Towards sustainable composites?

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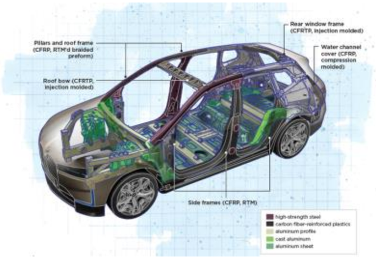
Composites will see rapid growth as enablers towards 2050 SSPs

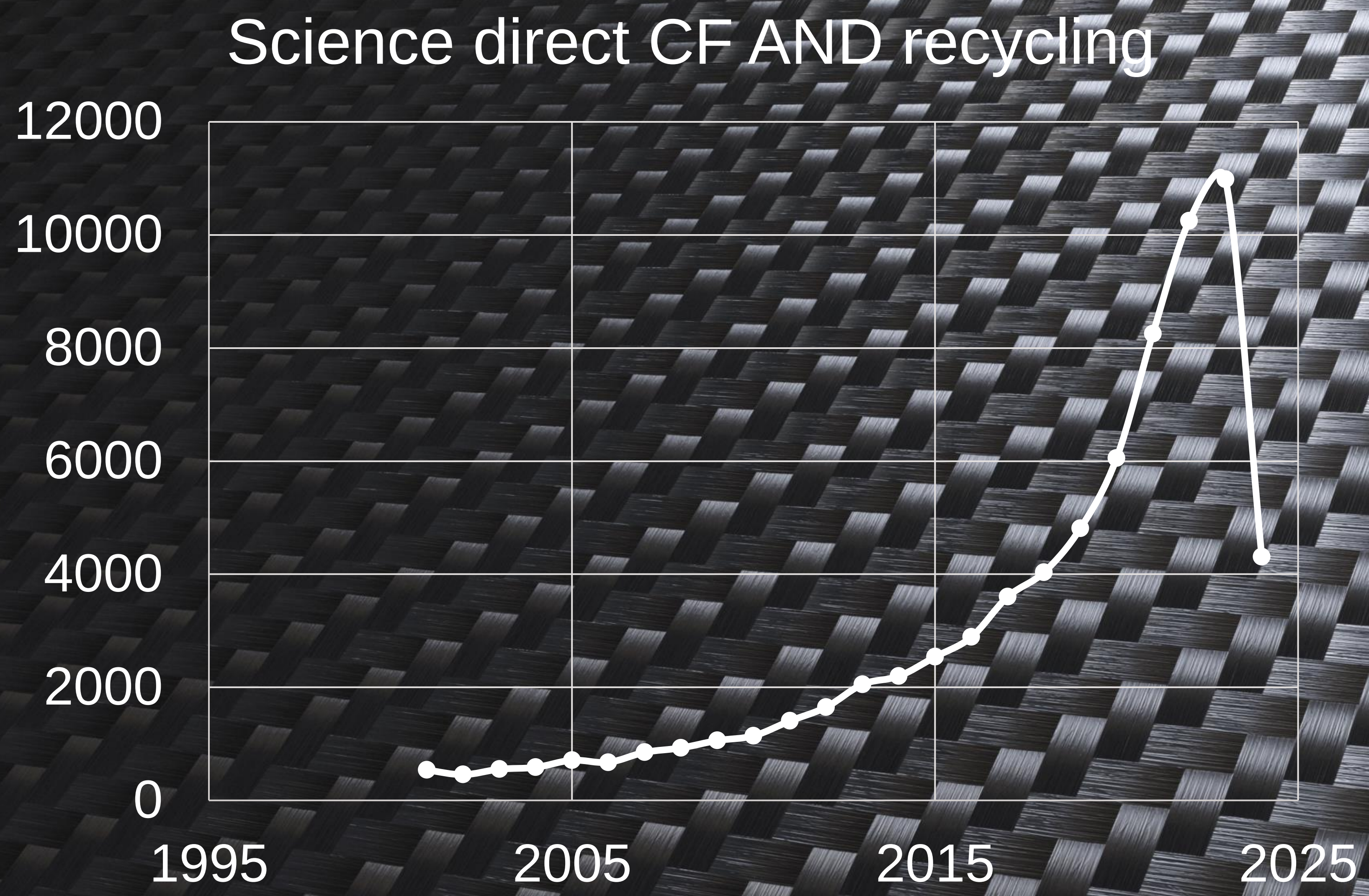
Main sectors / **Sub sectors**

Aerospace	Wind	Automotive	Hydrogen	Infrastructure	Consumer
☐ Civil wide body	☐ Wind on-shore	☐ Super cars	☐ CNG tanks	☐ Concrete rebar	☐ Bicycles
☐ Civil narrow body	☐ Wind off-shore	☐ Premium	☐ Auto Hydrogen	☐ Buildings	☐ Marine
☐ Evtol/drones	☐ Tidal	☐ EVs	☐ Aero Hydrogen	☐ Train	☐ Consumer
☐ Military	☐ Fuel cells	☐ Other	☐ Ground Hydrogen	☐ Other	☐ Other
☐ Other	☐ Other		☐ Rail Hydrogen		
			☐ Other		



Needed industrial sector segmentation 1980-2050 for EPFL model

CF AND recycling: Science Direct



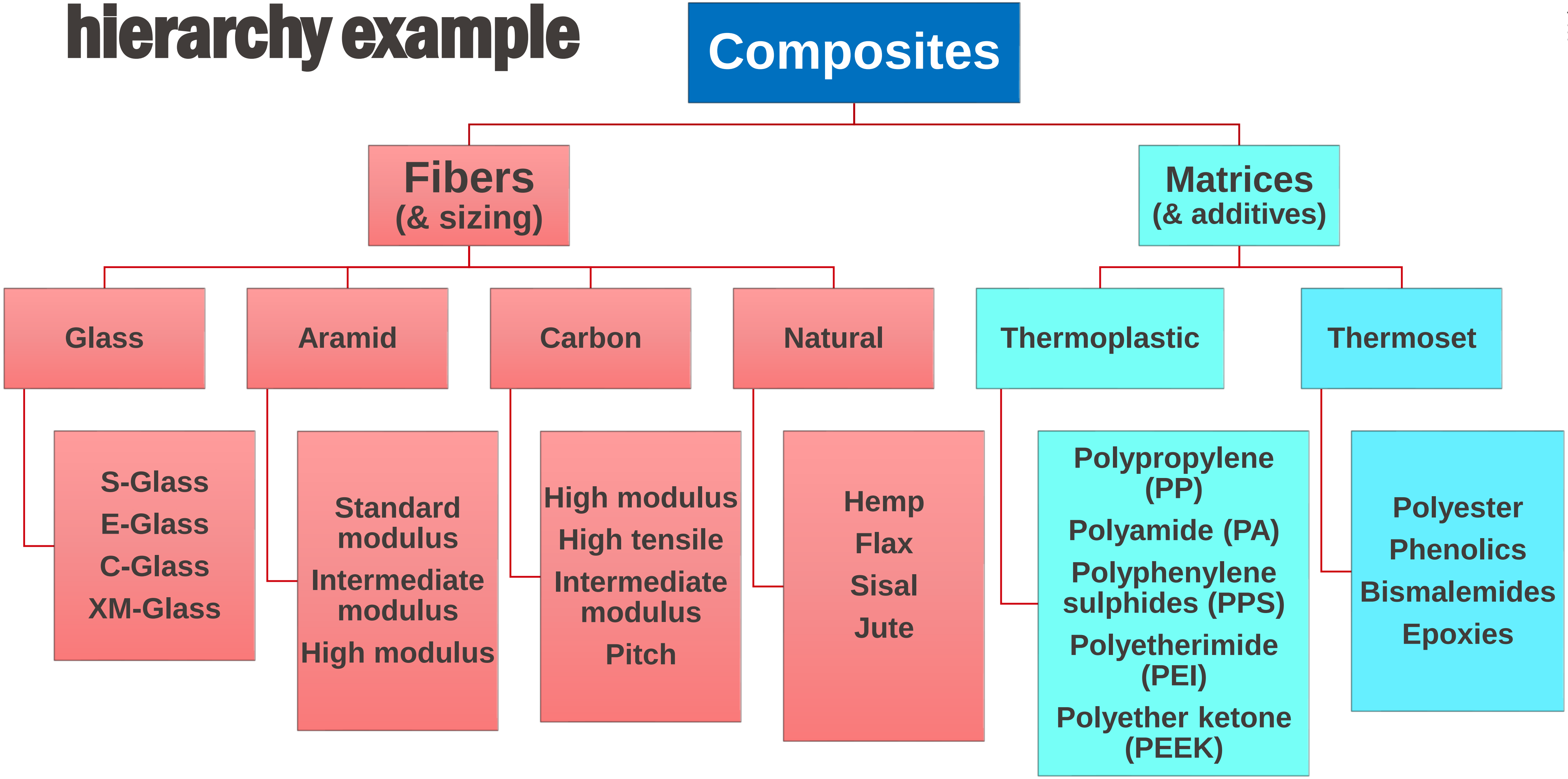
Question 1:
Does this correspond to an equivalent growth in CF recycling and recovery?

Question 2:
If NO, then why?

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

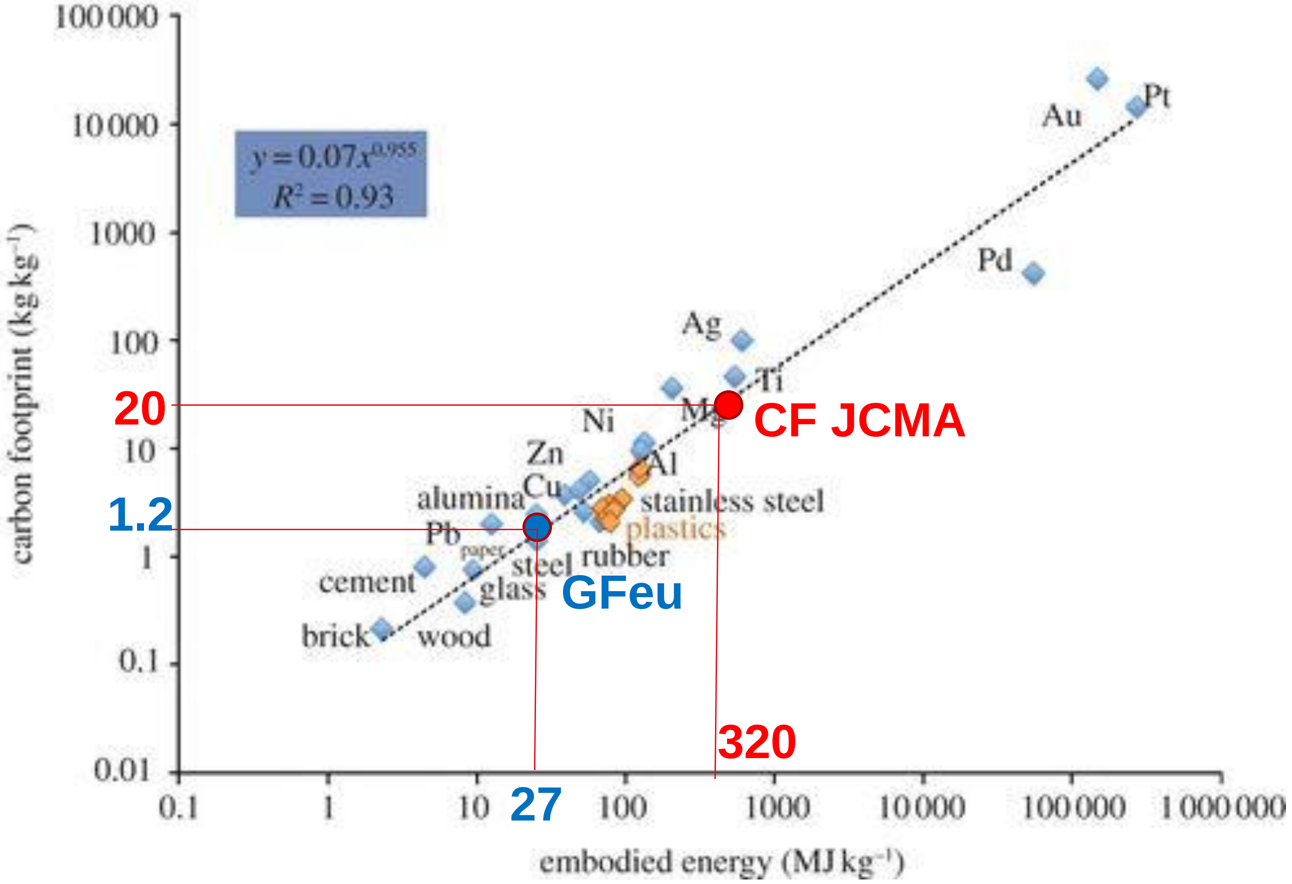
Question 4:
Can S&T solve this problem?

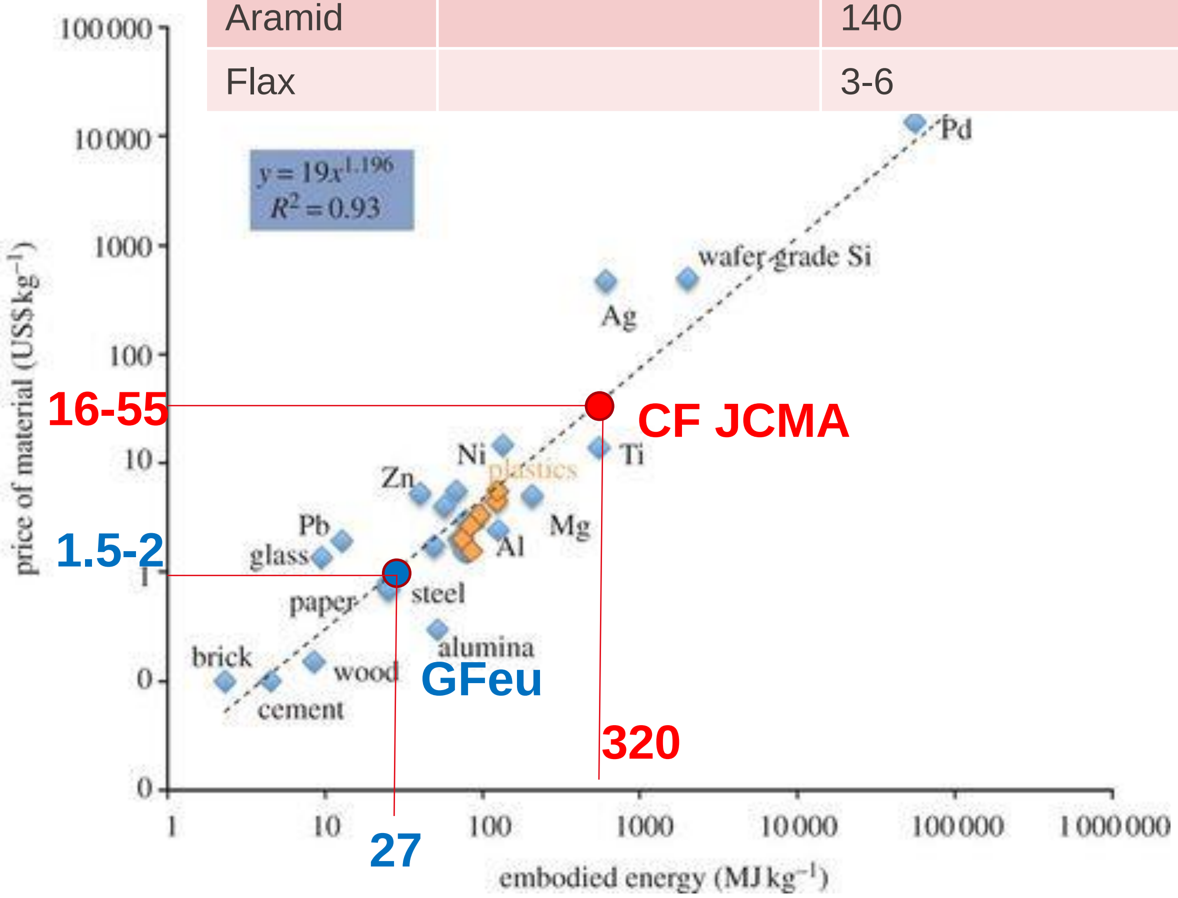
Polymer composite hierarchy example



CO2e vs. MJ/kg vs. $/kg

Fiber type	$kgCO_2e$/kg dry fiber	Energy Intensity MJ/kg
Glass	1.2	27-30
Carbon	19.8	318
Aramid		140
Flax		3-6





Energy intensity of derivatives and conversion drives environmental foot print and economics

The energy required to produce materials: constraints on energy-intensity improvements, parameters of demand (royalsocietypublishing.org)

Overview - Towards sustainable composite solutions

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

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

show.cgi (uvt.nl)

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 & <u>recovery</u>: min. 95% wt./vehicle/yr
reuse & <u>recycling</u>: min. 85% wt./vehicle/yr

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

TOMORROW (2015):

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

- 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

End-of-life vehicles Regulation - European Commission (europa.eu)

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)

End-of-life aircraft recycling offers high grade materials | Eco-innovation Action Plan (europa.eu)

LIFE 3.0 - LIFE Project Public Page (europa.eu)

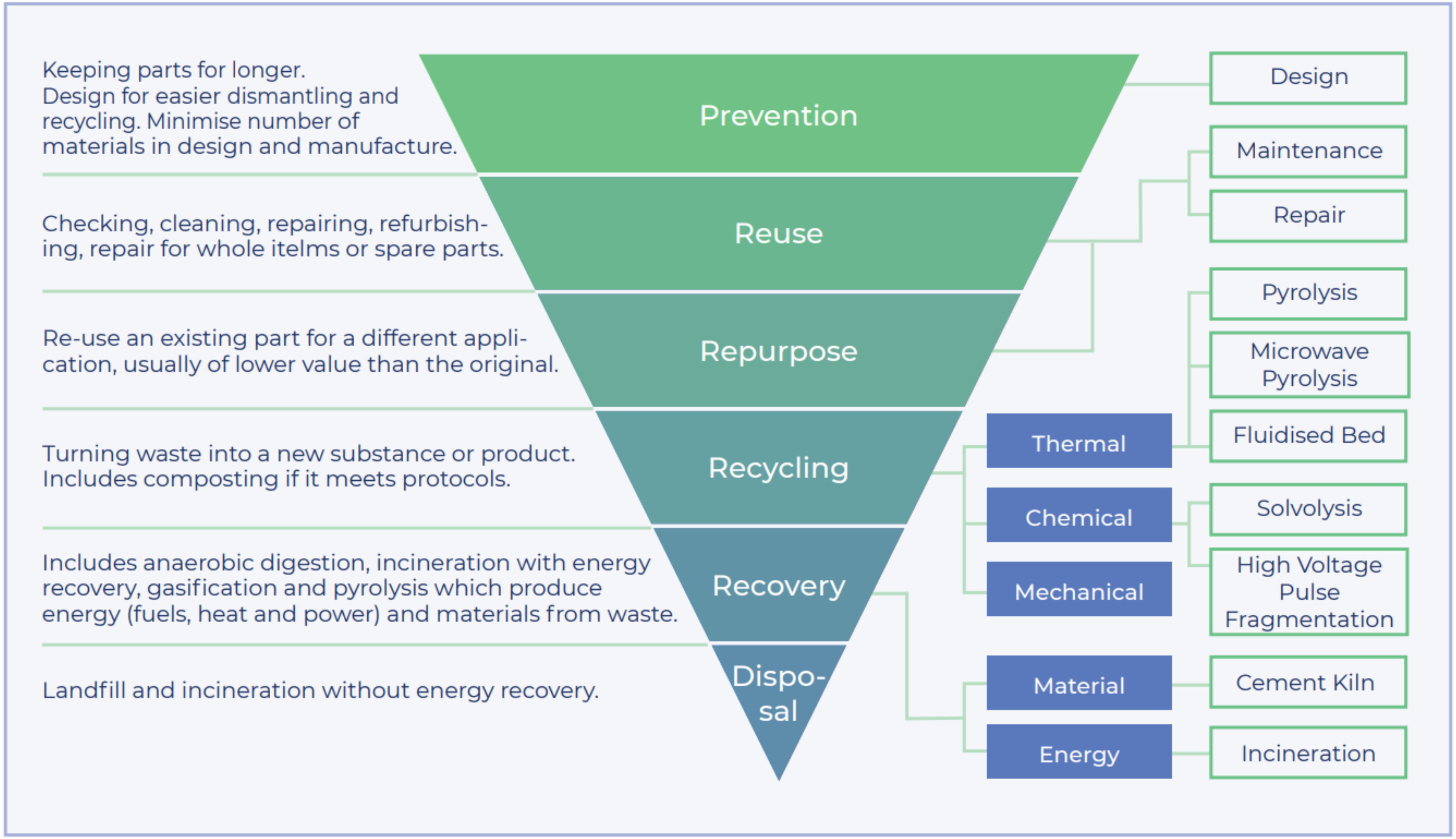
THE WORLD'S MOST ADVANCED MATERIAL HAS A DIRTY WASTE PROBLEM

- 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)]

What is in our waste and EL streams?

Thermosets

Cured / B-staged

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

Thermoplastics

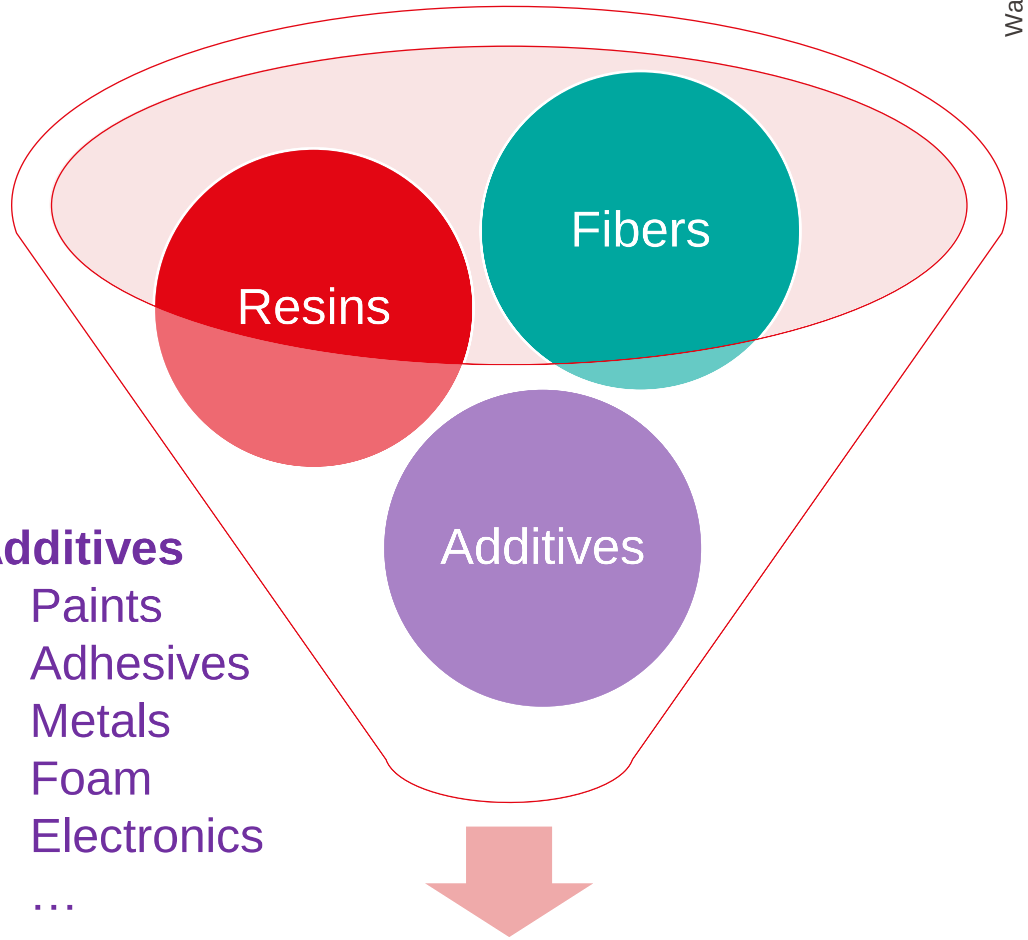
- PE
- PP
- PET
- PA
- PPA
- PC
- PEI
- PPS
- PEAK
- PEEK
- …

Fibers

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

Additives

- Paints
- Adhesives
- Metals
- Foam
- Electronics
- …



Our waste flow

- cm to 10's meters

Post industrial CF waste = post industrial $ money

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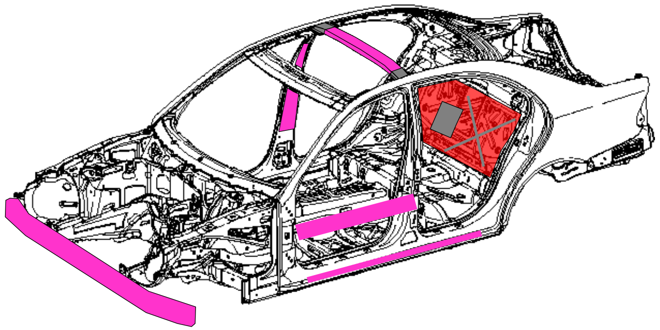
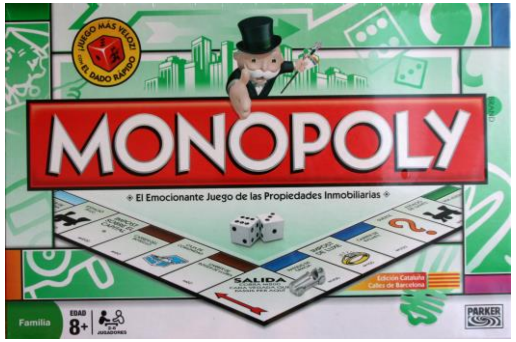
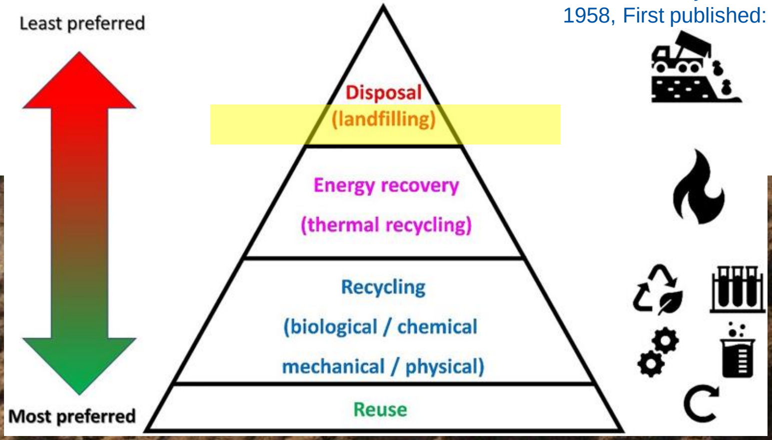




Composites waste management?

