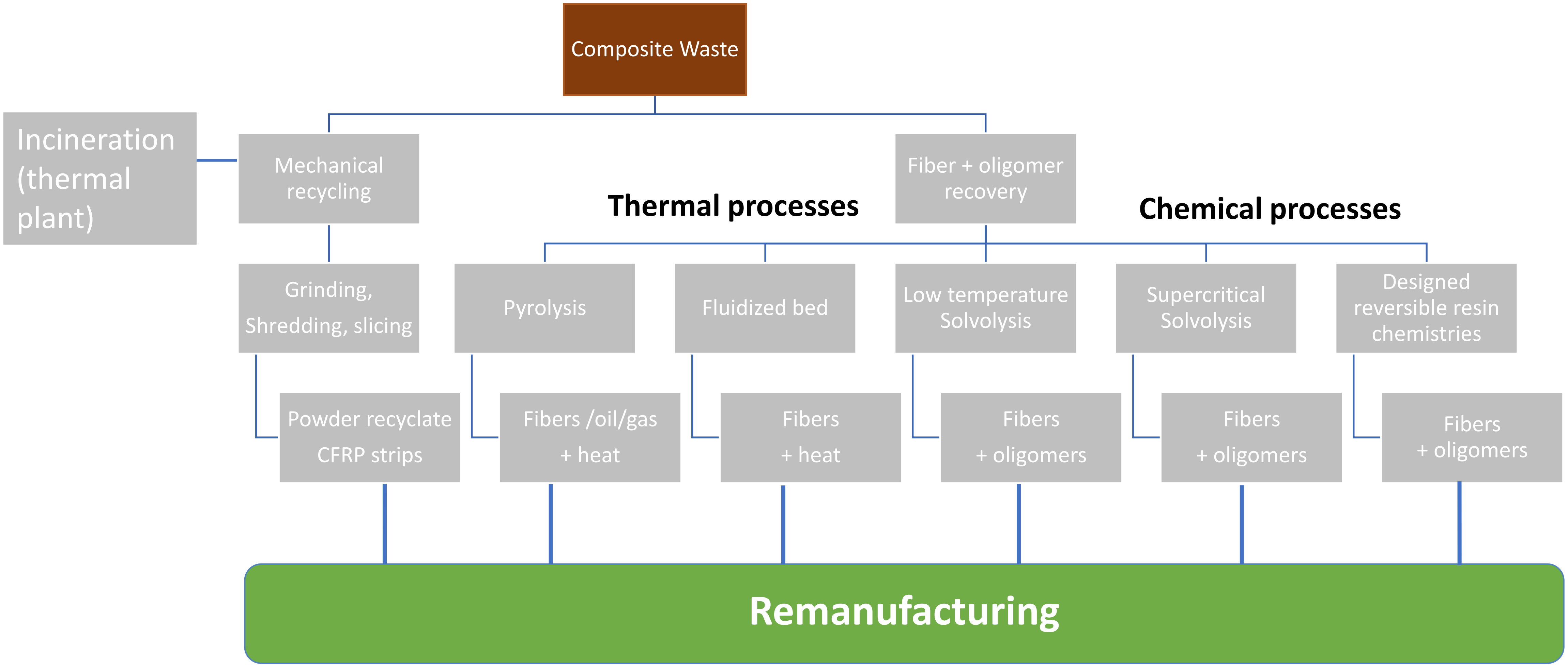
- End of life and recycling
- Bio-based / novel materials
- Circular composites
- Additive manufacturing
- Unmet challenges

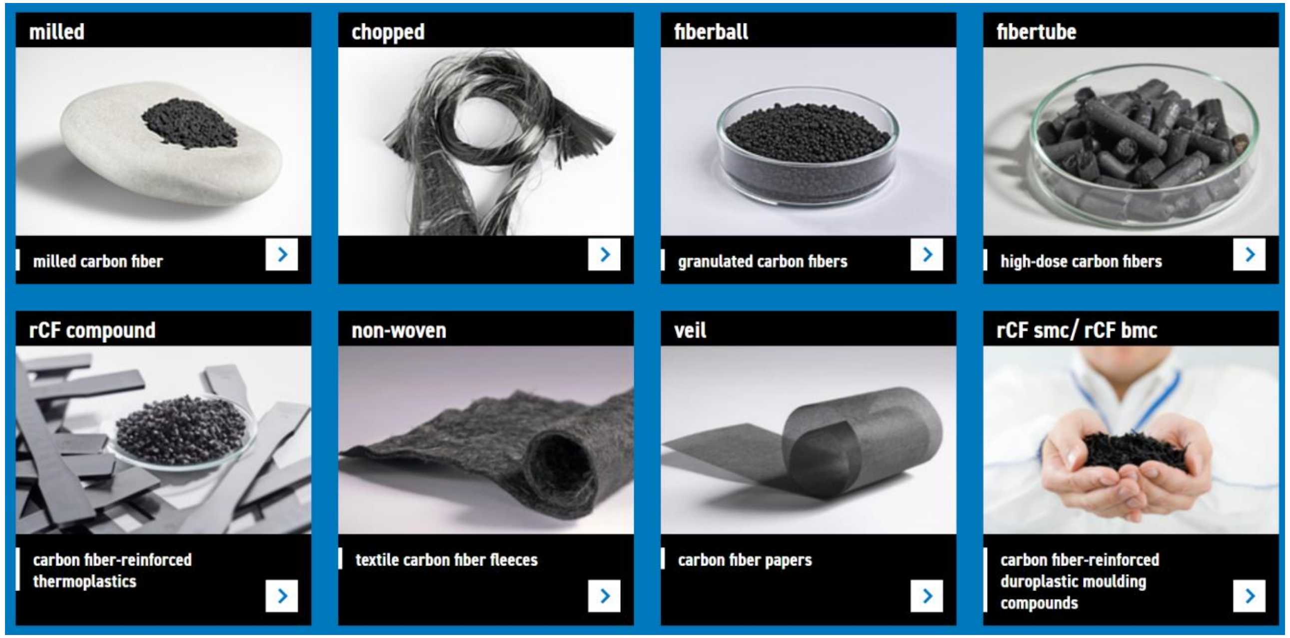


Recycling Routes



Adapted from Pickering, Composites Part A (2006)

Carbon fiber recycling & reuse

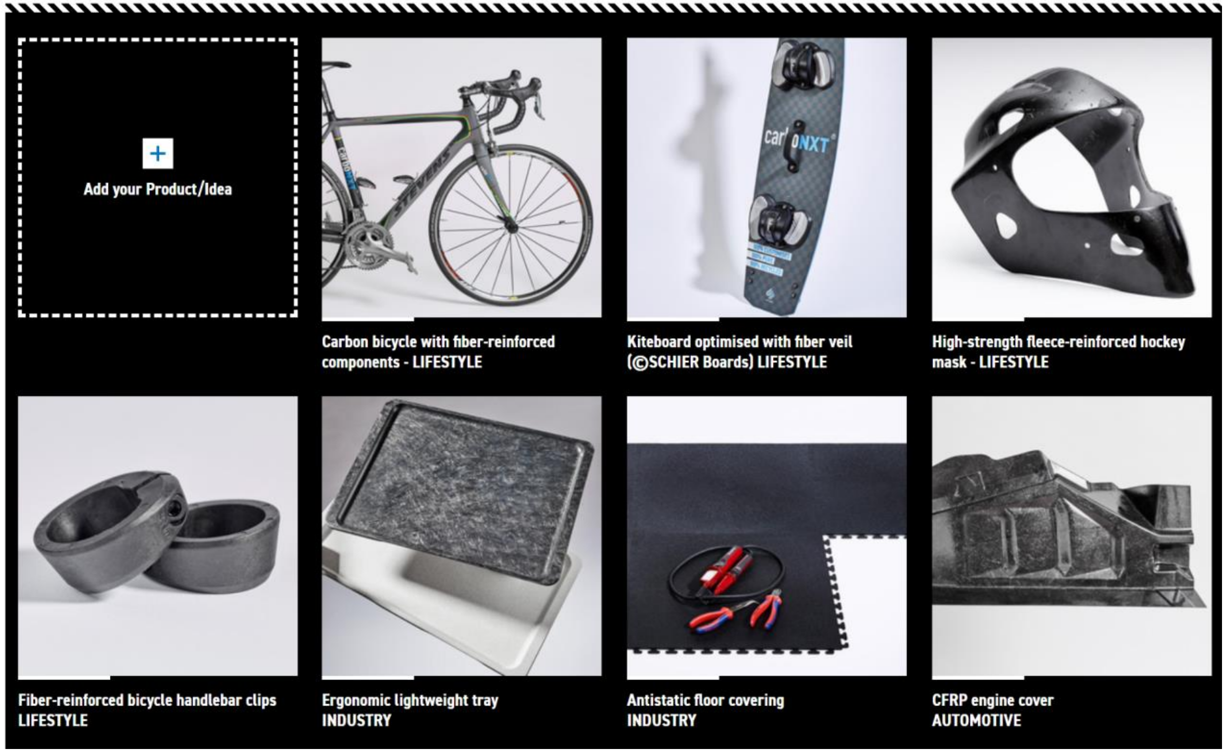


- Recovered CF material forms, 1000 T/yr

[Recycling of carbon fibre-reinforced plastics (youtube.com)]

