EuReComp

EUROPEAN RECYCLING AND CIRCULARITY IN LARGE COMPOSITE COMPONENTS

THE 3RD OPEN WORKSHOP

PRESENTATIONS

19 MARCH 2025

ATHENS, GREECE/ONLINE

Introduction - Welcome

3rd EuReComp Open Workshop

19 March 2025, Athens, NTUA

Project Coordinator: Prof. Costas Charitidis

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R-NANO

Welcome of Speakers and Participants

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Where we are → NTUA's Library and Information Centre

Founded in 1837, almost along with the modern Greek state, NTUA is the oldest Technical University in Greece. The school quickly introduced reforms to make it better able to respond to the domestic needs of reconstruction and industrial development. In Greek, NTUA is called "Ethnicon Metsovion Polytechnion". NTUA represents Freedom, Democracy, Independence, Education and Social Progress

The NTUA Library and Information Center dates back to 1837, while the official operation of the library began in 1914 under state law. It is considered to be one of the most prestigious Academic Libraries in Greece. Today the Library offers many electronic services, 240.000 books and 1500 scientific journals. All the members of NTUA, as well as the public, may use the Library services and material. The public has no right to borrow books.

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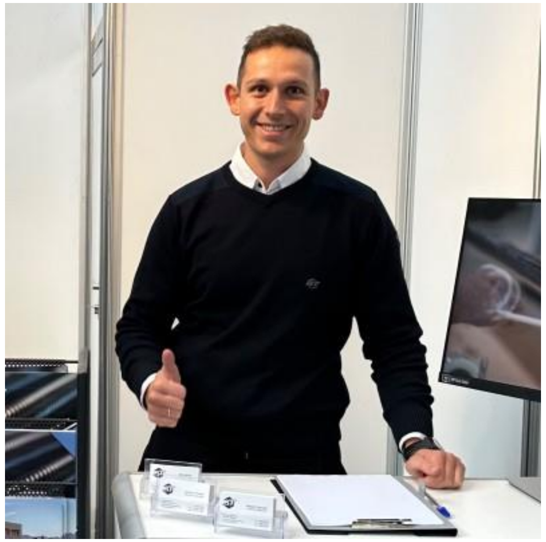
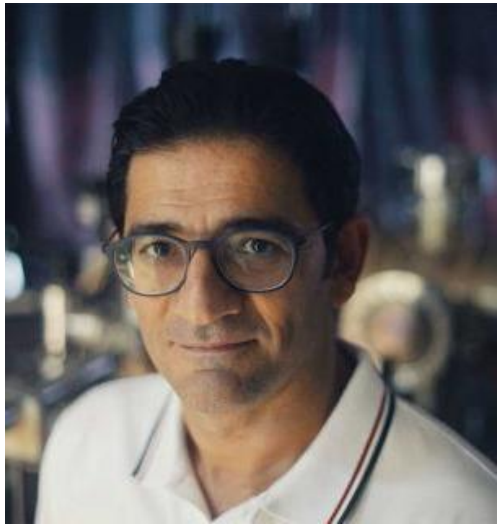
Lecturers within EuReComp



Kosmas Tiriakidis
Production Manager at B&T Composites



Eleftherios Amanatides
Professor at Patras University

Dionisis Semitekolos
Researcher in NTUA

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Invited Speakers from sister projects

Advancing Circularity: Bio-Based High-Performance Composites for Industry (The EU-Project rLightBioCom Project)

An MCDM-Based Decision Support System to Enable Circular Strategies for Composites (The RECREATE Project)

Large-Scale Recycling of Wind Blades in Commerial Products and Materials (The REFRESH project)

Development of Recyclable, Multifunctional Composites (REPOXYBLE project)

Holcim Circular Economy Strategy: From Construction Demolition Waste to End-of-Life Wind Turbine Blades Recycling (BLADES2BUILD Project)

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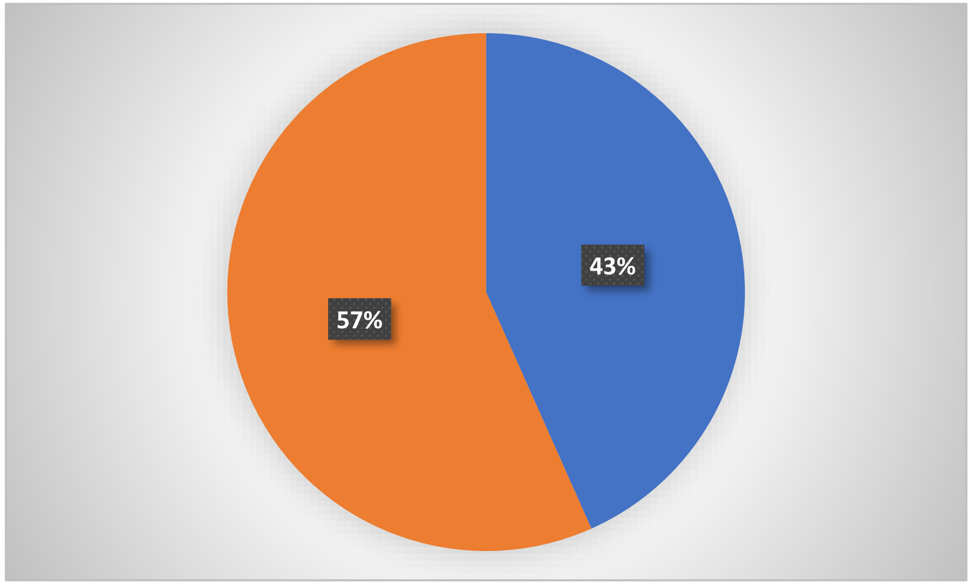
Participants – Audience Type and Size

<u>Type of audience:</u>

- Project Partners (Universities, Research Institutions, Companies)
- External Speakers
- People from companies/freelancers
- Master Students
- Undergraduate Students
- Erasmus Students
- Online participants

- **170** in total participants
- **85** in person attendees
- **85** online attendees

Gender Balance



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EuReComp In a Nutshell

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EuReComp in a nutshell

DURATION
48 months

9 EU countries

COORDINATOR
Prof C. Charitidis

STARTING DATE
01/04/2022

20 partners

BUDGET
~9 M euros

PROJECT ACRONYM/TITLE
EuReComp
European recycling & circularity
in large composite components

GA NUMBER
101058089
CALL: A digitized, resource-efficient
and resilient industry 2021

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EuReComp Consortium

20 Industrial and **academic partners** with **complementary and multidisciplinary expertise!**

- ✓ **2 IND**
- ✓ **11 RTO**
- ✓ **7 SME**

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EuReComp Mission

The **cumulating composite wastes** are more prominent than the needed new composites. The **aircraft** and **wind energy** sectors contribute to a major share.

Across all industries about 60% of waste **fibre reinforced** composites is **landfilled**, causing severe **societal and environmental issues**.

EU's **Circular Economy plan** seeks to reduce the landfill down to 10% by increasing the rate of **recycling.**

Stakeholders seek **advanced technologies** and **end-of-life options**, which promote the **recycling** of carbon fibres.

EuReComp project has a strong focus on **circularity**, setting out to provide **sustainable methods towards recycling and reuse of composite materials**, coming from components used in various industries, such as aeronautics and wind energy.

EuReComp pathways towards circularity:

- Repairing, repurposing and redesigning parts from end-of-life large scale products and
- Recycling and reclamation of the materials used in such parts

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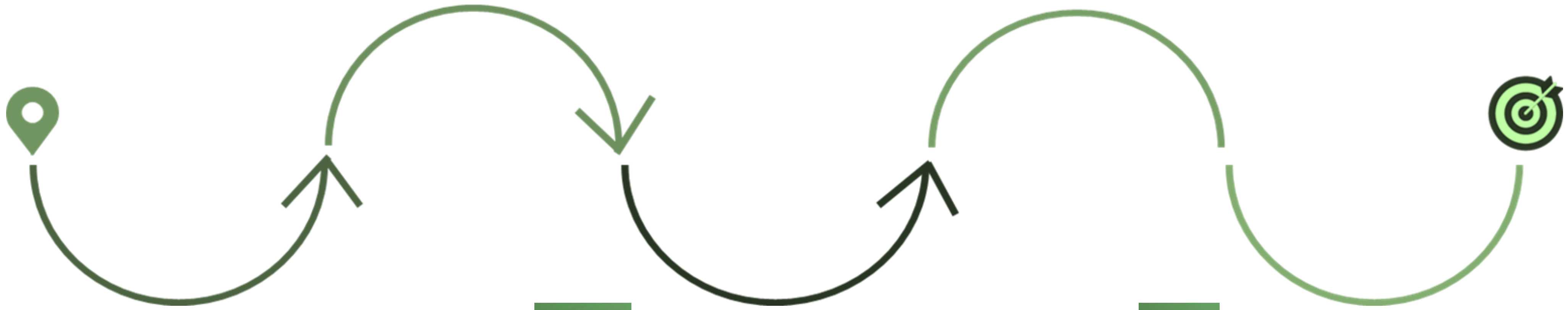
EuReComp Objectives

To develop and integrate novel solutions for a **higher reuse** of whole products and components

To develop tools to demonstrate the **circularity** and the **environmental benefits** of the solutions tested



To propose innovative **dismantling** and **sorting** systems enabling reuse and recycling of complex composite materials

Pilot demonstration of reuse/recycling approaches of composites & secondary raw materials

To consider the **co-design of learning resources** together with local and regional educational organizations for current and future generations of employees

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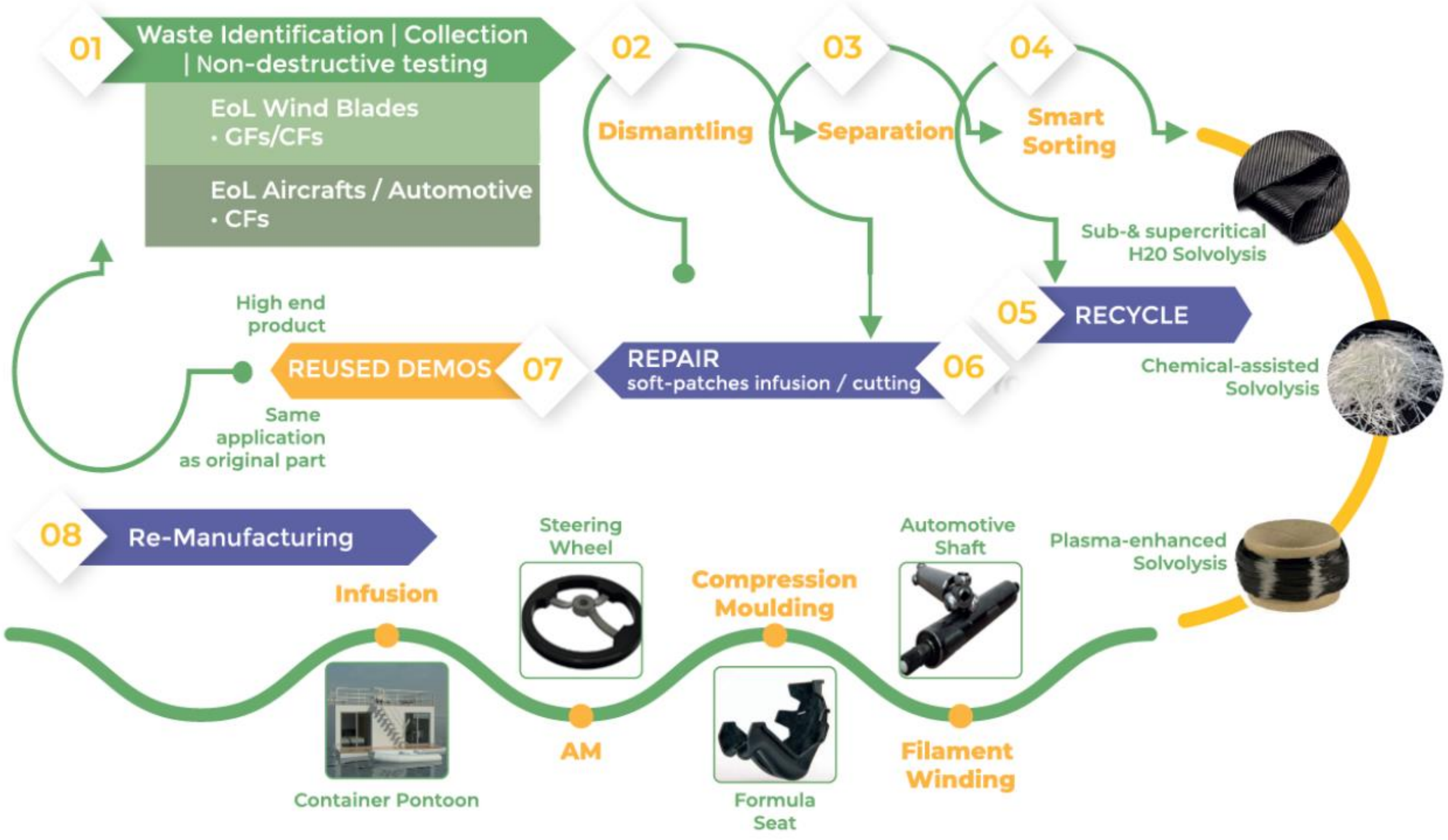
EuReComp Concept



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Content and Target of today's Workshop

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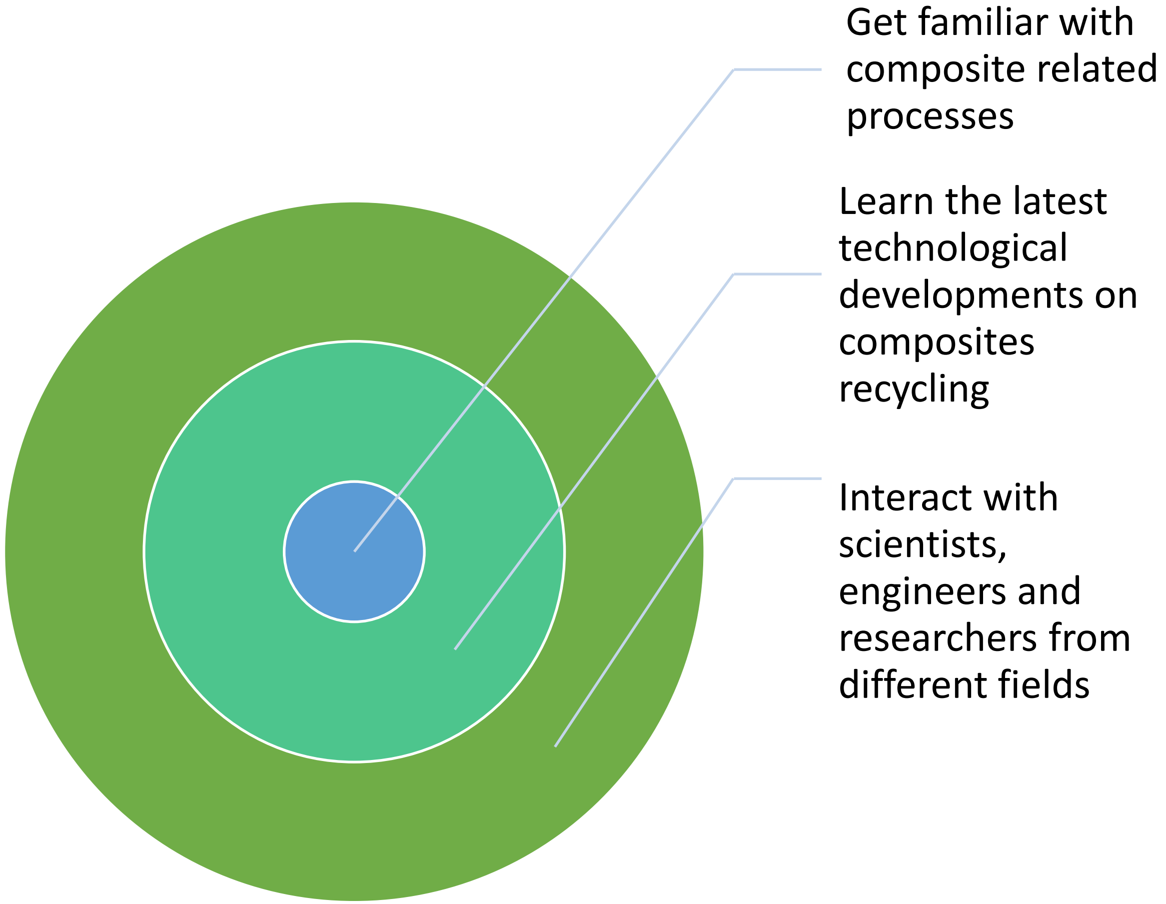
3rd EuReComp Open Workshop

Contents:

- Lectures from EuReComp partners on the “hottest” topics
- Presentations from External Invited Speakers on relevant to EuReComp Projects
- Brainstorming Session, including:
  - Problem solving and sharing ideas
  - Teamwork
  - Interactive poll surveys
  - Contest on the most creative idea and “souvenir gift”
- Demonstration Session. Visit on operative NTUA (R-Nano) Laboratories:
  - CF pilot production line (Melt spinning – Stabilisation – Carbonisation)
  - Nanomechanical Composites Testing Unit
  - Chemical Vapour Deposition Lab
  - Synthetic Chemistry Lab
  - Composites Solvolysis and Manufacturing Lab
  - CF Sizining Pilot line
  - Filament Extrusion Pilot line



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Acknowledgment

The research leading to these results has received funding from the European Union’s Horizon Europe Research and Innovation programme under Grant Agreement No 101058089.

Consortium

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Thank you!

Prof. Costas Charitidis

charitidis@chemeng.ntua.gr

National Technical University of Athens

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3rd EuReComp Workshop

Unveiling Filament winding

NTUA, Athens, Greece, 19/3/2025

Kosmas Tiriakidis, B&T Composites

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101058089.

B&T Composites produces advanced, hybrid, lightweight structures.

https://www.youtube.com/watch?v=ynCrrra2-Vs

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3rd EuReComp Workshop - Unveiling Filament winding

Industry

- High rotational speed rollers

Wind energy

- Couplings
- Light weight crane arms

Marine

- Torque transmission shafts
- On deck applications

Infrastructure

- GRP piping systems

Energy storage systems

-Type IV and type V high pressure tanks

Defense industry

-On going projects

Composite parts designed and developed
by us with an integrated sensing system designed and developed by us

B&T COMPOSITES
COMPOSING THE FUTURE

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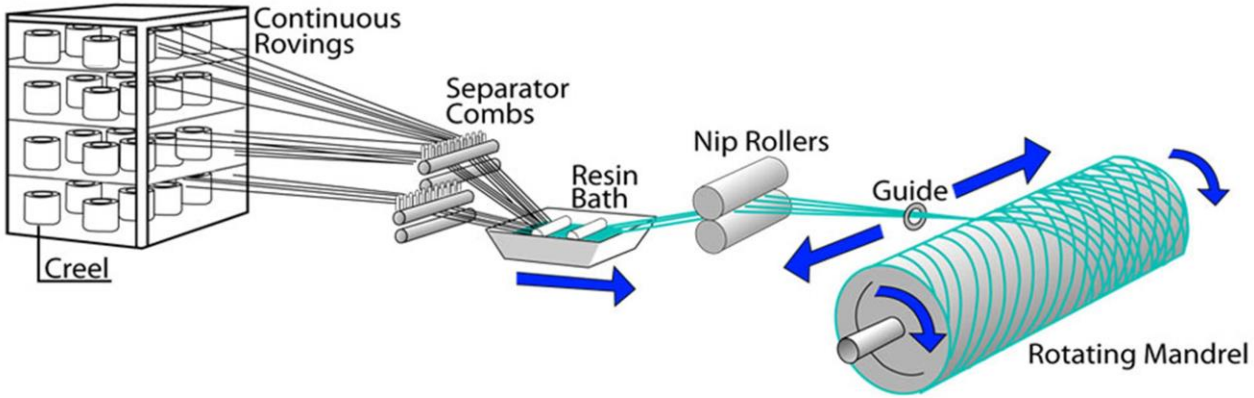
Filament winding is an advanced technology used to create composite structures that offer **outstanding strength-to-weight ratios.** The process involves carefully winding continuous fibers around a **cylindrical mandrel** in predetermined **patterns** and **orientations**.

The filament winding process step – by- step

1. Fiber strands are unwound and guided through a resin bath where they are impregnated with resin.
2. The resin-impregnated fibers are wound onto a rotating mandrel with precise control over orientation and tension.
3. Layers are built up as required by the design.
4. The composite is cured in an oven to achieve its final properties.
5. The finished product is removed from the mandrel using hydraulic rams or soluble/collapsible mandrels for complex geometries.

The mandrel rotates around its axis (**Axis 1 or X**), while simultaneously, the delivery eye (**Axis 3-4 or Z-W**), mounted on a carriage (**Axis 2 or Y**), moves horizontally in relation to the rotating mandrel's axis, placing the fibers in the desired pattern or angle.



Details of the manufacturing process

Most of the shapes generated through this process are surfaces of **revolution**, such as pipes, cylinders and spheres.

In filament winding, continuous reinforcements, such as roving, are wound onto a mandrel until the surface is covered and the **required thickness** is achieved.

The process uses raw materials, fiber and resin, in a fairly automated process with low labor, thus contributing to a low production cost.

The pre-programmed rotation of the mandrel and horizontal movement of the delivery eye produce the helical pattern depicted which is the simplest mode of operation of a helical winding machine.