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)

Pieces of wind turbine blades are buried in the Casper Regional... News Photo - Getty Images

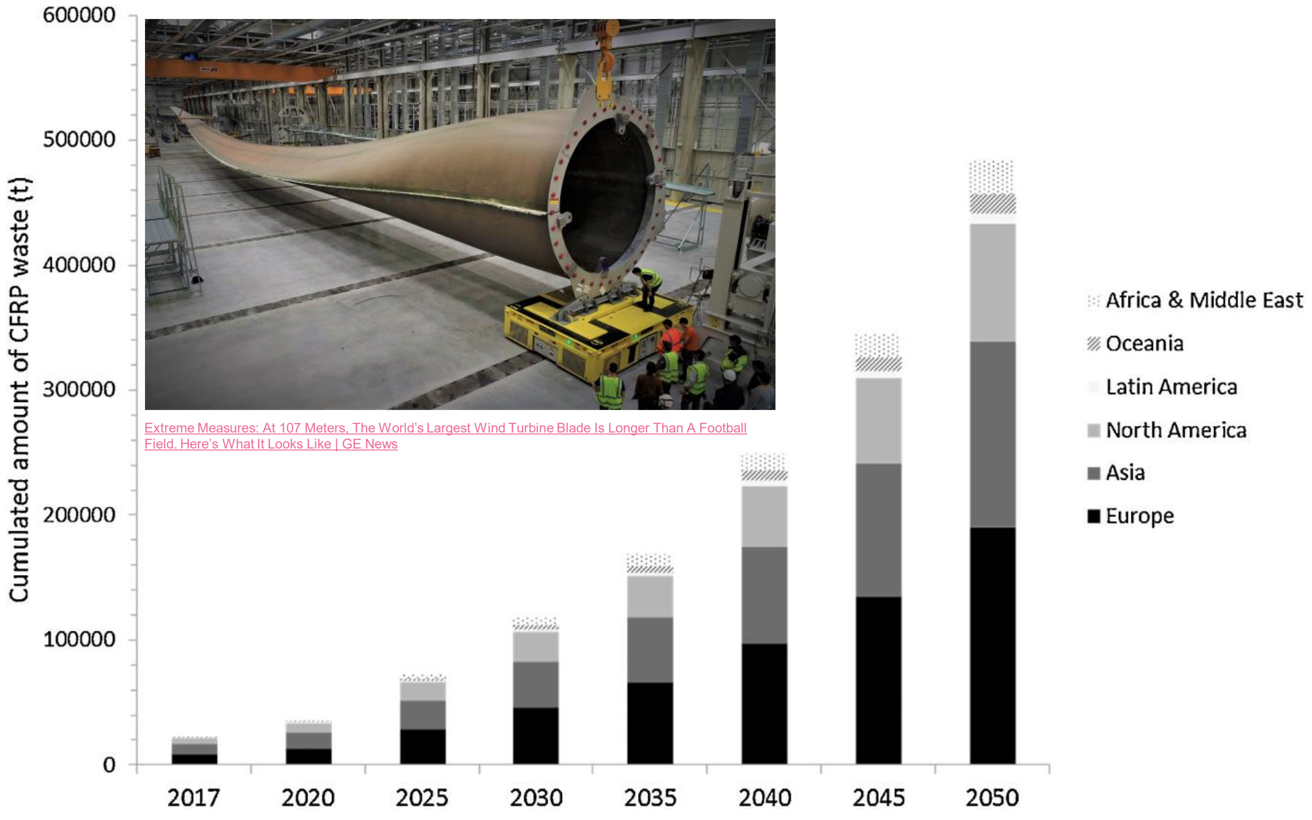
Bisphenol-A-Pollution-Wind-Turbines.pdf (wind-watch.org)
Abandoned Wells Can Provide Use for Pulverized Wind-Turbine Blades | Journal of Petroleum Technology | OnePetro
ACP_MicroplasticsFactSheet_March-2023.pdf (cleanpower.org)

Start by not throwing it

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

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

600kT

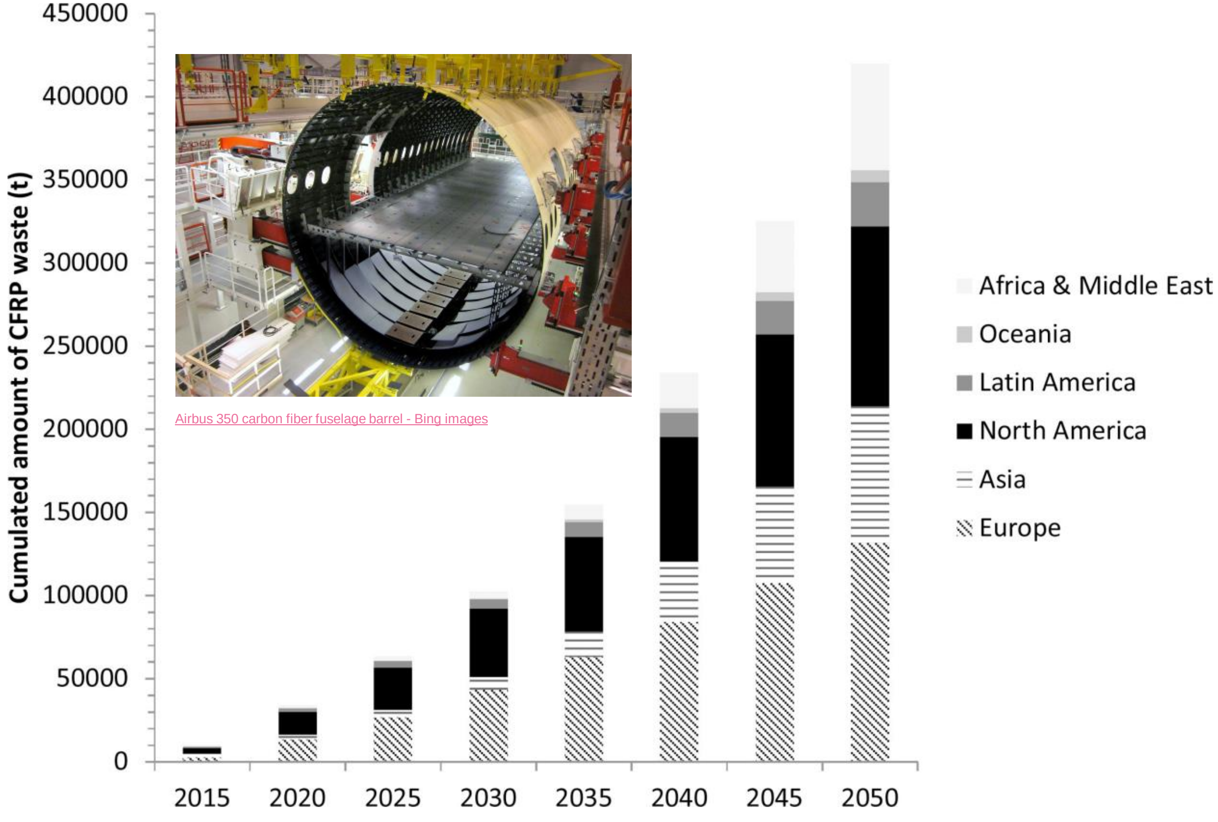


Anticipating in-use stocks of carbon fibre reinforced polymers and related waste generated by the wind power sector until 2050 - ScienceDirect

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

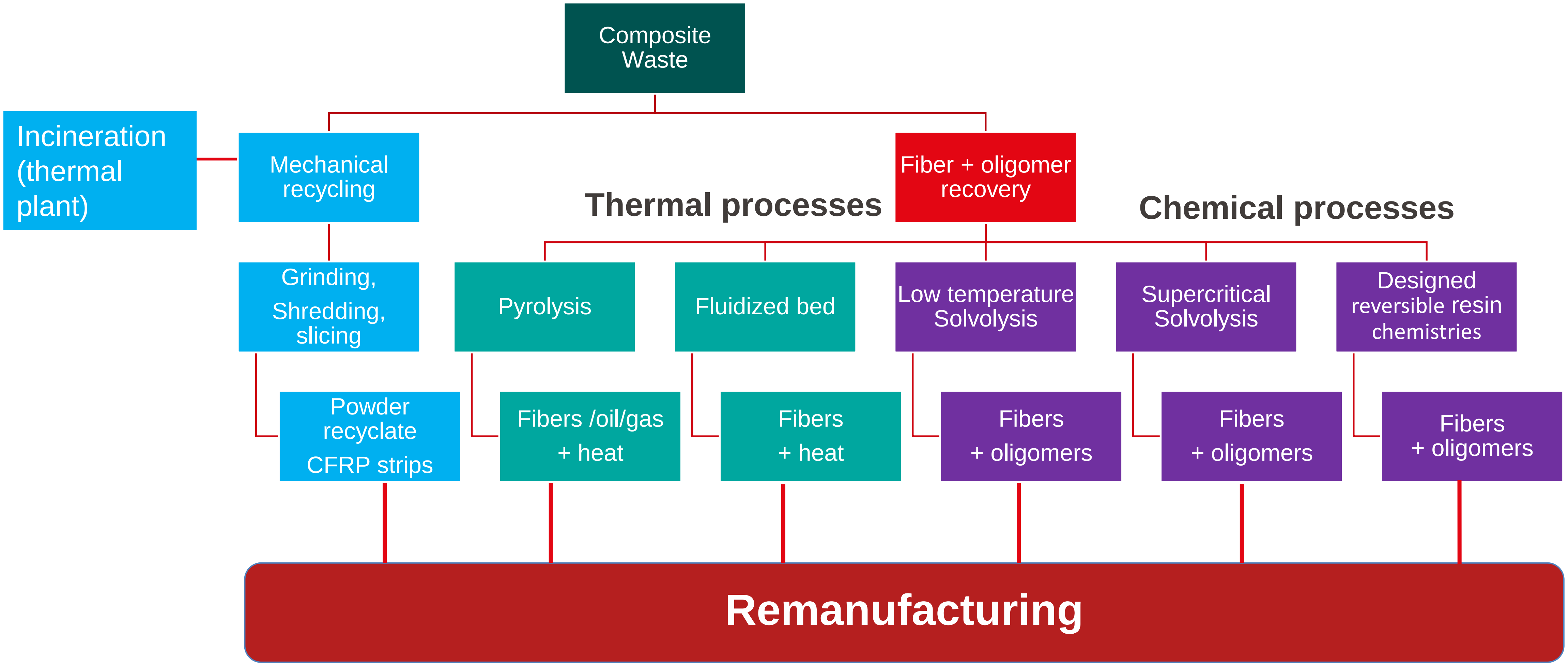
Anaële Lefeuvre[a], Sébastien Garnier[a], Leslie Jacquemin[a], Baptiste Pillain[b,c], Guido Sonnemann[b,c,*]

450kT



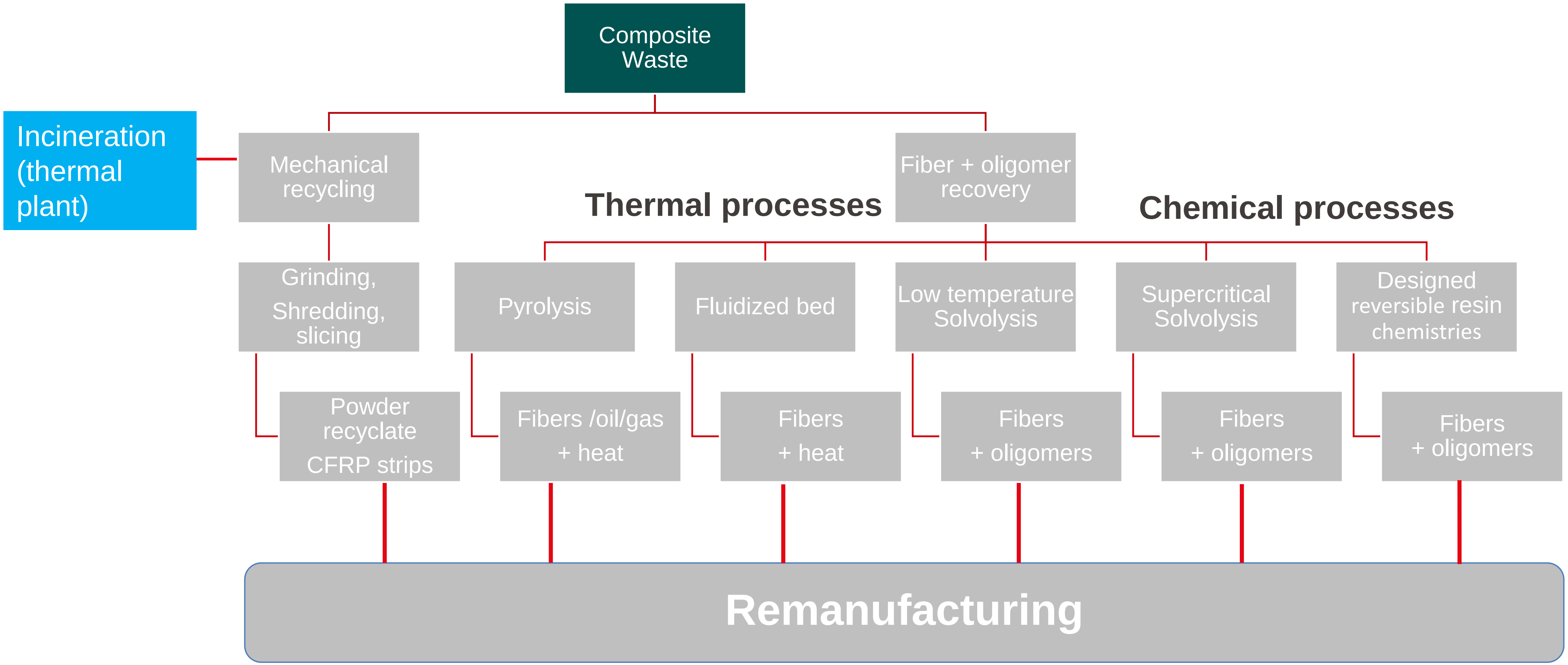
Anticipating in-use stocks of carbon fiber reinforced polymers and related waste flows generated by the commercial aeronautical sector until 2050 - ScienceDirect

Recycling Routes



Adapted from Pickering, Composites Part A (2006)

Recycling Routes



Adapted from Pickering, Composites Part A (2006)

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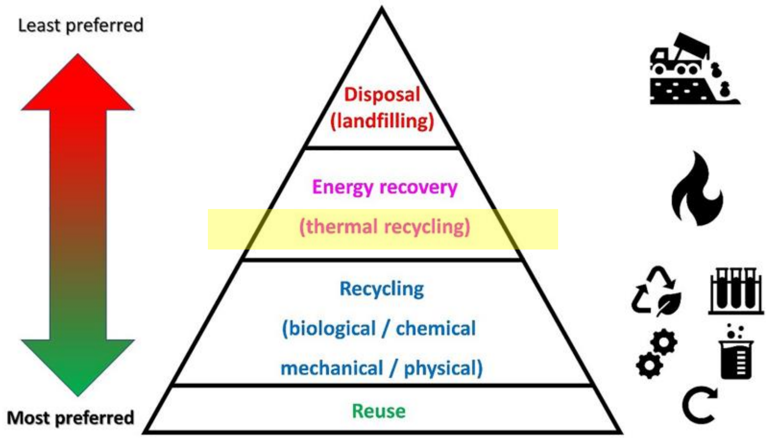
How the EU sees composites recycling



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)

EPFL

GF composites: Thermal plant feedstock

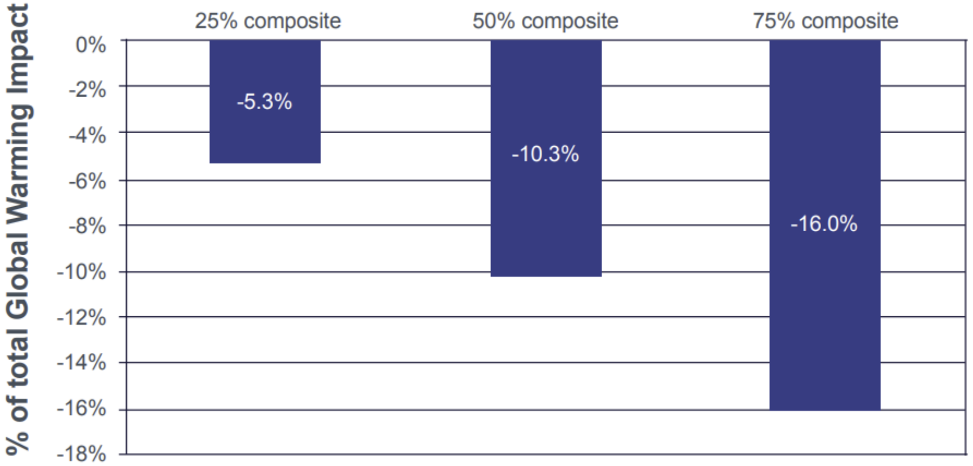
- Co-processing of End of Life/ composites used in cement manufacturing
  - highly effective source of energy
  - calorific values of~30,000 kJ/kg
- Glass fiber in oxide form, replacing hydrated or carbonated minerals in Portland cement
- Replacement of fossil fuels by non-recyclable & biomass waste, and use of alternative raw materials
  - Gives 15% CO_2 emissions reduction in the 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

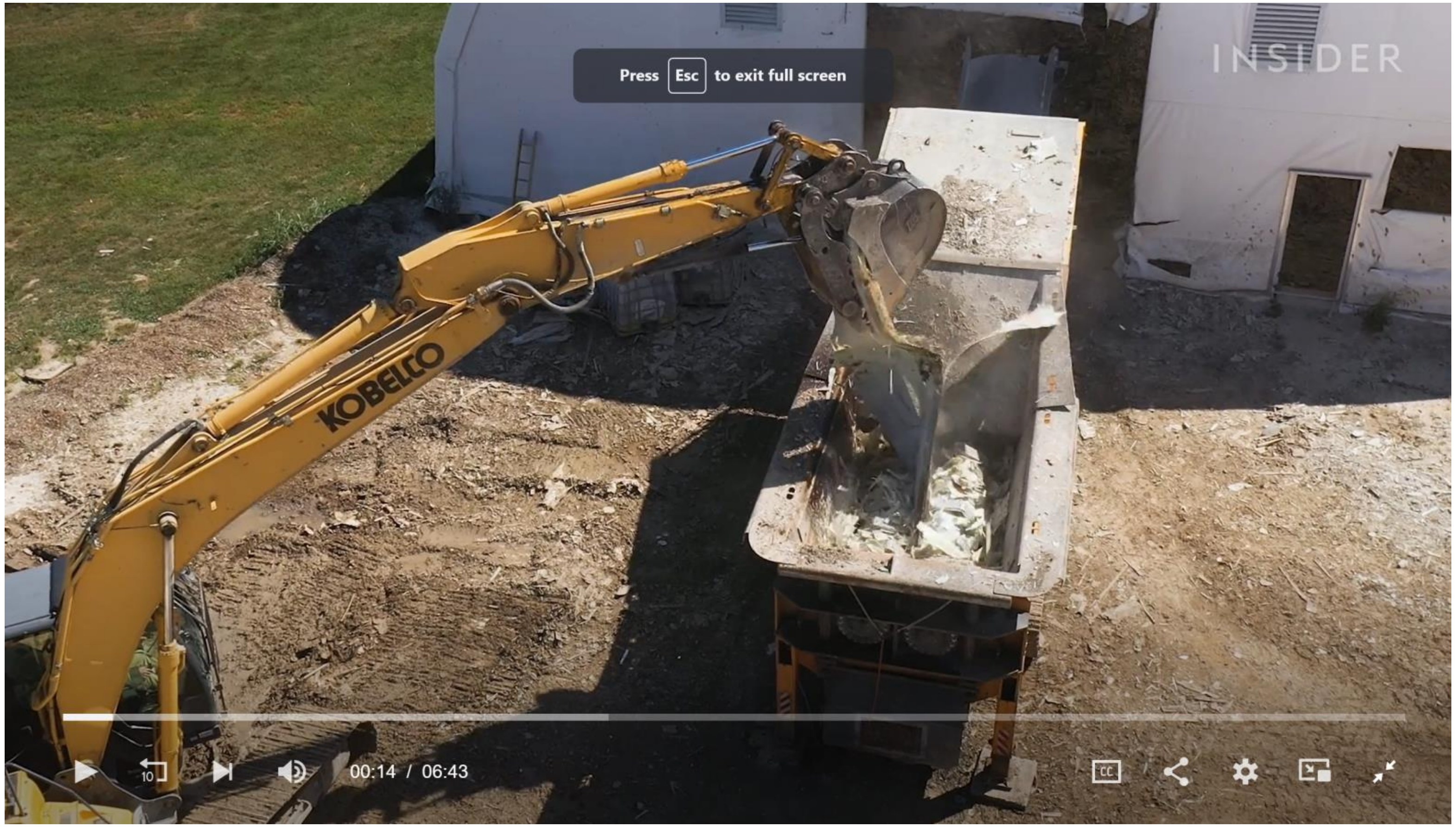
Fig.3 : Mobile sawing equipment to reduce transport costs
Courtesy: Zajons, Melbeck

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

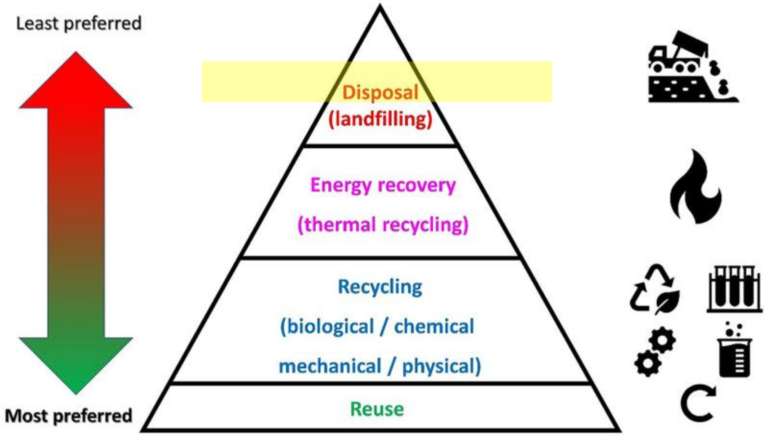


20130207_eucia_brochure_recycling.pdf

Shredding blades for cement feedstock



How One Company Keeps Wind Turbine Blades to Keep Out of Landfills (businessinsider.com)