1:45s – 6:11

- Products using recovered CF

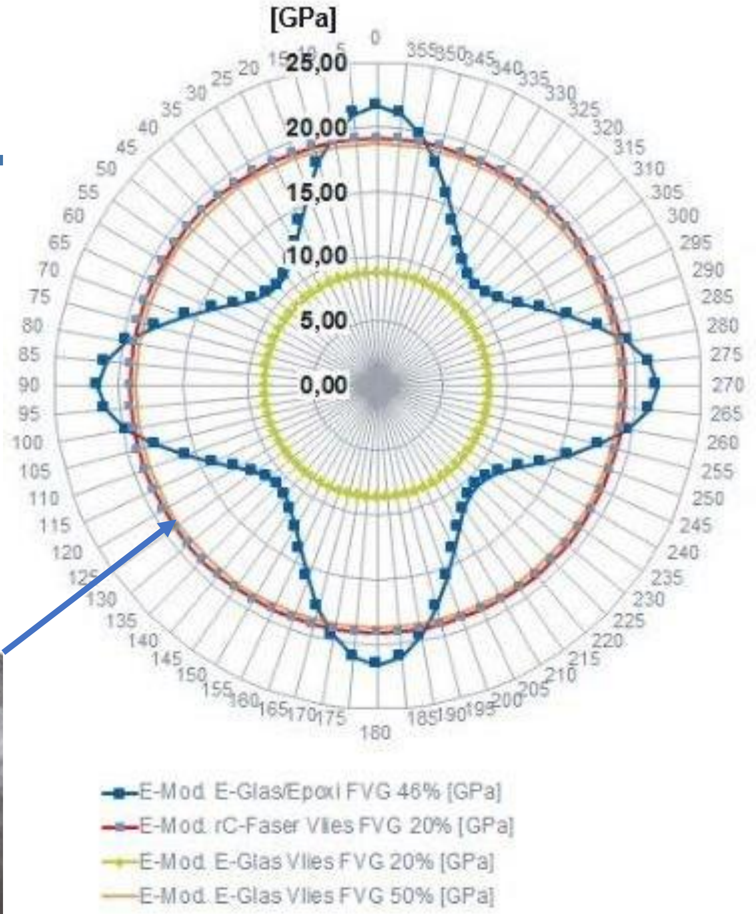


Procotex

- 2000 T/yr capacity
- Range of short fiber carbon materials
- Milling / cutting of CF waste
- Powder (60-300µm)
- Granulates
- Cut and resized fibers (300µm to 120mm)
- Fiber bundles (strands) 6mm

Gen 2 carbon

- Uses recycled carbon fiber to make
- Non-woven mats 50-500gsm, 1-2.5m wide
- Commingled with PP/PA/PEI/PPS
- Random fiber (isotropic)



[Recycling carbon fiber for structural applications | CompositesWorld]

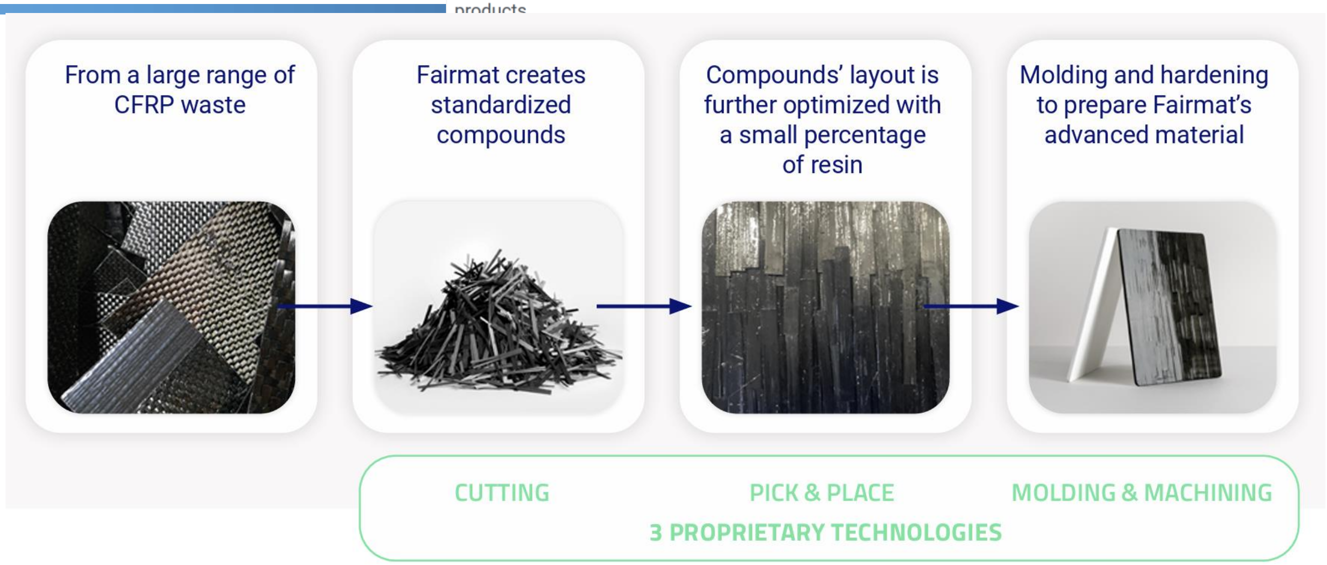
Fairmat

Published 11/29/2021

Hexcel, Fairmat partnership aims to recycle carbon fiber prepregs

Cuttoffs generated by Hexcel's European plants will be repurposed by the end of 2022 into high value-added products

- 5000 T/yr
- Recycle post-industrial waste from carbon fiber prepreg production
- Mechanical treatment, robotics & machine learning to cut
- Maintain fiber length