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Filament Winding Parameters to Define:

- Tension (N) on the tensioner
- Winding angle
- Sequence control of layers with different winding angles
- Number of fibers
- Bandwidth of the fiber batch
- Thickness control per layer
- Fiber winding speed

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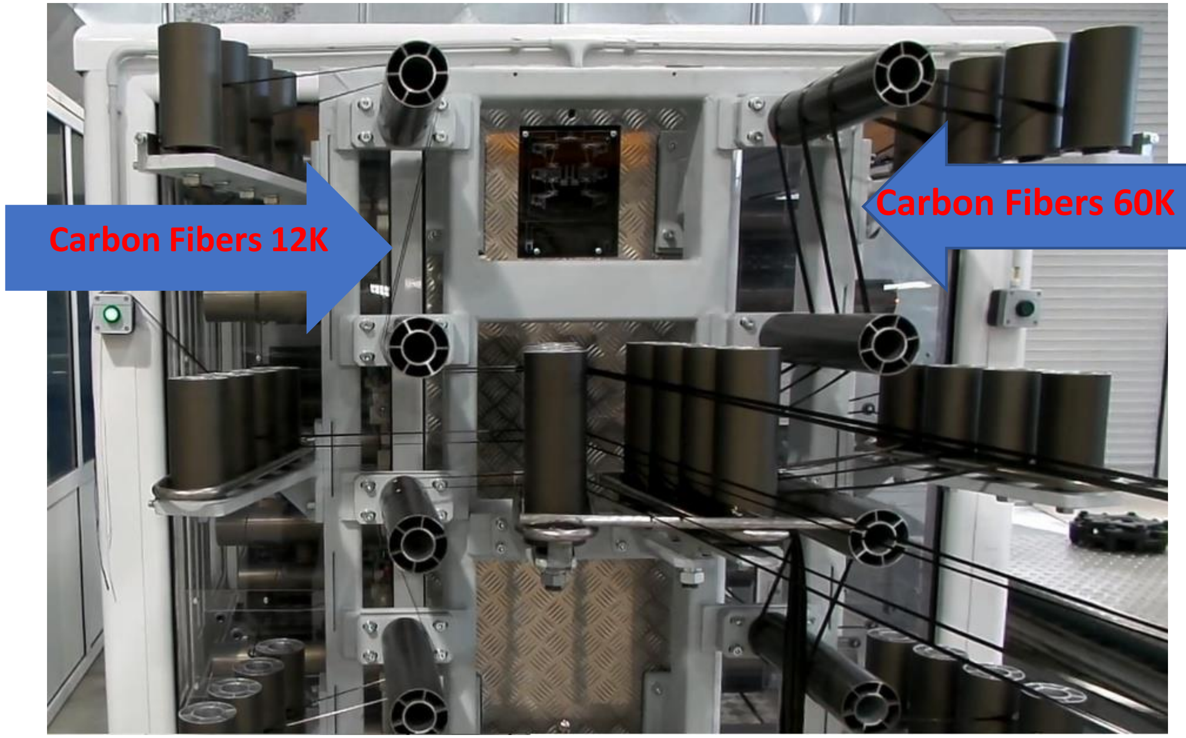
Tensioner

Fiber tension is critical in the filament winding method.

- the compaction is achieved through the tension of the fibers.
- It affects the percentage of fiber reinforcement and porosity content in the composite, which in turn affects the properties of the composite product.

Many studies are conducted regarding the influence of the applied tow tension during filament winding on the physical and mechanical properties of polymeric composite tubulars.

In B&T's electronic tensioner, the entire guiding of the fiber is made with hard anodized aluminum rollers.



The fiber tension depends on:

- The **type** of fiber.
- Its **geometry**.
- The **winding pattern** required on the rotating mandrel.

Fiber tension must be optimized to prevent:

- Excessive tension that may completely **break** the fiber.
- Surface fractures that could **weaken** the composite structure.

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Winding machine

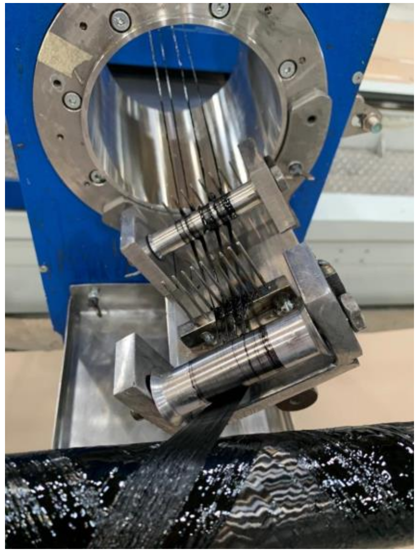
The mandrel rotates continuously while the delivery eye moves back and forth. The rotational speed of the mandrel and the linear speed of the delivery eye can be adjusted to produce any fiber orientation between **5^{o} and 85^{o}**, the latter called hoop winding.

Several back-and-forth travels of the carriage are needed to complete a lamina covering the mandrel. Such a lamina is always a two-ply balanced laminate at **±θ**. The fiber reinforcements are delivered from creel and tape racks, and through a tensioning device or brake that can be adjusted to control the tension in the reinforcement. Next, the reinforcement goes through a resin bath where it picks up resin. Then, the wet reinforcement is delivered through the delivery eye that is mounted on a carriage. In addition to the spindle rotation, the carriage and delivery eye can move in a number of ways designed to help place the reinforcement along complicated contours.

A four axes machine independently controls its:

- spindle rotation,
- horizontal carriage feed,
- delivery eye angle and yaw, and
- vertical carriage feed.

Winders employing fewer axes are used for simple parts such as golf shafts and larger numbers of axes are used for more complex components such as windmill blades.



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Rotating mandrels

Several types of mandrels have been developed to facilitate removal. The easiest alternative used for some pressure vessels is to use a **metallic liner** as a mandrel and leave the liner as an integral part of the end product.

Collapsible mandrels are made of segments that can be disassembled after the part is cured.

These are the most expensive mandrels, and thus they are used for large volume productions.

A soluble sand mandrel is made of sand and polyvinyl alcohol.

The mixture is cast in two or more parts, that when assembled, give the desired shape.

Extractor

When the curing is over, the mandrel with the composite on it, is taken out of the oven.

Using a crane, it is guided to the extractor and is fixed on the chuck.

Applying high pressure, the mandrel gets out of the composite.

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101058089.

Curing oven

After the winding process, the tubular products must be **cured** in an oven to harden the resin, solidify and get the final shape.

The curing cycle is according to the resin system requirements that is highly connected with the application of the end products.

Raw materials

- Wet reinforcements are commonly used as they combine fiber placement, impregnation, and consolidation in one step.
- Alternative materials like prepreg or wet rerolled material can be used but increase cost and complexity.
- Tension during winding compacts the material, with the maximum tension depending on fiber strength and feed rate.

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Maximum thickness of final parts

The maximum thickness that can be wound is limited by fiber slippage and wrinkling under the pressure of new laminae on top.

When the thickness is large, it may be necessary to stop winding and let the part cure partially, until the resin gels, before adding more laminae.

This slows the process resulting in additional cost.

Therefore, as with virtually all processes, relatively thin laminates are preferred from a production point of view.

Examining Parameters for New Materials

Introducing new materials into the filament winding process requires adjustments in

- **tension control**,
- **resin compatibility** and
- **curing profiles**.

New materials may have different **tensile strengths** or **thermal behaviors,** necessitating fine-tuning of machine settings and possibly new resin formulations to ensure compatibility and optimal performance.

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Differences Between New and Recycled Materials

Recycled materials often pose unique challenges due to their variable properties. For example:

- **Fiber integrity** in recycled materials may be lower, requiring modified tension settings to avoid breakage.
- **Resin adhesion** might vary, necessitating additional surface treatments or compatibility checks.
- The **curing process** might need adjustments to accommodate any changes in thermal stability or composite bonding characteristics.

Major limitations of the process

The major limitations of filament winding are
- **size** restrictions,
- **geometric** possibilities,
- the **orientation** of the fibers and
- the **surface finish** of the final product.

Void content may be high since no vacuum or autoclave is used and the resin cures at low temperature.
Production rates for filament winding processes vary greatly because the size of the part and the mandrel type dictate the amount of time needed to setup and remove a part from the winding machine. If setup and removal time are not considered, production rate is dictated by the feed rate at which fibers are wound onto the mandrel.
Feed rates vary according to the strength of the fiber used, typically 0.6–1.2 m/s for production using a wet fiber setup (Barbero, 2010)

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Thank you

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Plasma Enhanced Solvolysis for atmospheric pressure – low temperature recycling of Carbon Fibre Composites

3d Eurecomp Workshop

19/3/2025

Eleftherios Amanatides

Plasma Technology Lab. – University of Patras

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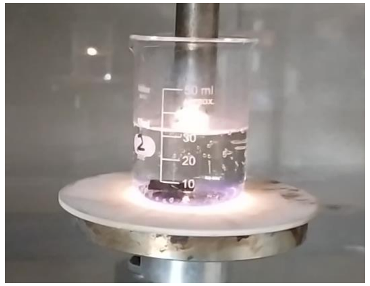
Plasma Technology Lab - Activities

EuReComp

ChemEngUP



Plasma - Liquids

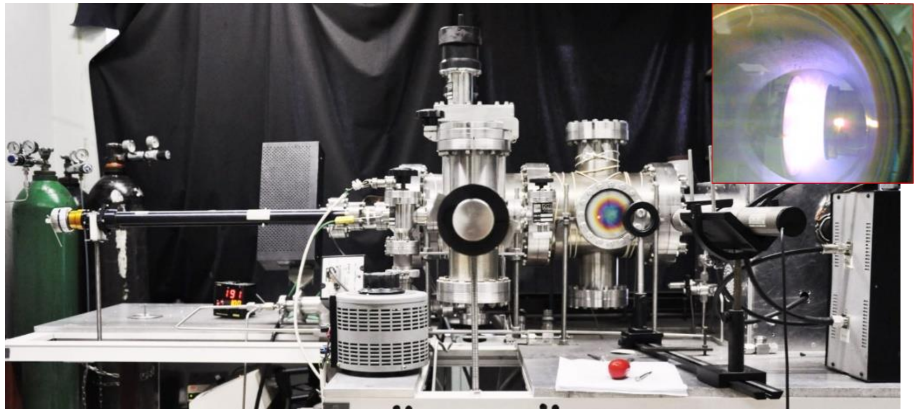
Plasma Processing

- Thin Film deposition, nanoparticles, surface treatment, grafting, etching
- Plasma Diagnostics, Simulation of plasma processes
- Atmospheric pressure plasma sources, dielctric barrier discharges and jets
- Plasma activation of liquids, plasma in contact with liquids, plasma inside liquids

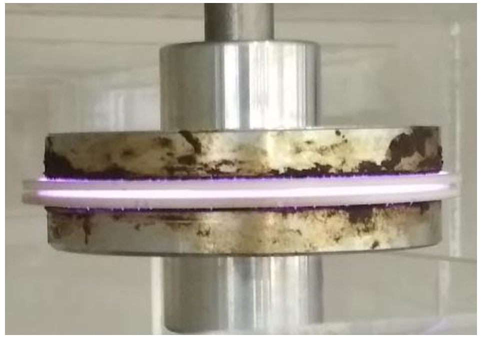
↔

Applications

- Photovoltaics
- Biomaterials, drug delivery
- Microfluidics
- Protective coatings
- Waste treatment
- Composites recycling



Low pressure plasmas



Atmospheric pressure plasmas

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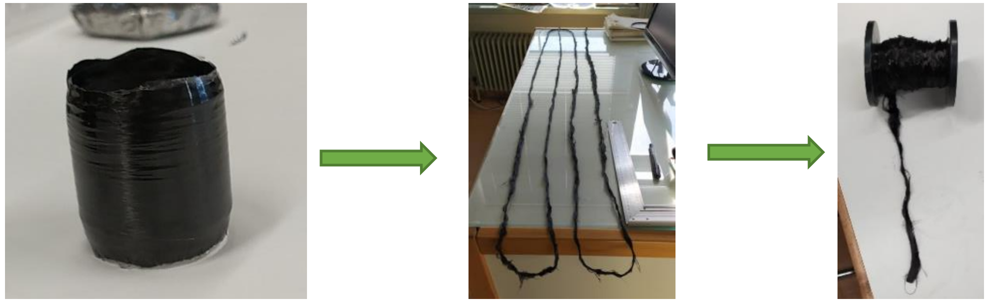
Overview

- ✓ Methods for CFs recovery from composites
- ✓ Thermosets and CFRPs chemical structure and cross-linked network
- ✓ Dissolution kinetics
- ✓ HNO_3 solvolysis of CFRPs
- ✓ Plasma Enhanced HNO_3 solvolysis of CFRPs
  - ✓ Recovery of short/chopped fibers
  - ✓ Recovery of continuous fibers
- ✓ Status and remarks



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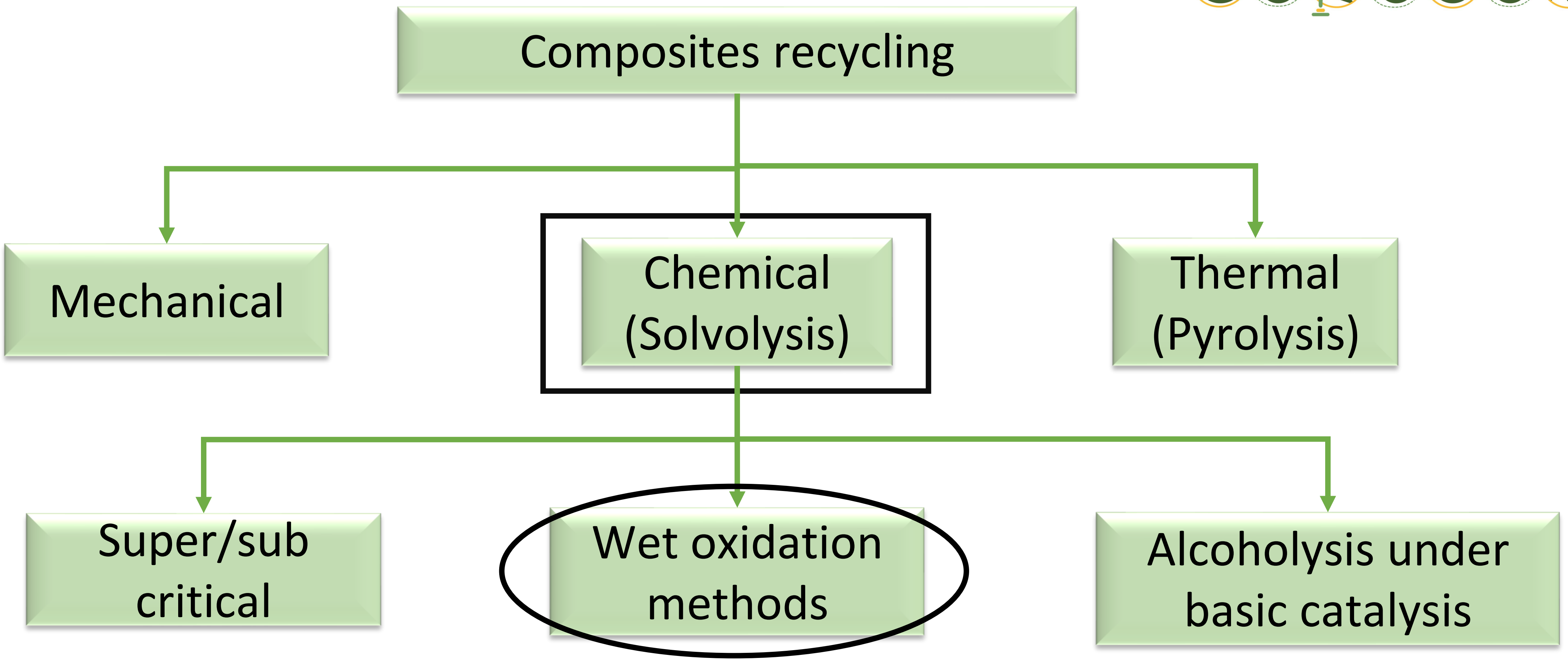
Methods for CFs recovery



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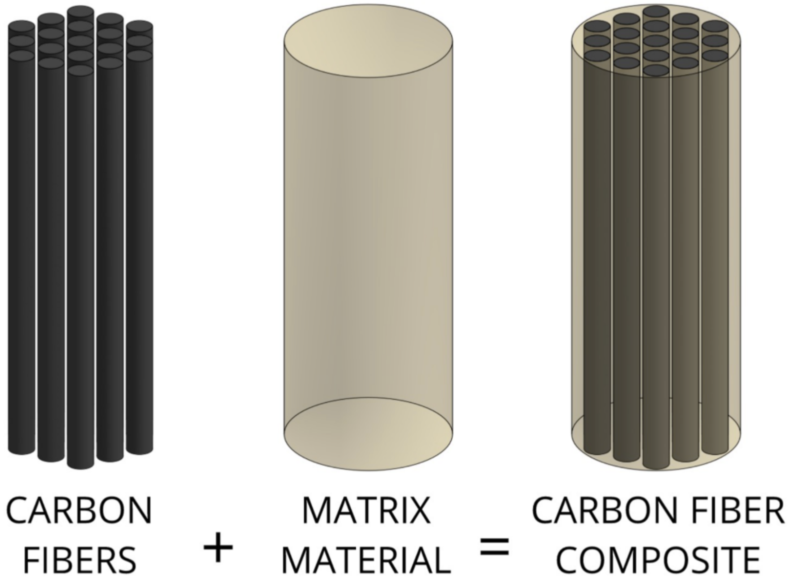
CFRPs – Chemical structure

FIBER REINFORCED COMPOSITES

FIBER
(carbon fiber, fiberglass, aramid)
+
MATRIX MATERIAL
(epoxy)
=
FIBER REINFORCED COMPOSITE

(common example)



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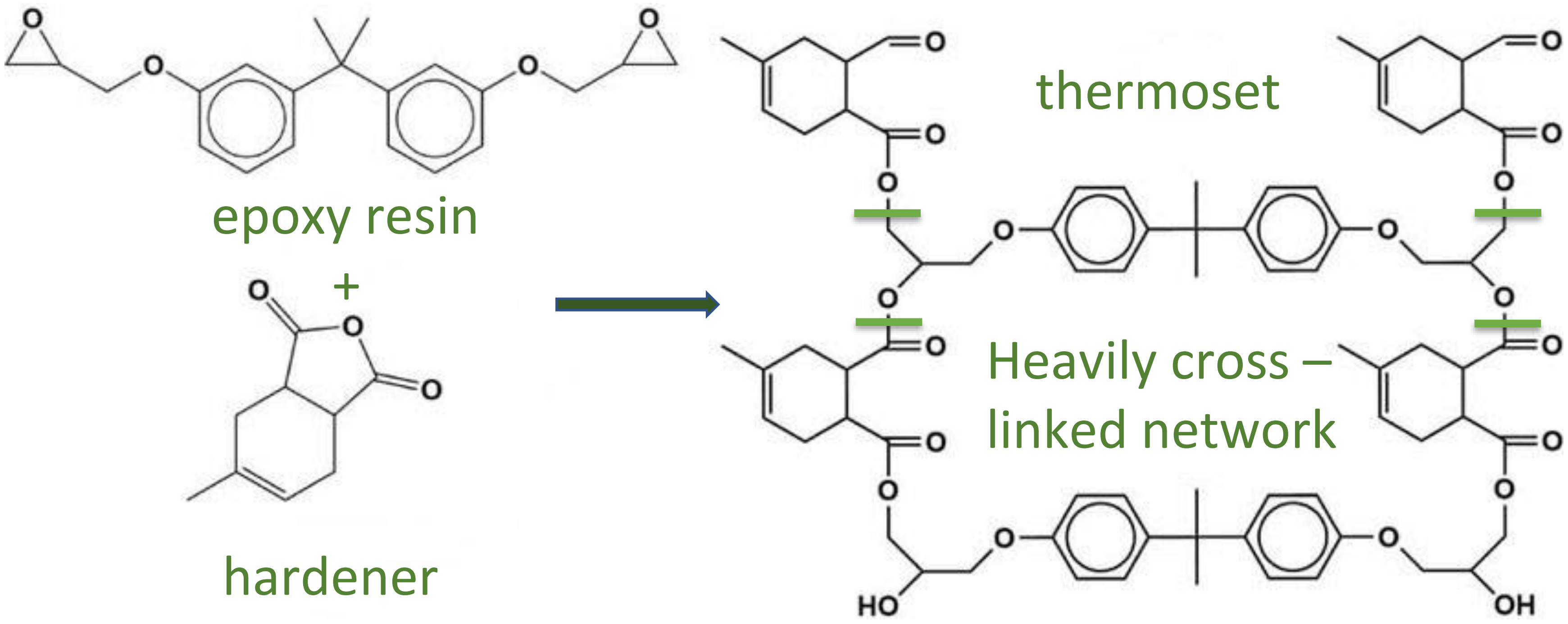
CFRPs – Chemical structure

Matrix material → Thermoset → Common Example

Bisphenol A (epoxy resin) - Tetrahydromethylphthalic anhydride (hardener)