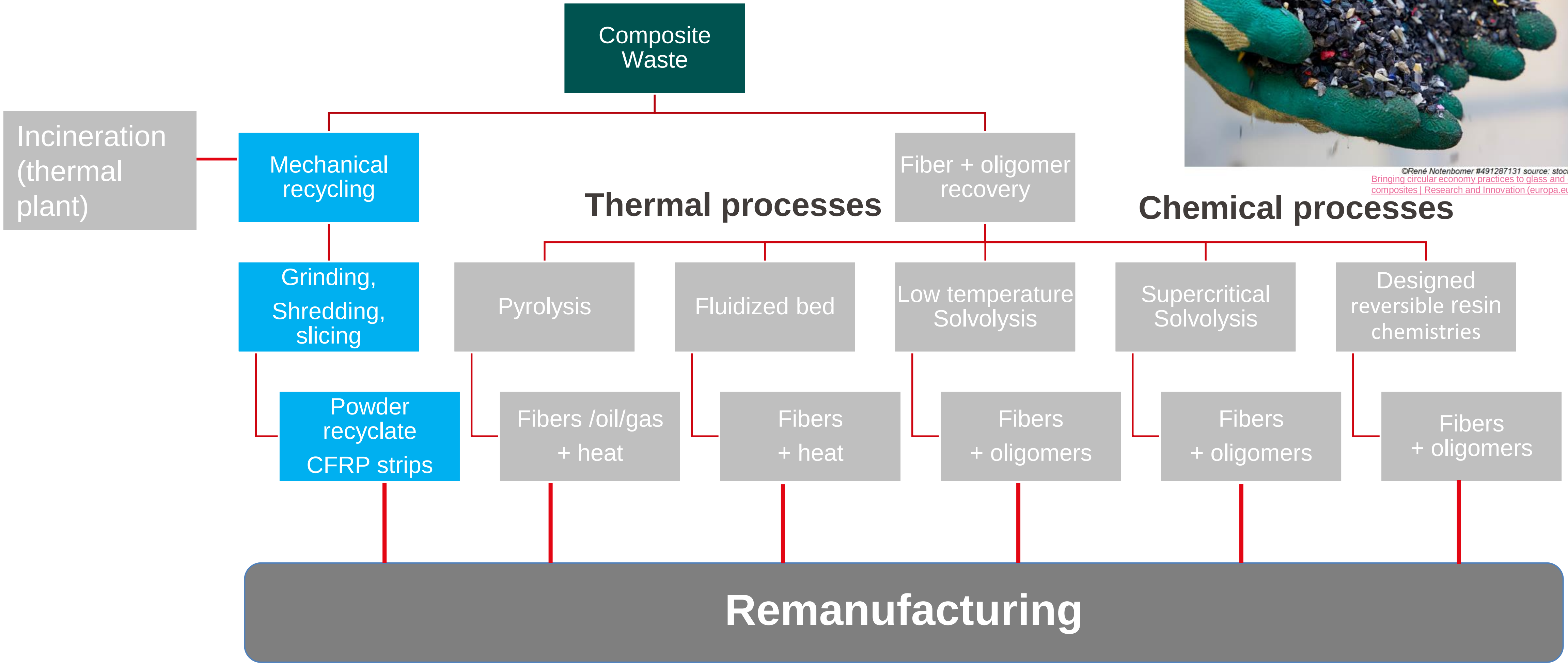


Journal of Polymer Science, Volume: 61, Issue: 17, Pages: 1937-1958, First published: 19 May 2023, DOI: (10.1002/pol.20230154)

EPFL

Recycling Routes

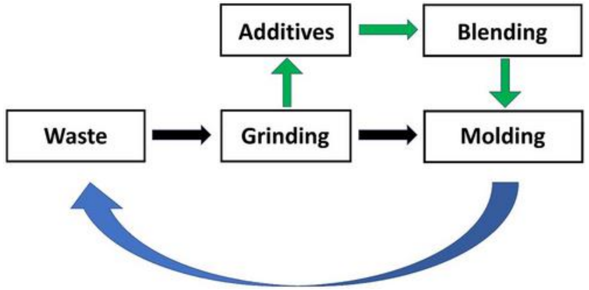
©René Notenbomer #491287131 source: stock.adobe.com 2023
Bringing circular economy practices to glass and carbon fibre composites | Research and Innovation (europa.eu)

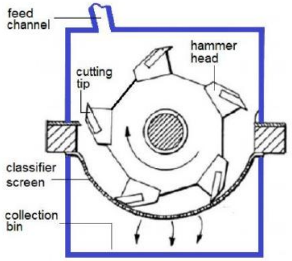


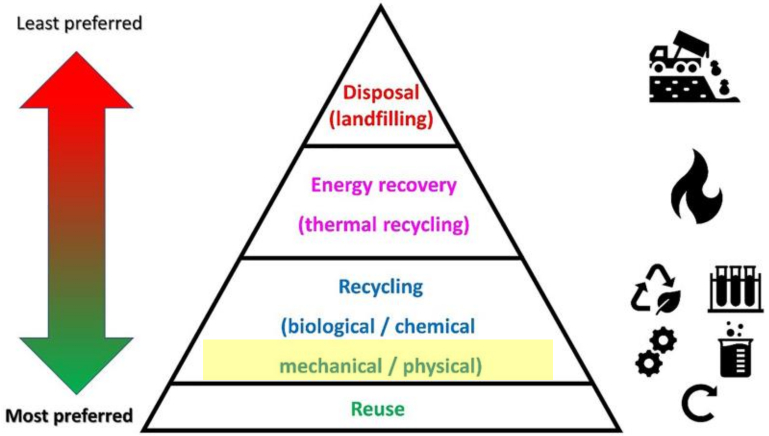
Adapted from Pickering, Composites Part A (2006)

Mechanical recycling (thermoplastic composites)

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







Composites Part A 139 (2020) 106110

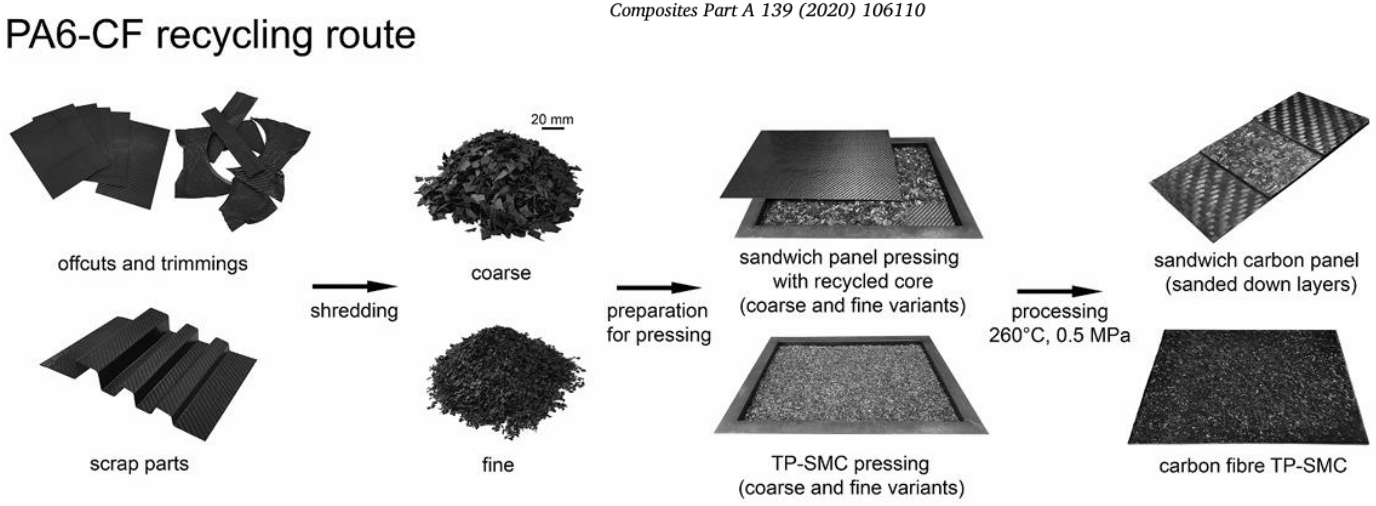


Fig. 1. Recycling routes for PP-GF and PA6-CF based TPCLs.

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

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

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Recycling Routes

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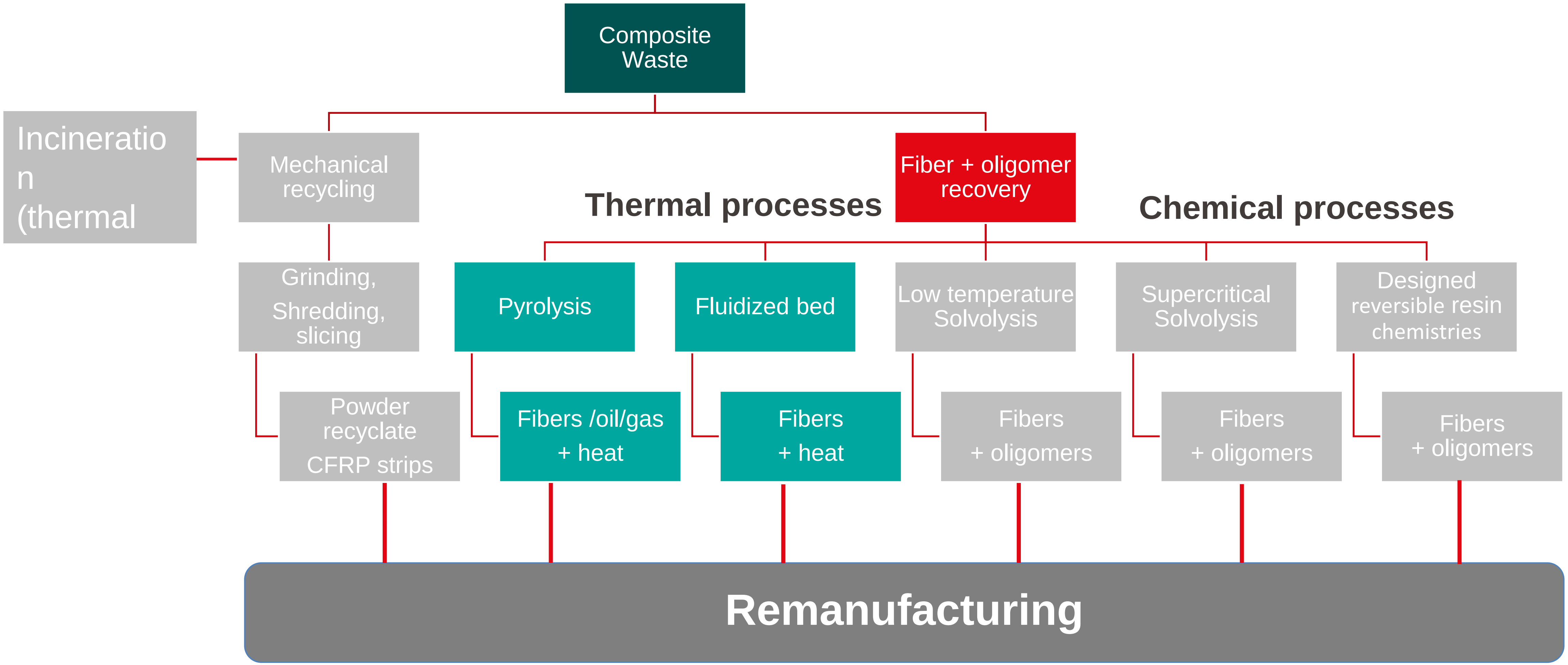
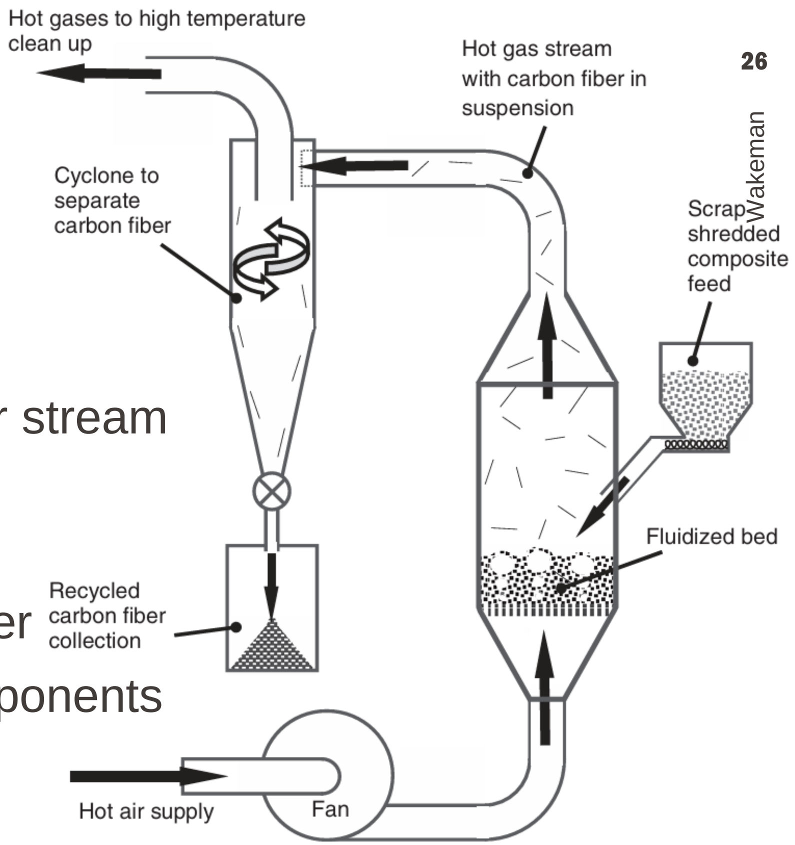


Adapted from Pickering, Composites Part A (2006)

EPFL

Fluidized bed recovery

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

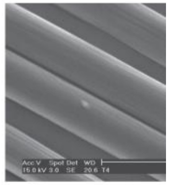
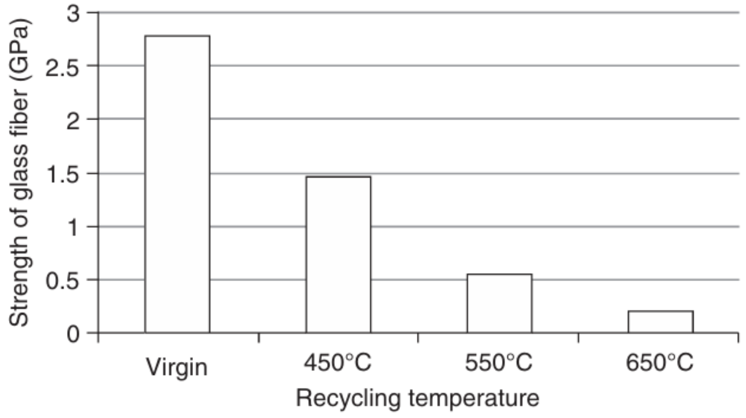


Figure 4. Recycled carbon fiber in a fluffy form.



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

PhD thesis_Fanran Meng_4201331_after correction_final.pdf (nottingham.ac.uk)

Recycling Thermoset Composite Materials - Pickering - Major Reference Works - Wiley Online Library

Pyrolysis

- Thermal degradation of resin / polymeric additives (absence of oxygen / nitrogen atmosphere)
- 400-500ºC
- 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

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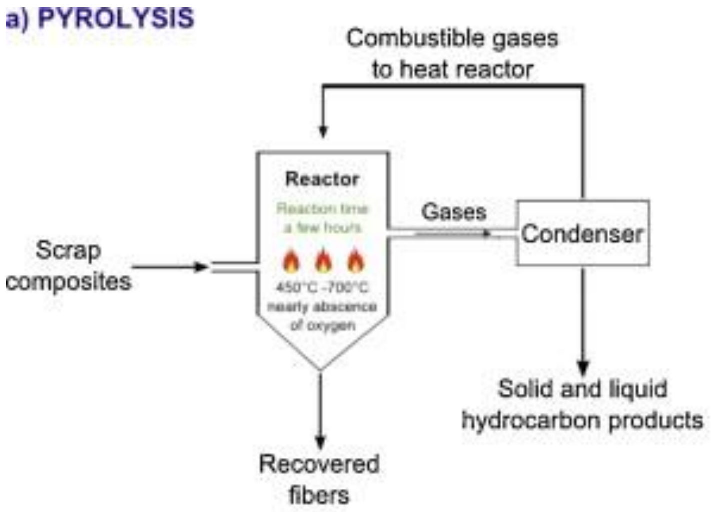


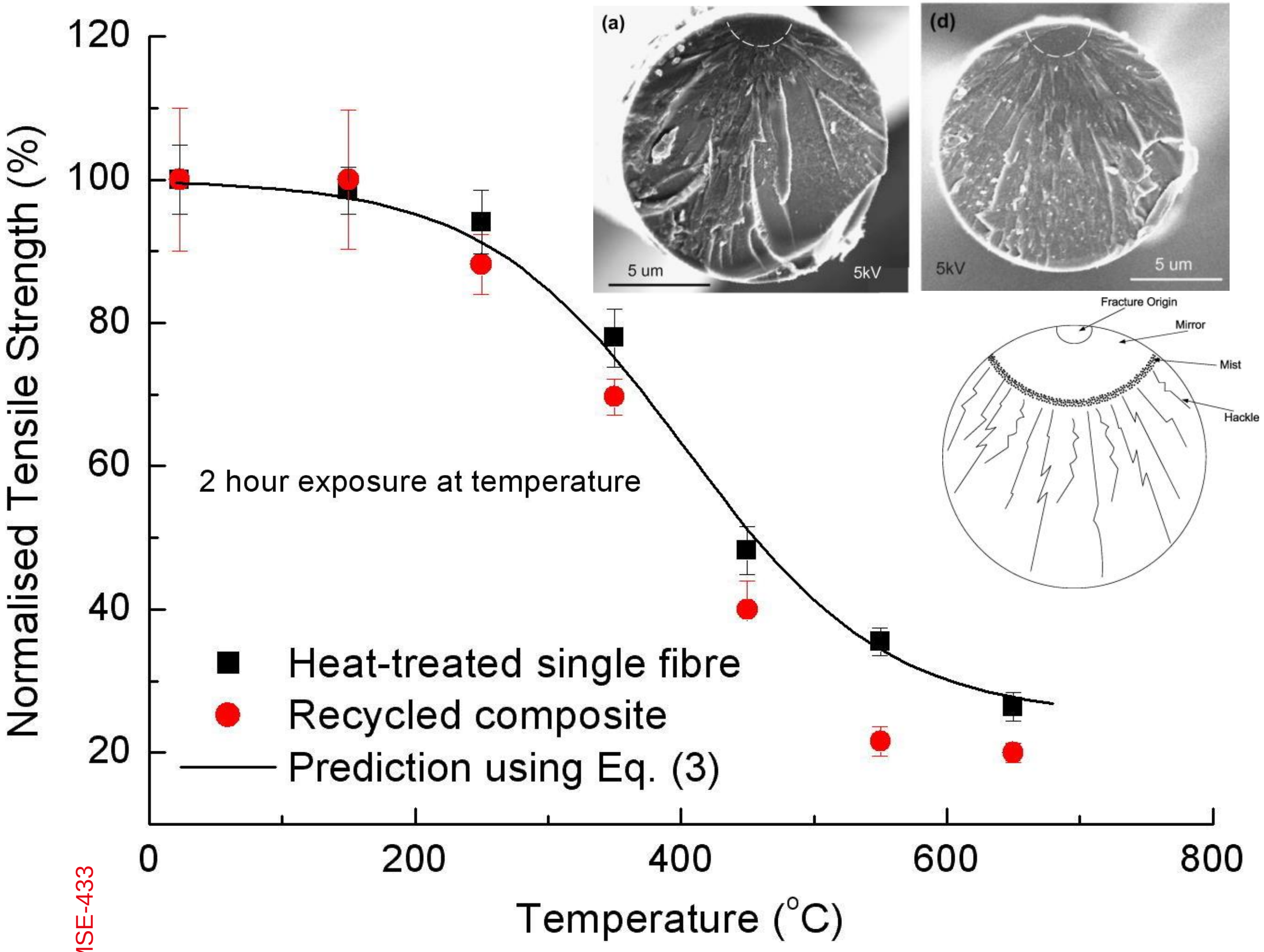
500ºC in Nitrogen

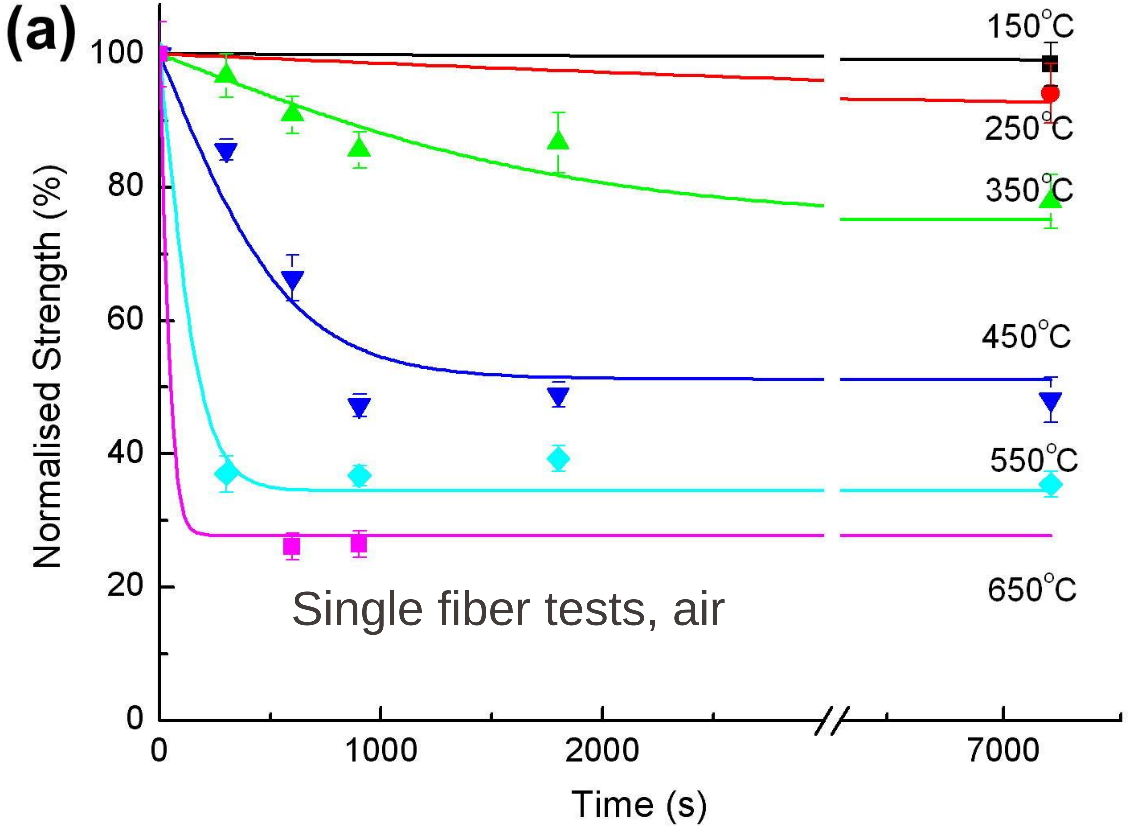
MITSUBISHI CHEMICAL ADVANCED MATERIALS | carboNXT

100% CARBON FIBERS (carbonxt.de)

Effect of pyrolysis on glass fiber properties

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





Mechanical properties of thermally-treated and recycled glass fibres - ScienceDirect

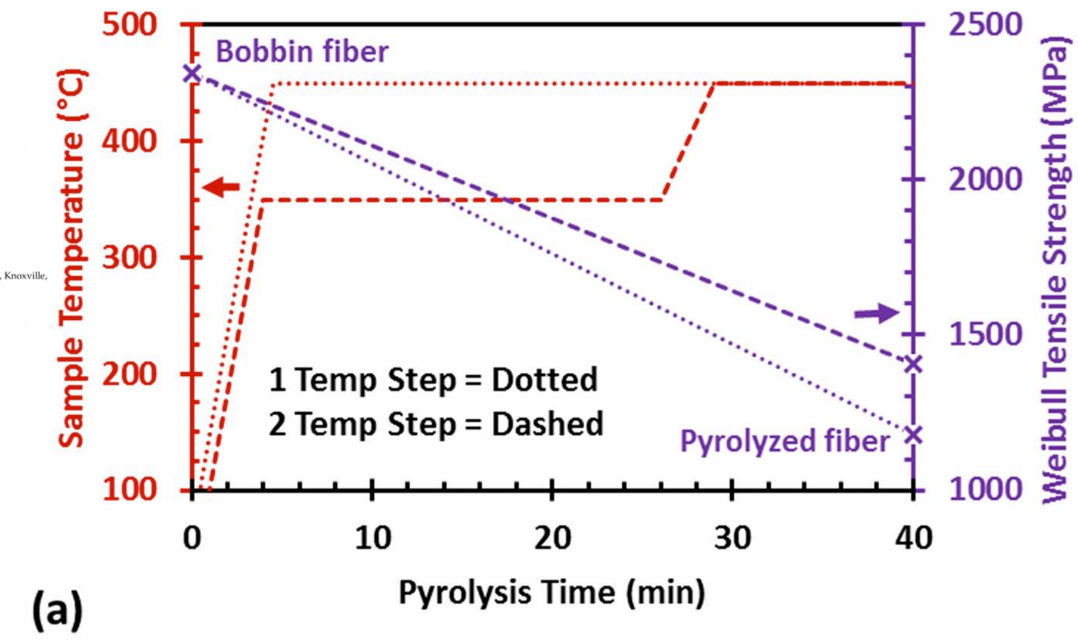
Two step pyrolysis

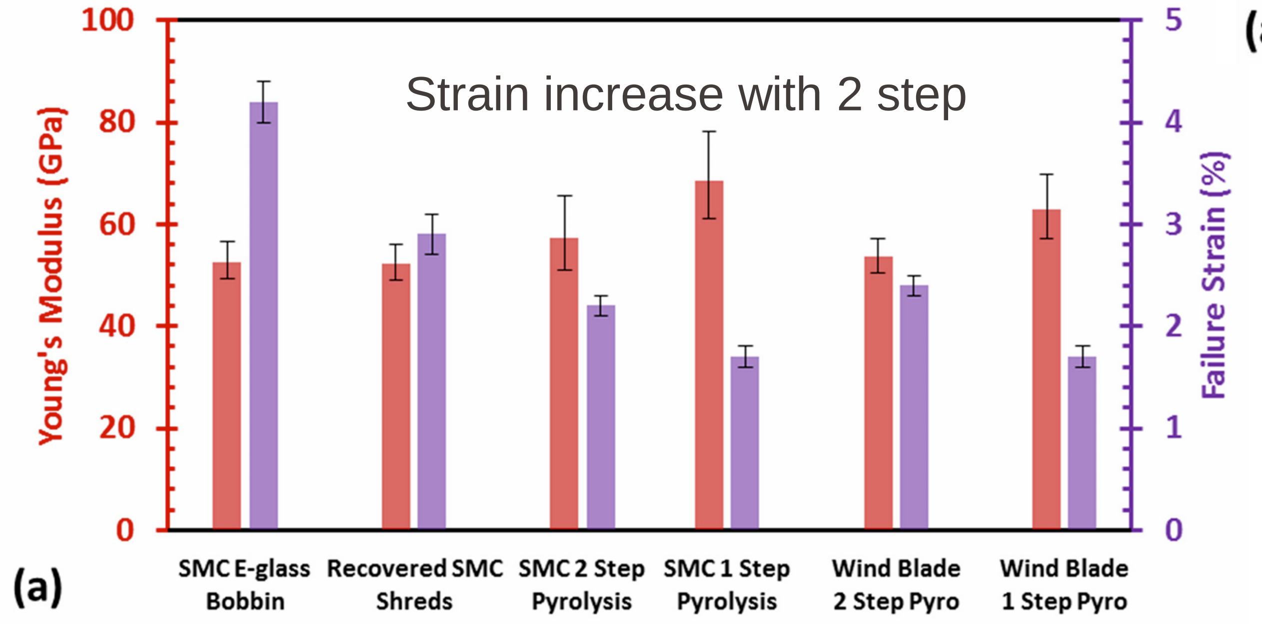
- Two step
  - 350ºC for 22minutes
  - 450ºC for 11 minutes
- Glass fiber structural changes