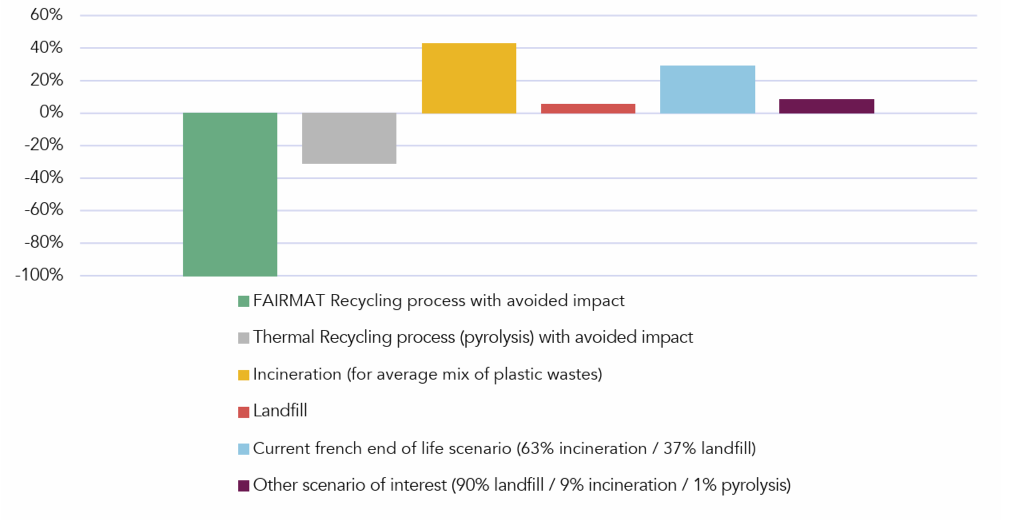
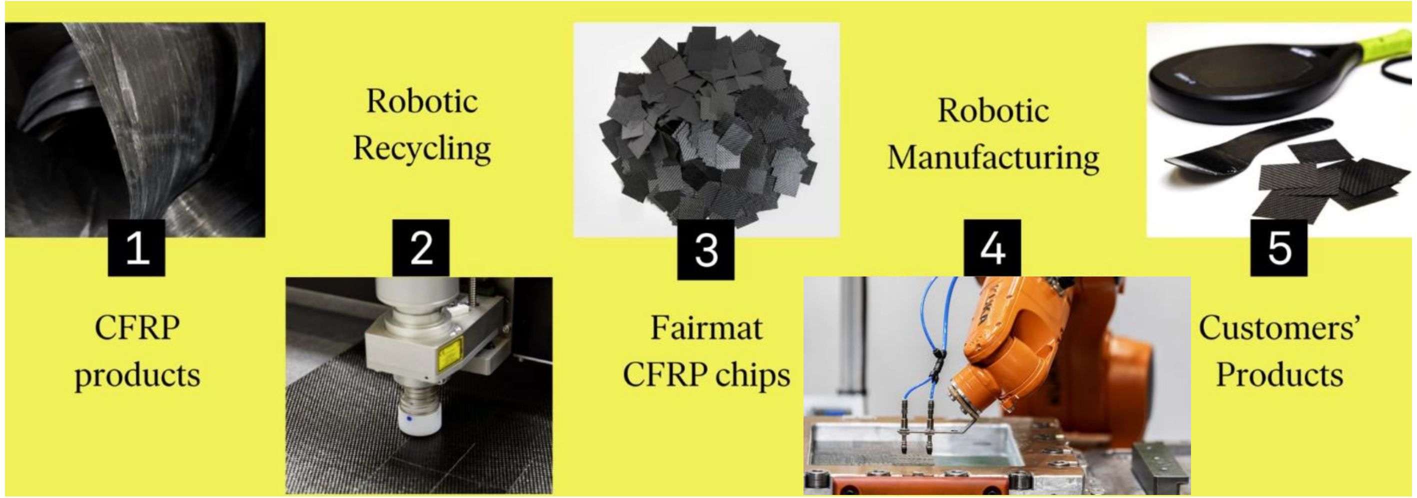


FIGURE 6: CARBON IMPACT COMPARISON BETWEEN FAIRMAT RECYCLING PROCESS AND OTHER END OF LIFE SCENARIOS CONSIDERING PRODUCTION OF RECYCLED MATERIAL



3.8 kgCO2e/kg Fairmat laminate

EPFL

[FAIRMAT - Unlock new possibilities with recycled carbon fiber]

LPAC Laboratory for Processing of Advanced Composites

(re) aligning recycled and recovered carbon fiber

- HiPerDiF (University Bristol)
  - Uses water jets to align fibers 1-12mm (4mm today, 6mm trade-off formability vs. strength, >8mm forms flocks and blocks)
  - Tensile modulus of 115 GPa and tensile strength of 1509 MPa Vf 55%
  - Tapes 6.35-50.8mm wide, kg/hr
  - Used for 3D printing, potential for filament winding

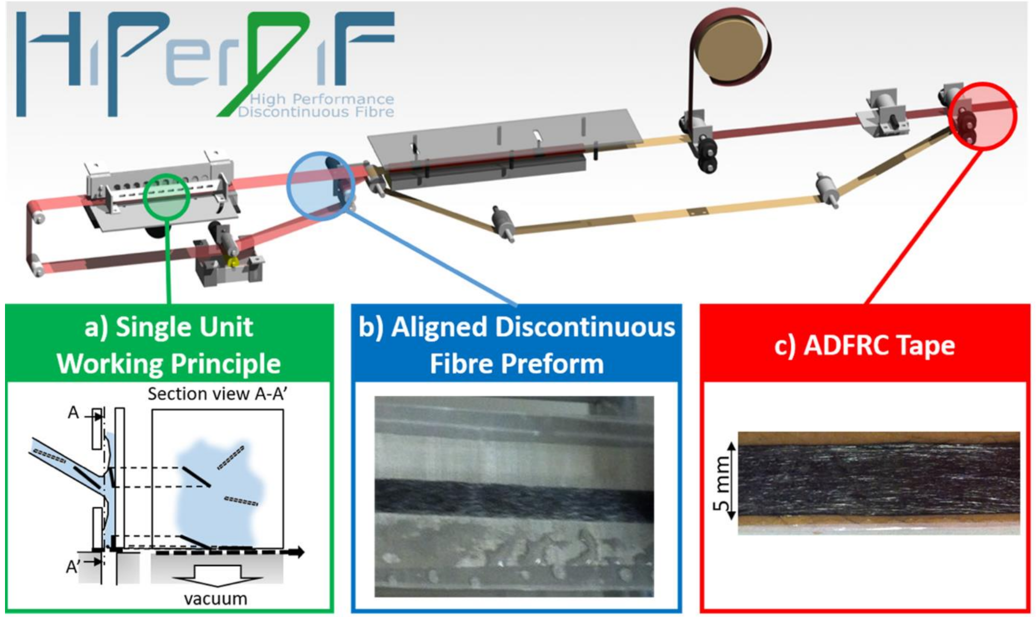
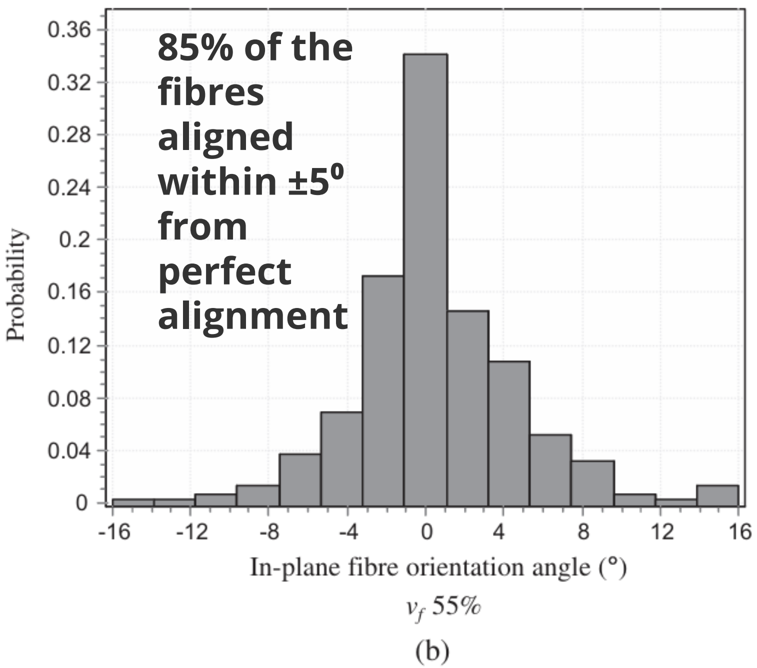
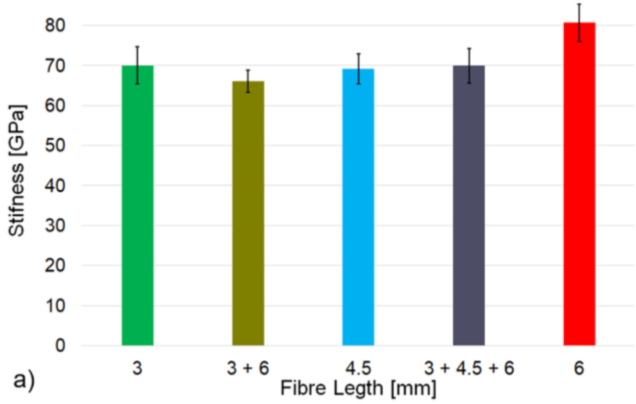
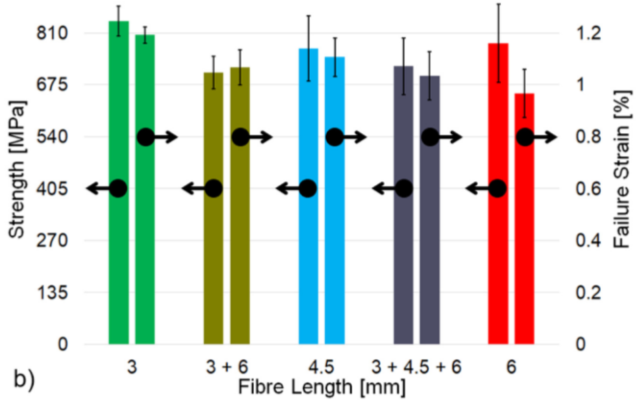