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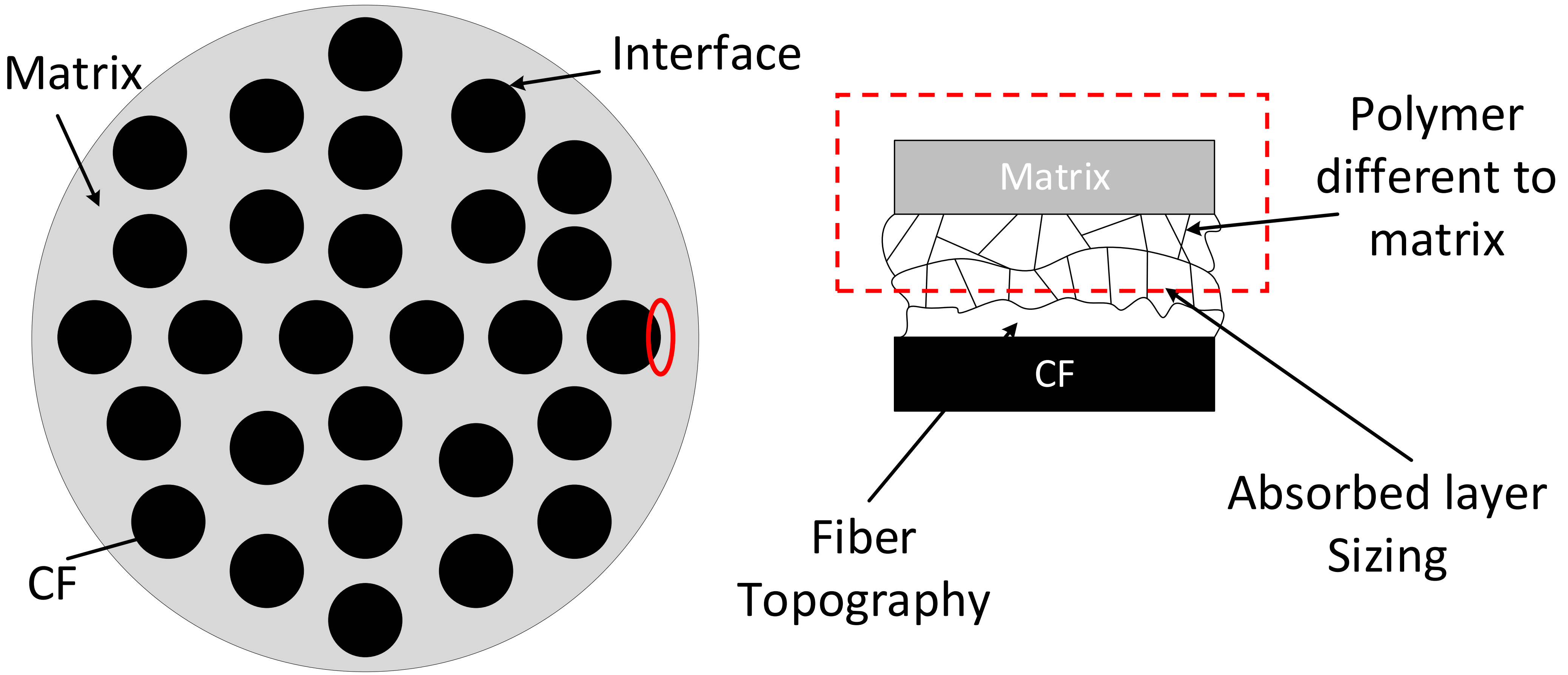
CFRPs – Chemical structure

Composite

Bisphenol A (epoxy resin) - Tetrahydromethylphthalic anhydride (hardener) – Carbon Fibers



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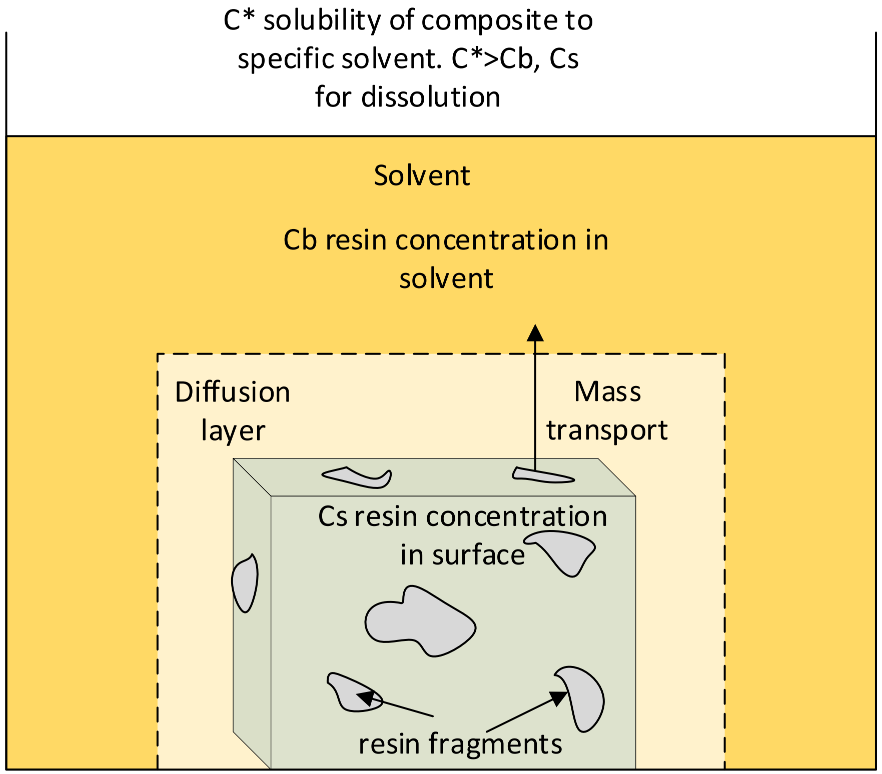
Dissolution kinetics – Driving forces

Dissociation rate: $r_D(t)$

Mass transport rate: $r_m(t)$

Pseudo equilibrium: $r_D = r_m = r(t) = k^* \cdot S(t) \cdot (C^* - C_b(t))$



Either reaction rate limited process

or mass transport limited process

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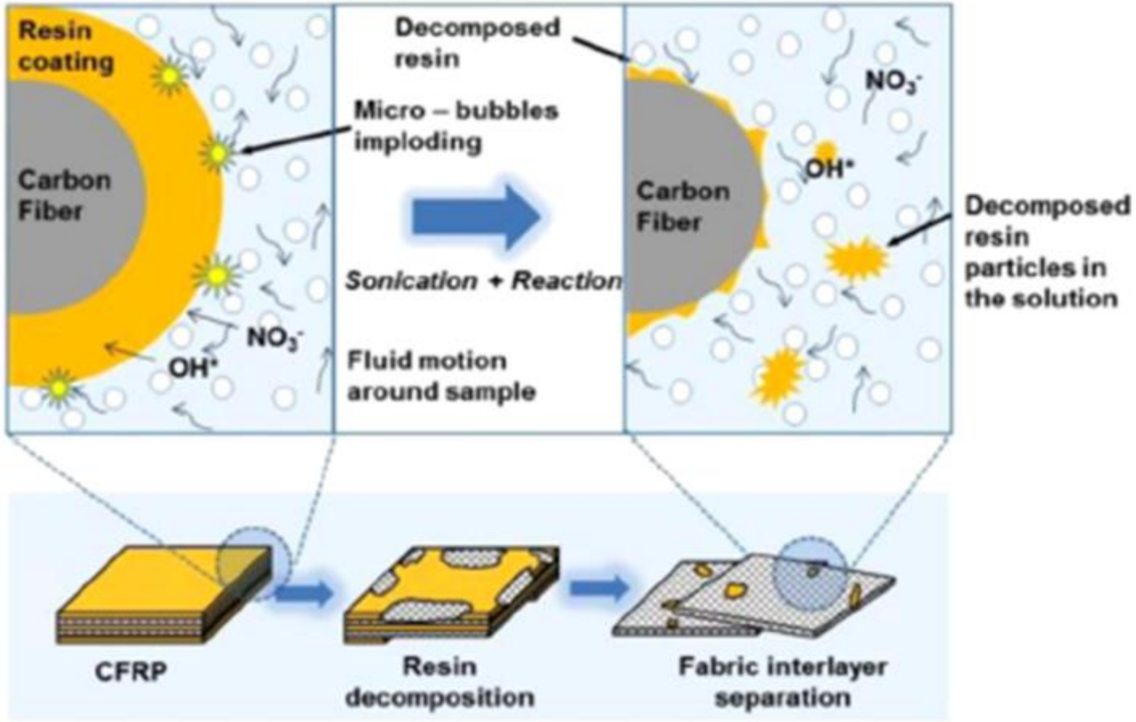
HNO_3 solvolysis of CFRPs

Excellent medium for oxidative degradation –
Good solvent for most resins ~300 g resin / L HNO_3



Mohan Das and Susy Varughese, ACS Sustainable Chem. Eng. 2016, 4, 2080−2087,
DOI: 10.1021/acssuschemeng.5b01497

- ✓ Main species involved in matrix fragmentation: H^+, OH*, NO_3^-, NO_2
- ✓ Main advantage: Decompose almost any type of resin
- ✓ Main disadvantage: Slow dissolution rates, 10 to 50 h required for complete dissolution of composites
- ✓ Wastes

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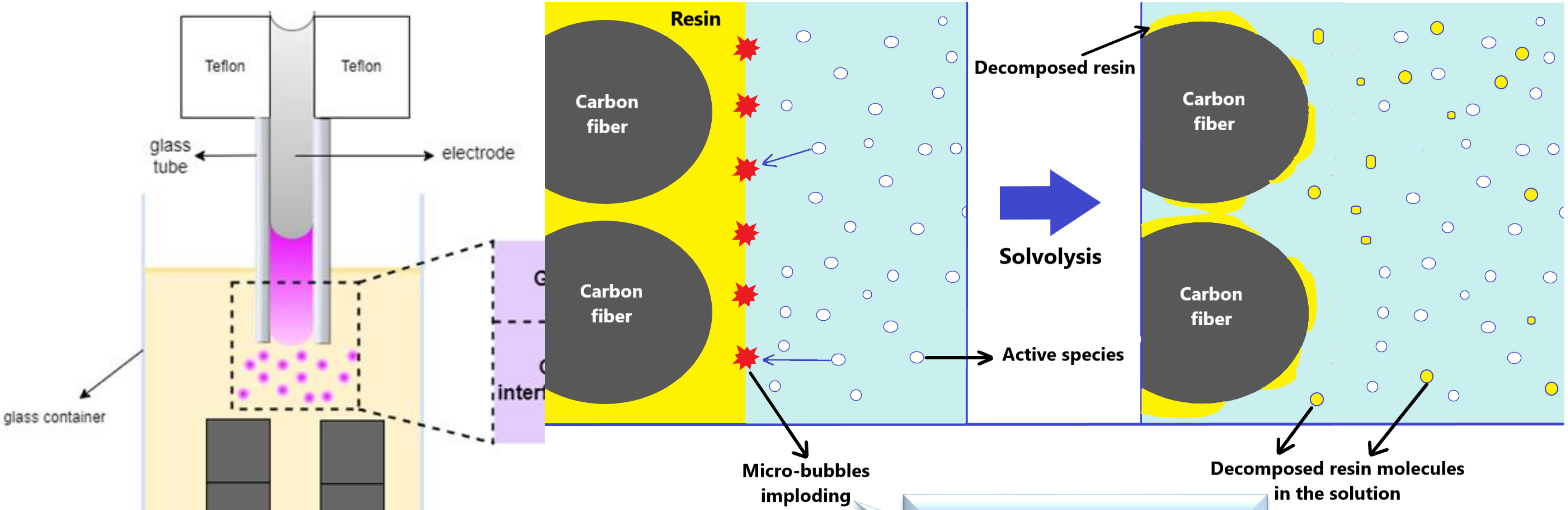
Plasma Enhanced HNO_3 solvolysis of CFRPs

Main objective: Application of plasma inside HNO_3 solution for enhancement of dissolution rate



Microbubbles explode at the composites surface which enhance the breakdown

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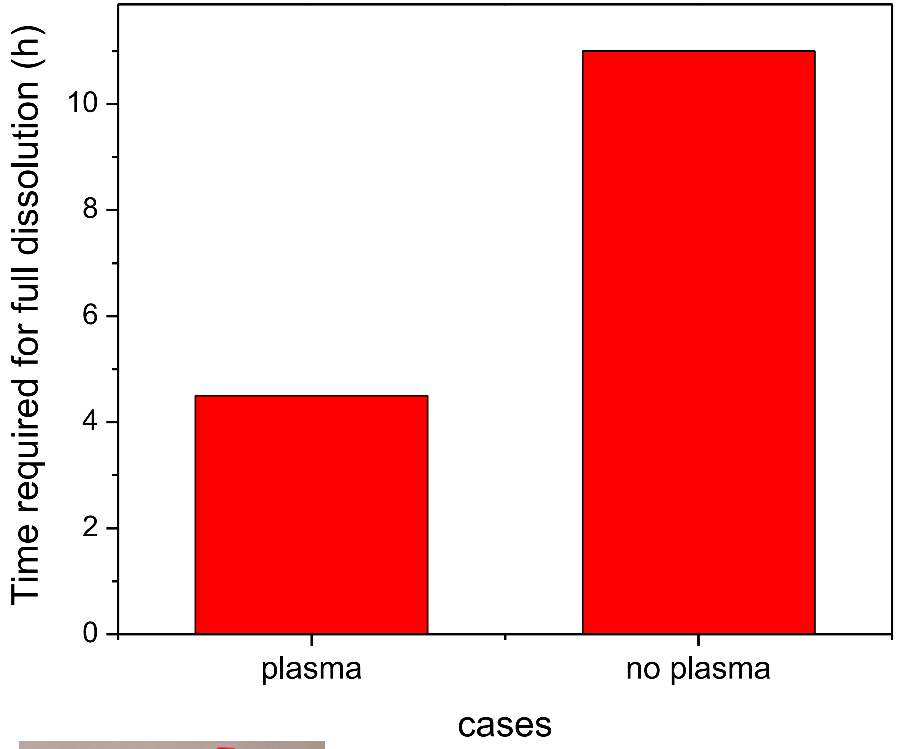
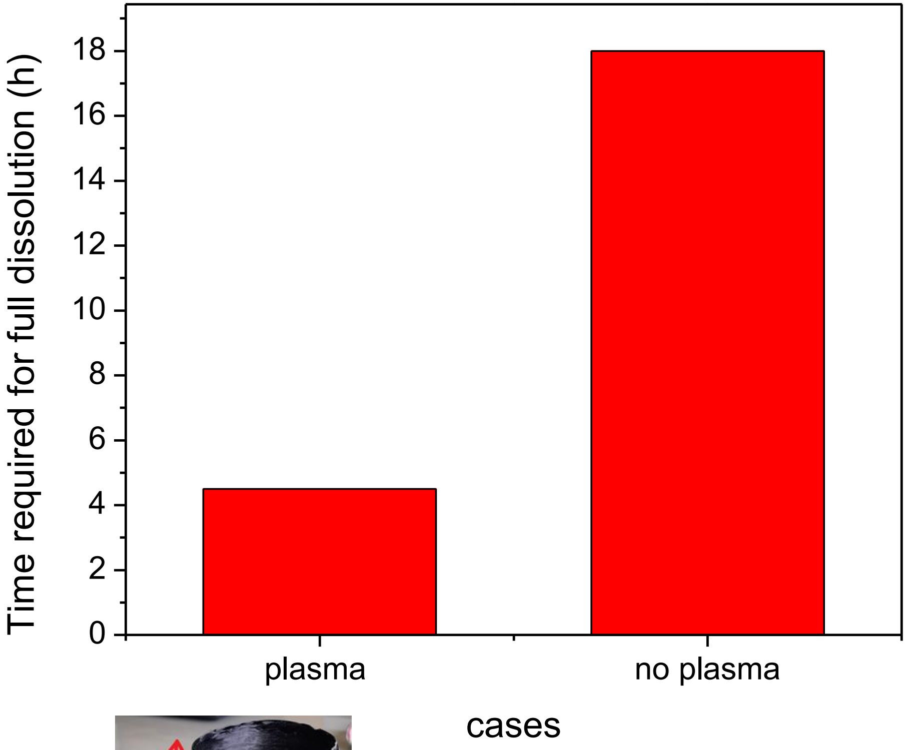
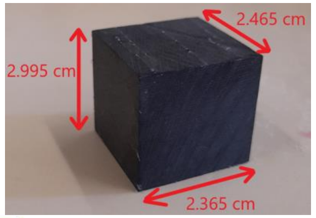
Plasma Enhancement – Works?

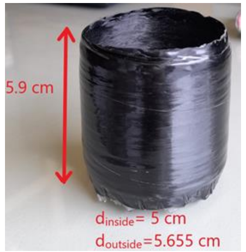
Solvent temperature in all cases ~ 90 ^{o}C, Atmospheric pressure







WTB scrap



B&T composites cylinders

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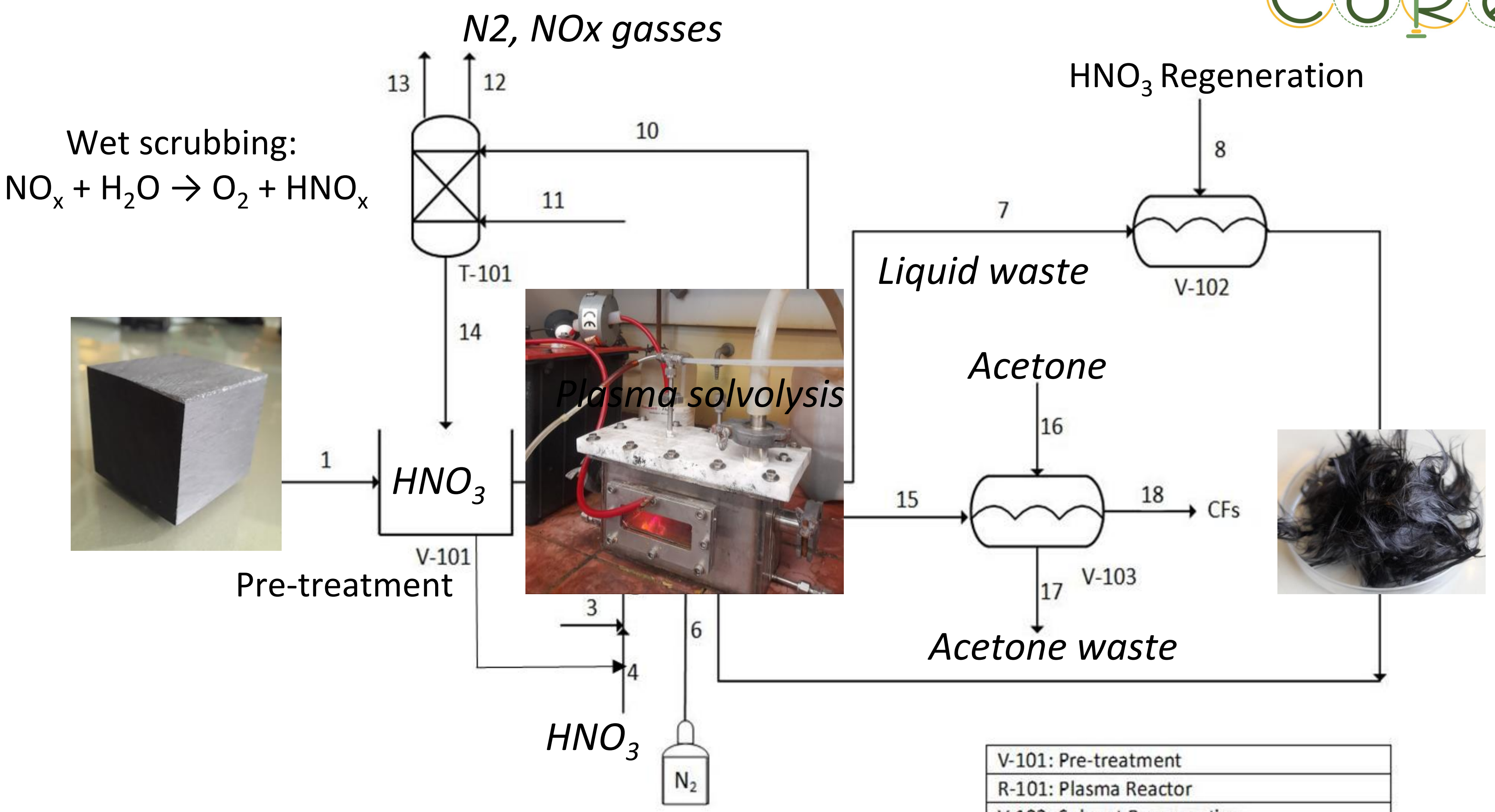
Process flowchart



V-101: Pre-treatment
R-101: Plasma Reactor
V-102: Solvent Regeneration
V-103: Fibers Cleaning
T-101: Wet Scrubber