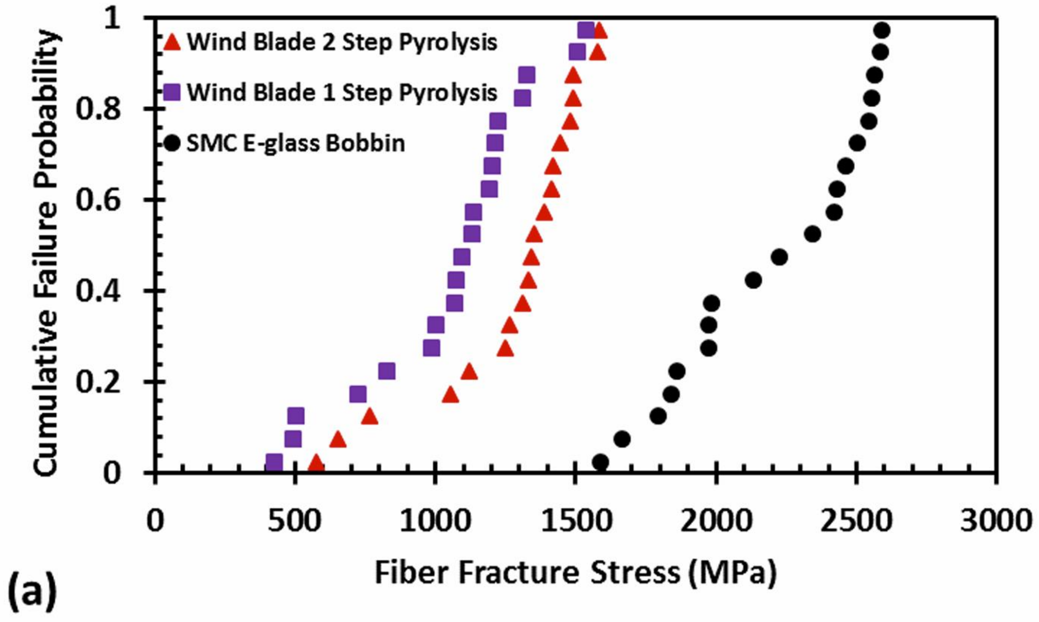
Recycling of Commercial E-glass Reinforced Thermoset Composites via Two Temperature Step Pyrolysis to Improve Recovered Fiber Tensile Strength and Failure Strain

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

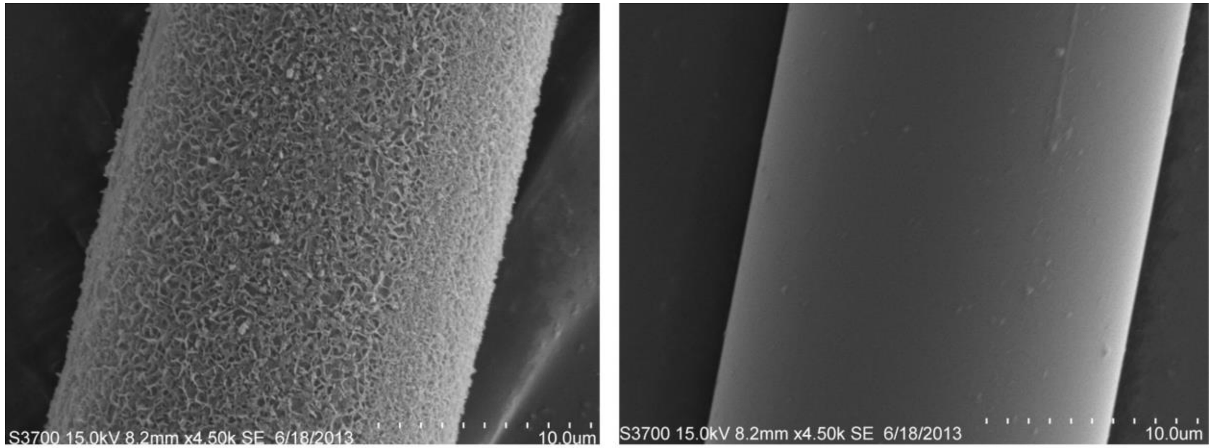






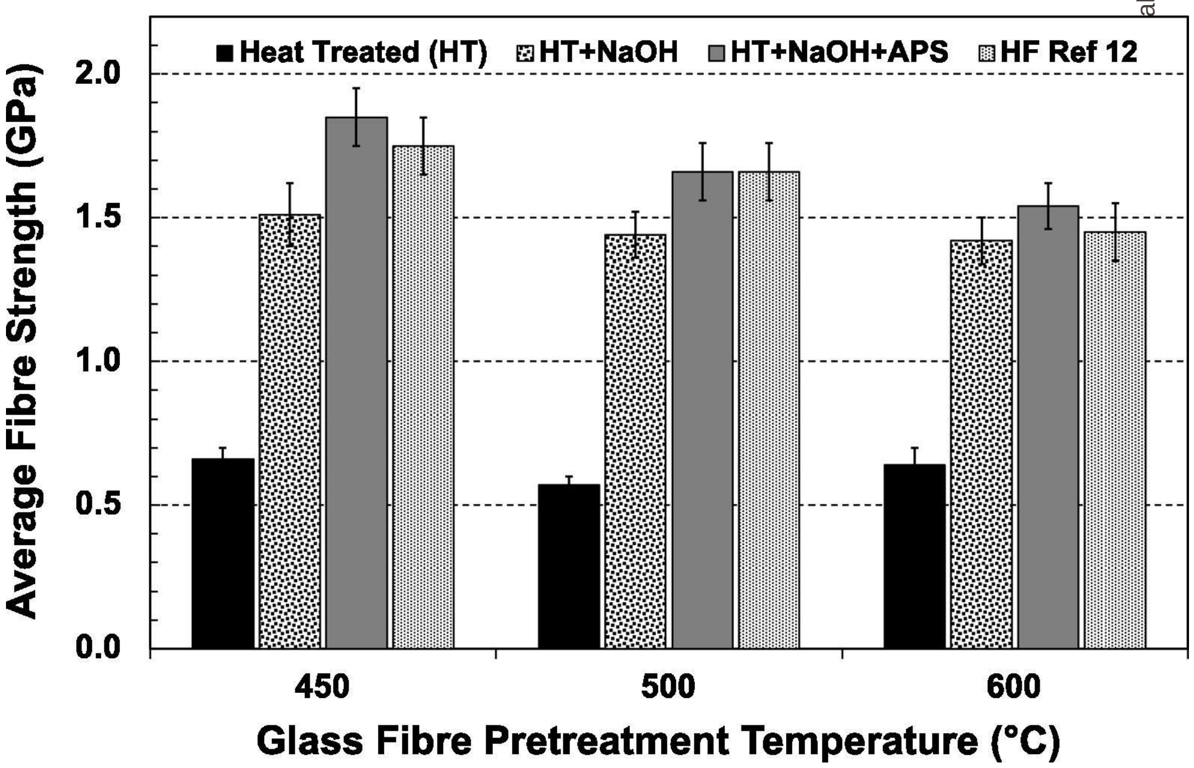
Glass fiber post treatment after pyrolysis

- 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



(a) (b)

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.

Regenerating the strength of thermally recycled glass fibres using hot sodium hydroxide - ScienceDirect

Effect of pyrolysis on carbon fiber

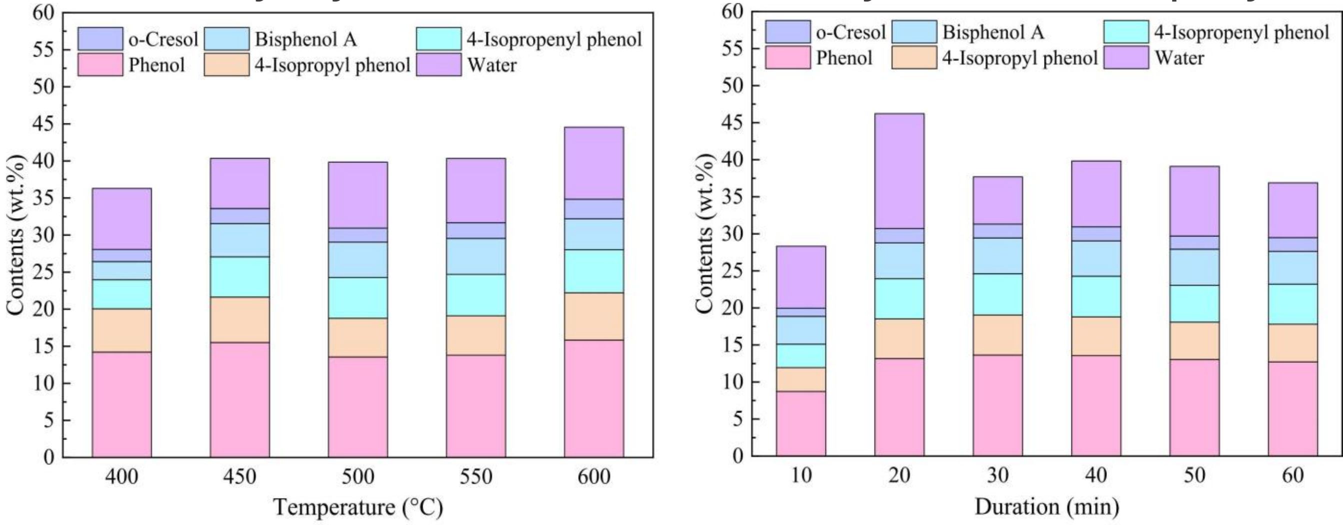
- Modulus generally maintained
- Strength reduction, process and parameter dependent
  - Lower end: SM 80%, IM as much as 55%
  - Upper end: pyrolysis temperature of 500ºC / 20 mins, 94%.
- Surface chemistry similar to virgin CF
- Some post heat in air/oxygen at 500-600ºC to remove pyrolytic char from 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].

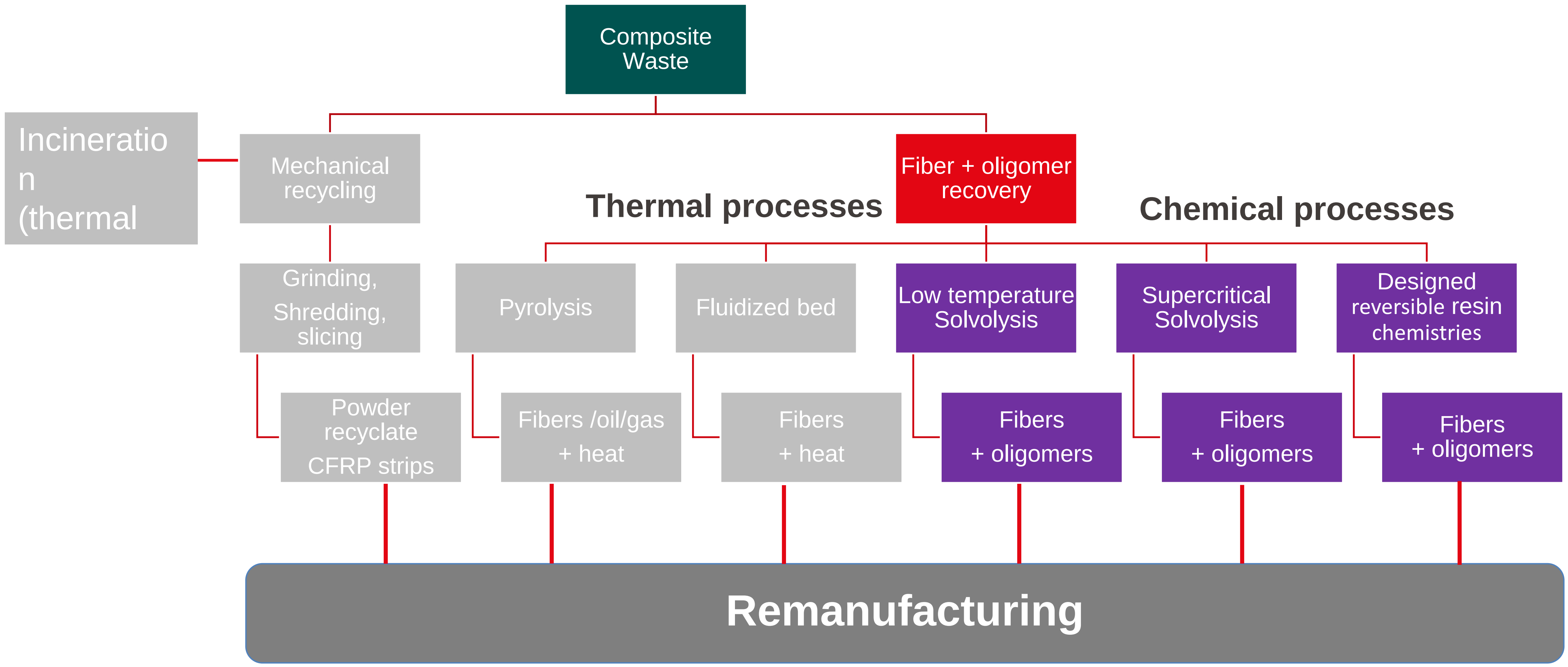
Pyrolysis oil candidate for re-synthesis into epoxy



(a)   (b)

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

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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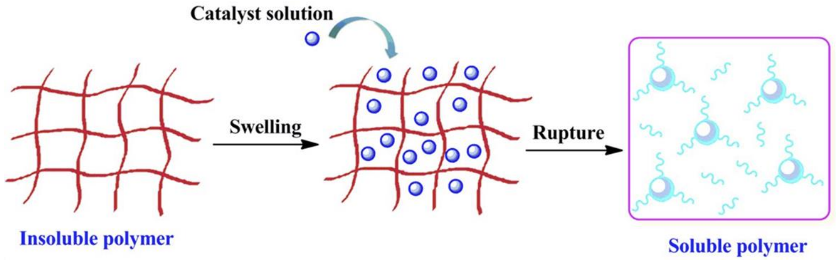
Chemical method #2	Almost 100	Jiang, et al [6]

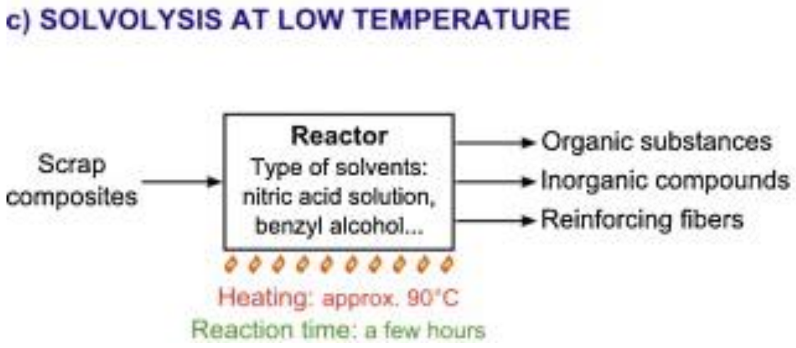
* Tensile strength retention was the ratio of tensile strength between recovered and virgin carbon fibers [7].

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

Low-Temperature Solvolysis

- Uses reactive solvents such as alcohol, ammonia 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
  - 180ºC, benzyl alcohol solvent and tri-potassium phosphate catalyst, 5-20hrs
  - Used for tennis rackets
  - 63 MJ/kg vs 286 MJ/kg virgin CF





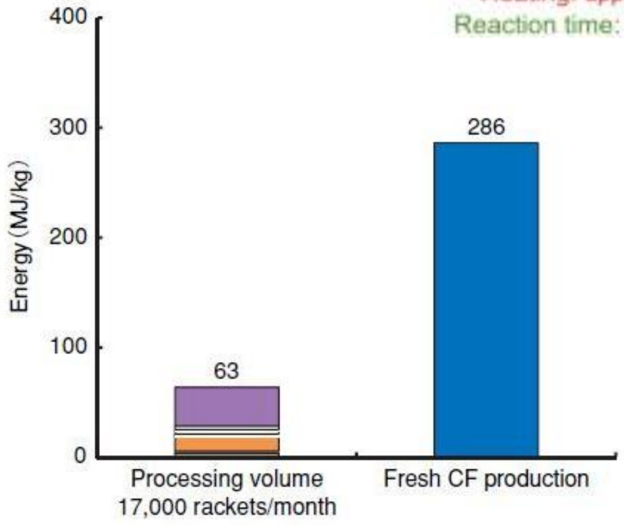


Figure 13 A comparison of energy of a recovered CF by dissolving method under ordinary pressure with a fresh CF on the market

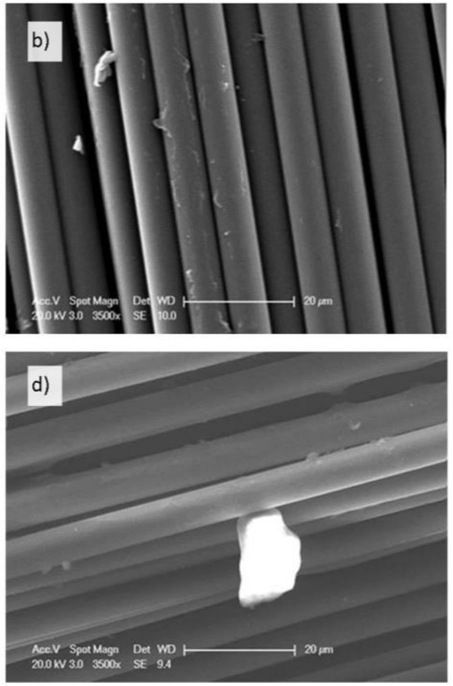
Item	Depolymerization under ordinary pressure
Organization	Hitachi Chemical
Temperature	200 ℃
Pressure	Ordinary pressure
Solvent	Benzyl alcohol
Catalyst	Alkali metal salt
Preprocessing	None
Processing capacity	12 tons/year (200 L x 2 baths)

Near- and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: State of the art - ScienceDirect

Recycling carbon fiber for structural applications | CompositesWorld

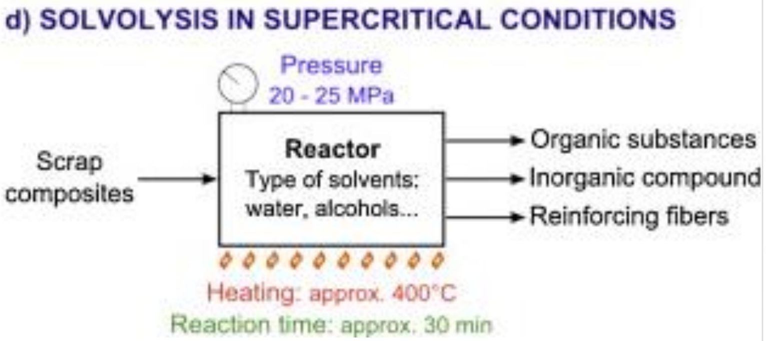
Supercritical solvolysis

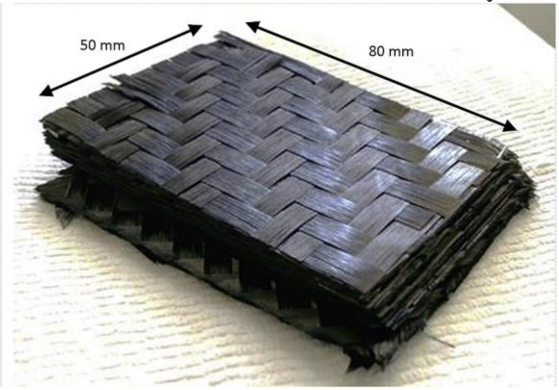
- Supercritical fluid
  - *Any substance at a temperature and pressure above its critical point, where distinct liquid and gas phases do not exist, but below the pressure required to compress it into a solid*
  - e.g. water 373°C, 220bar, alcohols, used as alternatives to organic solvents, and catalysts.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

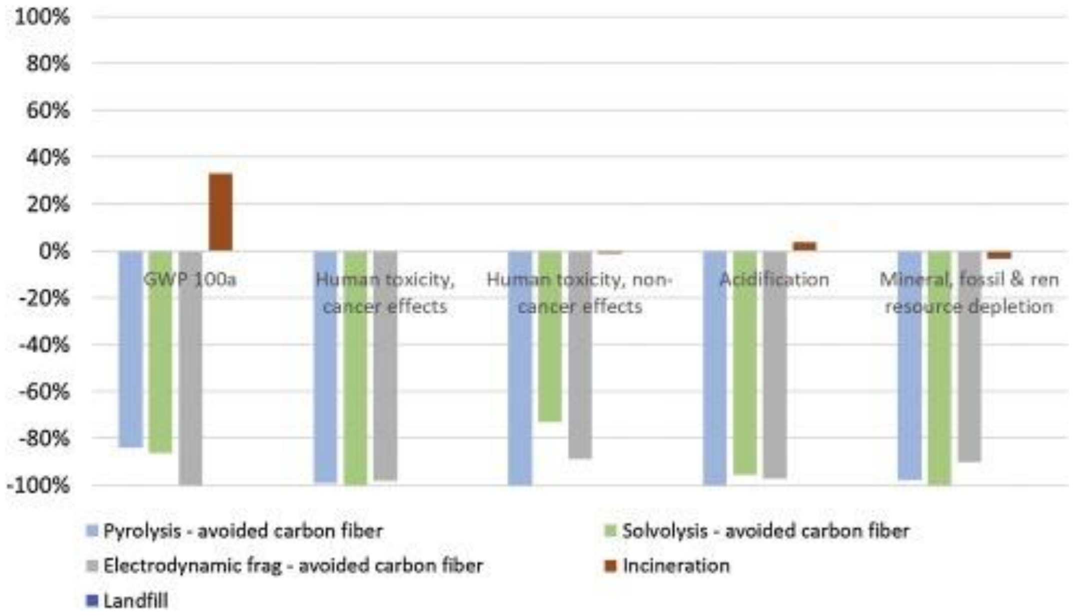


b) unwashed carbon fibres recovered after solvolysis; d) solid particle of partially degraded resin on slightly washed carbon fibres.