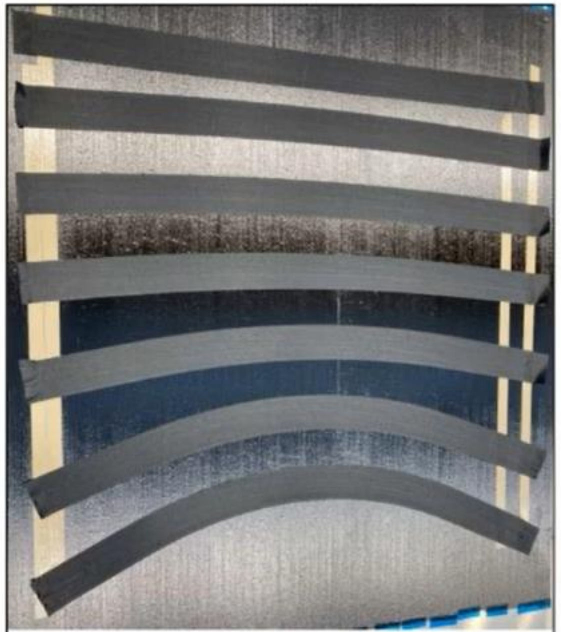
Figure 1. Schematic of the HiPerDiF alignment process.







AFFT TAPES | FORMABILITY

NCC Automated Tape Laying (ATL) 75mm width Continuous fibre tape	**NCC** Automated Tape Laying (ATL) 75mm width Lineat AFFT tape
 ATL with continuous fibre	 ATL with LiNEAT tape

Critical steering radius	**8m**	**0.8m**

slido

Please download and install the Slido app on all computers you use

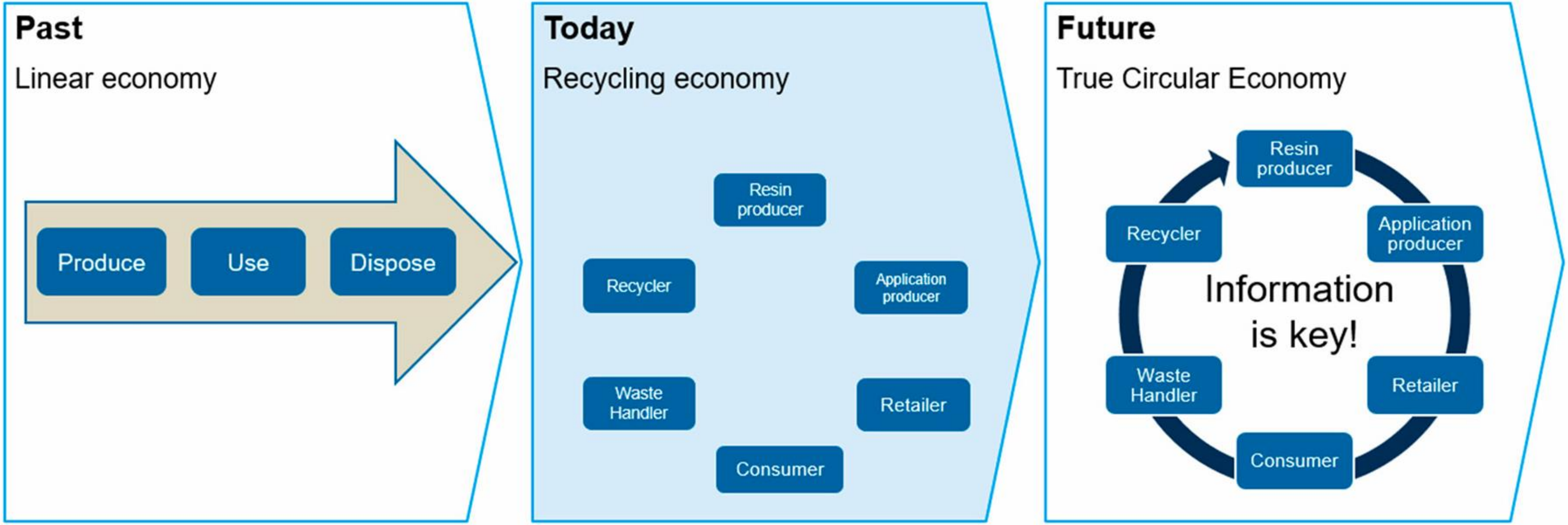
What is inhibiting the circularity of composites?

ⓘ Start presenting to display the poll results on this slide.

Question

- How to go from non-standardized waste to standardized raw materials?
- Traceability / supply chain …

We need a transition in business models …



[Polymers | Free Full-Text | Information-Based Plastic Material Tracking for Circular Economy—A Review (mdpi.com)]

Block chain technology

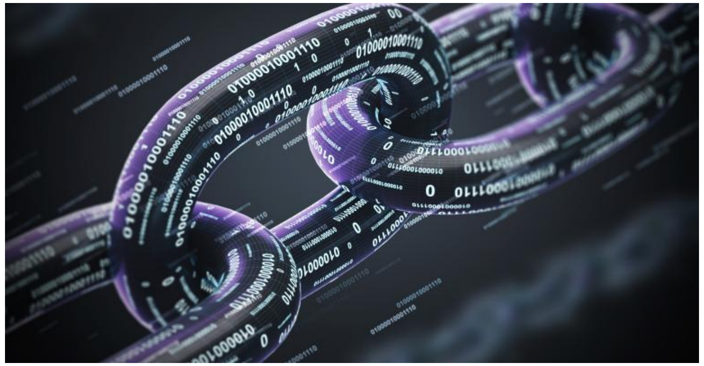
Digital distributed ledger that allows users to share and store secured and verifiable data

Marker is embedded into the plastic material, homogenously dispersed so it can be read with a scanner, information uploaded to blockchain platform

Survive mechanical recycling, marker remains traceable as plastic material goes through the value chain and physical recycling

e.g. marker coded with 4 data points:

1. type of plastic,
2. manufacturer,
3. percentage of recycled content,
4. number of times the material has gone through the entire value chain or loop count



Blockchain Traceability Plan for Recycled Plastic Waste Revealed (plasticstoday.com)

ChemChain | Track chemicals along the value chain

ChemChain - Blockchain platform to track chemicals along the value chain - YouTube