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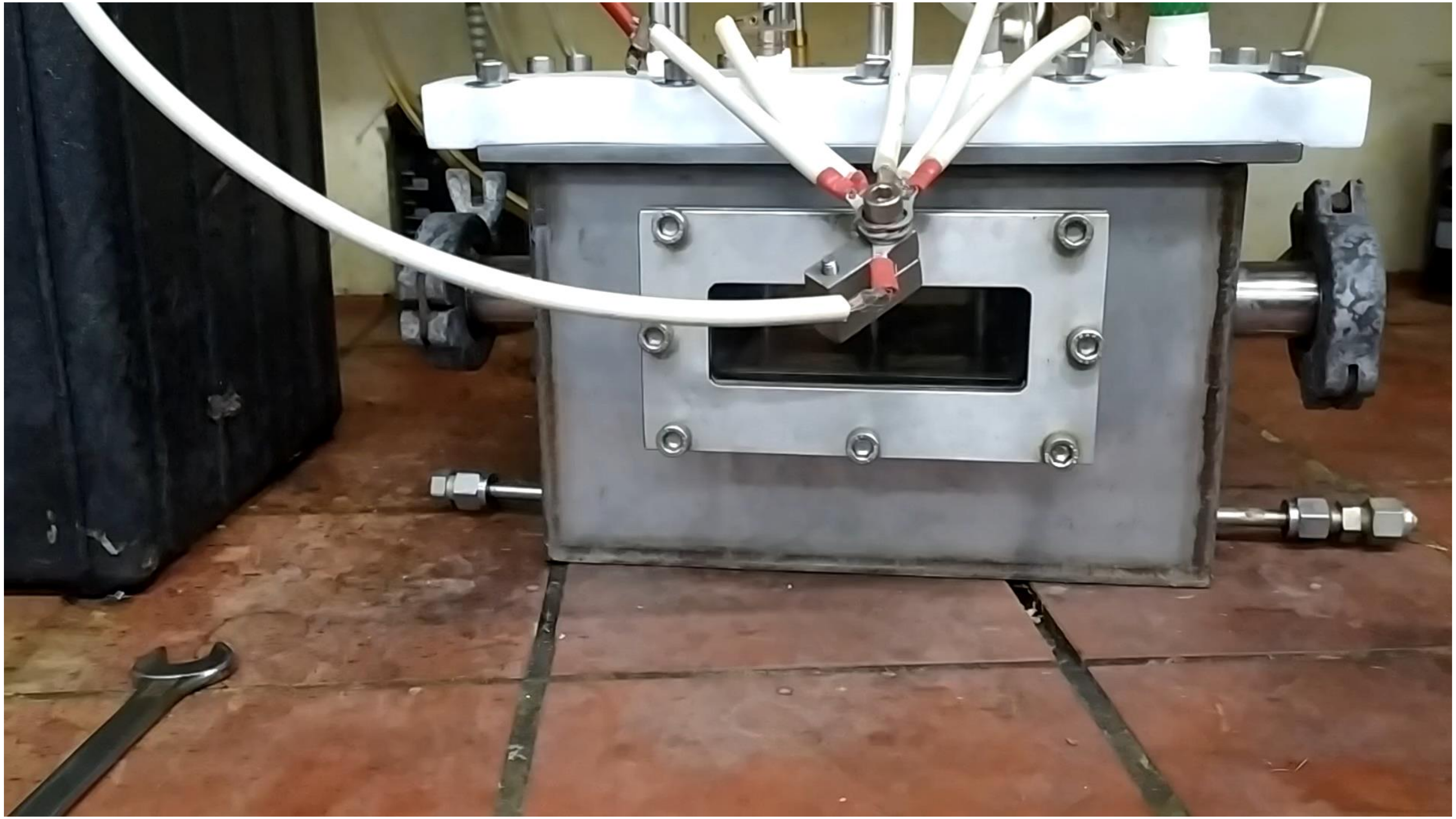
Plasma Reactor Setup



- ✓ Except of producing more oxidative species
- ✓ Bubbling and acoustic waves can enhance mass transport

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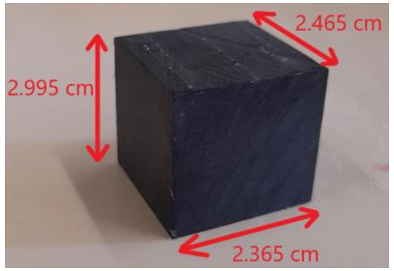
Case 1: Recovery of CFs from WTB scrap

Dissolution Kinetics investigation



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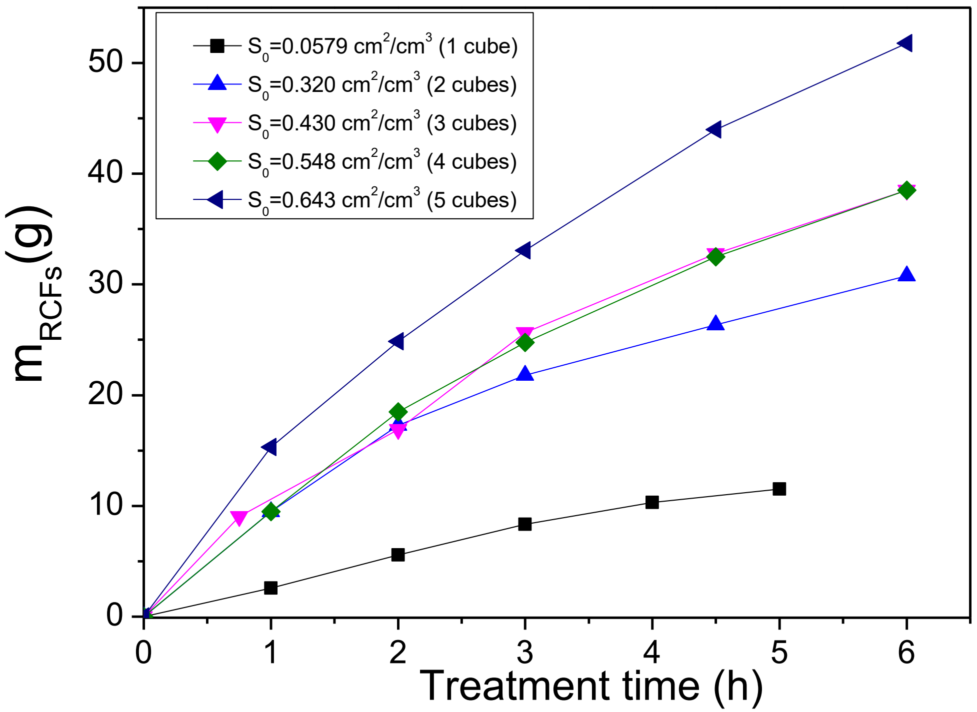
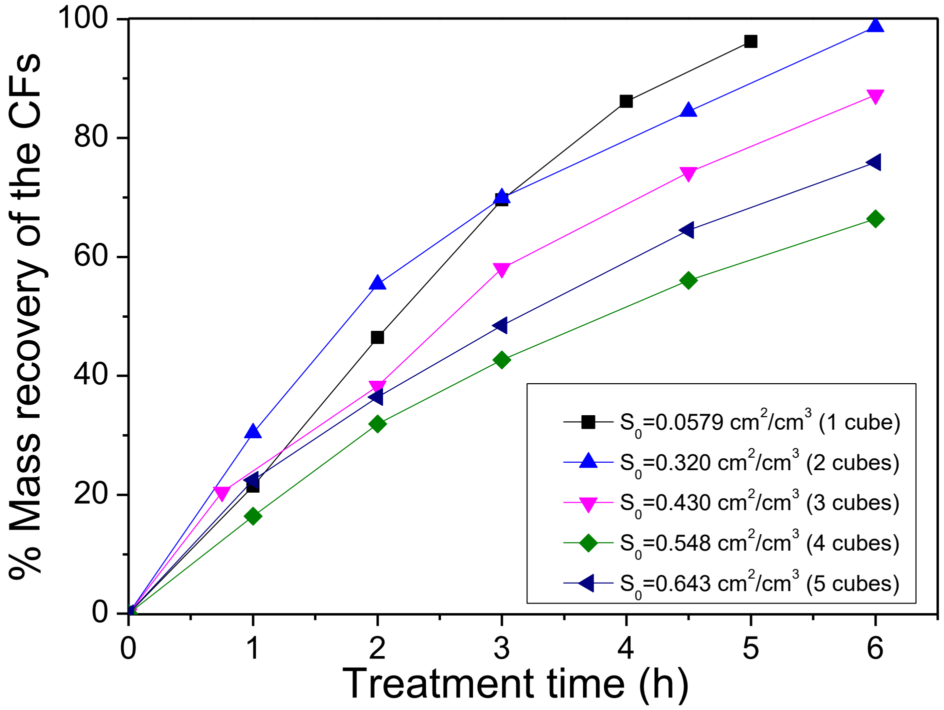
Case 1: WTB scrap / short fibers - CFs recovery

Same plasma conditions, same solvent volume, same temperature.
Parameter: Increase the number of cubes per dissolution run





- ✓ For each run: After 1 h process stopped, CFs released were collected, dried and weighted
- ✓ Retrieved mass of CFs increases with the number of cubes (higher initial composite mass)
- ✓ Higher % CFs recovery at smaller number of cubes (solvent excess relative to composite mass)

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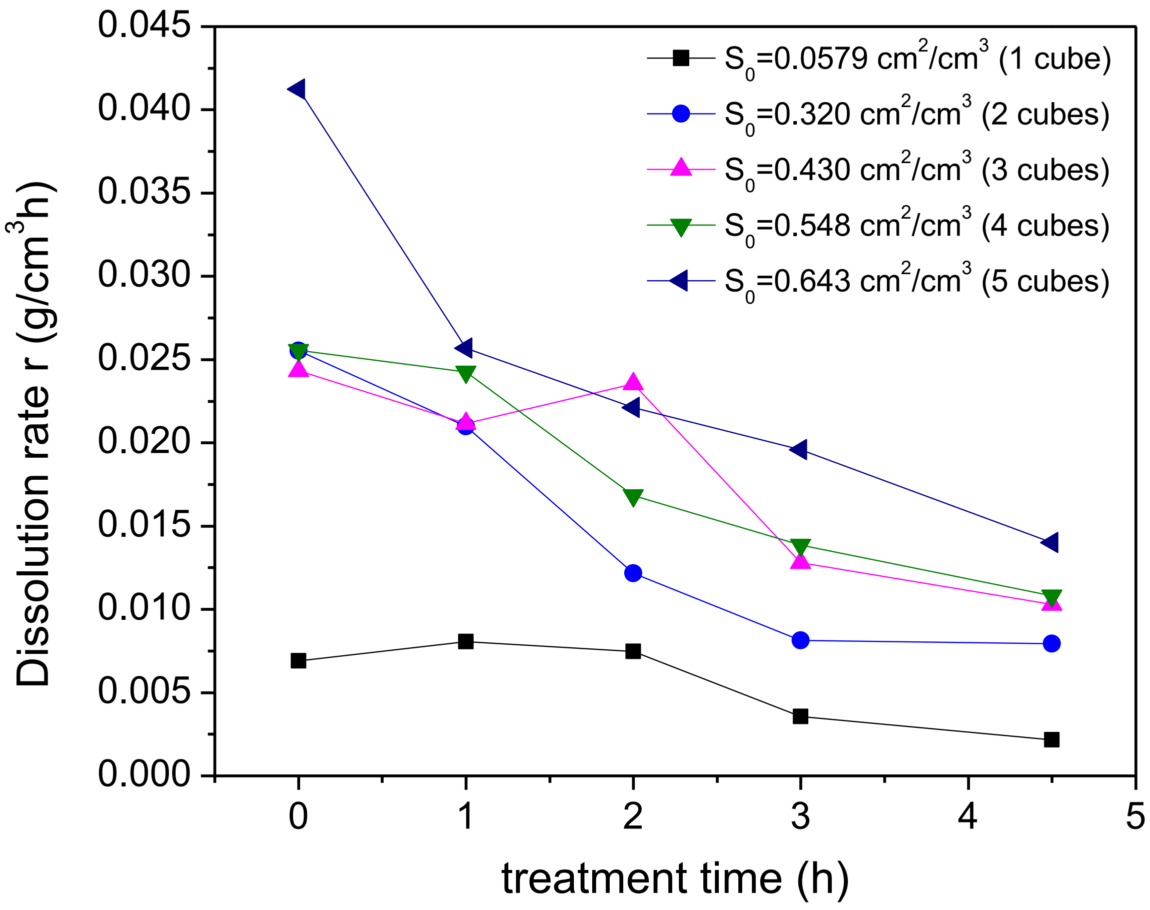
Case 1: WTB scrap / short fibers – Dissolution rate



$$r(t) = k^* \cdot S(t) \cdot (C^* - C_b(t))$$

- ✓ Rate drops with time because S is reduced and the concentration gradient decreases
- ✓ Experimental results are fitted quite well with above equation
- ✓ Lead to the calculation of an average solubility C^*~ 250 g matrix / 1 L solvent
- ✓ While k^* drops with the increase of composite mass (values from 0.2 to 0.04 cm/h)

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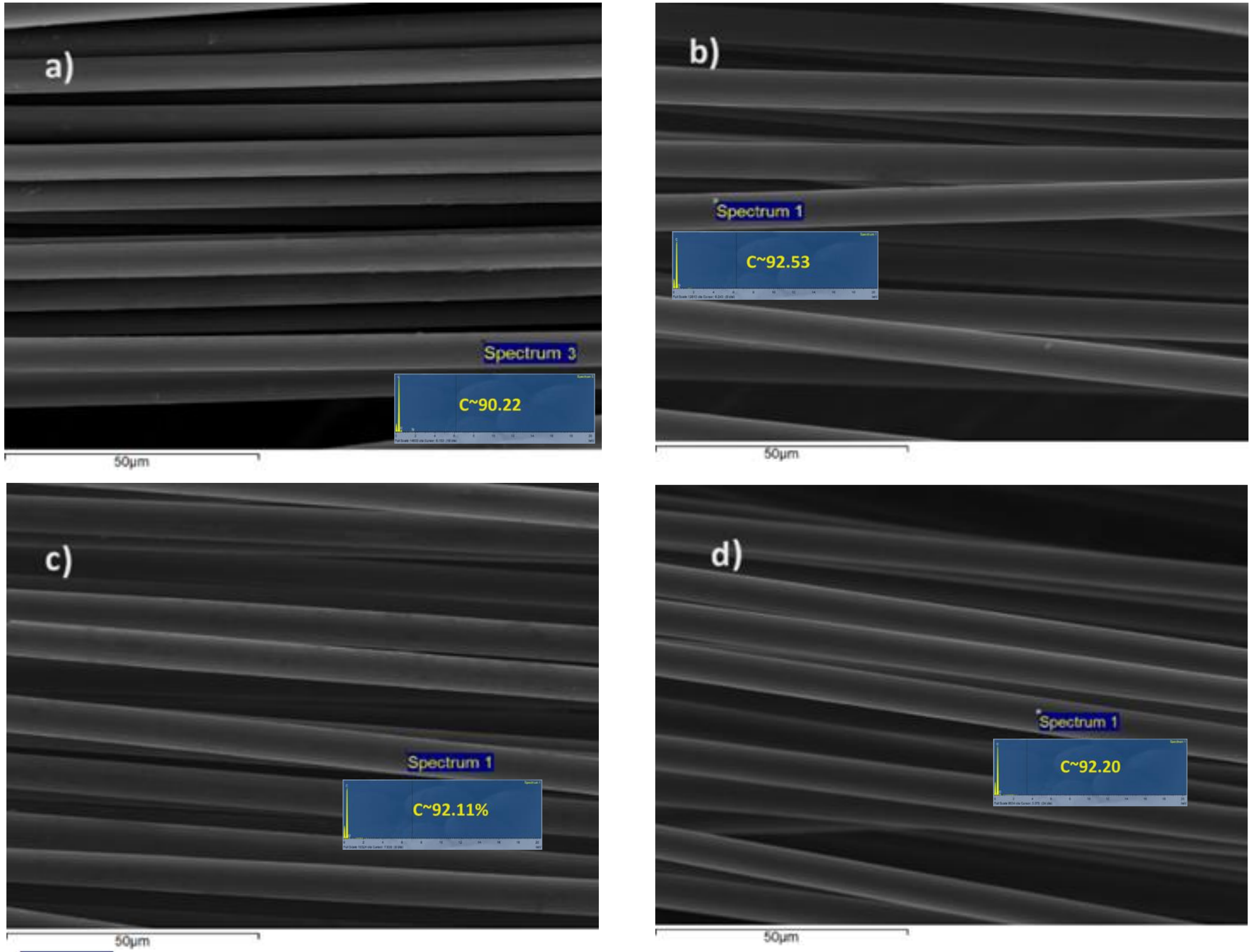
Case 1: WTB scrap / short fibers – SEM/EDS



SEM-EDX characterization of the RCFs after a) 2 hours, b) 3 hours, c) 4.5 hours and d) 6 hours of treatment

No surface damage, no residuals

Diameter ~7 μm

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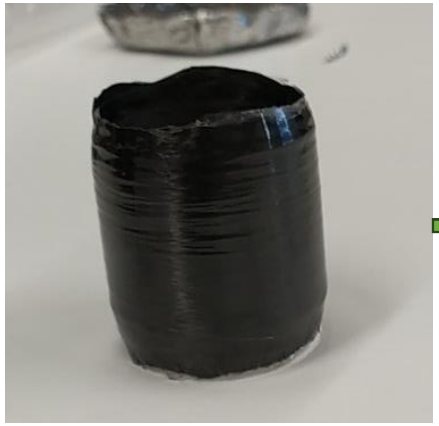
Case 2: Recovery of CFs from B&T composites cylinders

Continuous Fibers

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Case 2: B&T cylinders / continuous fibers – 24K vs 3K samples

Cylinders of 24K vs 3K CFs

- ✓ 24 K CFs are quite easily post-processed
- ✓ After drying are easily comped out
- ✓ Wrapped in bobbins and sent for further treatment (sizing)
- ✓ There is a loss of ~1K fibers during post treatment

- ✓ Not the same for 3K fibers
- ✓ Fluffy is formed after drying
- ✓ Fibers break every 1 to 2 m and was very difficult to untagle

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Case 2: B&T cylinders / continuous fibers – 3K samples

- To improve post processing of 3K samples two stainless steel grids, one for the outside and the other for the inside of the cylinder were placed during the dissolution process.

- The grids keep the fibers in place during the dissolution.

- After modifications the post processing of recovered fibers were easier without affecting dissolution time.

- 3K CFs easily wrapped in bobbins

- Each cylinder delivers ~100 m of continuous CFs!

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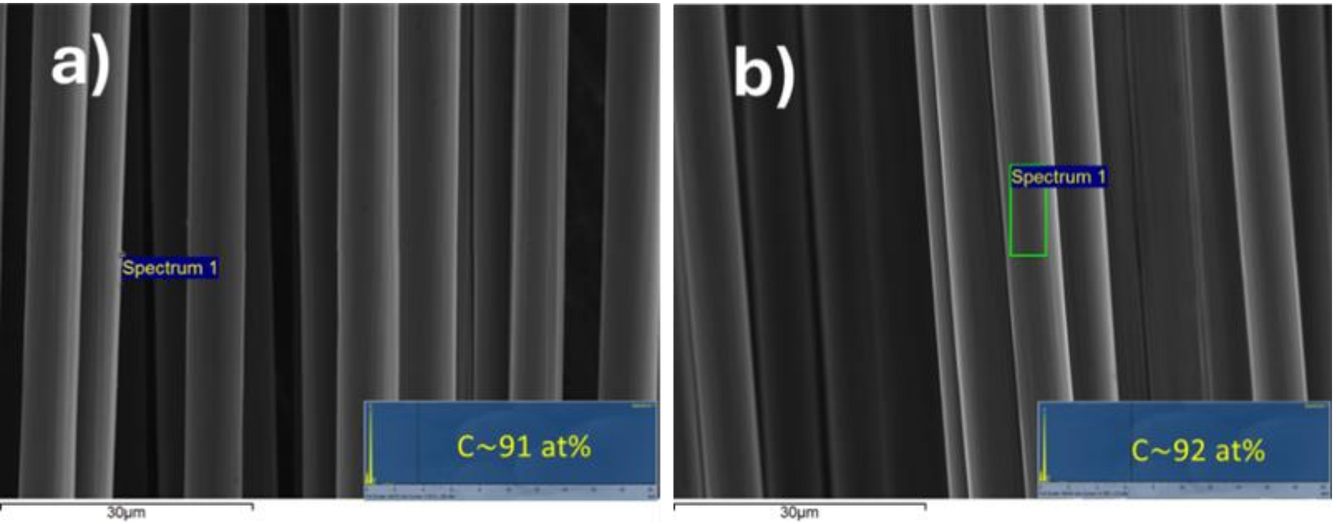
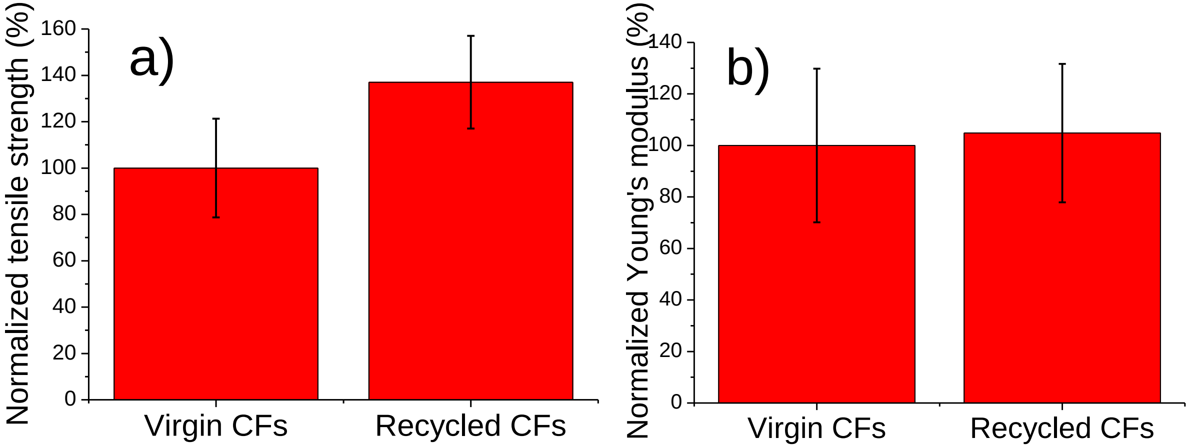
Case 2: B&T cylinders / continuous fibers – SEM/Single fiber tests