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







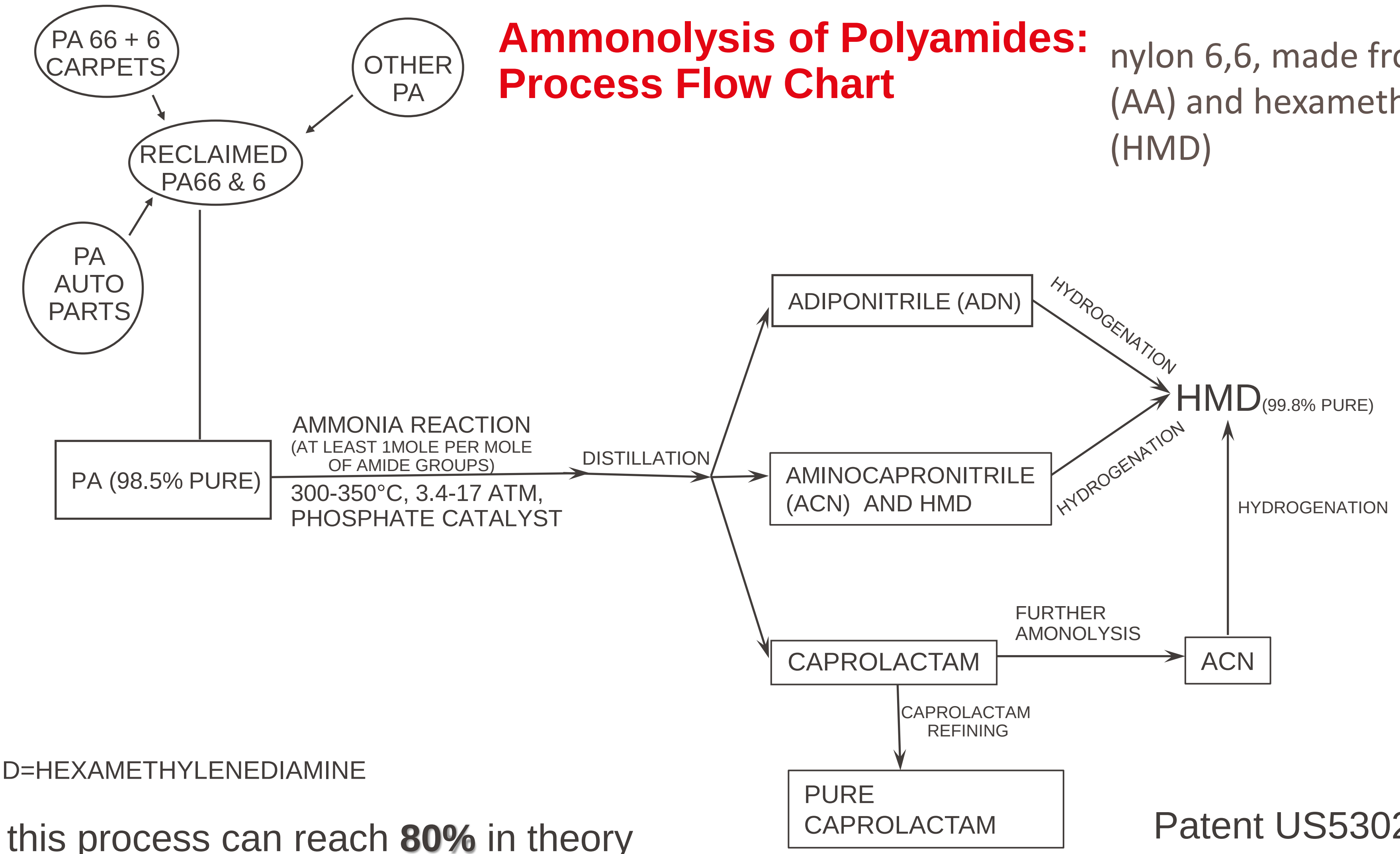
Near- and supercritical solvolysis of carbon fibre reinforced polymers (CFRPs) for recycling carbon fibers as a valuable resource: State of the art - ScienceDirect

Recycling of carbon fiber with epoxy composites by chemical recycling for future perspective: a review | Chemical Papers (springer.com)

PA chemical recovery (molecular recycling)

Ammonolysis of Polyamides: Process Flow Chart

nylon 6,6, made from adipic acid (AA) and hexamethylene diamine (HMD)

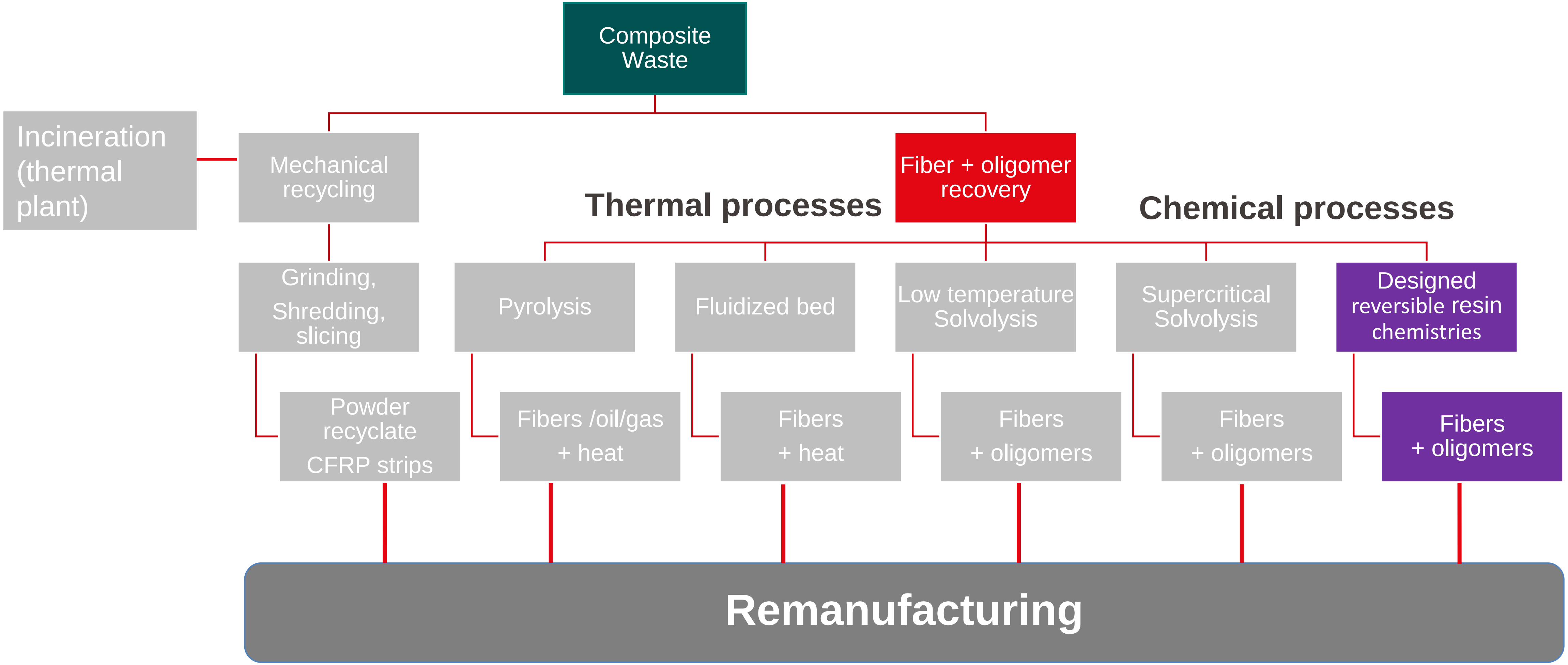


HMD=HEXAMETHYLENEDIAMINE

Yields on this process can reach **80%** in theory

Patent US5302756, Ammonolysis of Nylon, DuPont, 1994, McKinney

Recycling Routes

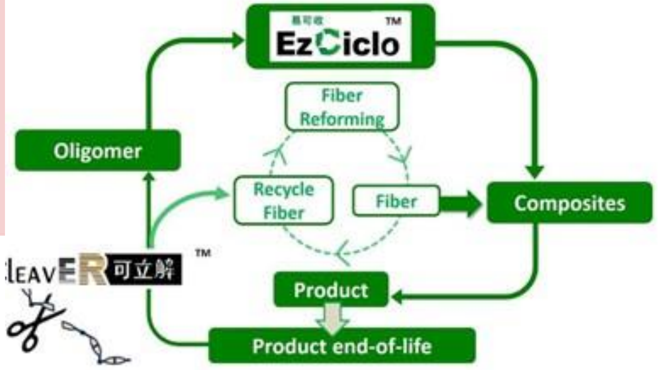


Adapted from Pickering, Composites Part A (2006)

Wind energy: recyclable blades

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

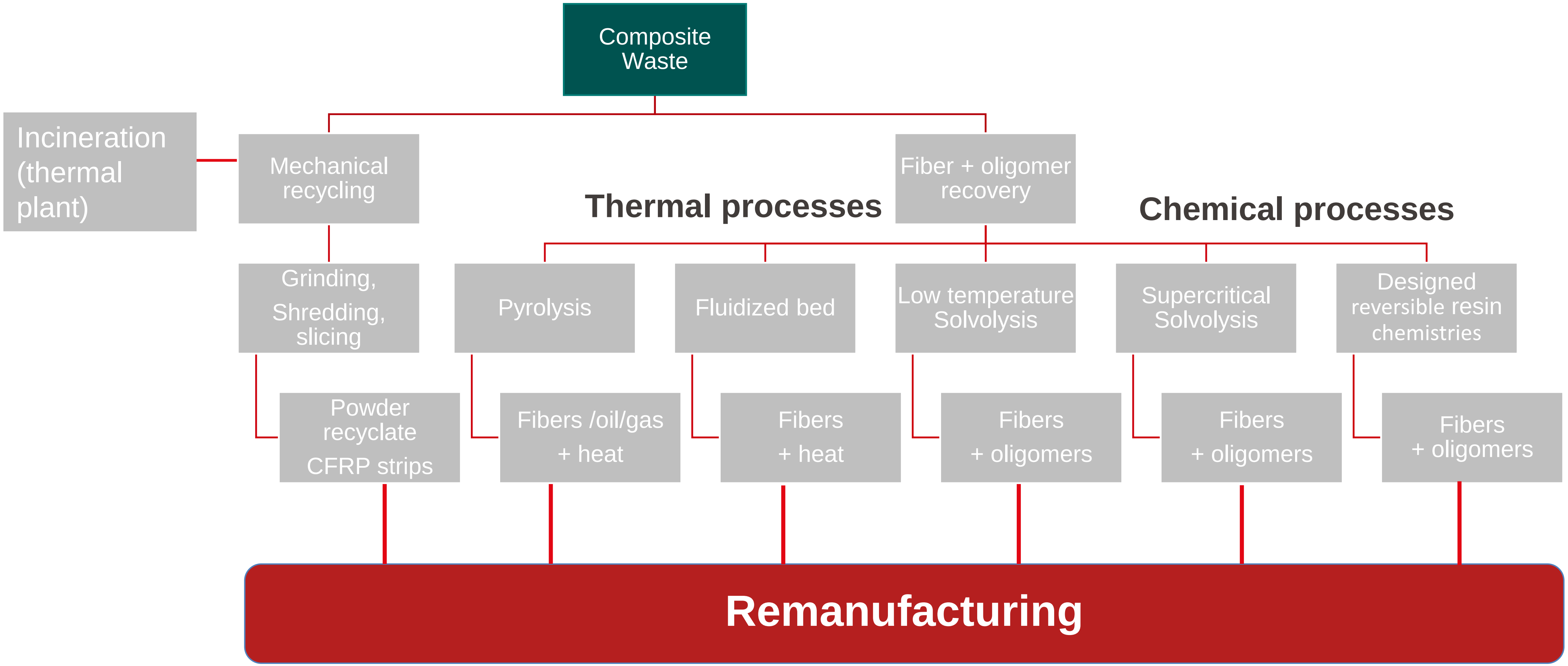
Novel resin	End of life	Recovery
• Chemical structure • Ketal diamines (recyclamine) in hardner • Can efficiently separate the resin from the other components	• Blade immersed into a heated mild acidic solution (solvolysis) • 140ºC , 4-5hrs	• Separates resin from the fiber glass, plastic, wood and metals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

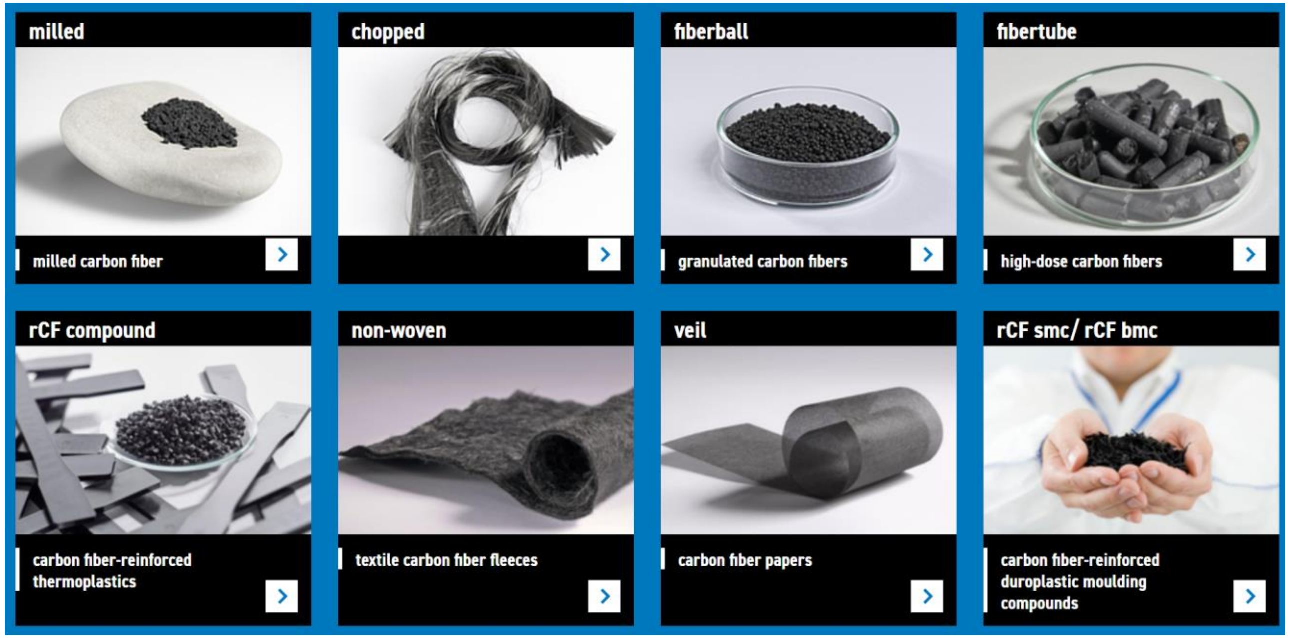
World's first "fully recyclable" wind turbine blades roll off production line | RenewEconomy

Recycling Routes



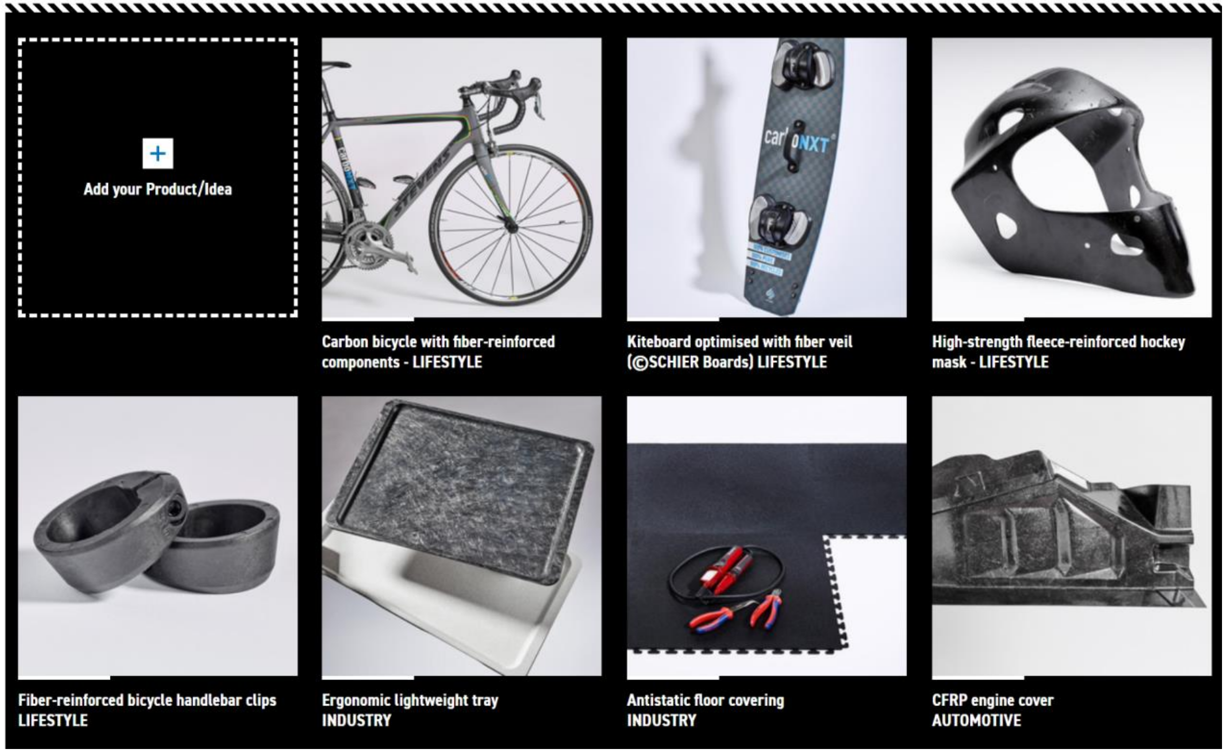
Adapted from Pickering, Composites Part A (2006)

Carbon fiber recycling & reuse



- Recovered CF material forms, 1000 T/yr

- Products using recovered CF



[100% CARBON FIBERS (carbonxt.de)]

MITSUBISHI CHEMICAL ADVANCED MATERIALS | carboNXT®

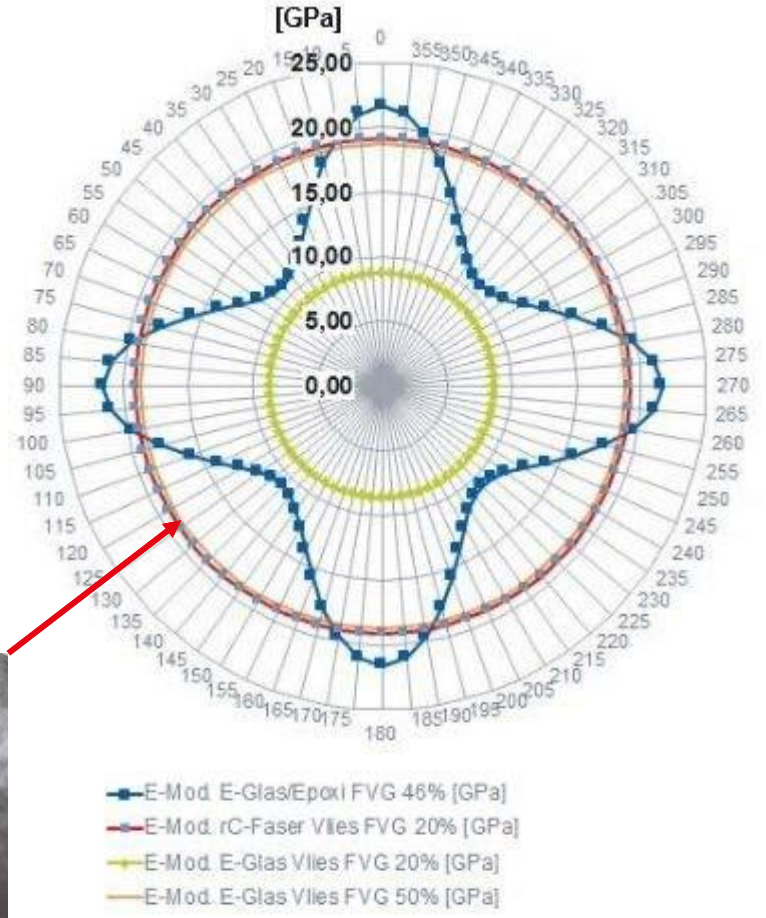
Procotex

- 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

Recycled Carbon - Procotex

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

G-TEX M - Gen 2 Carbon

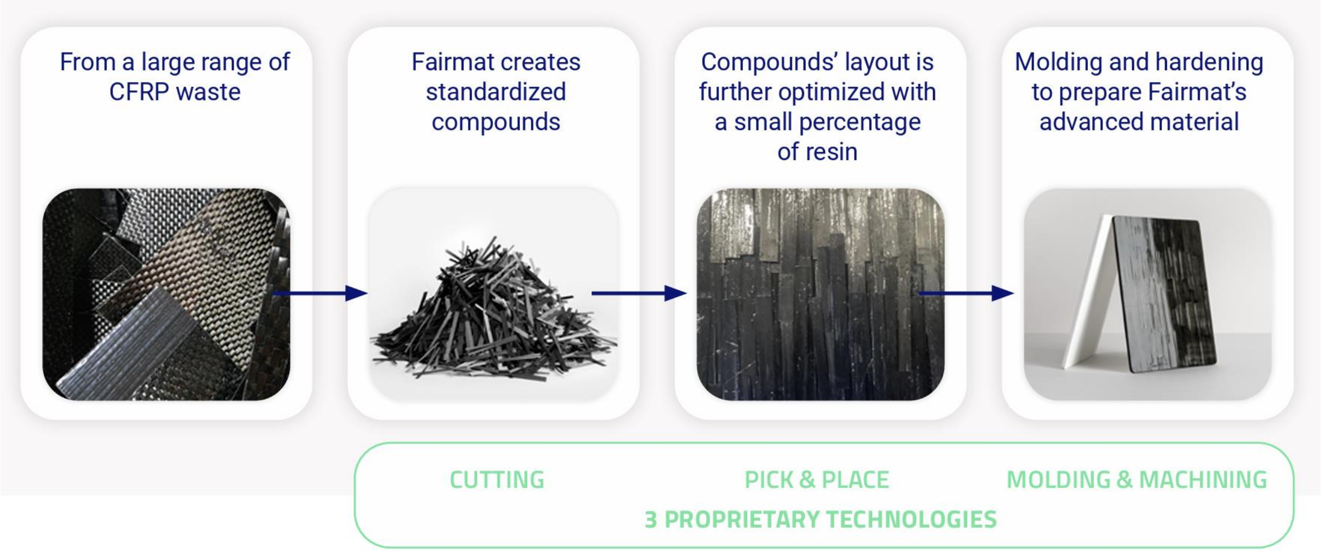
EPFL **Fairmat**

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

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



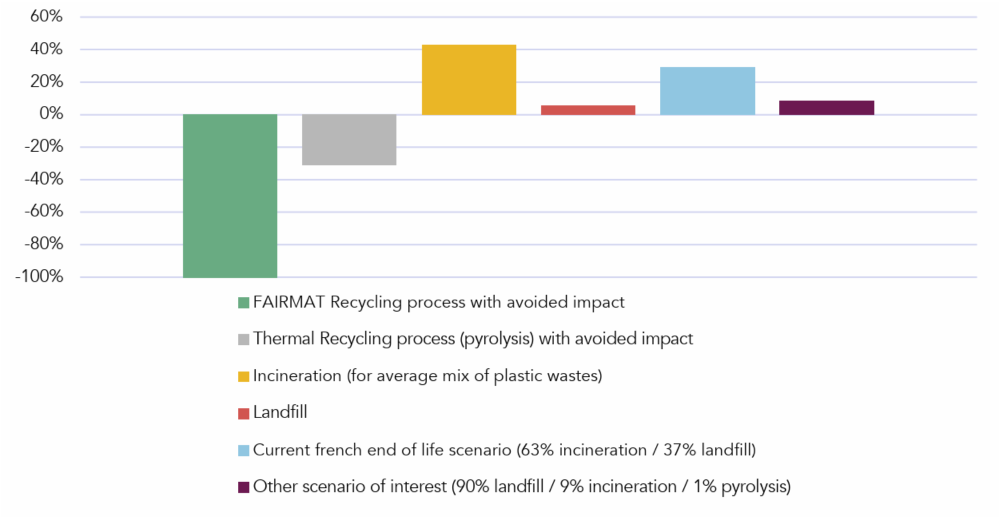
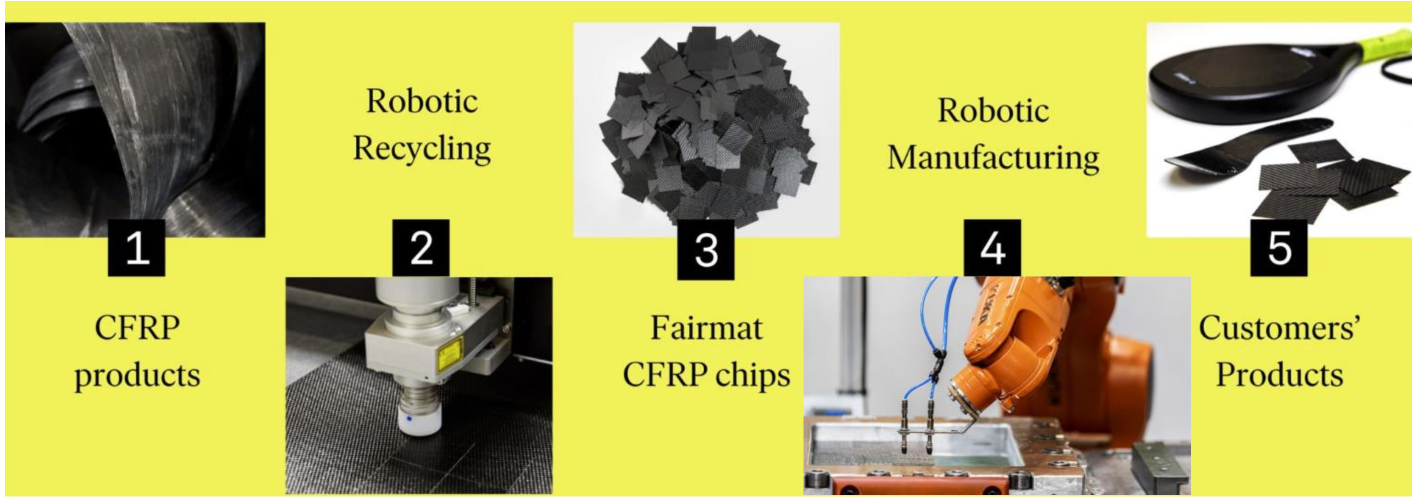