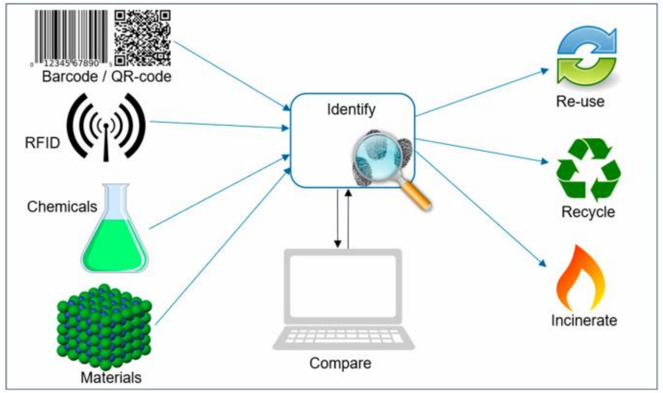
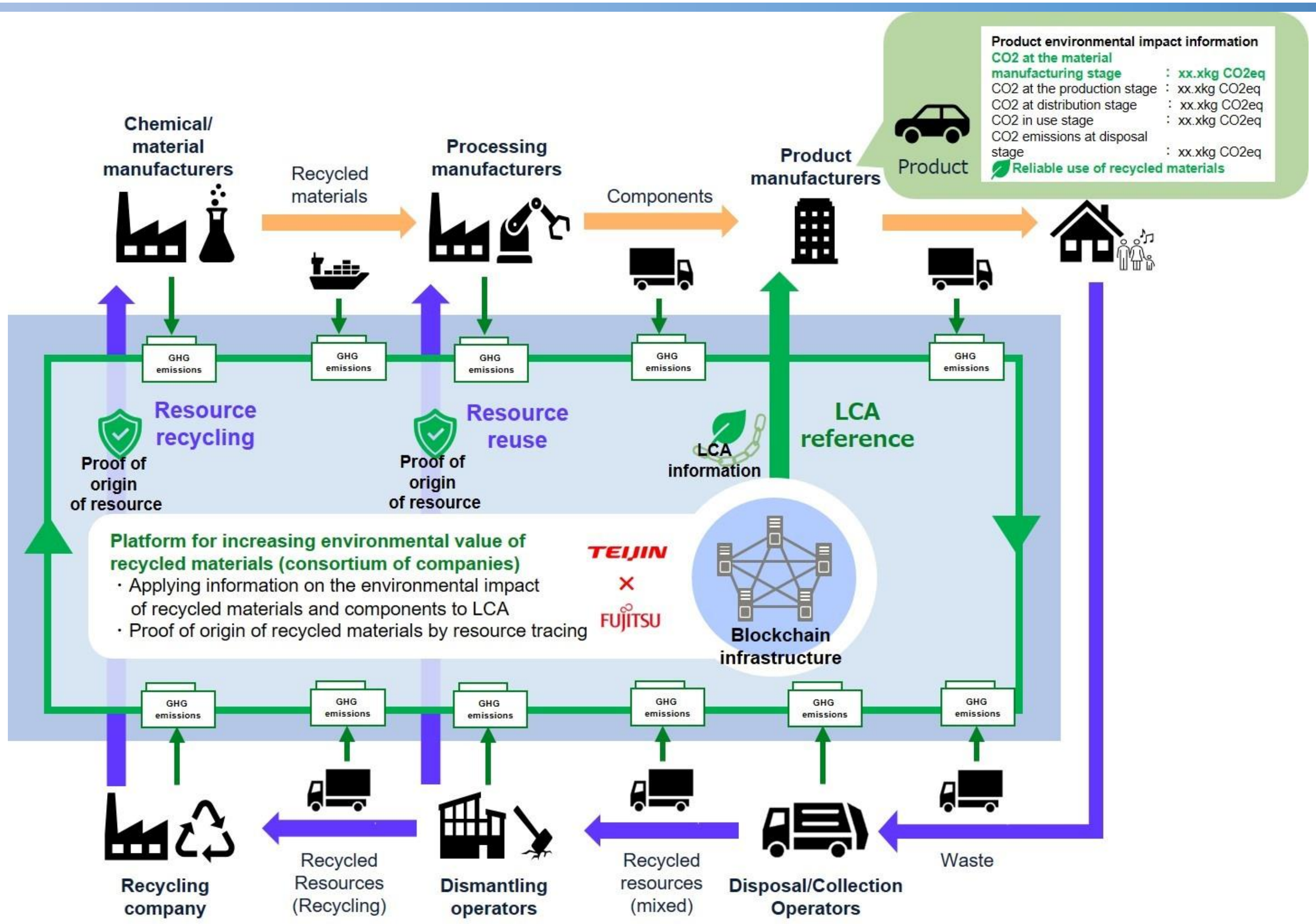
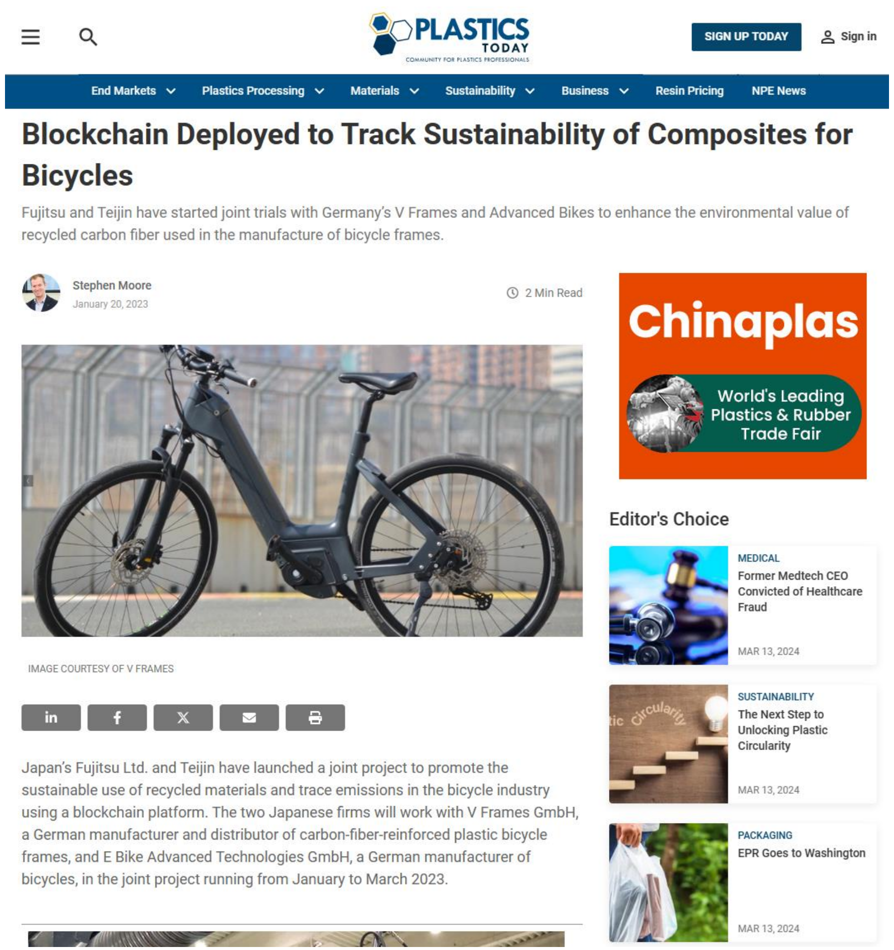


Figure 4. Options for physical tracking options in plastics recycling; Graphics from [37].

Block chain enabled carbon fiber composite recycling





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Blockchain Deployed to Track Sustainability of Composites for Bicycles

Fujitsu and Teijin have started joint trials with Germany's V Frames and Advanced Bikes to enhance the environmental value of recycled carbon fiber used in the manufacture of bicycle frames.

Stephen Moore
January 20, 2023
2 Min Read

IMAGE COURTESY OF V FRAMES

Japan's Fujitsu Ltd. and Teijin have launched a joint project to promote the sustainable use of recycled materials and trace emissions in the bicycle industry using a blockchain platform. The two Japanese firms will work with V Frames GmbH, a German manufacturer and distributor of carbon-fiber-reinforced plastic bicycle frames, and E Bike Advanced Technologies GmbH, a German manufacturer of bicycles, in the joint project running from January to March 2023.