Recycled

Virgin



SEM/EDS

- ✓ Very clean surfaces free from resin residuals
- ✓ C atomic content similar to virgin fibers

Single Fiber mechanical properties

- ✓ ~ 40% increase on single fiber tensile strength
- ✓ ~5% increase on Young modulus

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Remarks

Now

36 months before

Deliver:

continuous fibers of good quality with a repeatable process

Two new plasma reactors for treatment of rectangular and cylindrical composites

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Remarks

Measure and calculate important process parameters for process sustainability

- ✓ Energy Required: ~ 10 kWh / Kg CFs (~180 kWh required for production of 1 kg virgin CFs)
- ✓ Recovery Rate: ~ 0.2 kg CF /(kg CFRP ·h)
- ✓ Solvent loss rate: ~0.015 L / (1L solvent · h)

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Acknowledgment

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- ✓ **Thomai Tiriakidou**, B&T Composites for the composites supply and discussions
- ✓ **Carlos Carneiro, Andreia Araújo**, Inegi for the supply of WTB composites
- ✓ **Prof K. Tserpes**, Laboratory of Technology & Strength of Materials (LTSM-UP), Department of Mechanical Engineering and Aeronautics, University of Patras for the mechanical tests of the fibers.
- ✓ **Dionysis Semitekolos, Kate Trobeta, Prof K. Charitidis**, Research Lab of Advanced, Composite, Nano Materials & Nanotechnology, Department of Materials Science and Engineering of National Technical University of Athens for sizing and mechanical testing of the fibers

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Sizing effect on reclaimed continuous carbon fibres' properties extracted from recycled automotive composite parts

3rd EuReCOMP workshop

19/03/2025, NTUA

Dionisis Semitekolos, R-Nano Lab NTUA

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Content Overview

I. Recycling process

II. Pilot scale sizing line

III. Recycled fibre characteristics

IV. Optical microscopy analysis & results processing

V. Mechanical testing

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Introduction

Sizing treatment is considered to be a simple and cost-effective process during which a thin, homogenous polymeric layer is formed on the surface of the CFs

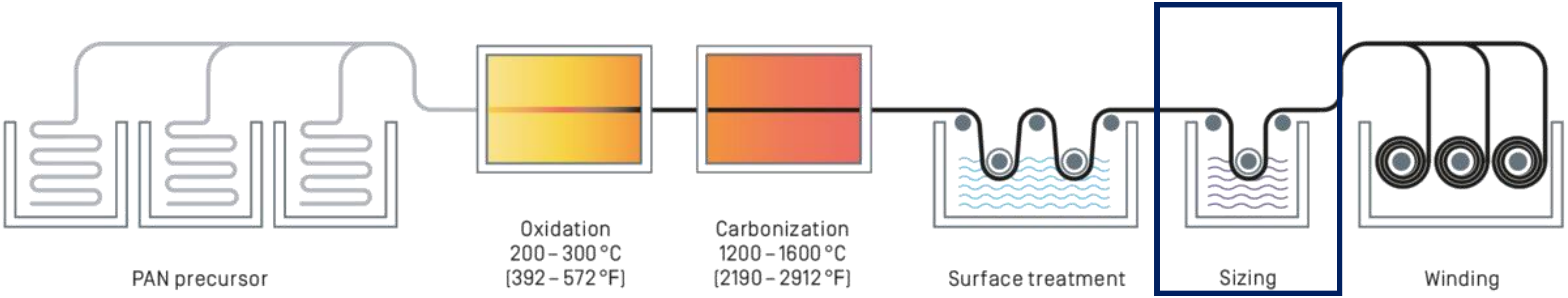

Image from:
https://www.sglcarbon.com/en/carbon-fibers-and-cfrp/

The sizing formula includes one or several polymeric compounds, a coupling agent, a lubricant and a number of additives (plasticizers, adhesion promoters, rheology modifiers etc.)

The functions of sizing can be summarized in the following:

a) Protection of the CFs during handling and manufacturing process of CFRPs and moreover, from the environmental influences and induced stress due to transportation.
b) Improvement of adhesion between the CFs and the polymeric matrix.

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Recycling processes

Composite specimen manufactured with Filament Winding

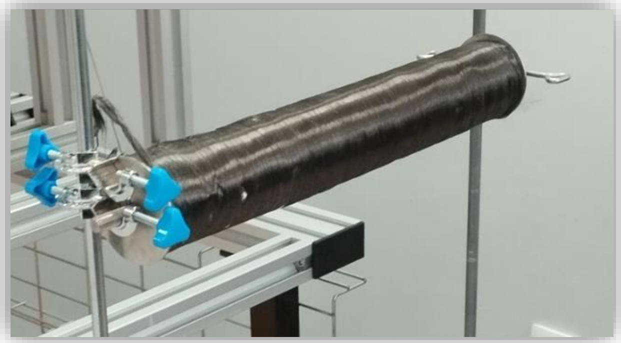
Plasma assisted solvolysis

Chemical assisted solvolysis

Continuous Carbon Fibre Reclamation

Plasma assisted solvolysis

or Chemical assisted treatment



Continuous recycled Fibre winding

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Continuous fibre sizing line

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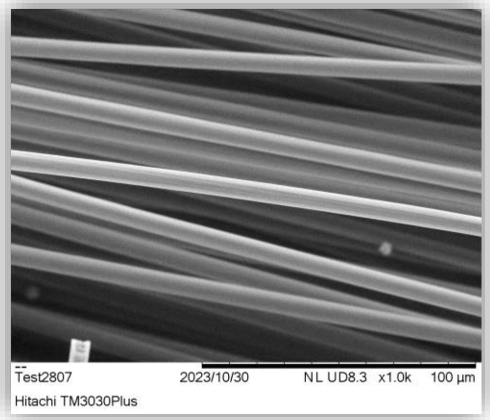
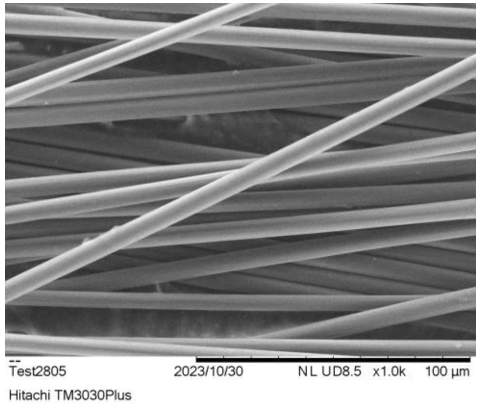
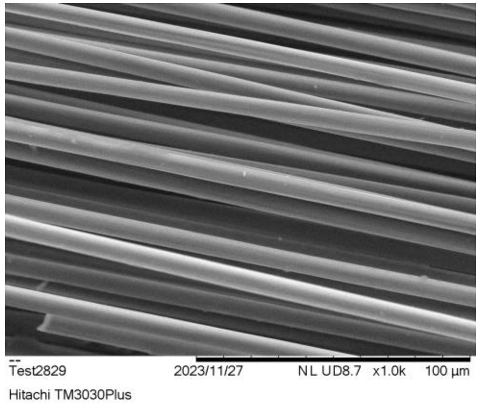
SEM investigation



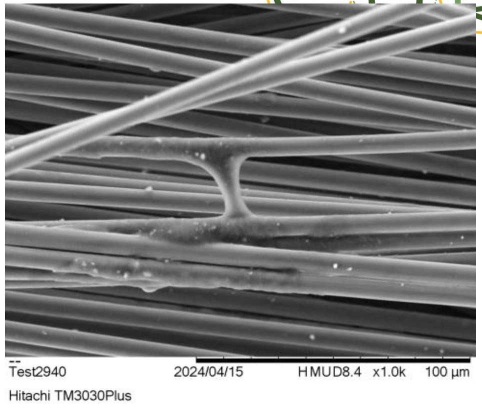
Reference Fibre x1000



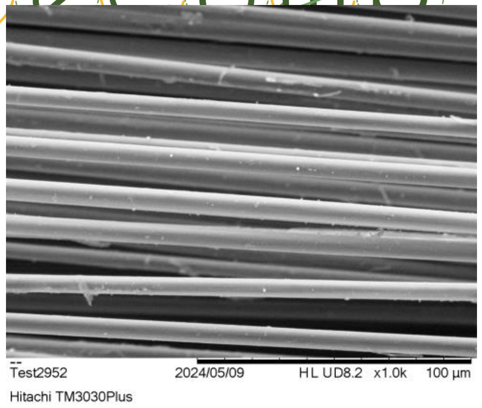
Plasma Recycled Fibre x1000



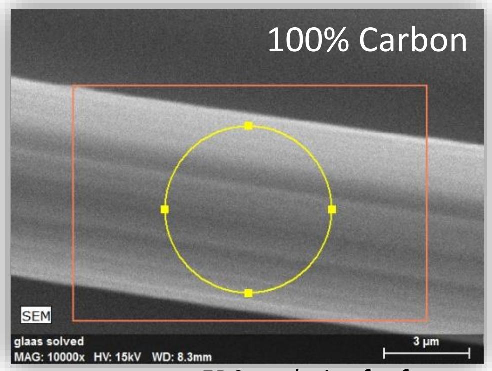
Plasma Recycled & Sized Fibre x1000



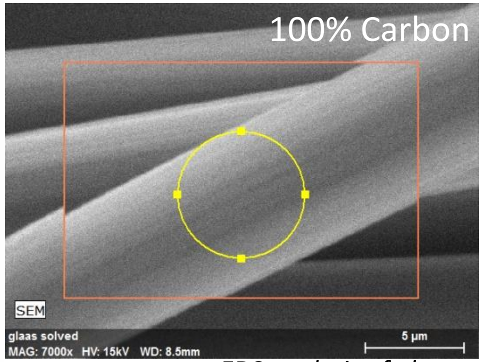
Chemically Recycled Fibre x1000



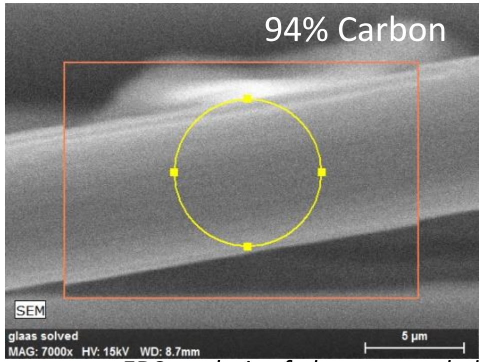
Chemically Recycled & Sized Fibre x1000



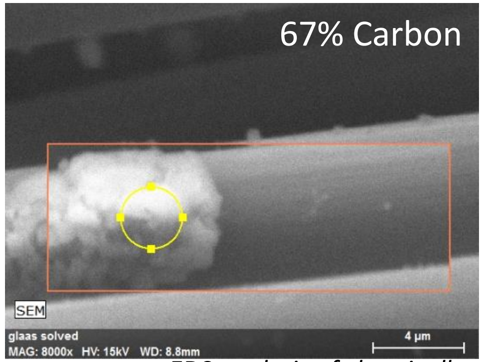
EDS analysis of reference fibre



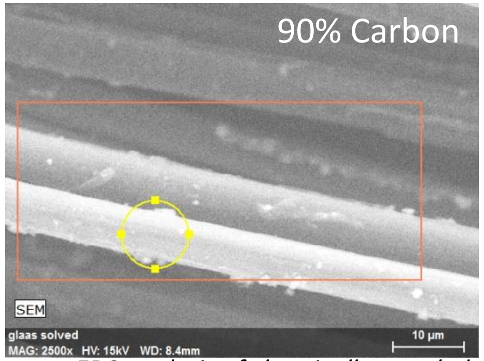
EDS analysis of plasma recycled fibre



EDS analysis of plasma recycled & sized fibre



EDS analysis of chemically recycled fibre



EDS analysis of chemically recycled & sized fibre

Reference Results:
- *Smooth rigged surface*

Plasma Results:
- *No resin residues after recycling*
- *No visual filament damage*
- *Good surface morphology after sizing*

Chemically assisted Results:
- *Few resin residues after recycling*
- *No visual filament damage*
- *Few resin spots after sizing*

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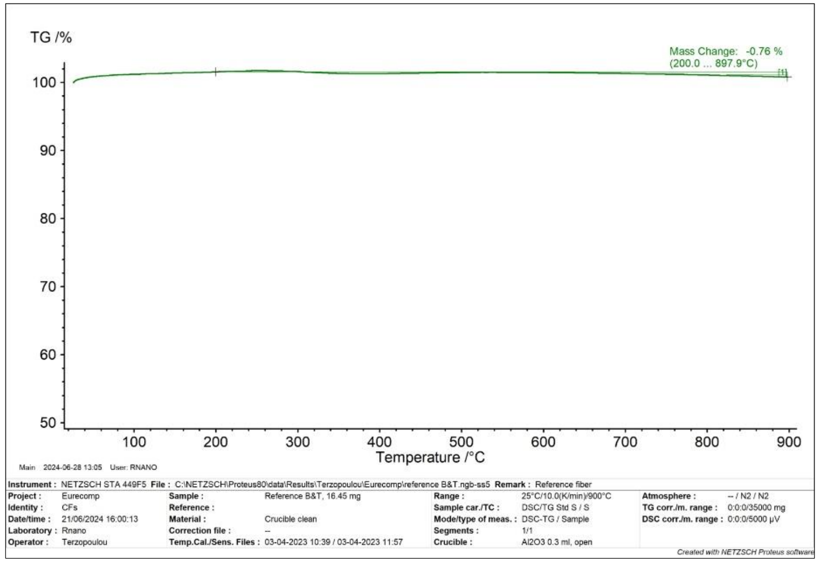
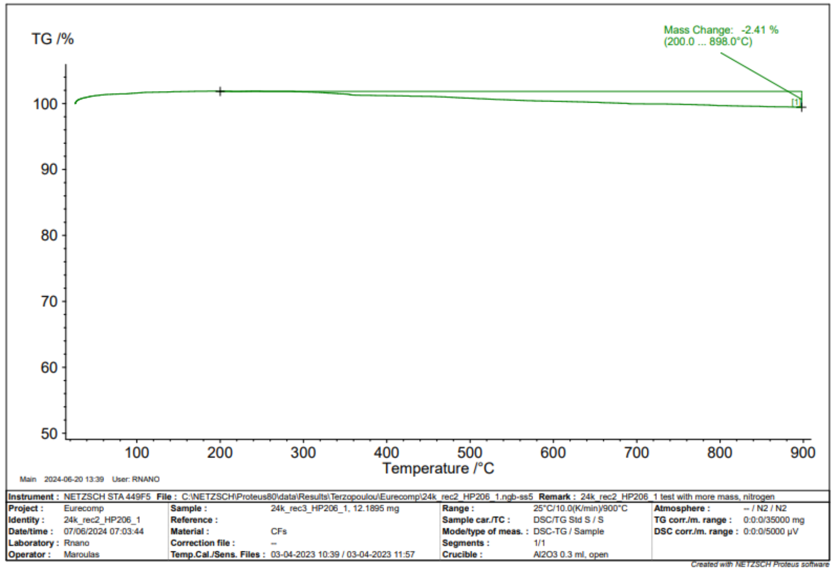
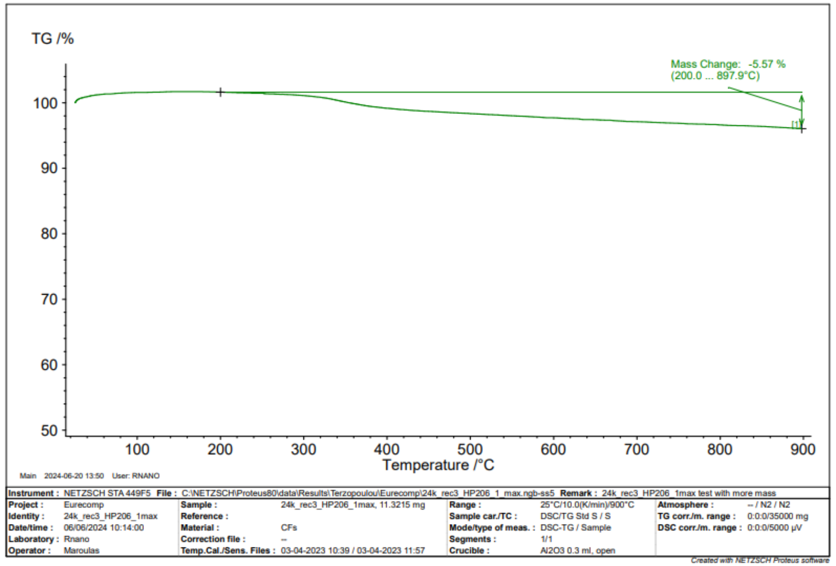
TGA investigation



Reference Fibre



Plasma Recycled & Sized Fibre



Chemically Recycled & Sized Fibre

TGA Results:

- *CF maintain their structural integrity for both recycling cases*
- *There is ~3% resin residue on the CF from chemically recycling process*

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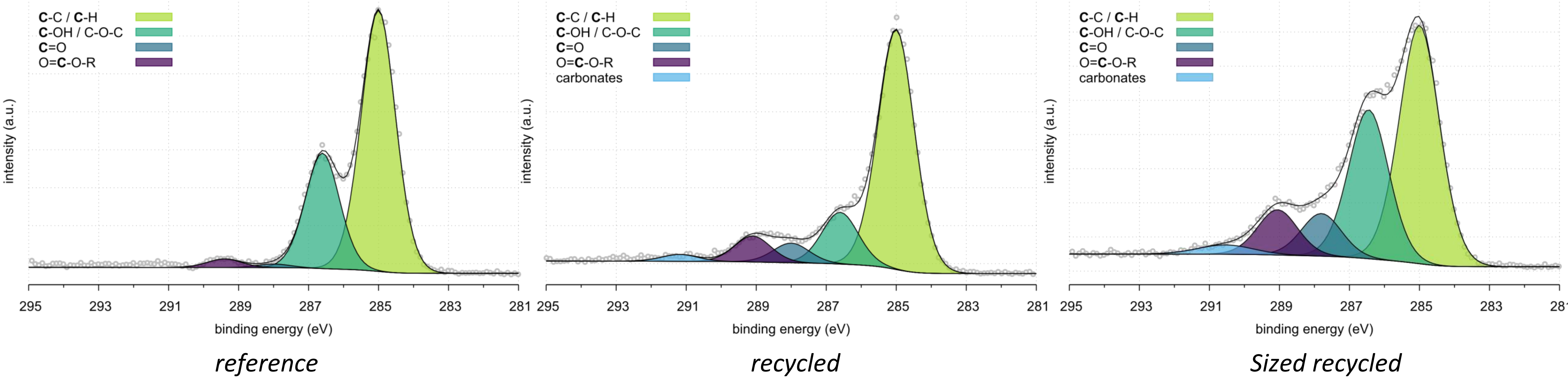
XPS investigation



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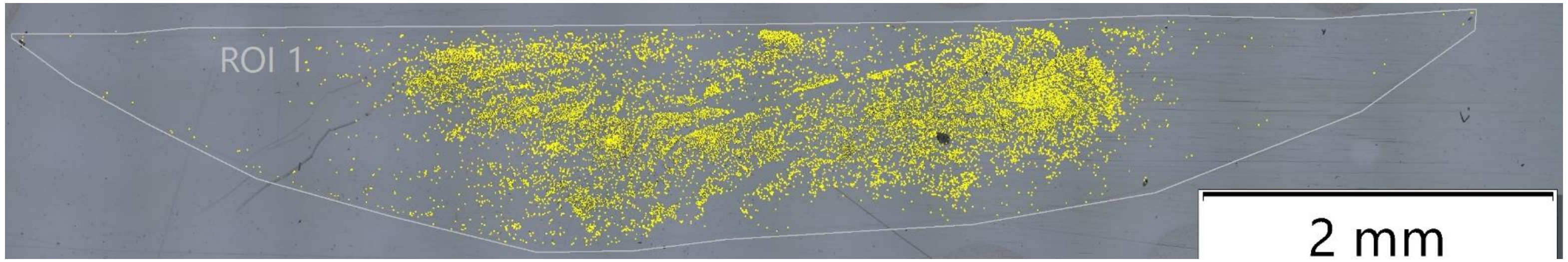
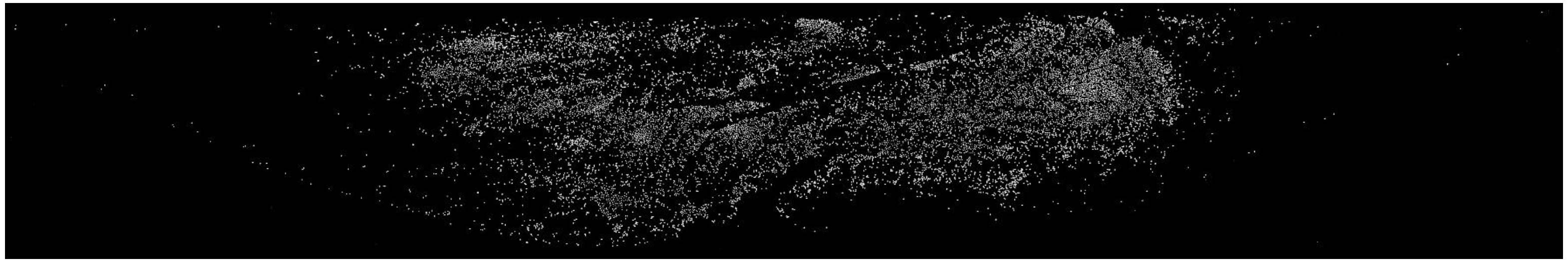
Microscopy investigation