Figure 6: Carbon impact comparison between Fairmat recycling process and other end of life scenarios considering production of recycled material



3.8 kgCO2e/kg Fairmat laminate

[FAIRMAT - Unlock new possibilities with recycled carbon fiber]

(re) aligning recycled and recovered carbon fiber

Wakeman

- 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

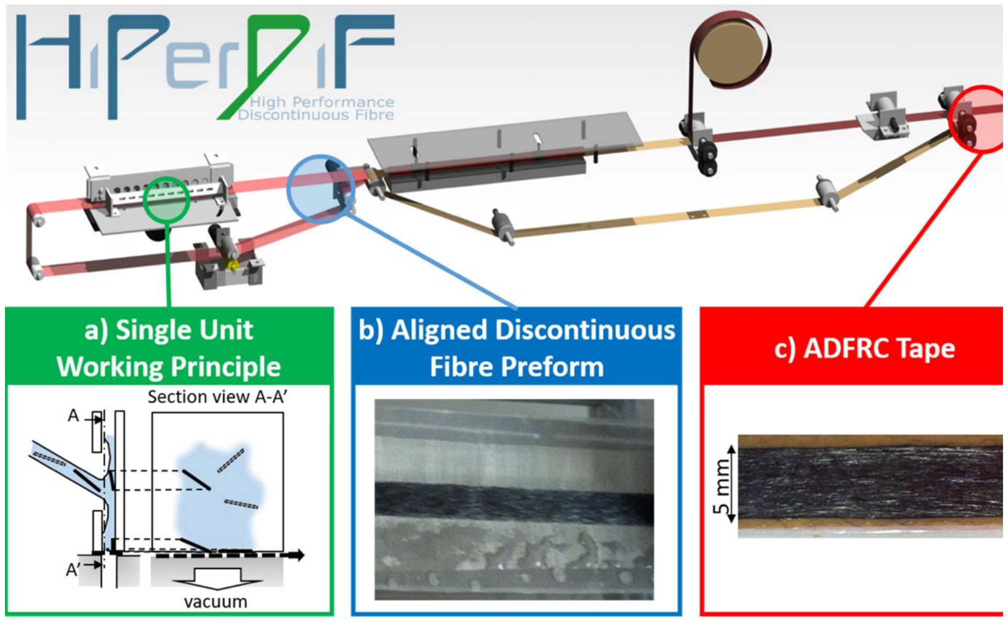
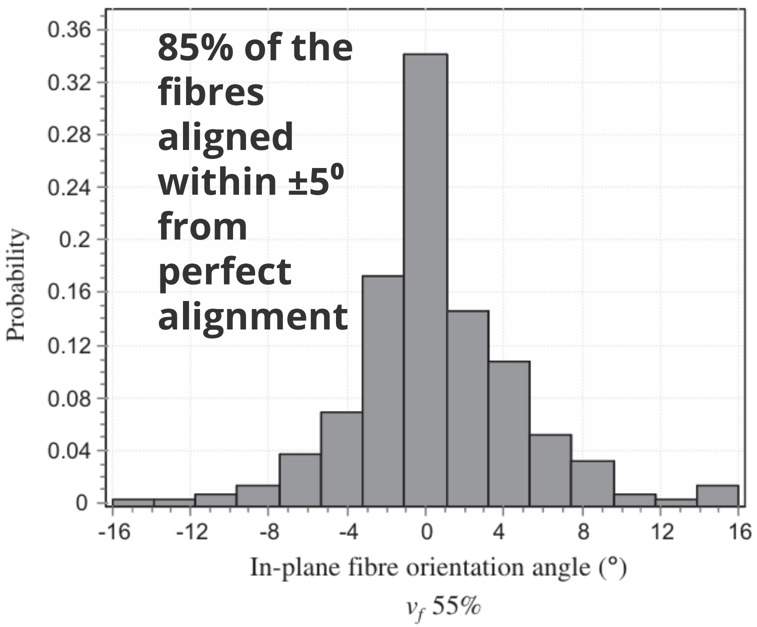
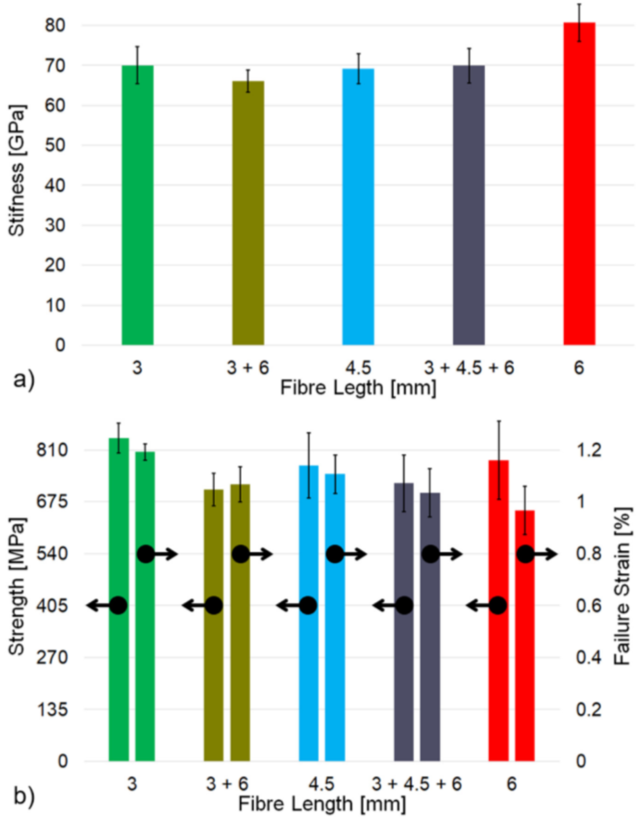


Figure 1. Schematic of the HiPerDiF alignment process.



(b)



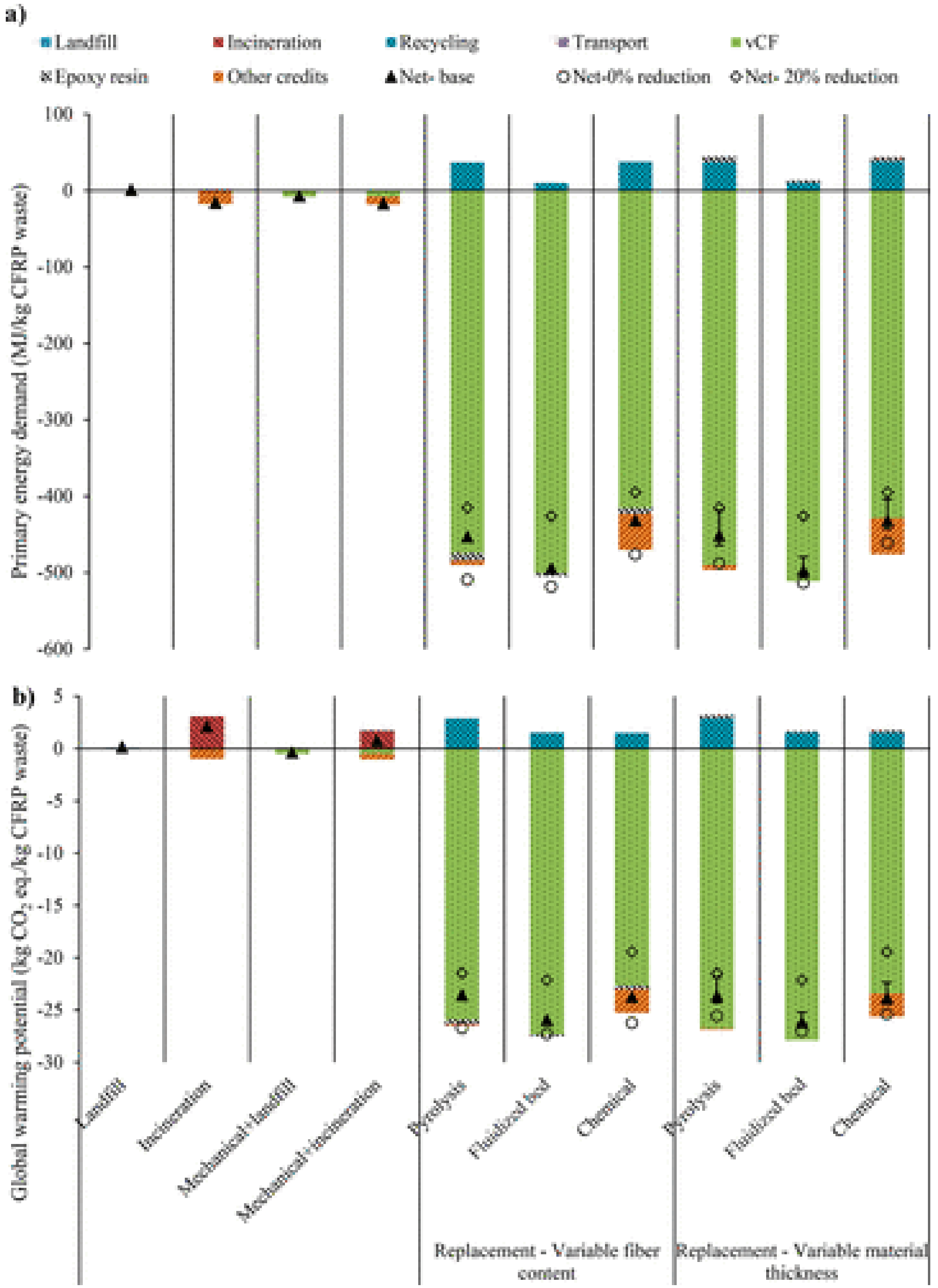
J. Compos. Sci. | Free Full-Text | Remanufacturing of Woven Carbon Fibre Fabric Production Waste into High Performance Aligned Discontinuous Fibre Composites (mdpi.com)

A novel manufacturing method for aligned discontinuous fibre composites (High Performance-Discontinuous Fibre method) - ScienceDirect

EPFL

Recycled CF LCA

- Recycling processes can achieve
  - Global warming potential (GWP) from −19 to−27 kg CO2eq
  - Primary energy consumption (PED) from −395 to−520 MJ per kg CFRP
  - Superior environmental performance to conventional composite waste treatment technologies
  - All process significant improvement vs. landfill and incineration

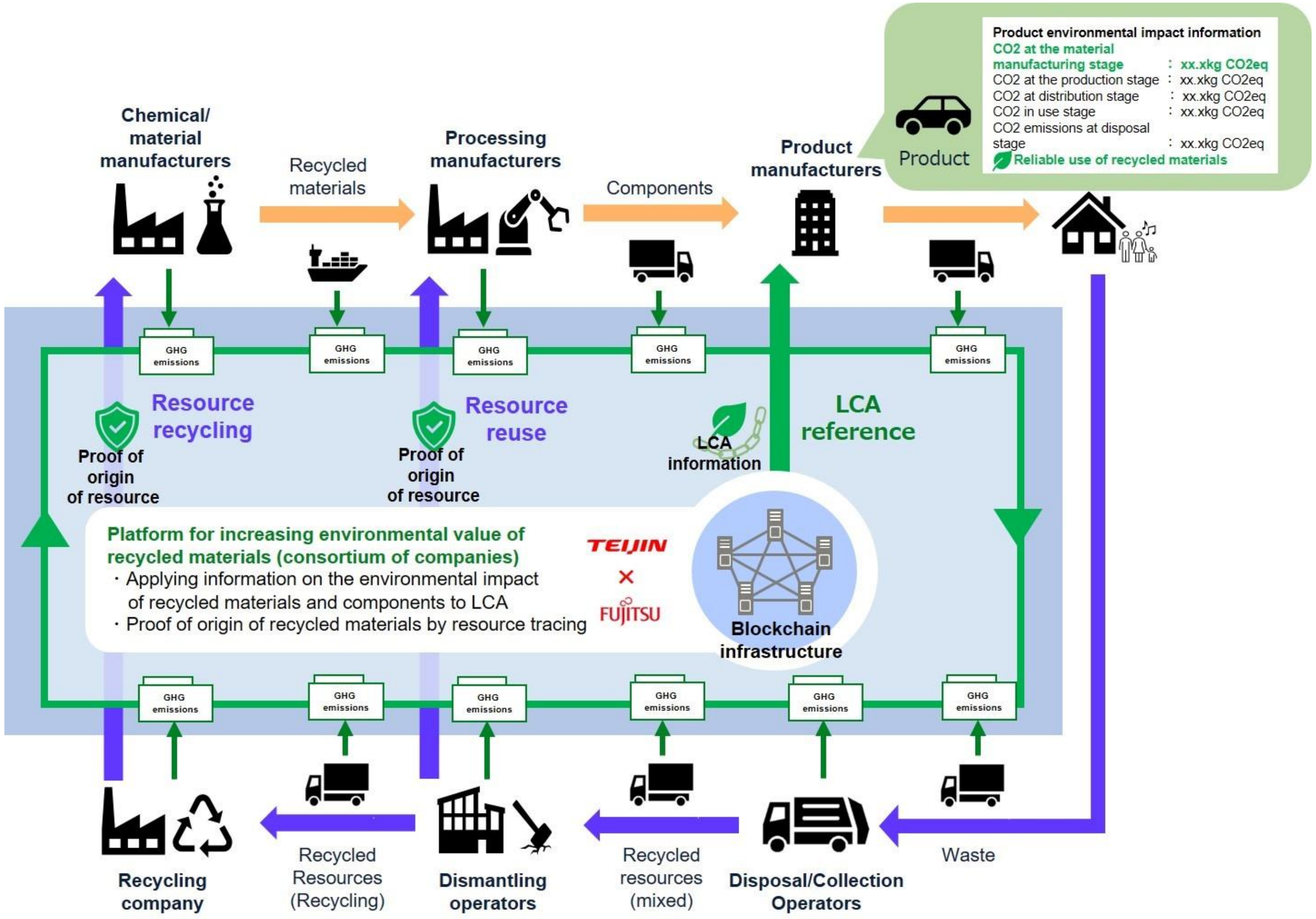


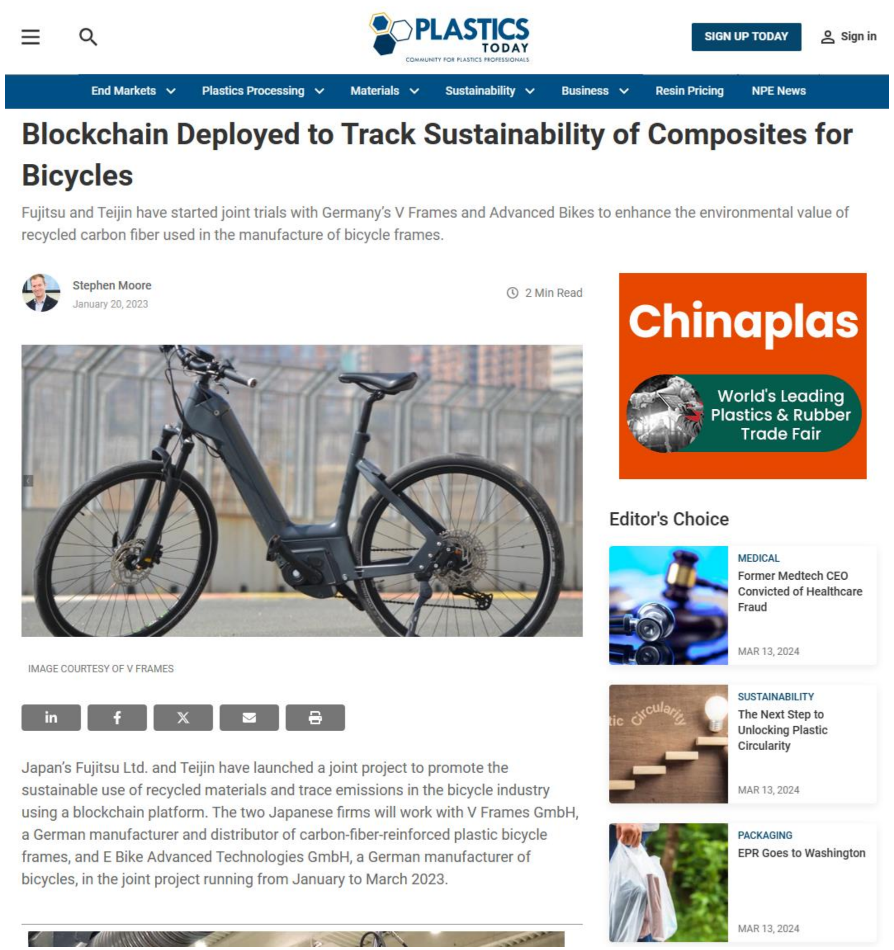
[Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options (acs.org)]

Question

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

Block chain enabled carbon fiber composite recycling




PLASTICS TODAY

SIGN UP TODAY | Sign in

End Markets | Plastics Processing | Materials | Sustainability | Business | Resin Pricing | NPE News

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

MEDICAL
Former Medtech CEO Convicted of Healthcare Fraud
MAR 13, 2024

SUSTAINABILITY
The Next Step to Unlocking Plastic Circularity
MAR 13, 2024

PACKAGING
EPR Goes to Washington
MAR 13, 2024

[Teijin, Fujitsu to develop blockchain-based commercial platform for recycled materials manufacturing | CompositesWorld]

[Blockchain Deployed to Track Sustainability of Composites for Bicycles (plasticstoday.com)]

Overview - Towards sustainable composite solutions

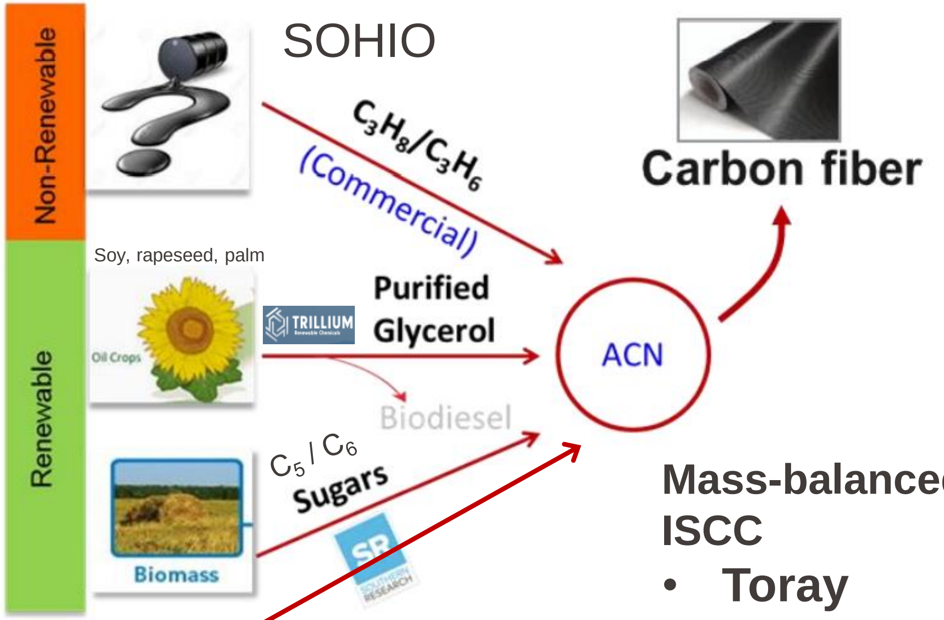
- End of life and recycling
- Bio-based materials
- Additive manufacturing
- Unmet challenges

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

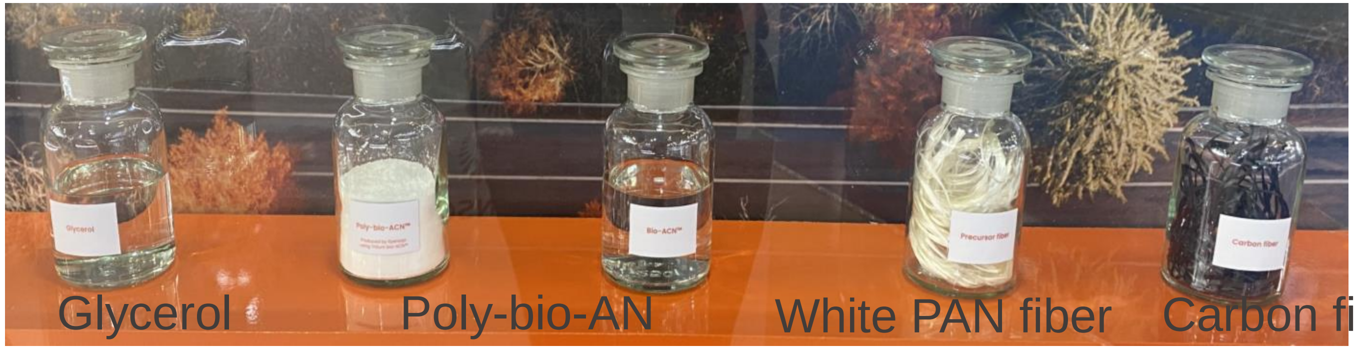


Bio-methane to bio-attributed propylene

Routes to ACN

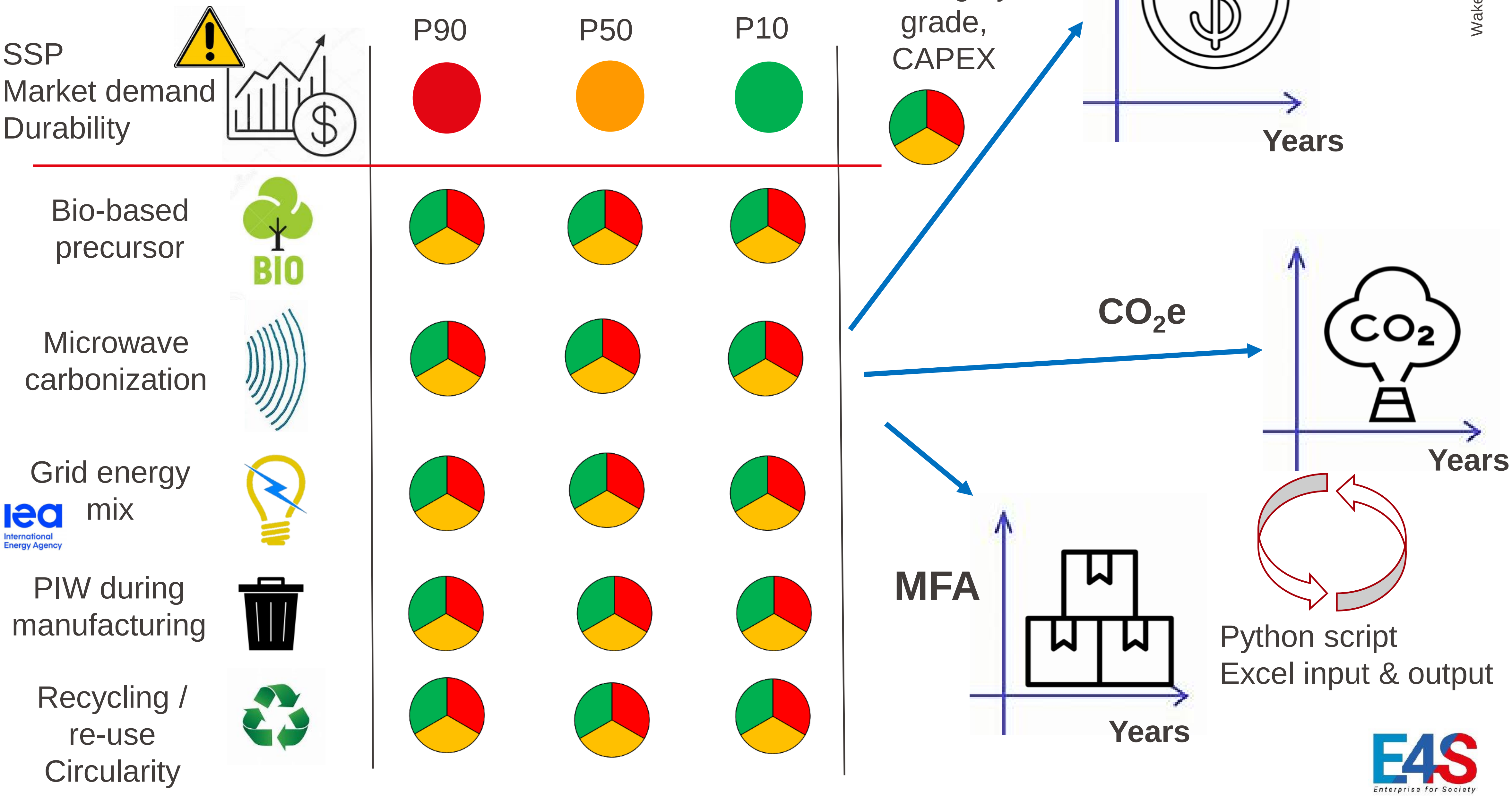
Mass-balanced ISCC
- **Toray**
- **Teijin**
- **Ineos**

SYENSQO



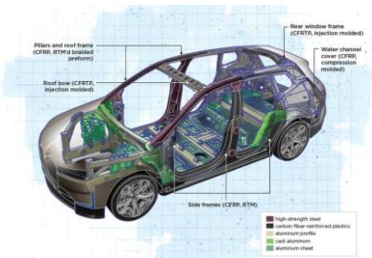
"Syensqo to Showcase Sustainable Mobility and Technology Collaborations at JEC 2024." Accessed: May 14, 2024. [Online]. Available: https://polymer-additives.specialchem.com/news/product-news/syensqo-jec-world-2024-carbon-fiber-applications-000233226