Editor's Choice

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MAR 13, 2024

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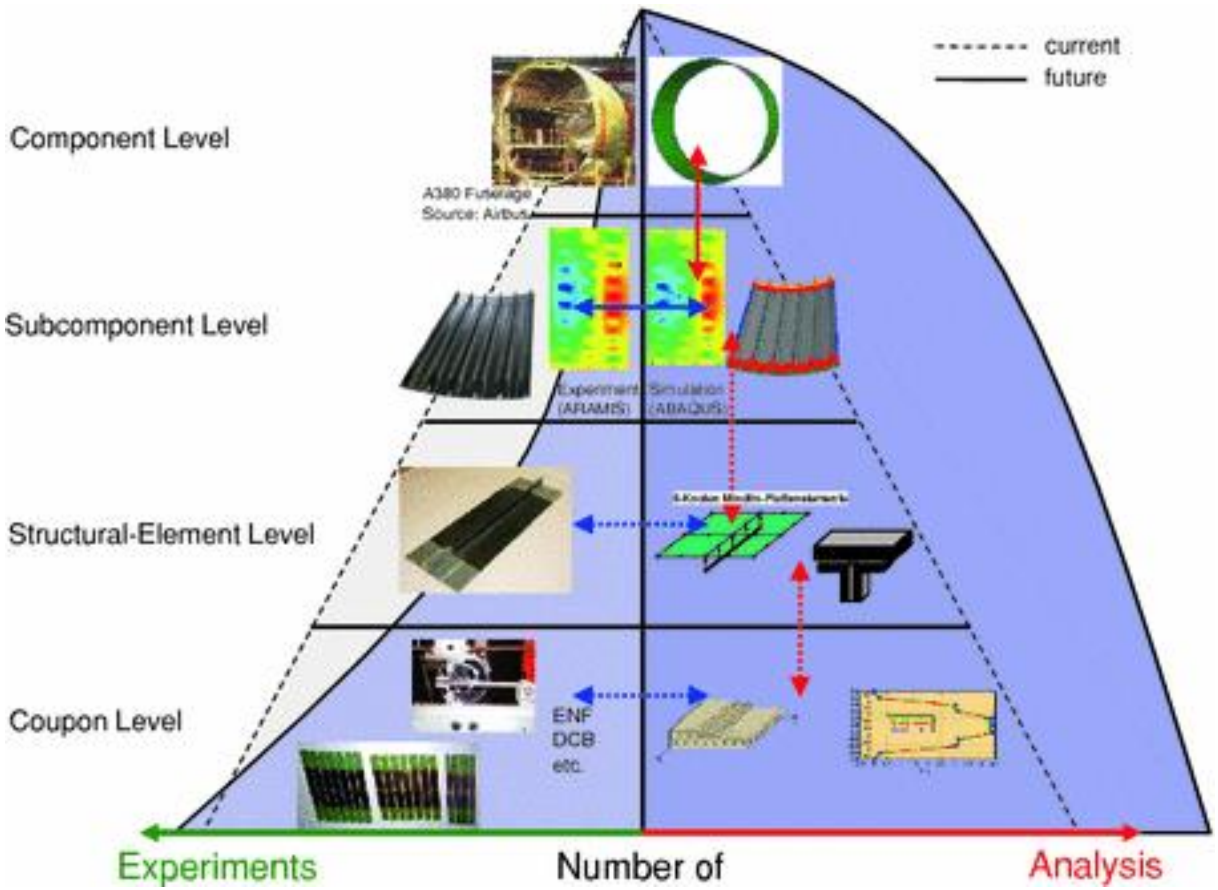
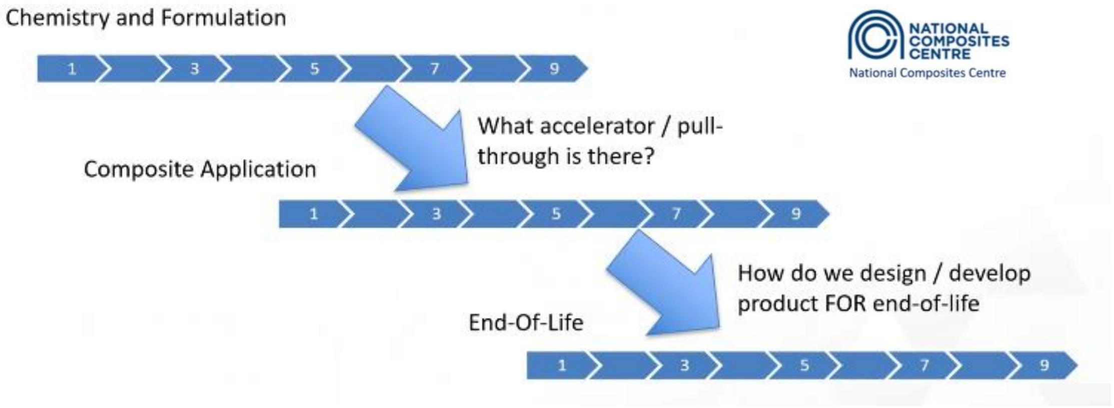
Virtualization to compress technology readiness



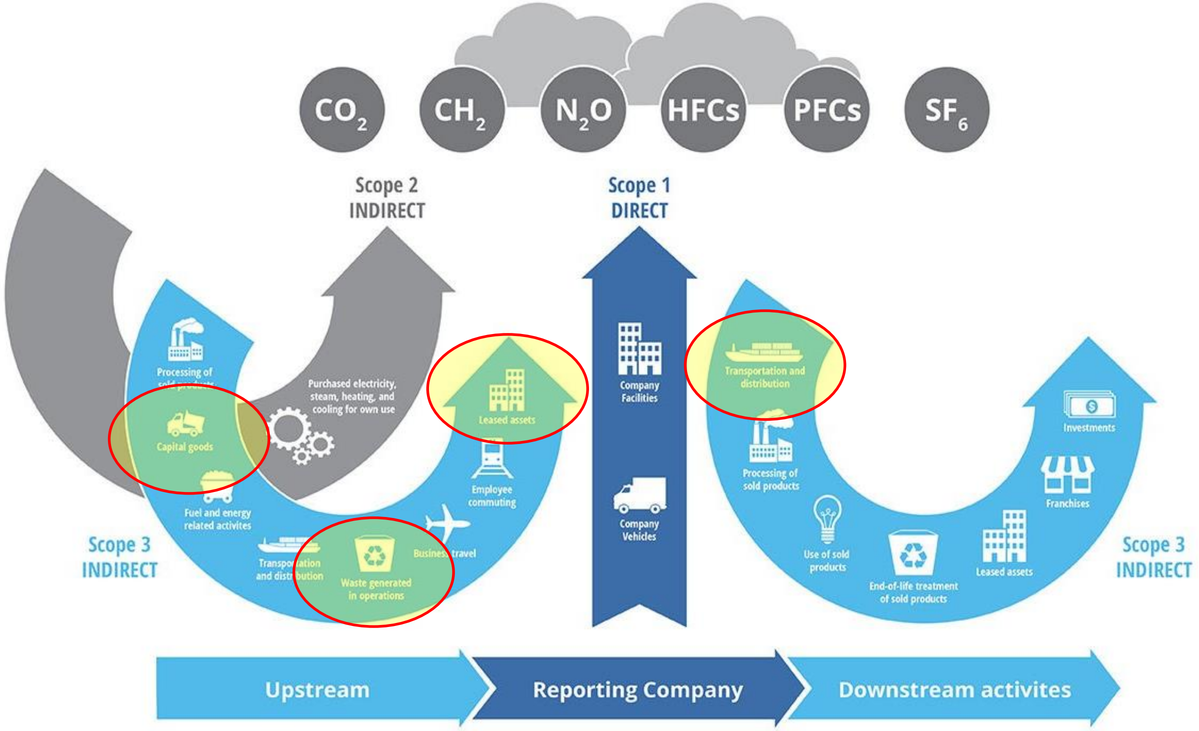


- Testing pyramid needed to approve CF materials
- Requalification through TRLs across supply chain (material, design, part making, ELV).
- Need concurrent TRL processes to reduce time to market and 1st revenue.

[Validation Approach for Robust Primary Carbon Fiber-Reinforced Plastic Structures | SpringerLink]