Filament count 14856 ± 1294

Software Olympus



Filament count 23700 ± 1391

ImageJ

Filament count 23725 ± 820

Python

Python scripts available at:
https://zenodo.org/records/13970508
https://doi.org/10.5281/zenodo.13970508

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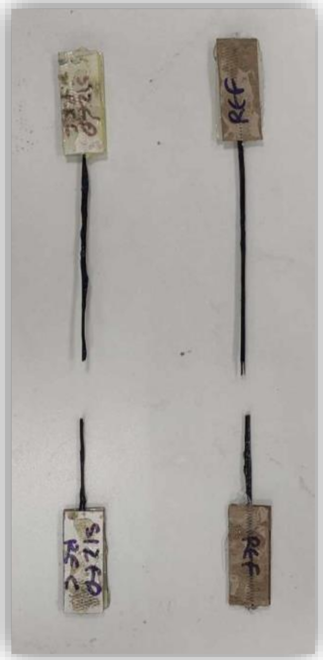
Mechanical tests

Results of tensile testing on CF bundles

Specimen	*Tensile strength (GPa)*	*% difference to Ref_CF*
Ref_CF	2.7 ± 0.3	N/A
Ch_rCF	2.2 ± 0.2	-18
Sized_Ch_rCF	2.4 ± 0.3	-11
Pl_rCF	2.1 ± 0.3	-22
Sized_Pl_rCF	2.4 ± 0.4	-11

Results of tensile testing on single CFs

Specimen	*Tensile strength (GPa)*	*% difference to Ref_CF*
Ref_CF	3.60 ± 0.38	N/A
Ch_rCF	3.04 ± 0.48	-15.6
Sized_Ch_rCF	3.29 ± 0.21	-8.6
Pl_rCF	3.15 ± 0.38	-12.5
Sized_Pl_rCF	3.30 ± 0.28	-8.3



- Filament exhibits a 10% decrease in the sized recycled fibre
- Unsized fibre exhibits quite lower tensile strength (~22%), probably due to the non uniform shape of the rod

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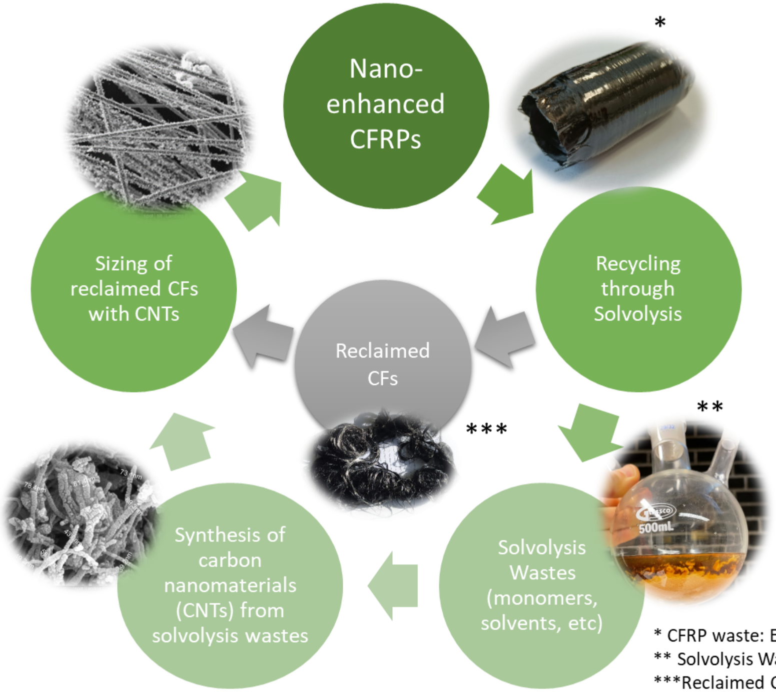
Achievements & Future steps

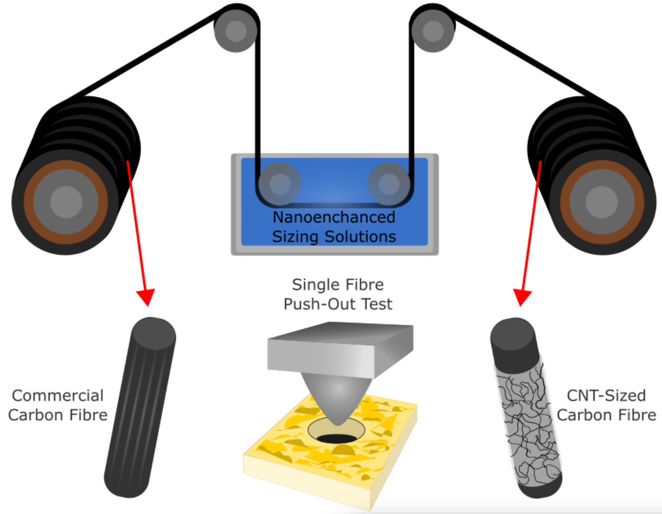
Fibre filaments	Goal (m)	Completed (m)	Demo
3k	1000 (testing) + 1600	2600	Steering wheel
24k	1200 (testing) + 4500		Shaft & seat

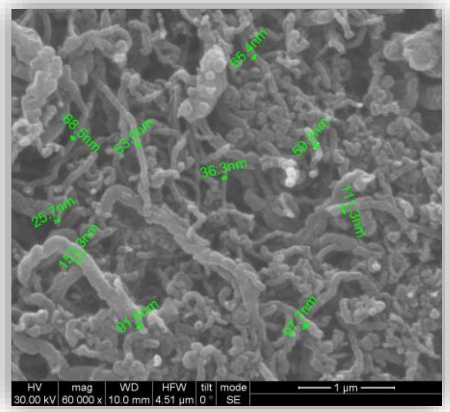


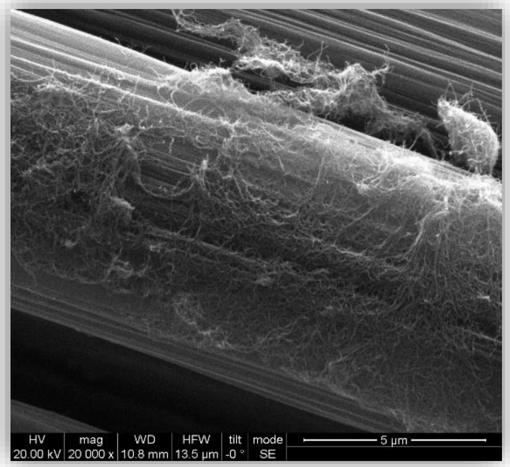
Advantages:

- **Exploitation of solvolysis wastes** (major issue of the recycling process)
- Synthesis of **high-added value nanomaterials** (e.g. CNTs) from waste streams
- **Enhancement** of reclaimed Carbon Fibres and properties **improvement**
- New **nano-enhanced CFRPs** produced from recycled materials
- **Circularity** in the composites value chain

* CFRP waste: EoL part from B&T made by filament winding
** Solvolysis Wastes: By-product of Solvolysis process of SUT
***Reclaimed CFs: Achievement of UPATRAS through plasma enhanced solvolysis







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Thank you!

Dionisis Semitekolos
diosemi@chemeng.ntua.gr
R-Nano Lab NTUA

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High-Performance Composites / **Low Environmental Impact**

r-LightBioCom

Advancing Circularity: Bio-based High-Performance Composites for Industry,

EU-Project: r-LightBioCom

3rd EuReComp Workshop
Technical University of Athens, Greece

Mohamadreza Nasirzade Tabrizi MSc, Dr. Nataliia Hudzenko, Dr.-Ing. Bernd Wetzel,

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Grant Agreement Project No 101091691.

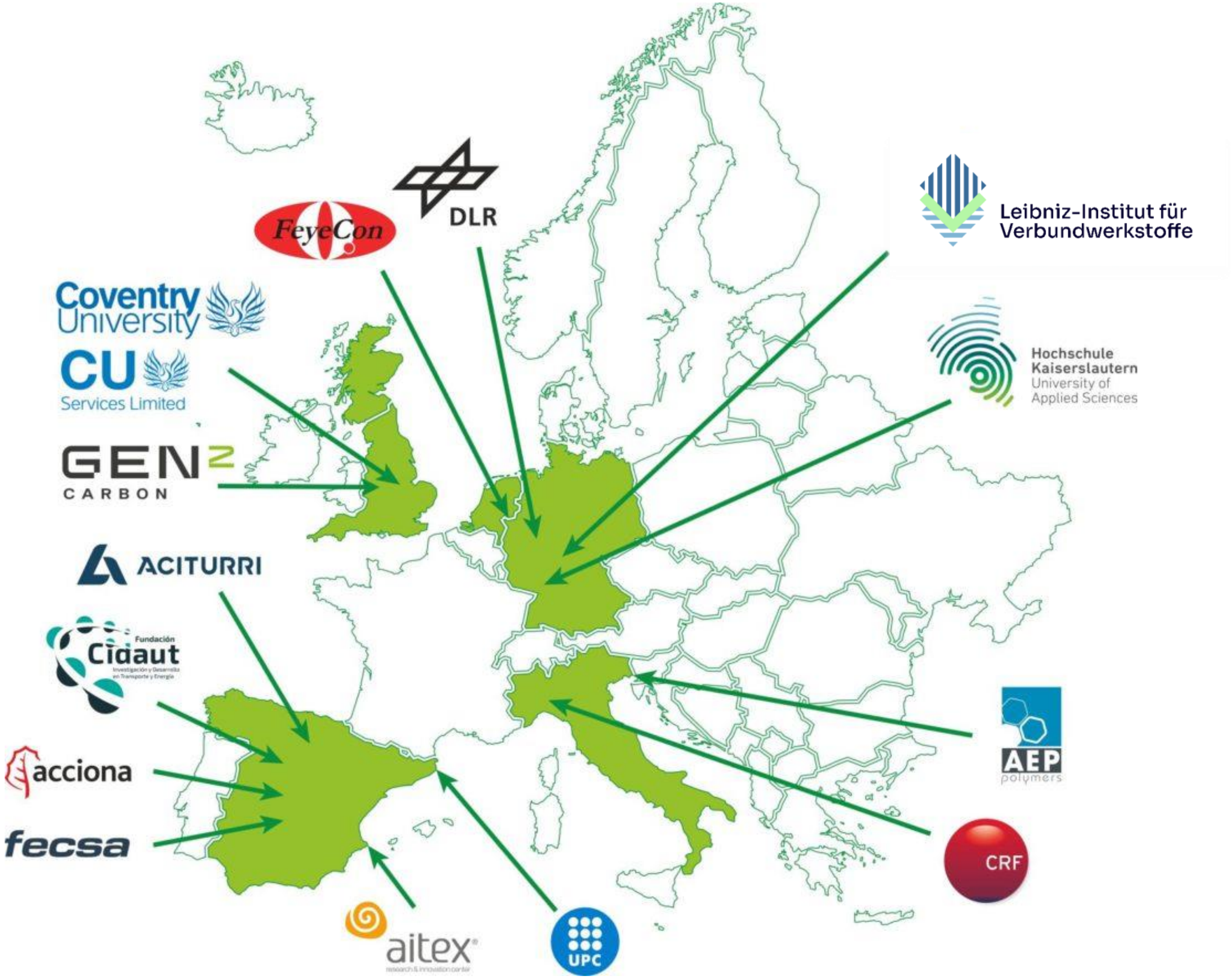
Project Consortium

14 Project partners, 5 countries

4 research institutions

3 universities

8 industrial partners



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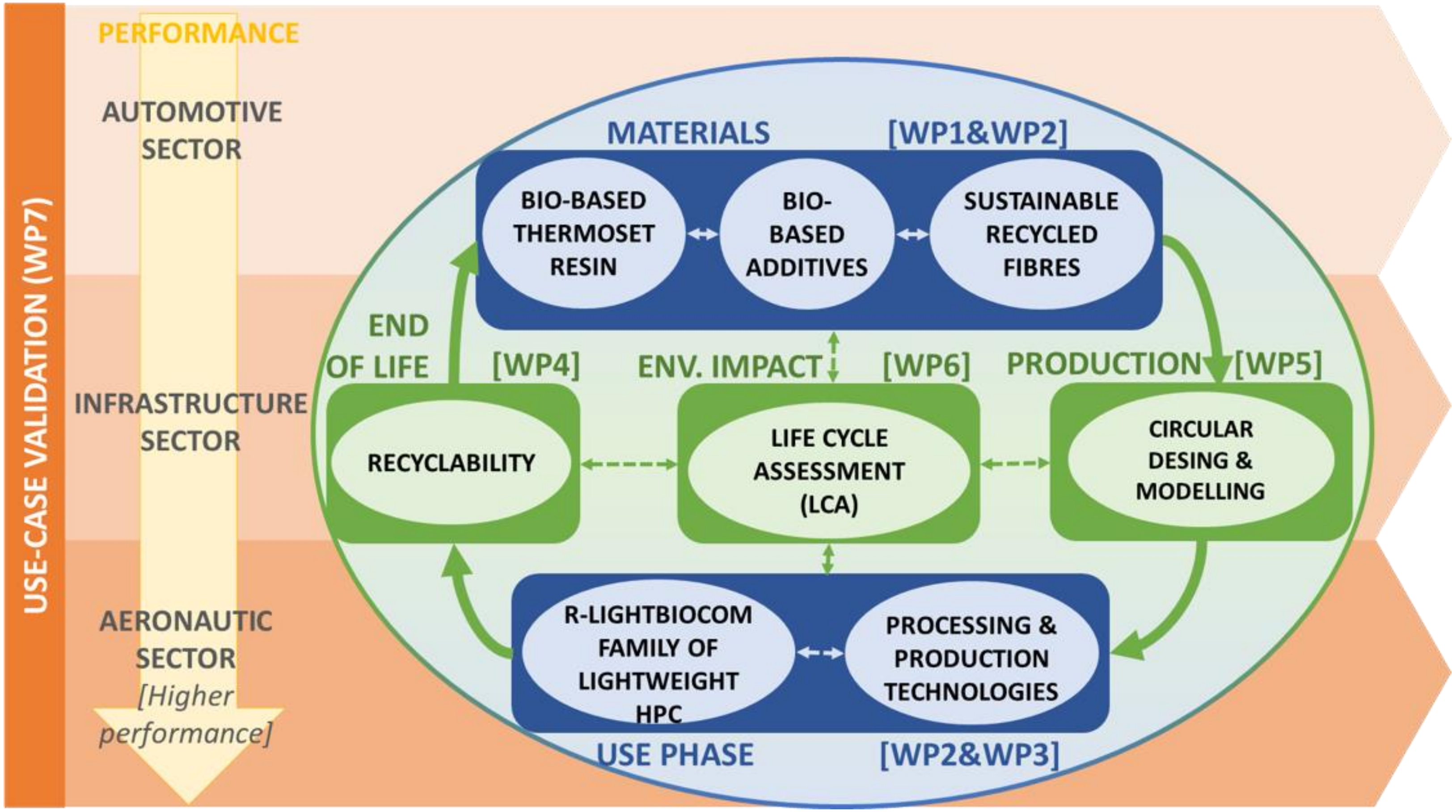
About the Project

Leibniz-Institut für Verbundwerkstoffe

Mission: Promote a paradigm shift from current linear composite value chains to circular ones.

Objectives:



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Shift from Linear to Circular Value Chains in Composites

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Composite Use Cases:

Automotive:
Exterior and Interior Components

Infrastructure: Tunnel Lining Applications

Aeronautics:

Vertical Stabilizer Panel

IVW's Contribution to the Project

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- **Dispersing procedures** of bio-additives, for targeted use-case requirement
- **Introduction of bio-based thermosetting polymers** as matrices
- **Curing procedures**
- **Material's performance characterization**
- **Up-scaling** of formulations with in-line monitoring of the dispersing quality
- **Recycling procedures**

  Solvolysis, Redox-based dissolution, Epoxydolysis at atmospheric/high pressure,

  MW-irradiation: in Super Critical Liquids, and combined with different extraction processes

- **Re-using** of recyclates → Epoxy recyclates, Recycled fibers

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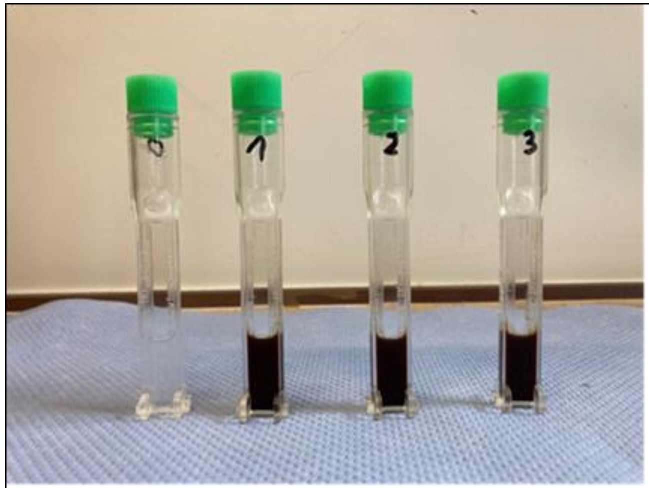
Ongoing Research: Dispersion Process and Nanoparticle Stability

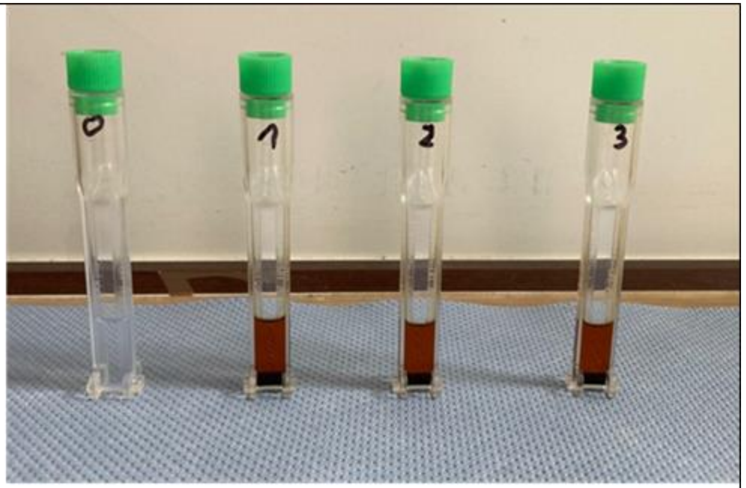
Functionalized Lignin Nanoparticles dispersion in low-viscosity thermoset system.

Dispersion of fillers in resin @IVW

Resulting Dispersion



After Manufacturing in Dissolver



After Sedimentation in Lumisizer

Stable Dispersions reached after 30 Min. in Dissolver

Stable Dispersions after accelerated Sedimentation Test

Ongoing Research: Eco-Efficient Curing Procedures for Bio-Resins

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Reduction of Curing Time and Temperature

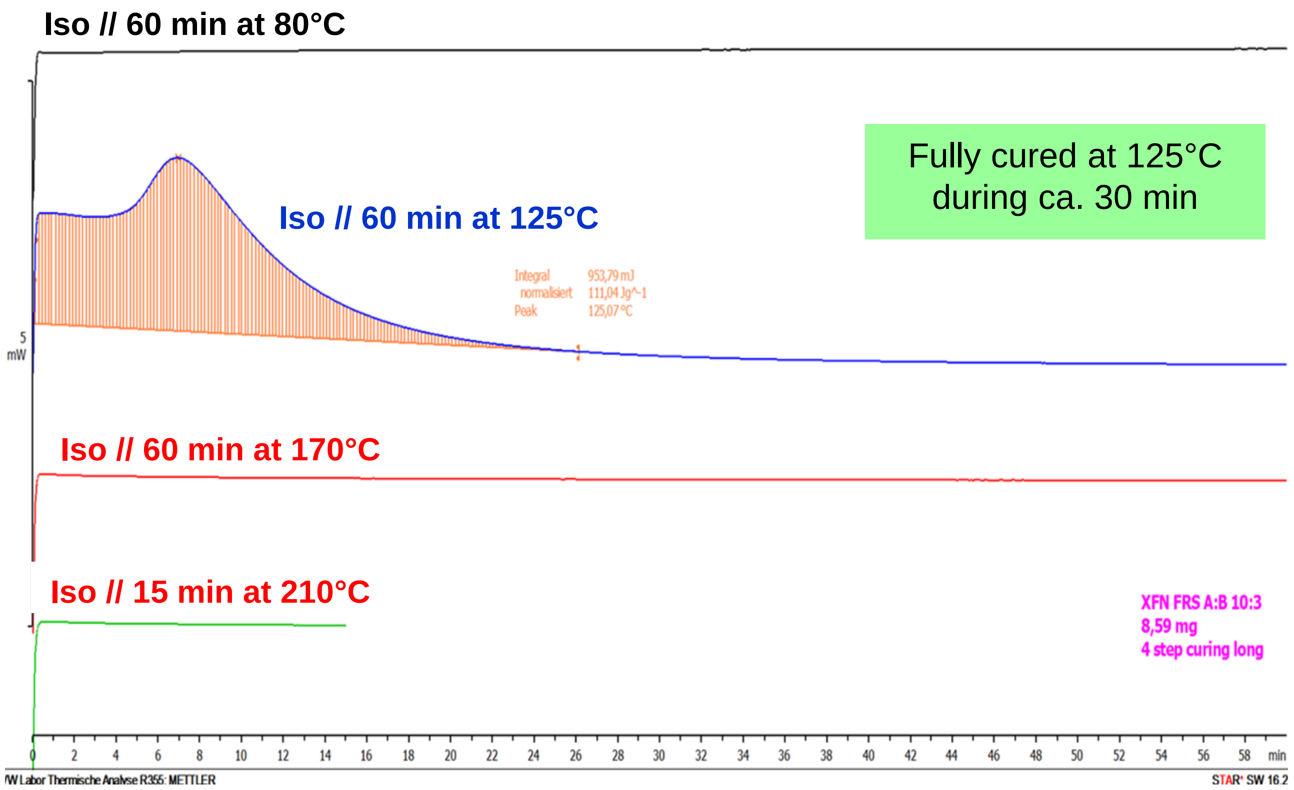
Development of curing profile for a commercial bio-resin with ~65 wt.% of bio-content in the cured matrix.