Monte Carlo simulation



Composites will see rapid growth as enablers towards 2050 SSPs

Main sectors	Aerospace ✓	Wind ✓	Automotive ✓	Hydrogen ✓	Infrastructure ...	Consumer ...
Sub sectors	☐ Civil wide body	☐ Wind on-shore	☐ Super cars	☐ CNG tanks	☐ Concrete rebar	☐ Bicycles
	☐ Civil narrow body	☐ Wind off-shore	☐ Premium	☐ Auto Hydrogen	☐ Buildings	☐ Marine
	☐ Evtol/drones	☐ Tidal	☐ EVs	☐ Aero Hydrogen	☐ Train	☐ Consumer
	☐ Military	☐ Fuel cells	☐ Other	☐ Ground Hydrogen	☐ Other	☐ Other
	☐ Other	☐ Other		☐ Rail Hydrogen		
				☐ Other		

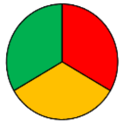


Needed industrial sector segmentation 1980-2050 for EPFL model

E4S Enterprise for Society

EPFL

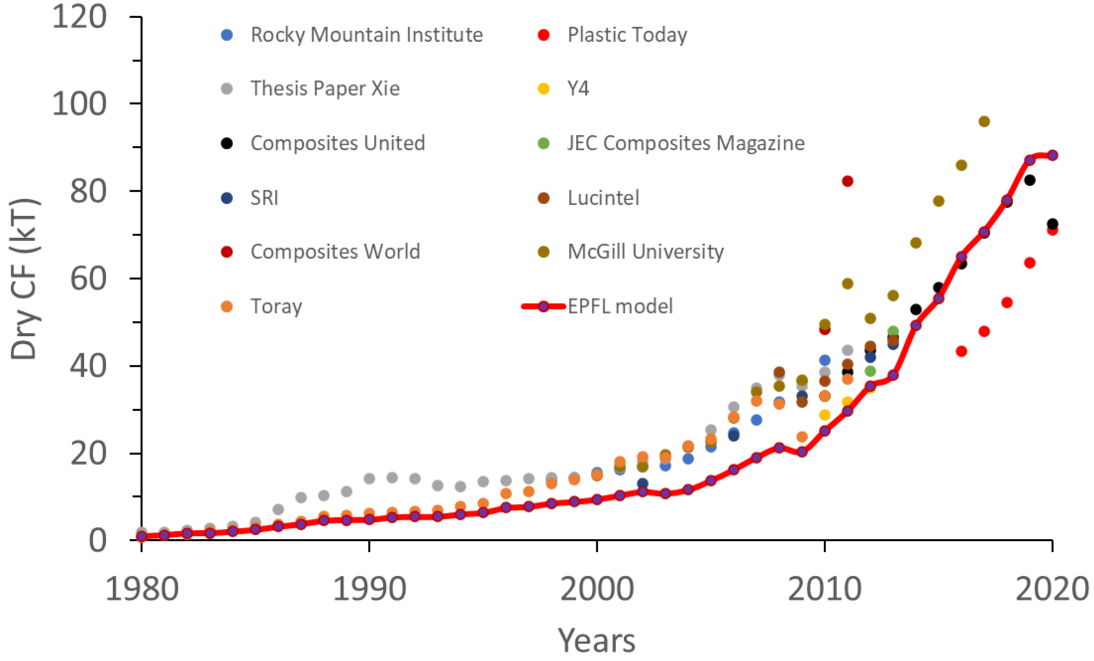
EPFL model of dry carbon fiber historical demand 1980-2020

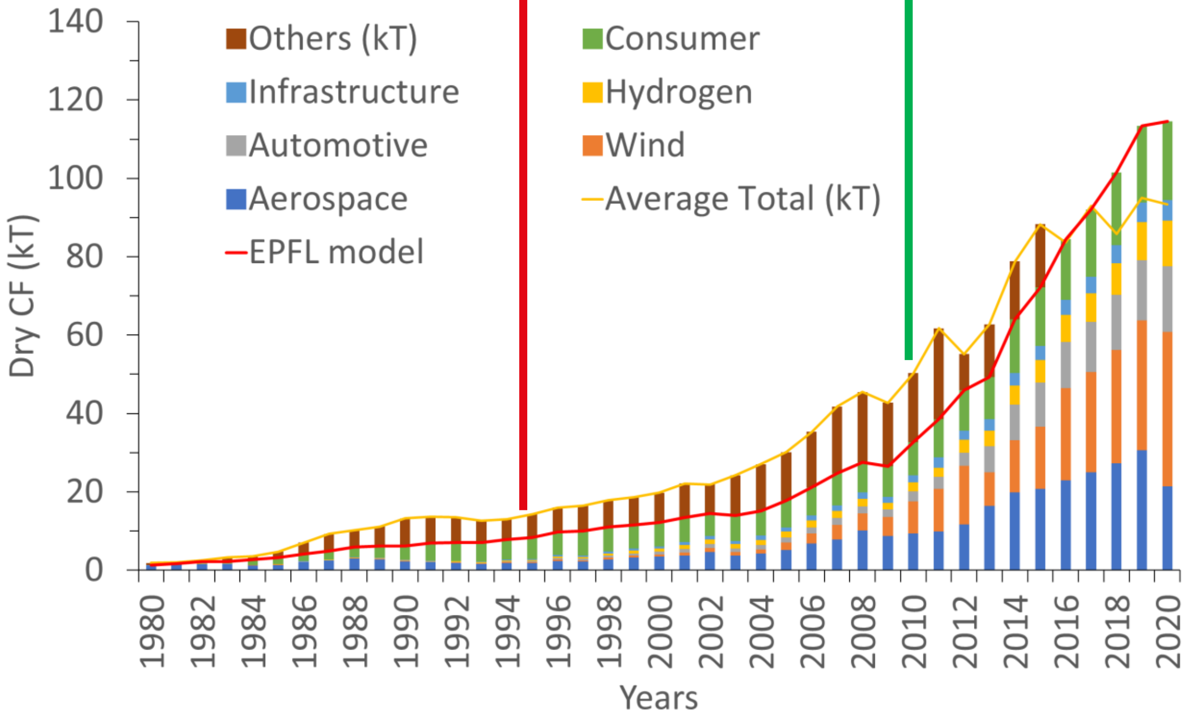


Durability by sector and sub-sector

Wakeman

Durability is the delay to reach end of life and enter recycling / disposal scenarios





Data used in MFA (circularity versus time)

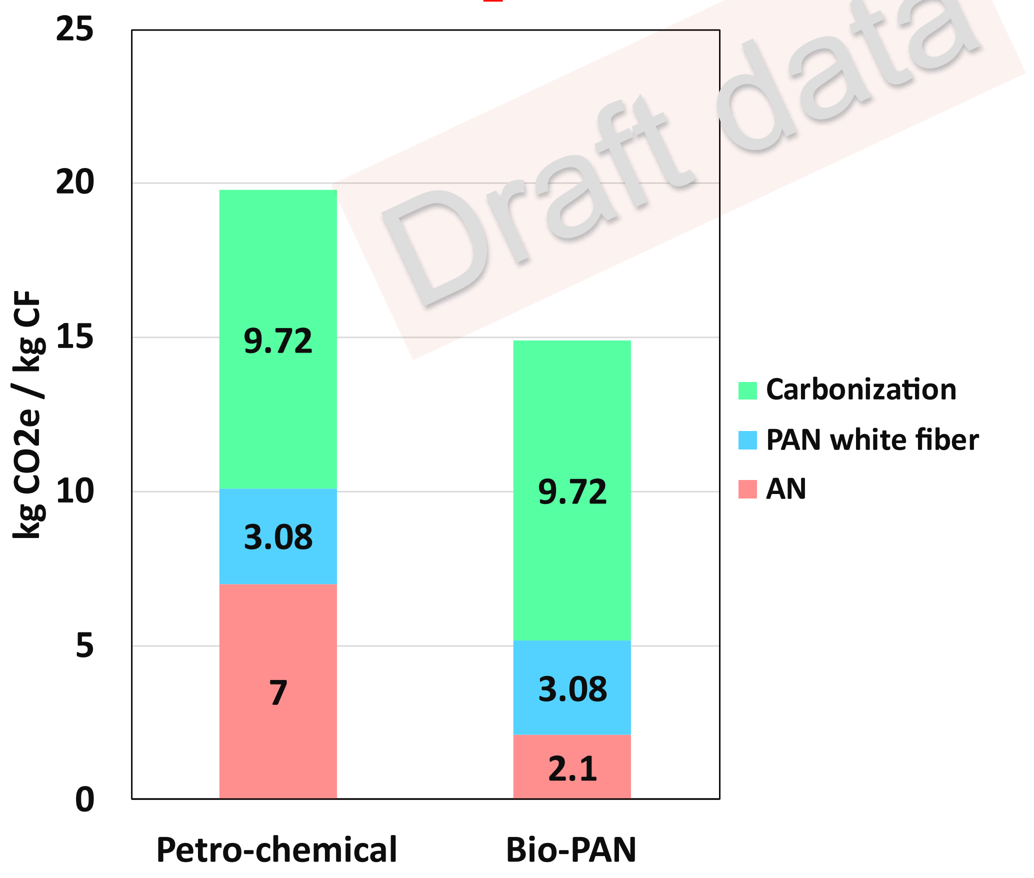
Preliminary data subject to revision

E4S Enterprise for Society

kg CO2e/kg AN or CF: Effect of bio-mass / bio-attributed AN

- Traditional AN (SOHIO)
  3.5 to 6.6 $kgCO_2e/kg$ AN [1]
- Bio-based AN
  - 70% reduction (Trillium)
  - Assumed here as 1.05 $kgCO_2e/kg$ AN
- PAN white fiber [2]
  - 5.04 - 3.5 kg = 1.54 $kgCO_2e/kg$ PAN
- Carbonization [3]
  - 9.72 $kgCO_2e/kg$ CF

JCMA 19.8 $kgCO_2e/kg$ CF [4]



(4)carbonfiber.gr.jp/english/tech/pdf/lci2022_en.pdfcarbonfiber.gr.jp/english/tech/pdf/lci2022_en.pdf

(1) M. A. Morales-Mora, E. Rosa-Dominguez, N. Suppen-Reynaga, and S. A. Martinez-Delgadillo, "Environmental and eco-costs life cycle assessment of an acrylonitrile process by capacity enlargement in Mexico," *Process Safety and Environmental Protection*, vol. 90, no. 1, pp. 27–37, Jan. 2012, doi: 10.1016/j.psep.2011.10.002.
(2) K. Kawajiri and K. Sakamoto, "Environmental impact of carbon fibers fabricated by an innovative manufacturing process on life cycle greenhouse gas emissions," *Sustainable Materials and Technologies*, vol. 31, p. e 10.1016/j.susmat.2021.e00365.
(3) https://www.harperintl.com/wp-content/uploads/2011/09/JEC-Draft-20120323-Post-Presentation-Edits.pdf

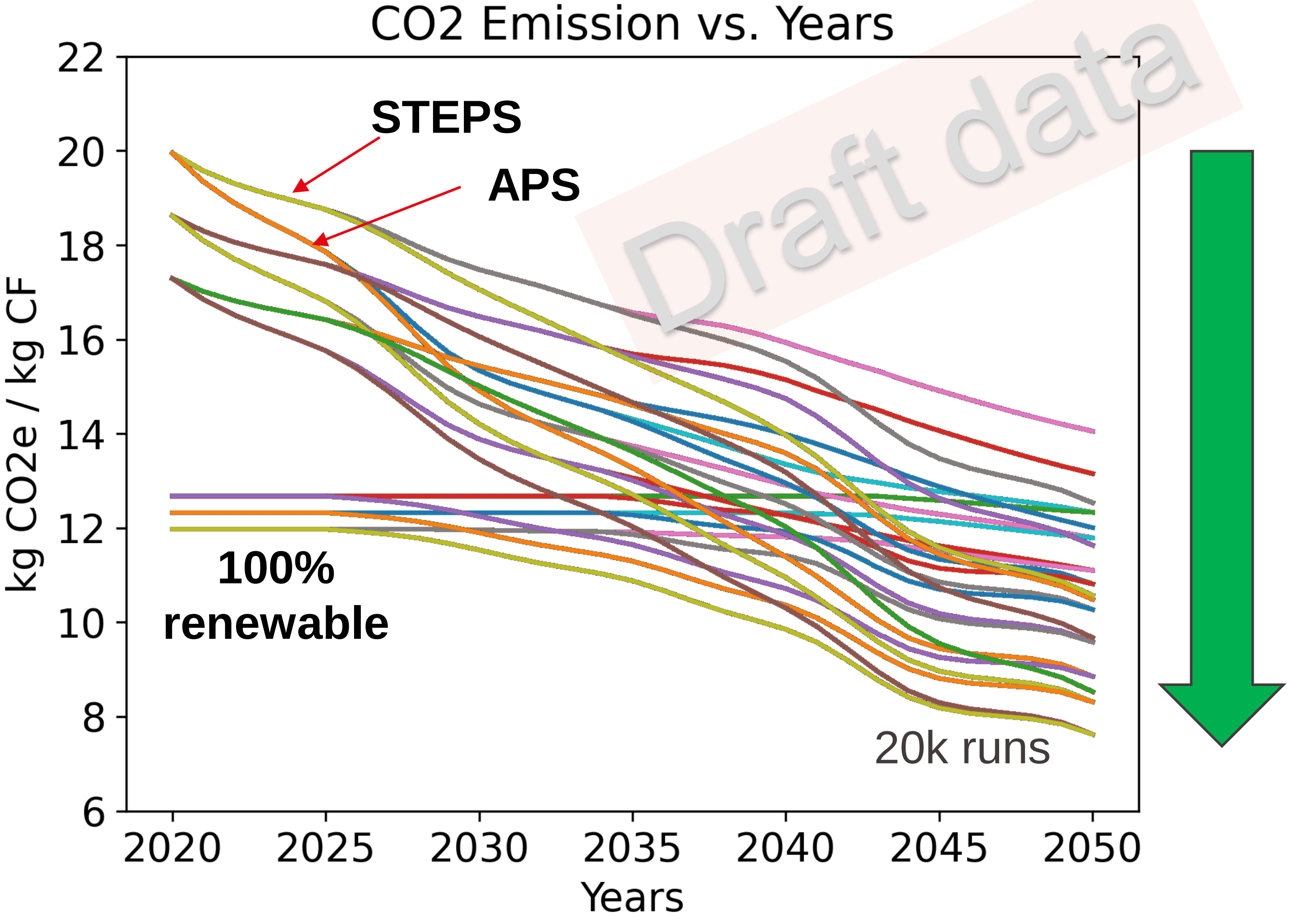
Preliminary data subject to revision

kg CO2e/kg CFv predicted to 2050

- Precursor (bio-AN vs. PC-AN)
- Lower energy carbonization (microwave, 50%)
- Grid energy mix on carbonizatior
  - IEA models vs. time
    - STEPS
    - APS
    - 100% renewable
- Carbonization energy
  - Harper = 20.6 to 28.2 kW.hr / kg
  - Translated to new grid mix ($kgCO_2e/kW.hr$) scenarios vs. time

processing-advancements-within-reach.pdf (harperintl.com)

JCMA 19.8 $kgCO_2e/kg$ CF



Preliminary data subject to revision

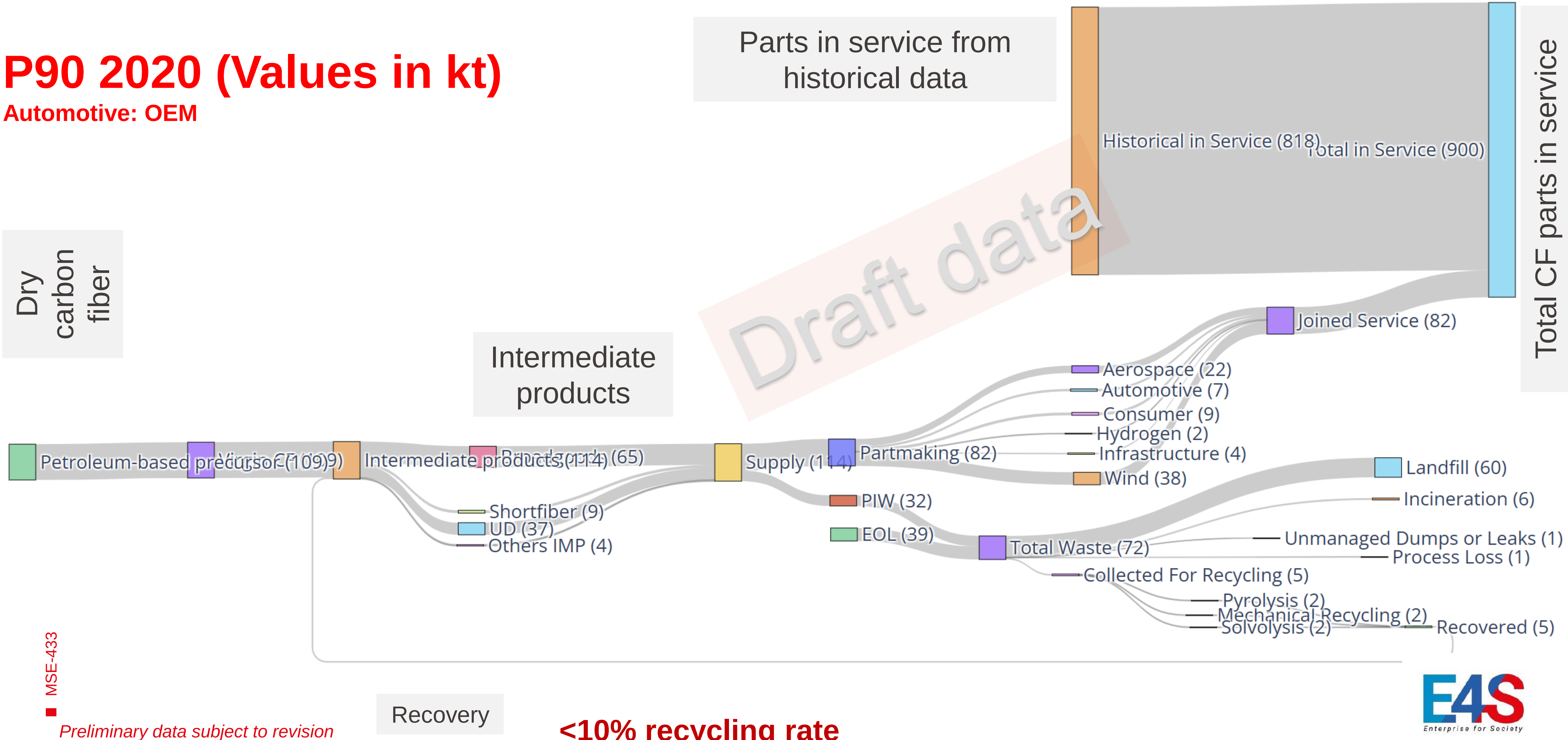
Dynamic MFA: Sankey Diagram (draft data)

Wakeman

Sankey Diagram (kT) for P90 Scenario in 2020

P90 2020 (Values in kt)

Automotive: OEM



Preliminary data subject to revision

<10% recycling rate

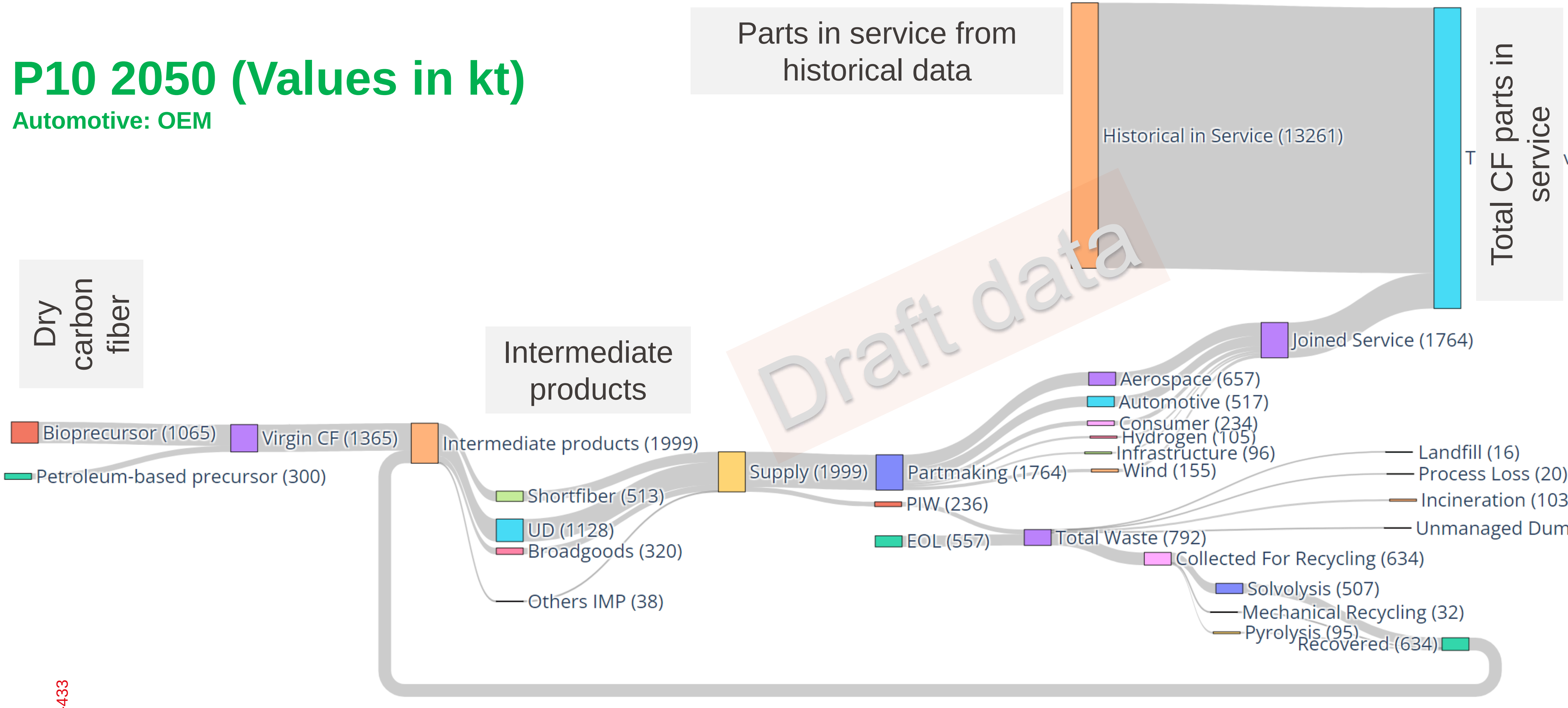
E4S Enterprise for Society

Dynamic MFA: Sankey Diagram (draft data)

Sankey Diagram (kT) for P10 Scenario in 2050

P10 2050 (Values in kt)

Automotive: OEM



Recovery

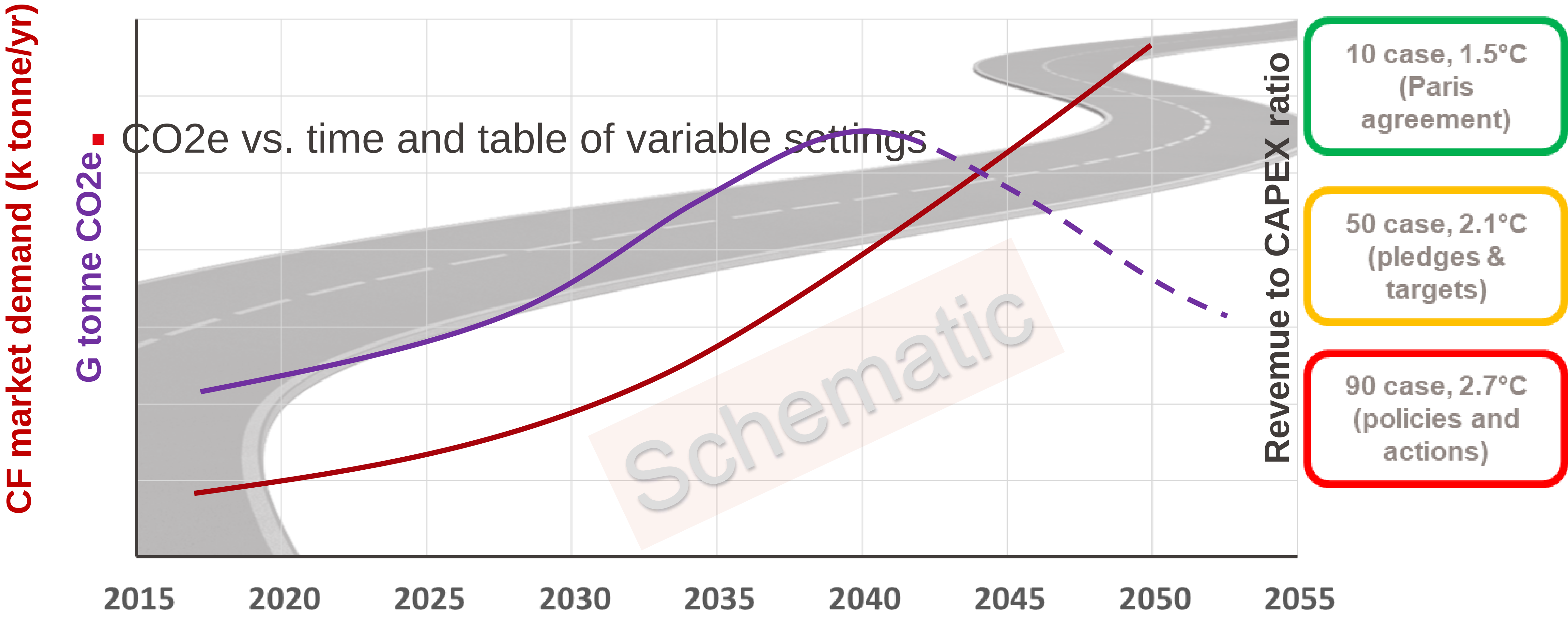
65% waste is recycled

Preliminary data subject to revision

75
Wakeman

P90, 2.7oC SSP vs. P10, 1.5oC SSP

- CO2e vs. time and table of variable settings



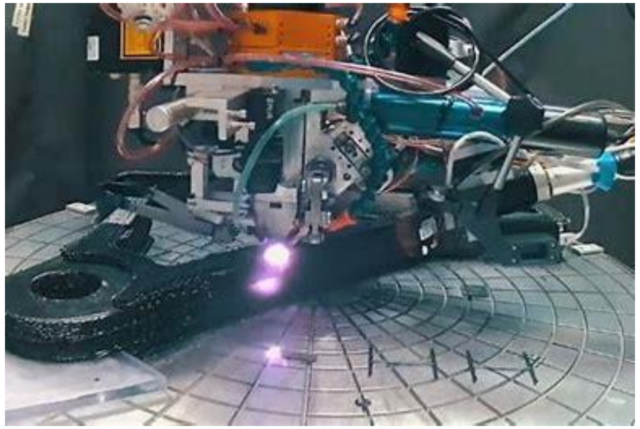
- Effect of SSPs on market growth and scaling of enabling technologies