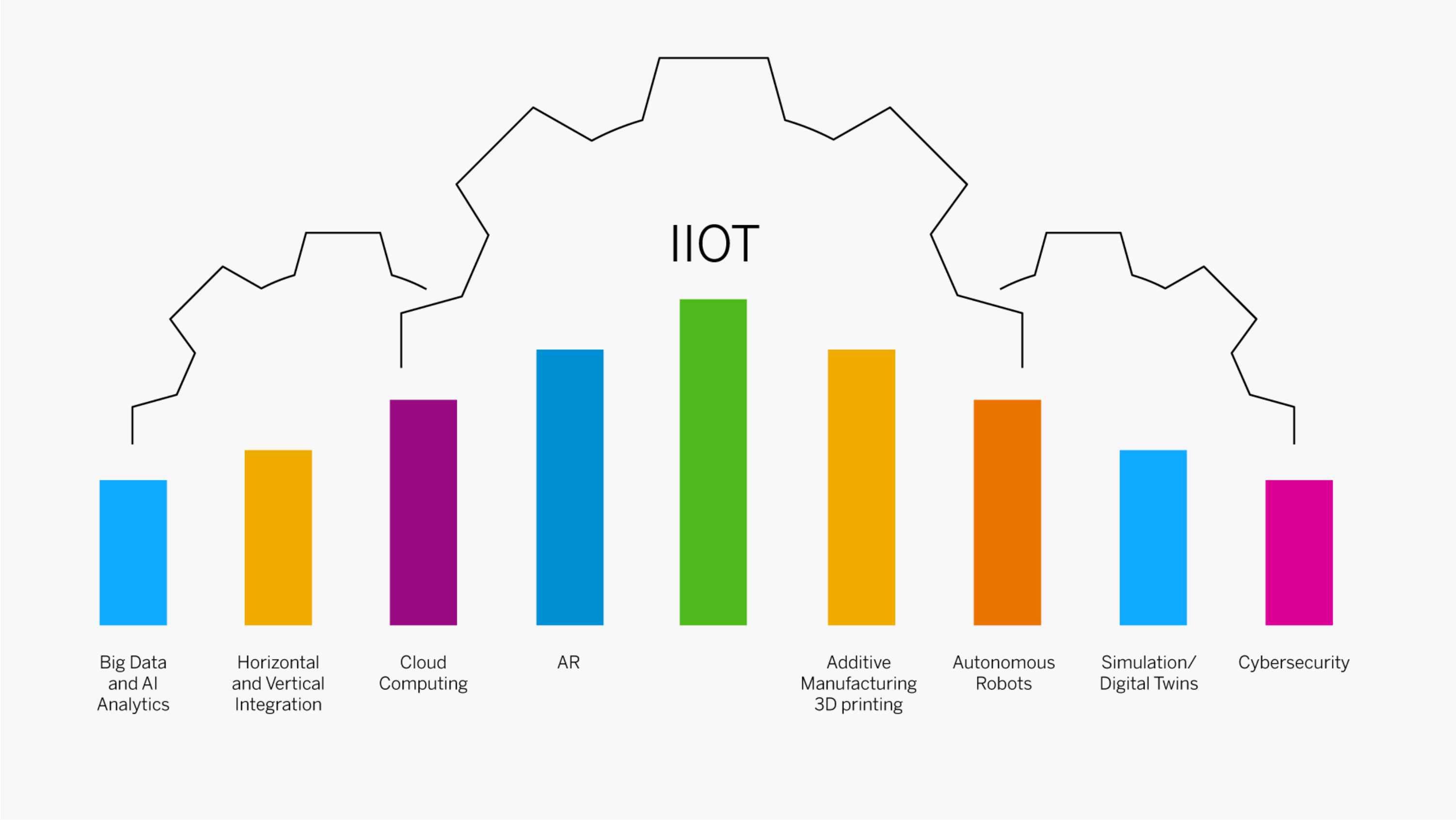
Overview - Towards sustainable composite solutions

- Policy
- End of life and recycling
- Bio-based materials
- Additive manufacturing
- Unmet challenges

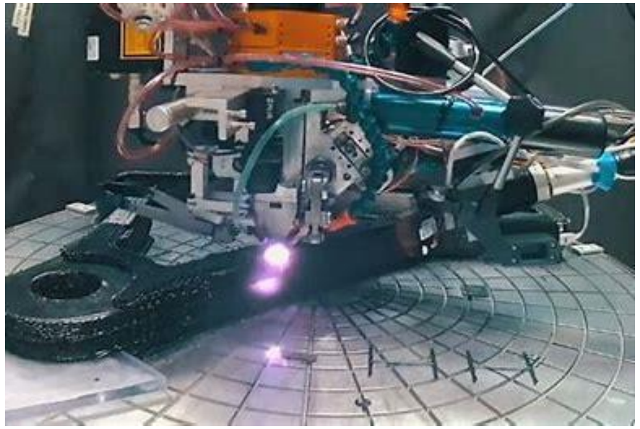


Manufacturing transformation

- Ind 4.0
- IoT
- Sensor miniaturization
- Cloud data
- Digital transformation
- Additive manufacturing
    - Dispersed manufacture / reduced shipping
    - Flexible / customization
    - Design freedom
    - Lower CAPEX/unit
    - Reduce tooling investment



Continuous carbon fiber 3D printing examples



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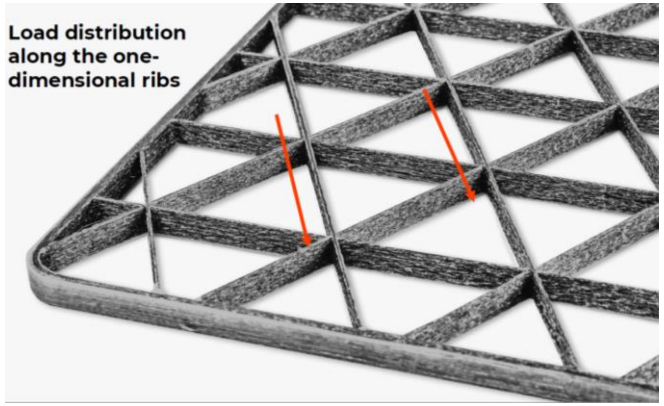
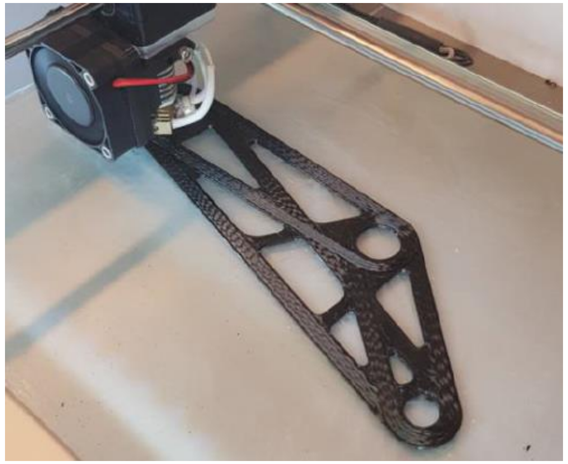


Anisoprint

Ingersoll

Arris



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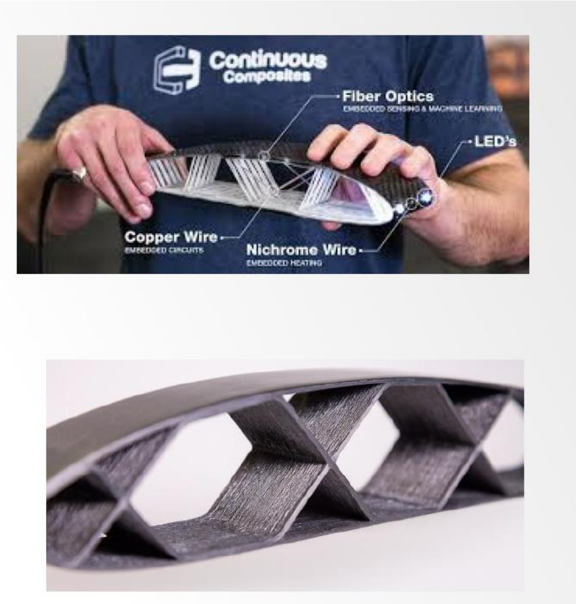
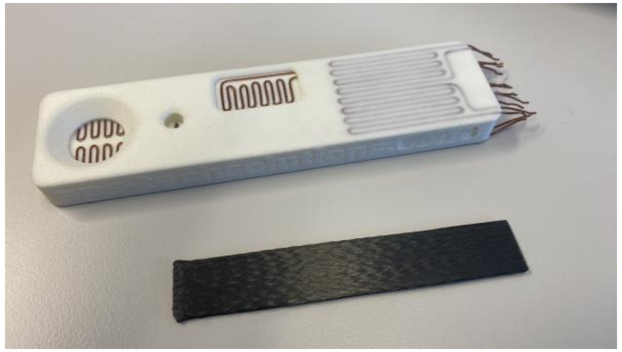