→ Increase of heating rate by factor of 5

Curing time saved: 75 %

Temperature saved: 10 %

(from 140 to 125°C)



Differential Scanning Calorimetry (DSC)

Ongoing Research: Functionalized Lignin Nanoparticles Formulation

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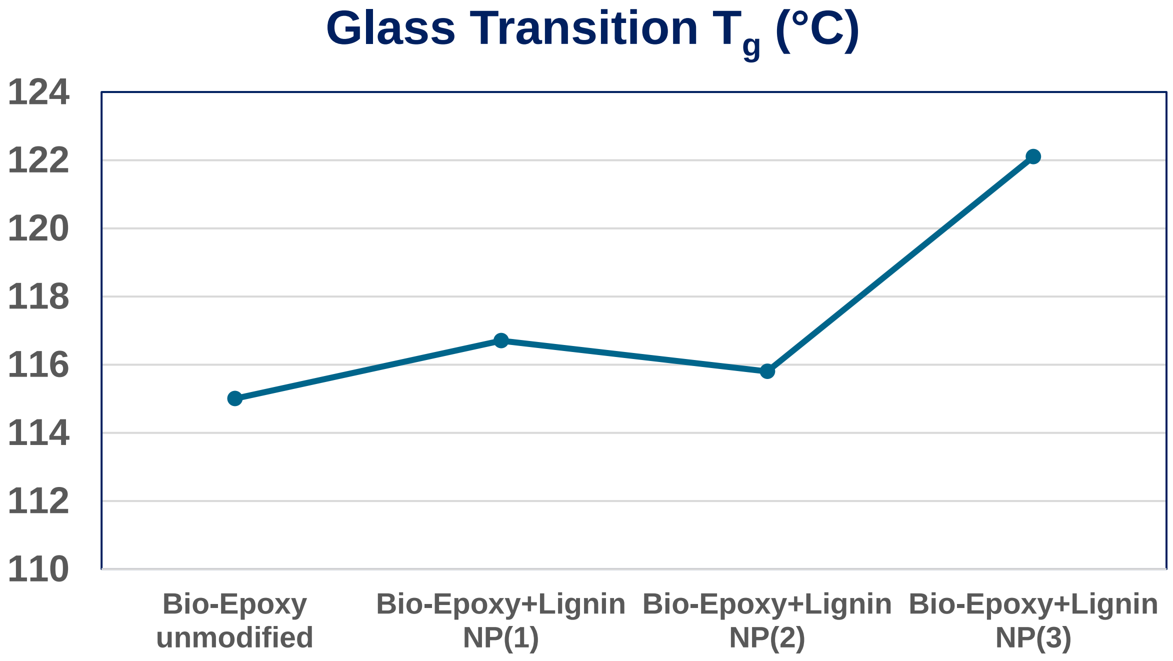
- Enhance filler-polymer bonding by functionalized lignin nanoparticle
- Enhance the dispersion quality in low-viscosity bio-based epoxy
- Investigation of thermal property and curing profile of modified epoxy matrix (2.5 phr), with different funtionalized group of lignin nanoparticles.



Different functionalizations for various use cases

Method: Differential Scanning Calorimetry (DSC)

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Ongoing Research: Prepregs from Bio-Resins and Natural Fibres

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Selection of the suitable epoxy resin allowed adjusting the storage time, viscosity, property profile, and optimization of energy consumption during storage (cooling)

→ All prepregs are flexible and tack-free at RT

Prepregs keep their (mechanical) properties

Up to 6 weeks at ~25°C, RH 45%,

Up to 1 week at ~34°C, RH 50%

Up to at least 5 months at -5°C in freezer

Epoxy/flax fiber prepreg cured by Hot-press

Rheological properties of matrices were investigated to define parameters for prepreg processing

Laminates were manufactured and characterized. Process will be upscaled.

Ongoing Research: Up-scaling of Formulations with in-line Monitoring of the Dispersing Quality

Bio-resin + Recyclates or Lignin NP

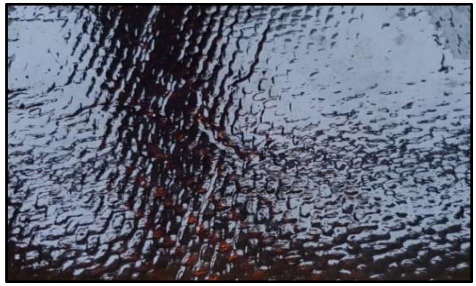
Dispersion of fillers in resin @IVW

Prepreg manufacturing SMC @IVW

Laminate manufacturing @IVW

Cured Laminate

Composite



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Ongoing Research: **Development of Recycling Procedures**

Focus:

- **Epoxy/Carbon Fiber (CF) composites** and **PA6/CF composites**

  → Coming: Use recycled **Aramid fibers**.

Methods:

- **Microwave reactor** with non-toxic solvent
  - Microwave reactor with PA6/CF and NF/Bio-EP samples in Natural Deep Eutective Solvents (NADES) and Acidic solutions

    → Ongoing research on process adjustment
- **Glass reactor** and Acidic solution with both composites are under investigation, with successful high degree removal of PA6 from CF and Bio-EP from NF

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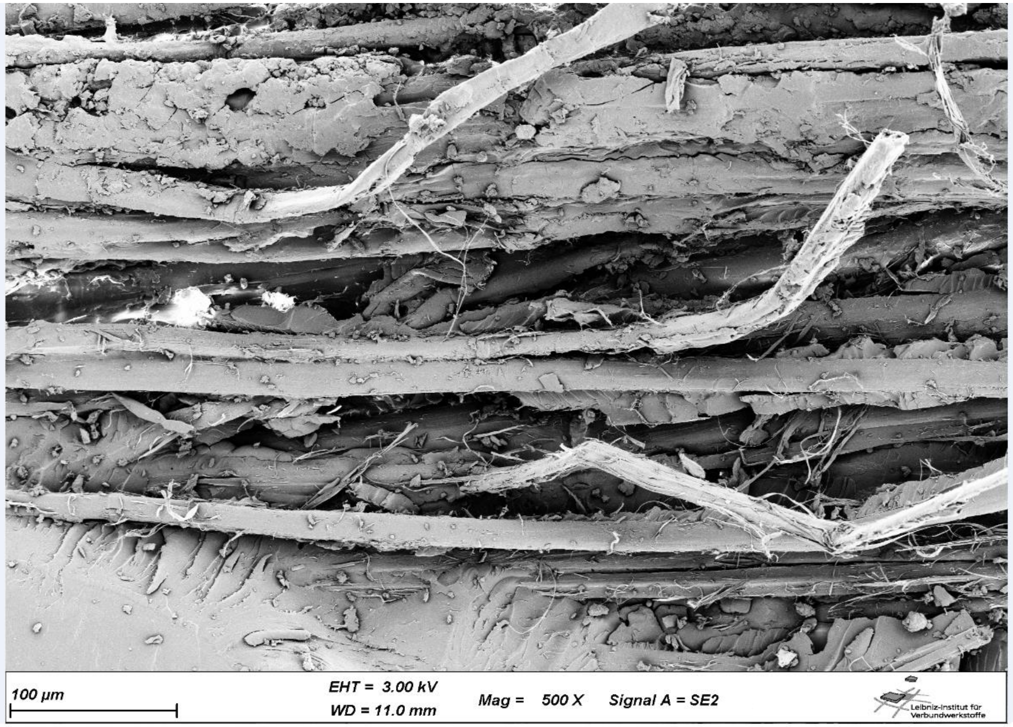
Ongoing Research: Development of Recycling Procedures

SEM pictures of Bio-Epoxy/Natural fiber composite, before and after recycling in the MicroWave reactor

Recycled NF+Bio Epoxy (60/40)



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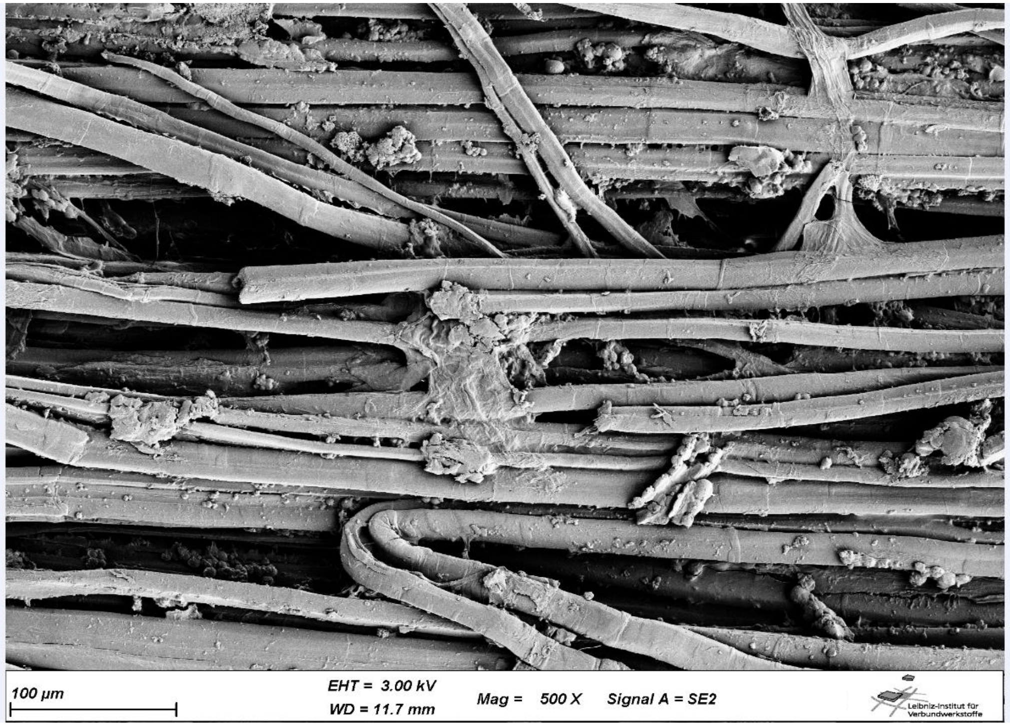

After

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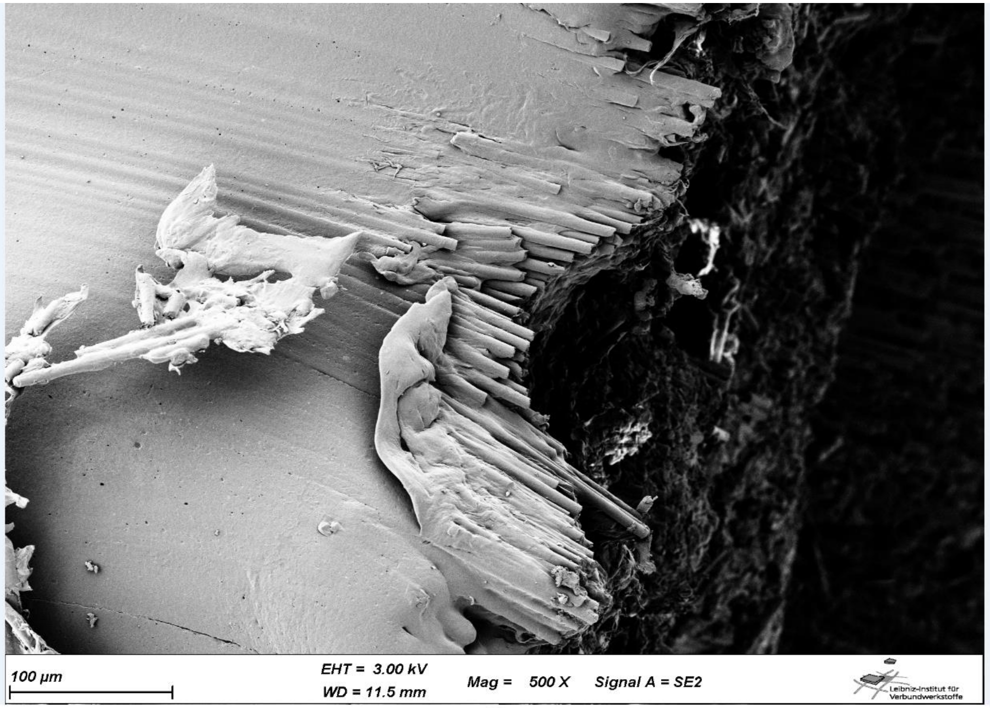
Ongoing Research: Development of Recycling Procedures

SEM pictures of Polyamide6/Carbon fiber composite, before and after recycling in the MicroWave reactor

Recycled CF/PA6, (60/40)



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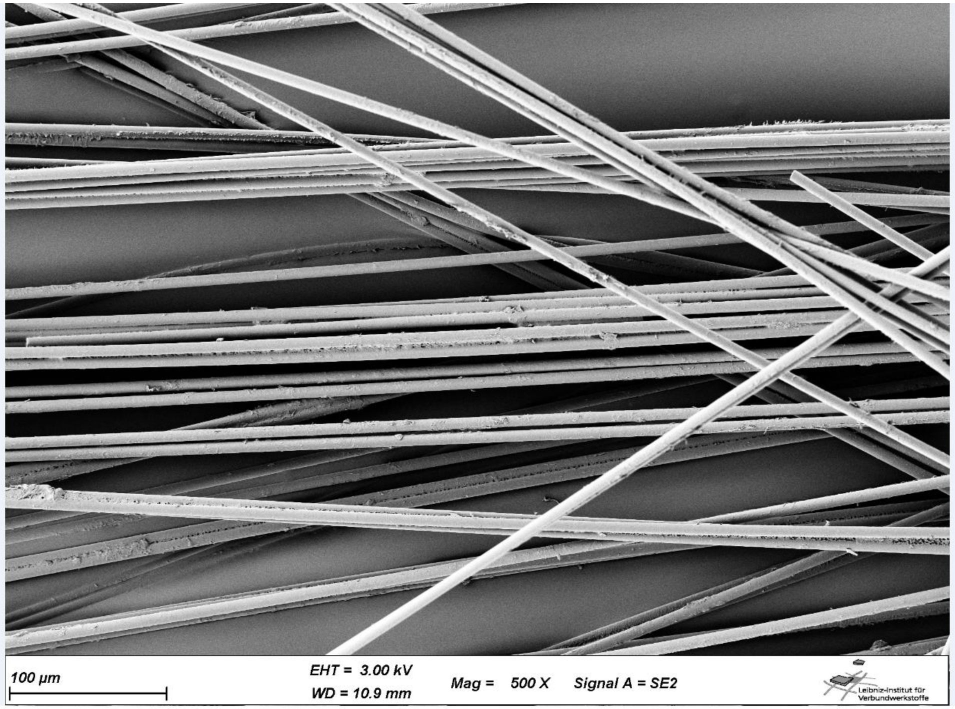

After

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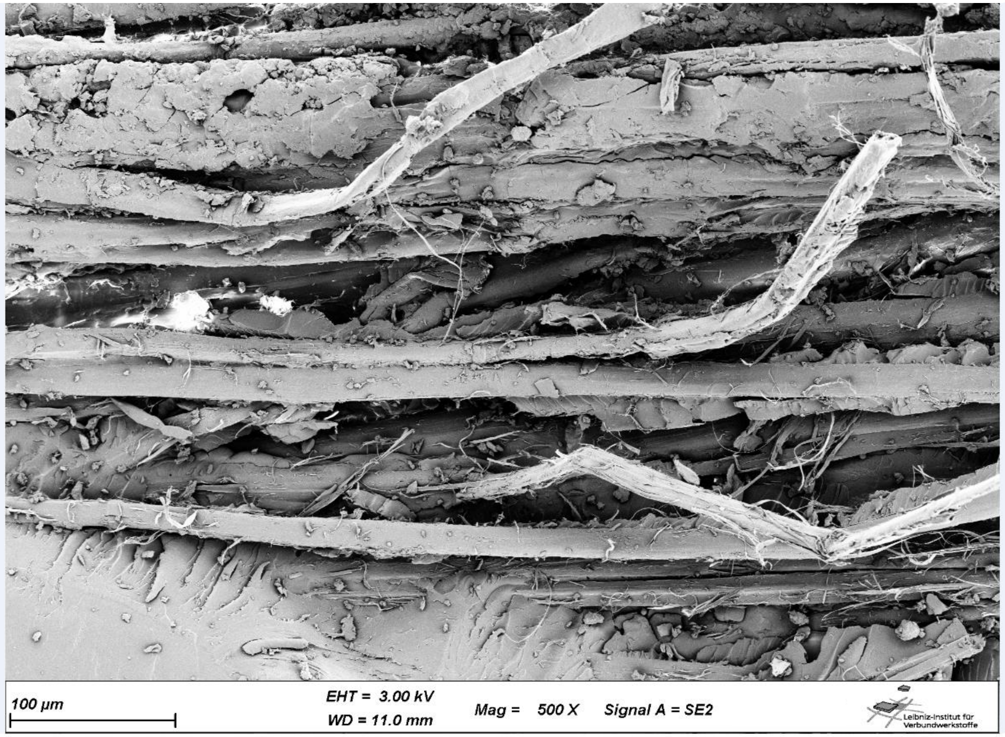
Ongoing Research: Development of Recycling Procedures

SEM pictures of Bio-Epoxy/Natural fiber composite, before and after recycling in the Glass reactor

Recycled NF+Bio Epoxy

(60/40)



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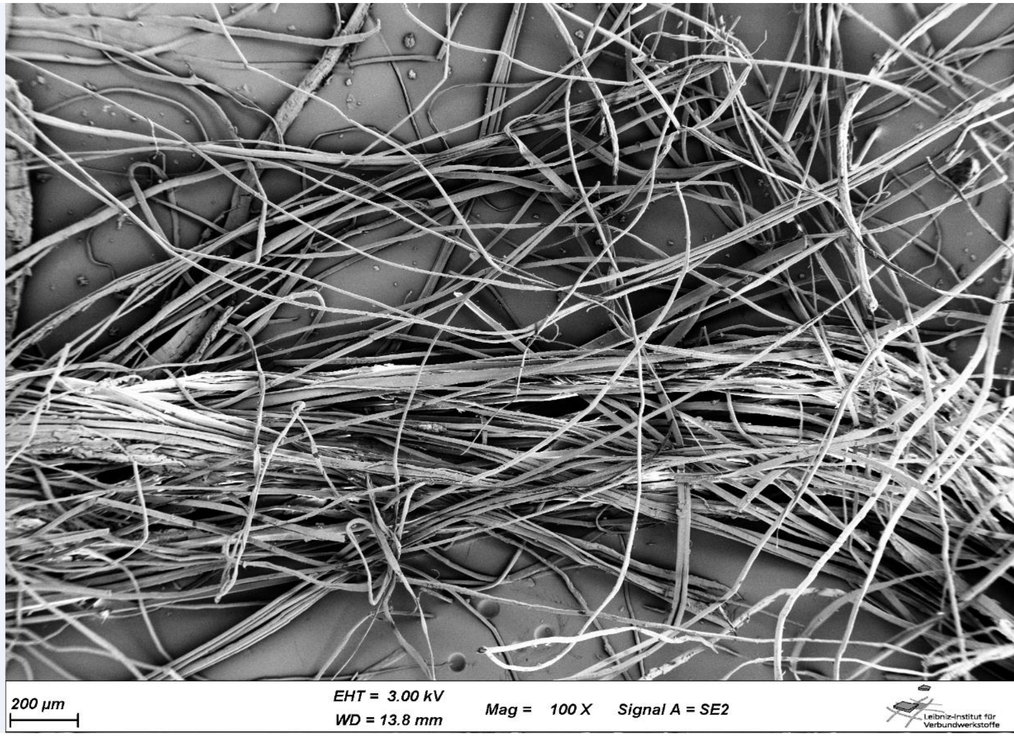