Overview - Towards sustainable composite solutions

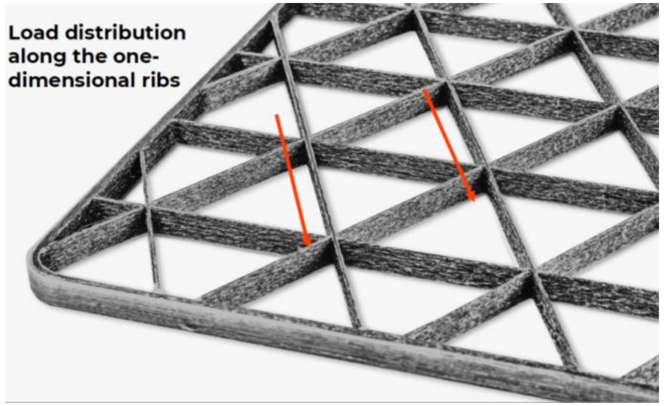
- End of life and recycling
- Bio-based materials
- Additive manufacturing
- Unmet challenges

Continuous carbon fiber 3D printing examples

Wakeman



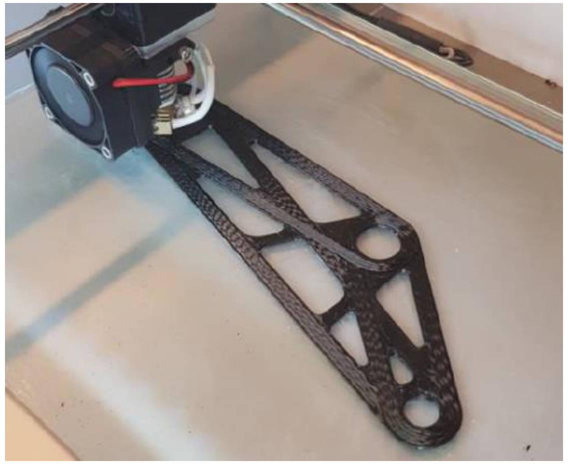
Arevo



Anisoprint

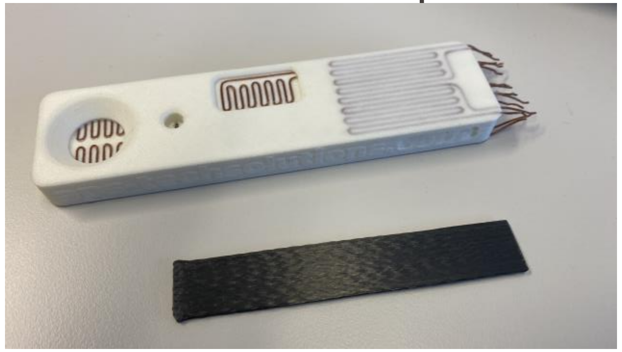
Ingersoll

Arris



9tlabs

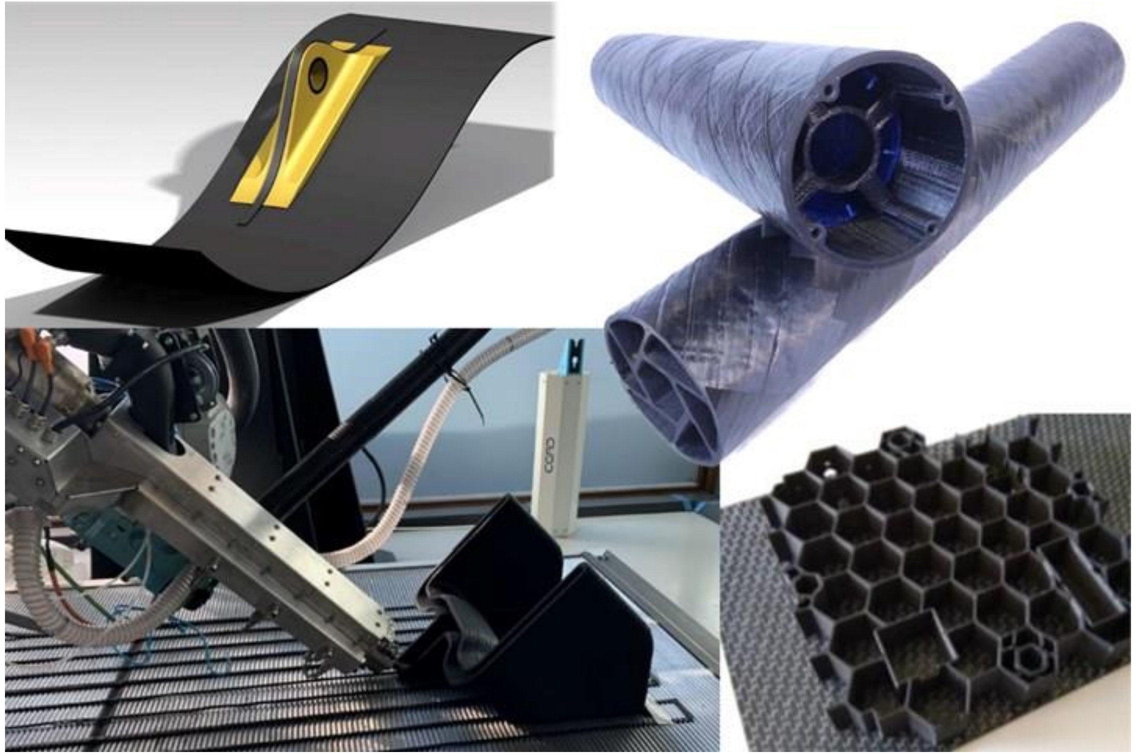
Continuous composites



APS

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

Merging of AM with composites manufacturing

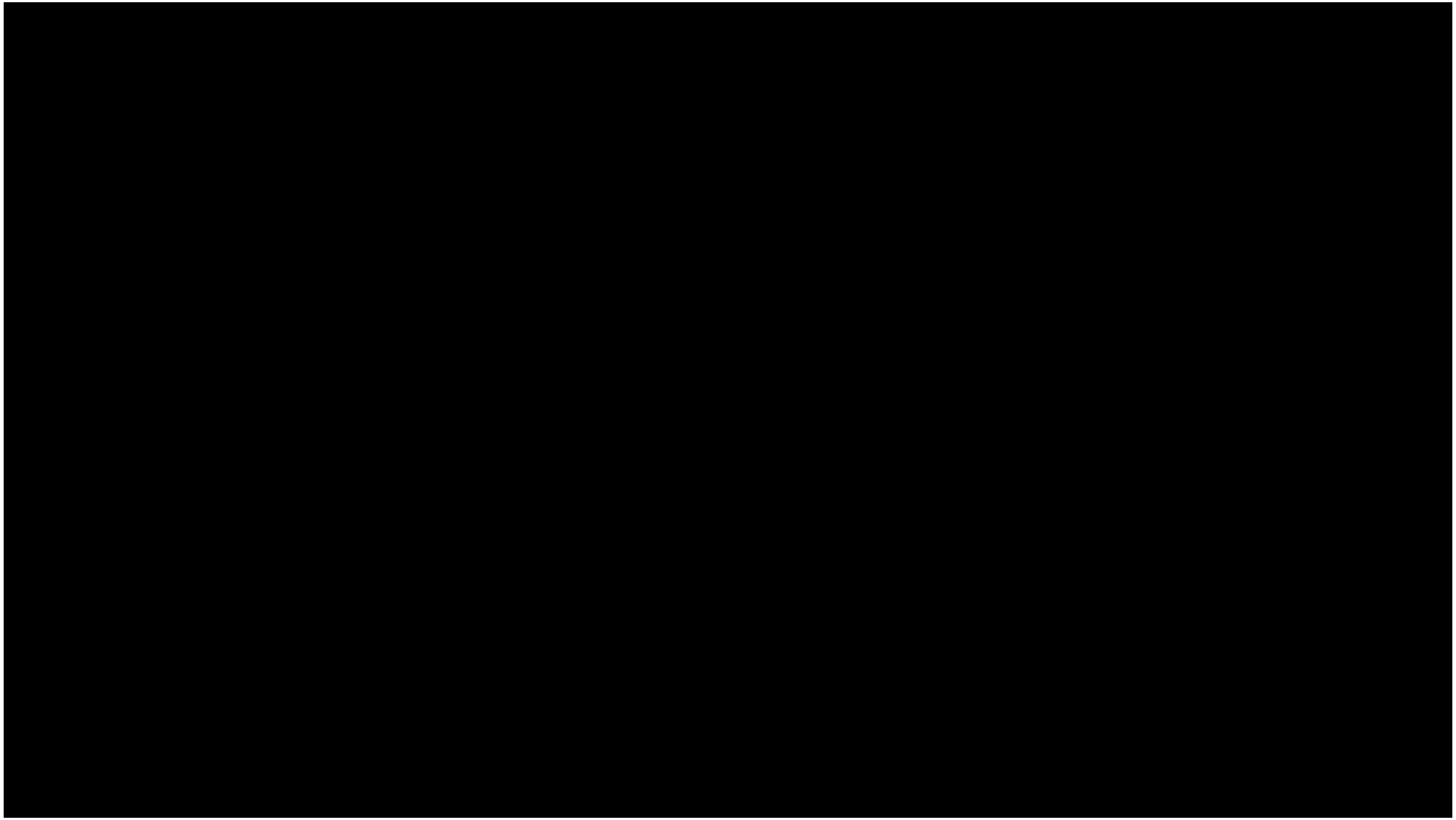


- Overprinting onto pre-made CFRP surfaces and brackets *(top left)*,
- hybridizing processes such as 3D printing and filament winding *(top right)*,
- 3D printing cores onto AFP laminates and AFP skins onto 3D-printed cores *(bottom right)*
- CEAD AM Flexbot 3D printing at 45 degrees *(bottom left)*.

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

[Future composite manufacturing - AFP and Additive Manufacturing | CompositesWorld]

Merging of AM with composites manufacturing



Electroimpact Continuous Fiber 3D Printing - YouTube 1min20s

Overview - Towards sustainable composite solutions

- End of life and recycling
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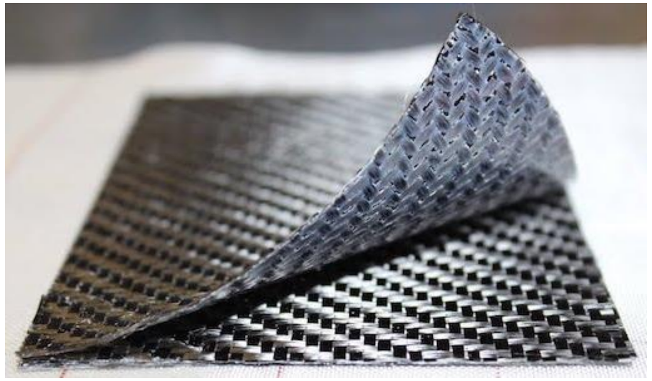
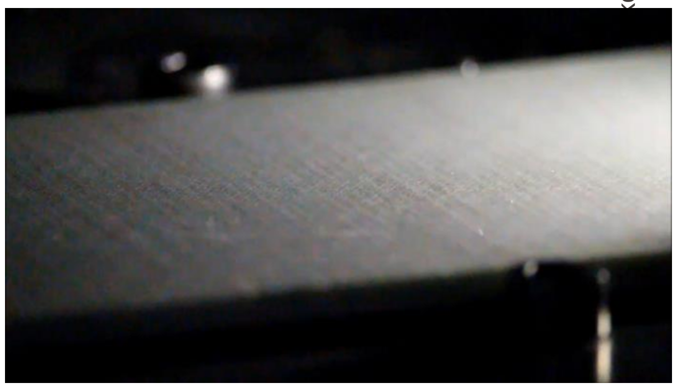
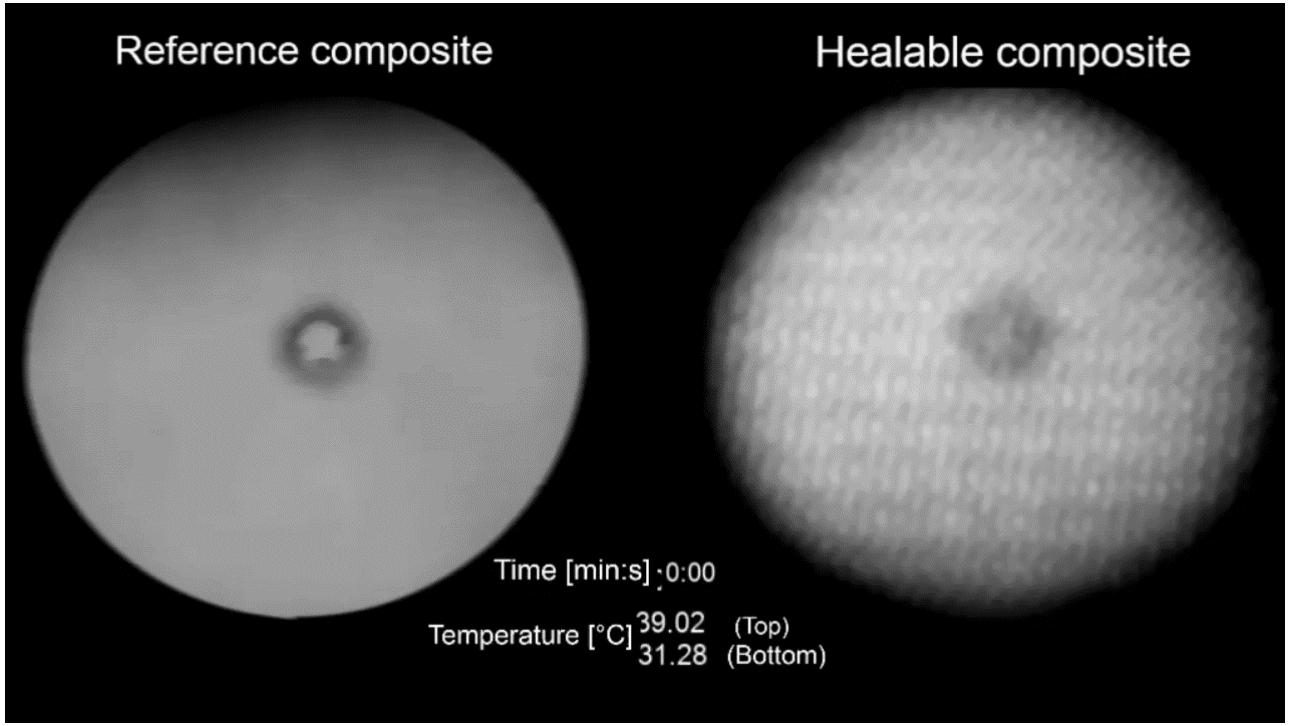
- Additive manufacturing
- Unmet challenges

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.

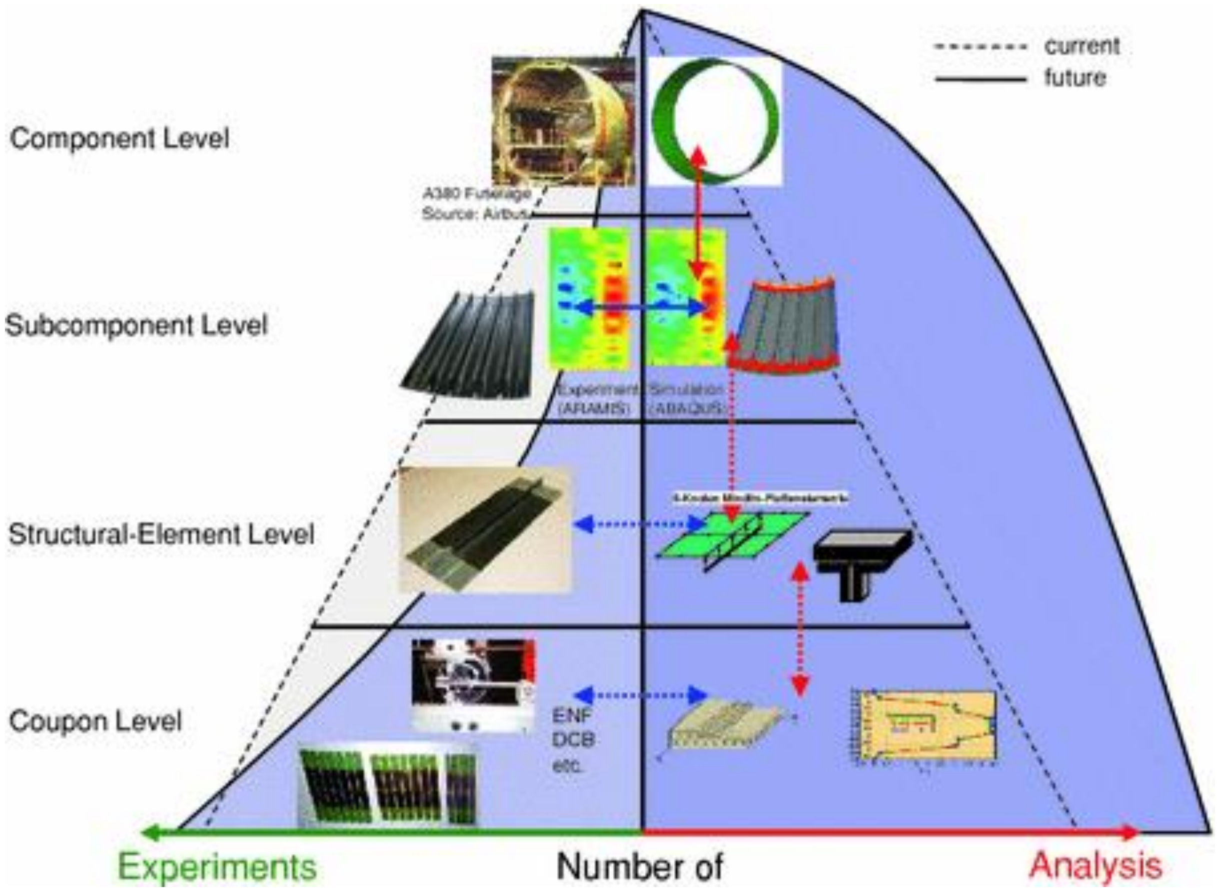


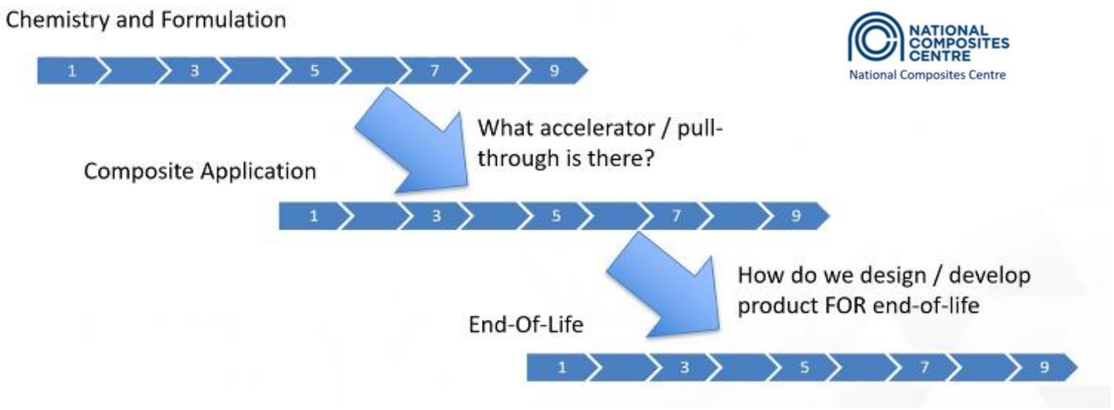




Welcome - CompPair Technologies Ltd - Healable composite

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

Challenges and opportunities to FRPC circularity

Technical

- 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

Market

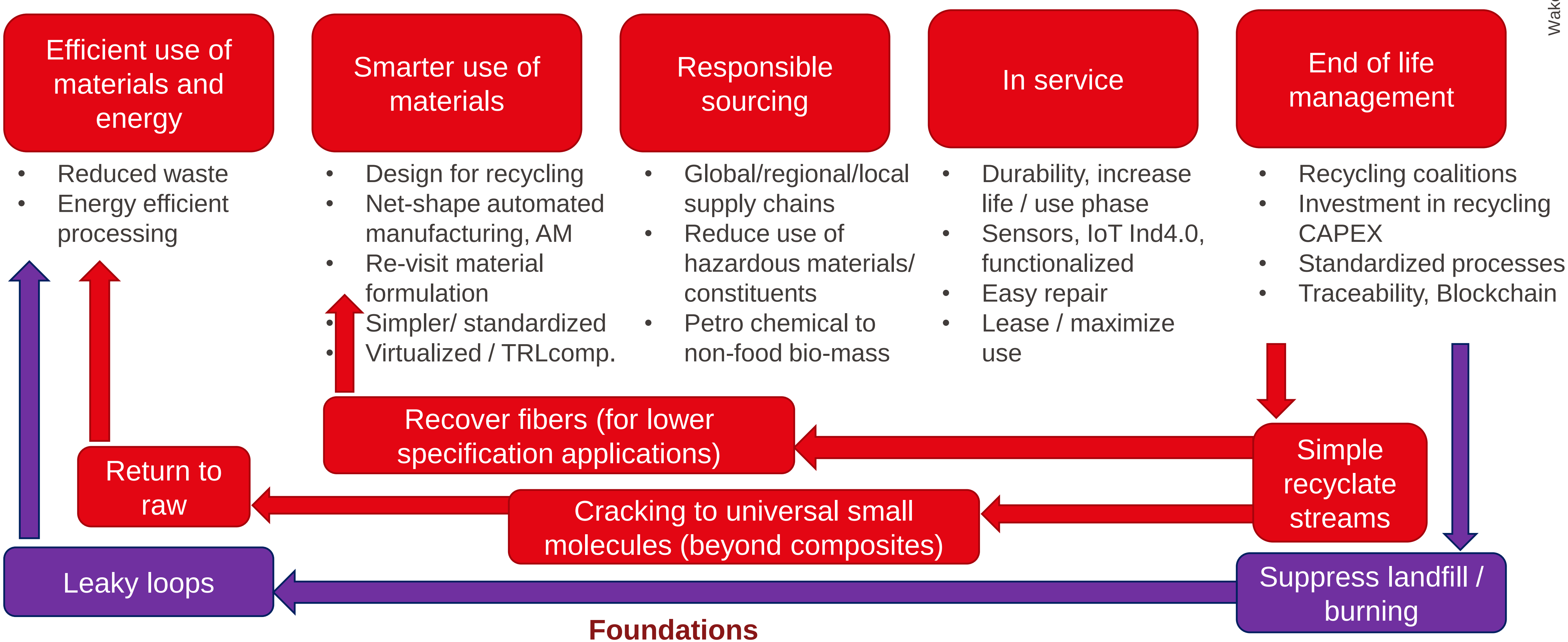
- Constraints along value chain
- Financial, Social, Behavioral, Logistical
- Risk in developing recycling infrastructure versus waste supply heterogeneity
- Issues developing economies of scale for recycling
- Risk that recovered fiber can cost more (not always) than virgin fibers

Policy

- 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

Circularity of Polymer Composites (baxcompany.com)

Summarizing: a sustainable composites industry?



Foundations

Legislation & incentives	**Collaboration Respect & Trust**	**NetPositive: Regenerative**	**Tech. innovation, entrepreneurship**	**Use renewable energy**

Create bigger circles (rather than small complex expensive circles)