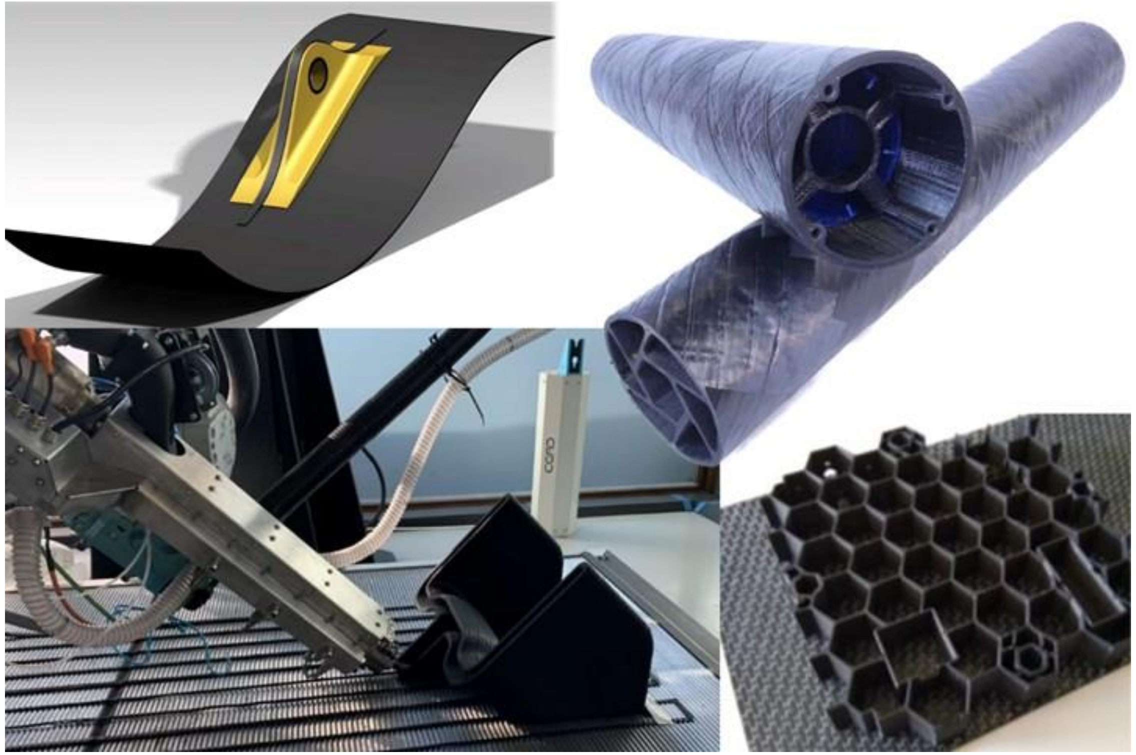
Continuous composites



APS

[(92) 3D printing of continuous carbon fiber | LinkedIn]

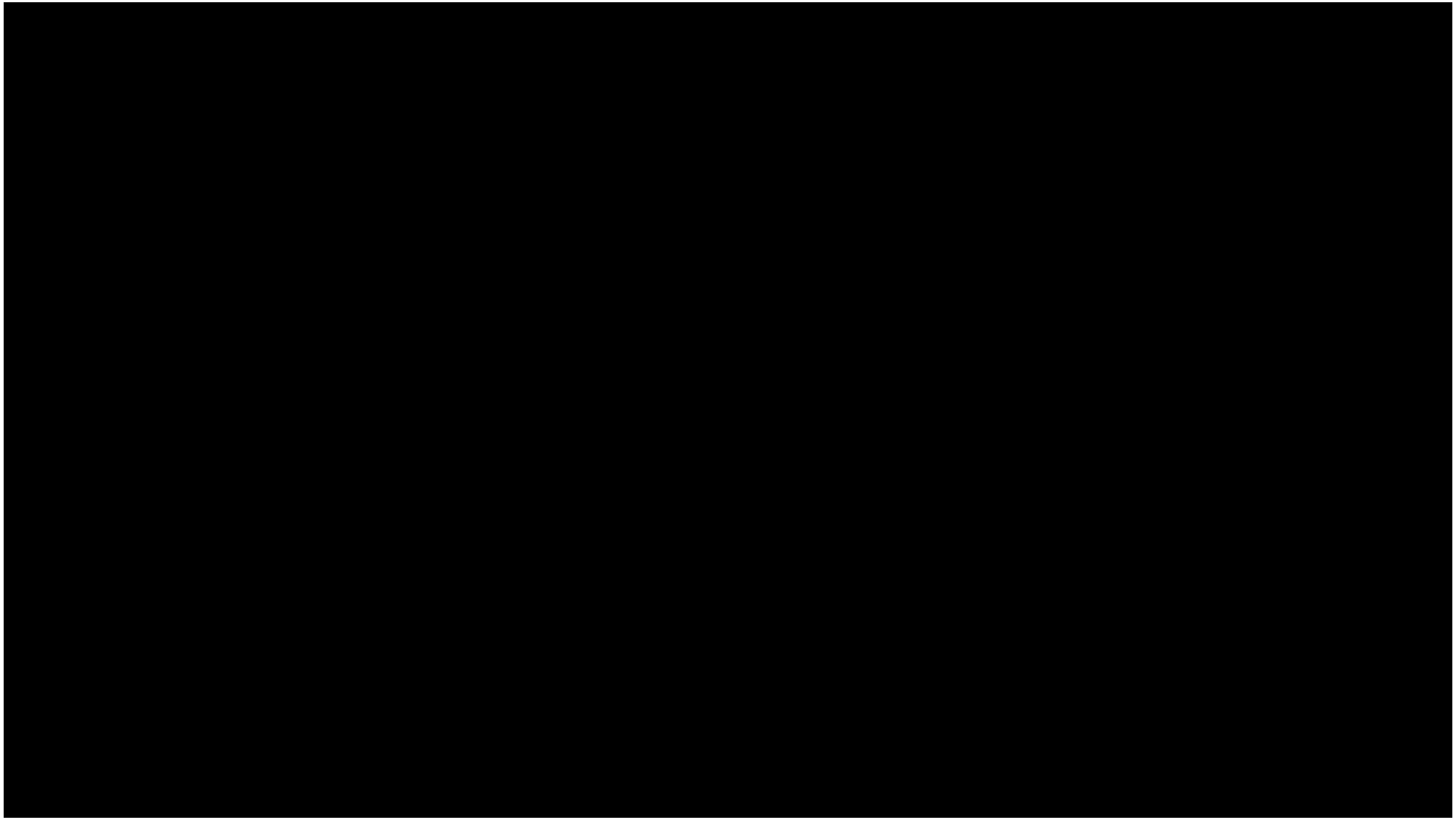
Merging of AM with composites manufacturing



- Overprinting onto premade CFRP surfaces and brackets *(top left)*,
- hybridizing processes such as 3D printing and filament winding *(top right)*,
- 3D printing cores onto AFP laminates and AFP skins onto 3D-printed cores *(bottom right)*
- CEAD AM Flexbot 3D printing at 45 degrees *(bottom left)*.

[Coriolis Composites - Cpico #additivemanufacturing machine 🛠 - YouTube]

Merging of AM with composites manufacturing



Electroimpact Continuous Fiber 3D Printing - YouTube

1min20s

Overview - Towards sustainable composite solutions

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- Circular composites
- Additive manufacturing
- Unmet challenges

Challenges and opportunities to FRPC circularity

Technical	Market	Policy
• Limitations of materials • Complexity and dimensions of parts (e.g. bike frames to wind turbine blades) • Wide variety of existing materials, even different CF grades • Endless material combinations • Makes sorting for recycling difficult	• Constraints along value chain • Financial, Social, Behavioral, Logistical • Risk in developing recycling infrastructure versus waste supply heterogeneity • Issues developing economies of scale for recycling • Risk that recovered fiber can cost more (not always) than virgin fibers	• Inadequacy, lack of local national or European regulations • Some are outdated, others deemed too strict • Waste is still considered a hazardous waste not a resource • Limits trade and reuse and treatment • Contradictory agendas

Summarizing: a sustainable composites industry?

Efficient use of materials and energy

- Reduced waste
- Energy efficient processing

Smarter use of materials

- Design for recycling
- Net-shape automated manufacturing, AM
- Re-visit material formulation
- Simpler/ standardized
- Virtualized / TRLcomp.

Responsible sourcing

- Global/regional/local supply chains
- Reduce use of hazardous materials/ constituents
- Petro chemical to non-food bio-mass

In service

- Durability, increase life / use phase
- Sensors, IoT Ind4.0, functionalized
- Easy repair
- Lease / maximize use

End of life management

- Recycling coalitions
- Investment in recycling CAPEX
- Standardized processes
- Traceability, Blockchain

Simple recyclate streams

Recover fibers (for lower specification applications)

Cracking to universal small molecules (beyond composites)

Return to raw

Suppress landfill / burning

Leaky loops

Foundations

Legislation & incentives	Collaboration Respect & Trust	NetPositive: People, planet, profit	Tech. innovation, entrepreneurship	Use renewable energy

EPFL

Create bigger circles (rather than small complex expensive circles)

LPAC Laboratory for Processing of Advanced Composites