After

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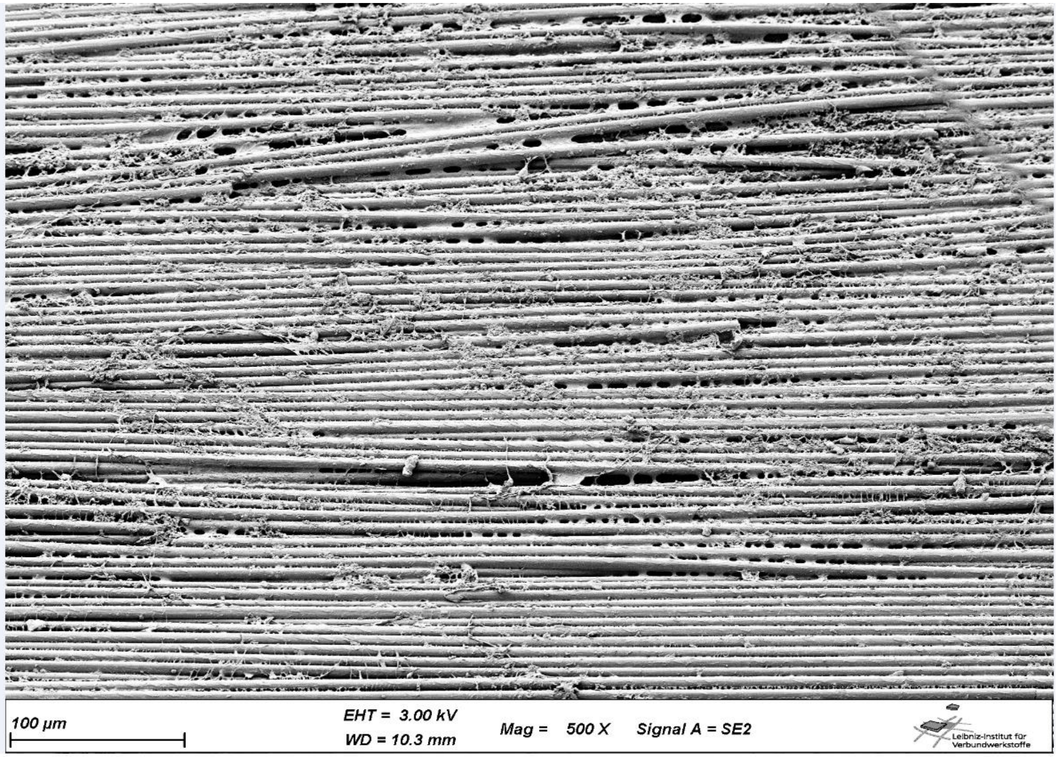
Ongoing Research: Development of Recycling Procedures

SEM pictures of Polyamide6/Carbon fiber composite, before and after recycling in the Glass reactor

Recycled CF/PA6

(60/40)



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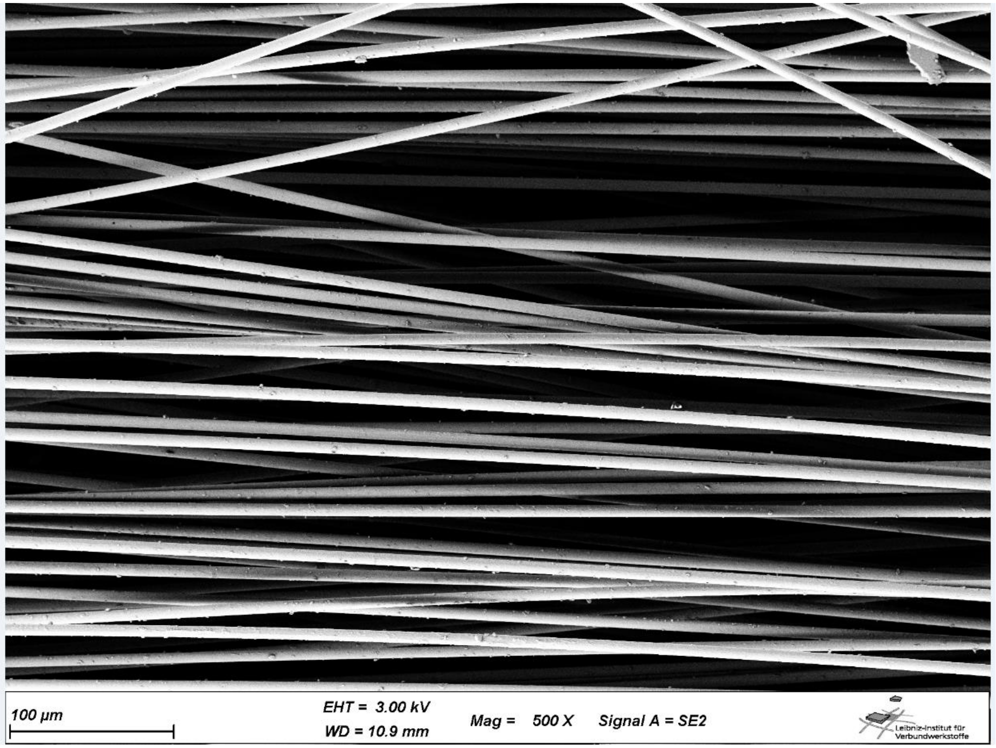

After

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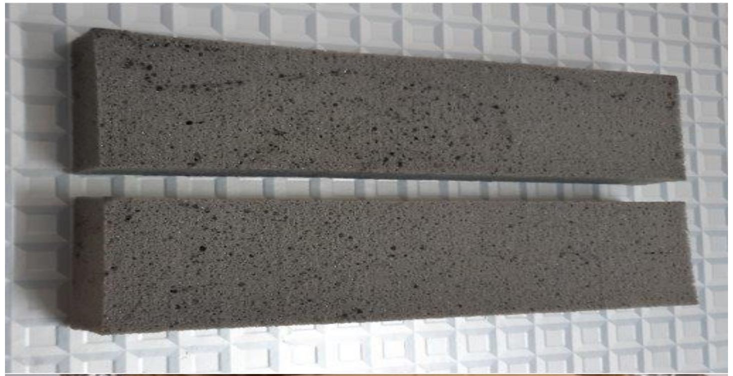
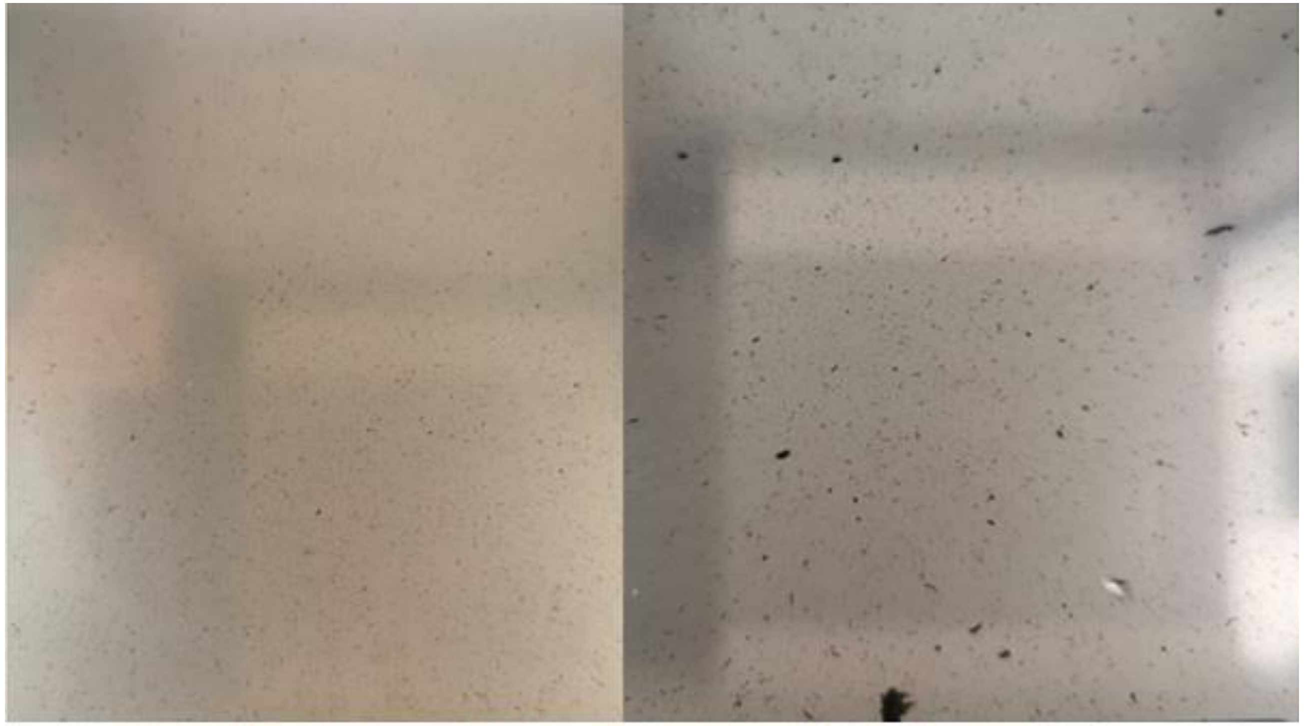
Ongoing Research: Re-using of Recyclates

Using building block of recycled Phenolic resin in **PUR foams**

Good compatibilty up to 10 phr → Characterization on-going



Using building block of recycled Phenolic resin in **Bio-epoxy matrix**



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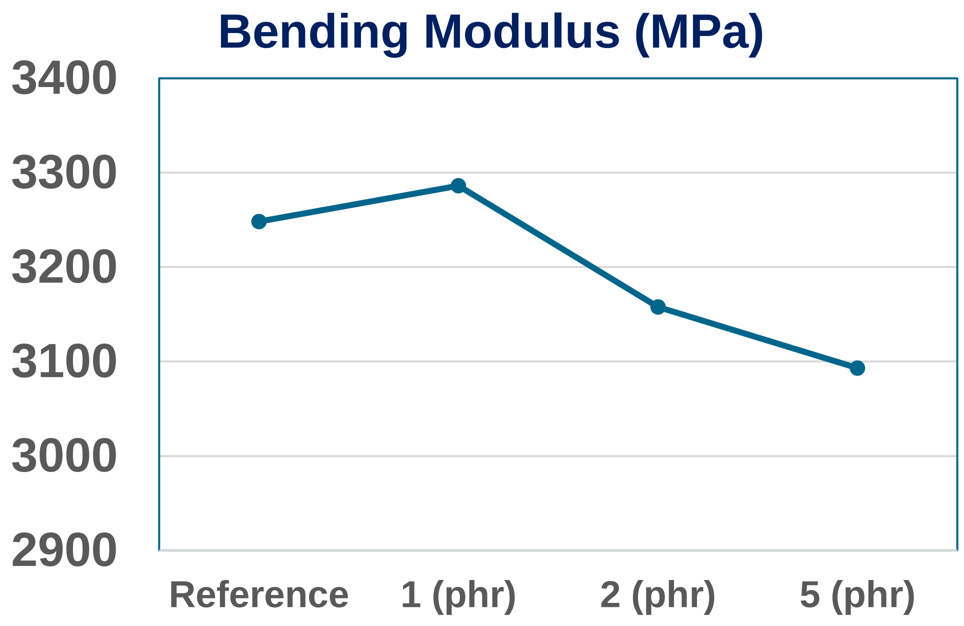
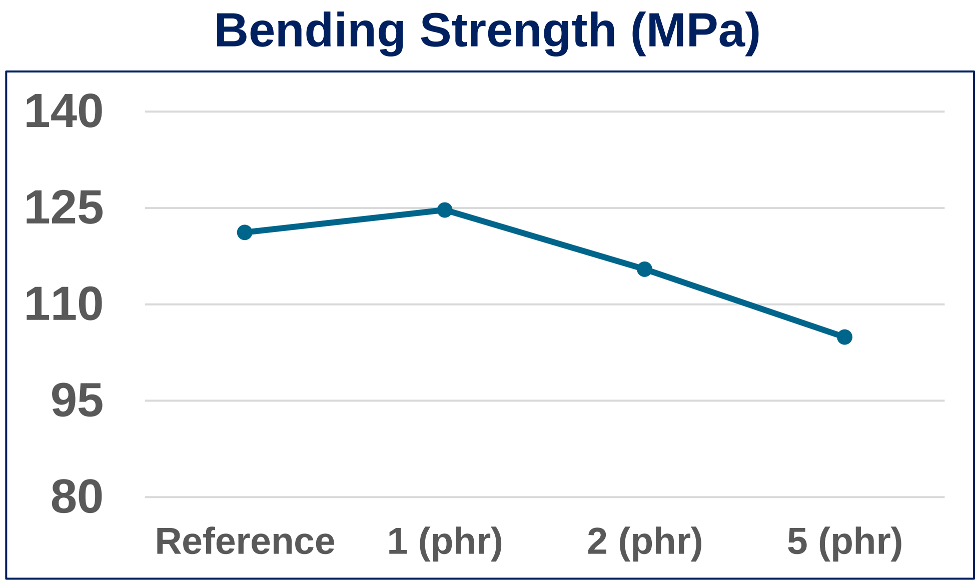
Ongoing Research: Re-using of Recyclates

Using building block of recycled Phenolic resin in Bio-epoxy matrix

- 1, 2 and 5 phr samples tested, higher amount formulations ongoing
- 3-Point bending test utilized for mechanical property investigation





DIN EN ISO 178, Load rate: 2 mm/min

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Ongoing research: Re-using of Recyclates

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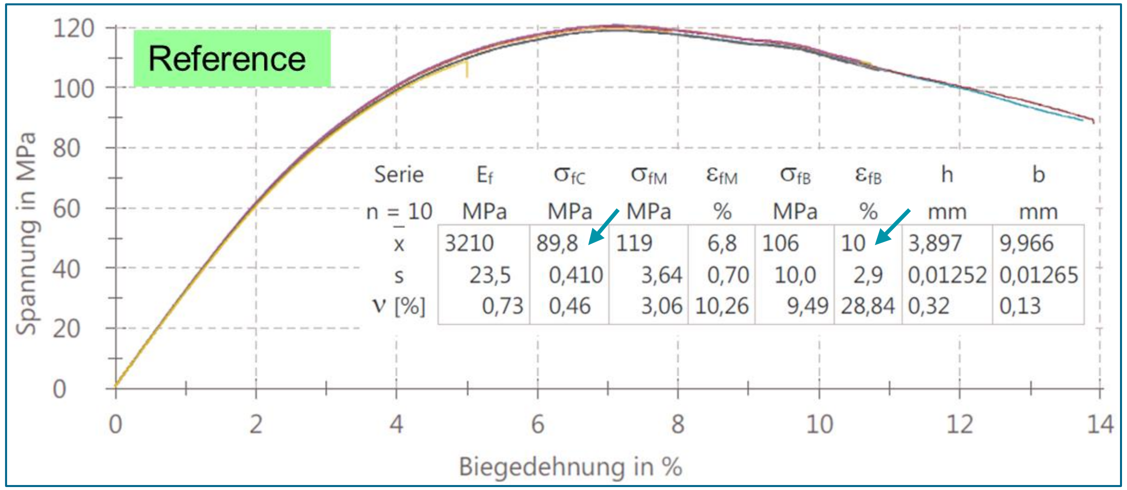
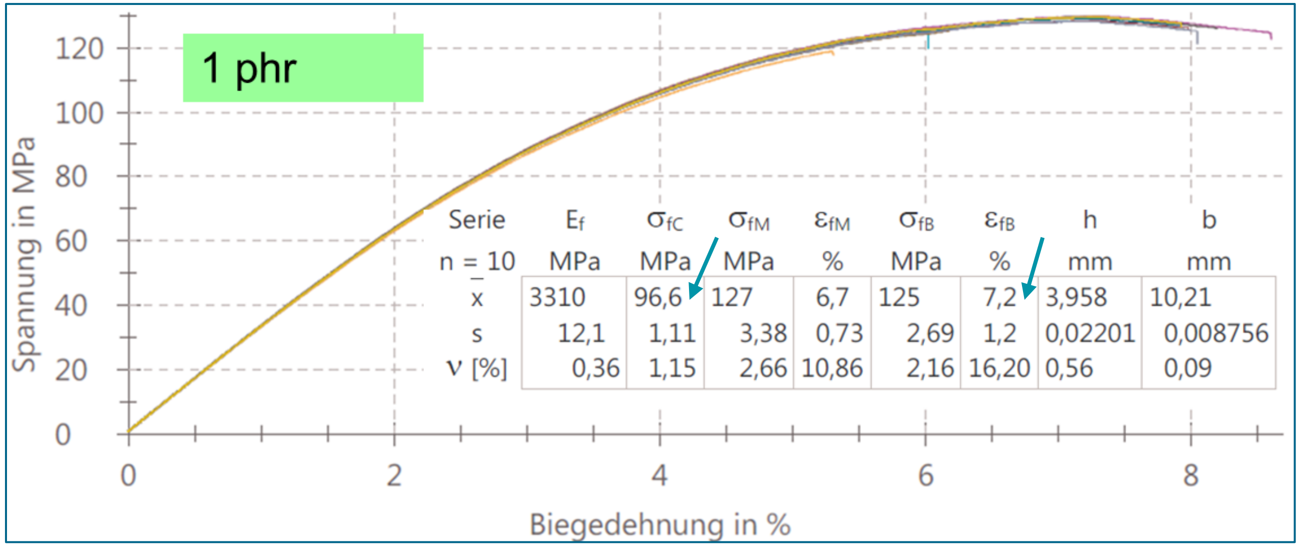
Using building block of recycled Phenolic resin in Bio-epoxy matrix

- 3-Point bending test utilized for mechanical property investigation



Serie	E_f	σ_{fC}	σ_{fM}	ε_{fM}	σ_{fB}	ε_{fB}	h	b
n = 10	MPa	MPa	MPa	%	MPa	%	mm	mm
$\bar{x}$	3210	89,8	119	6,8	106	10	3,897	9,966
s	23,5	0,410	3,64	0,70	10,0	2,9	0,01252	0,01265
ν [%]	0,73	0,46	3,06	10,26	9,49	28,84	0,32	0,13



Serie	E_f	σ_{fC}	σ_{fM}	ε_{fM}	σ_{fB}	ε_{fB}	h	b
n = 10	MPa	MPa	MPa	%	MPa	%	mm	mm
$\bar{x}$	3310	96,6	127	6,7	125	7,2	3,958	10,21
s	12,1	1,11	3,38	0,73	2,69	1,2	0,02201	0,008756
ν [%]	0,36	1,15	2,66	10,86	2,16	16,20	0,56	0,09

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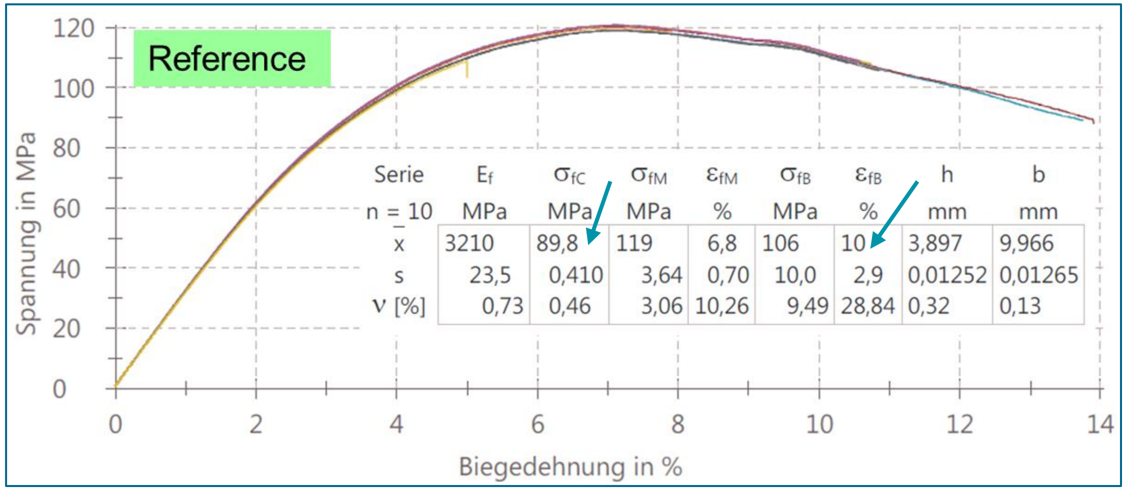
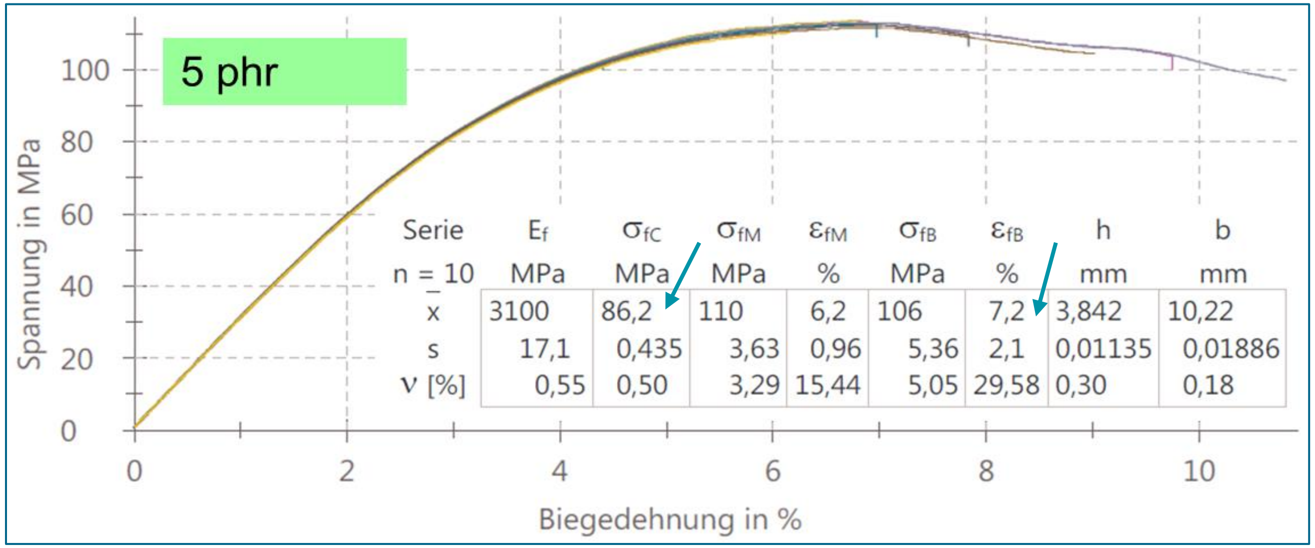
Ongoing research: **Re-using of recyclates**

Leibniz-Institut für Verbundwerkstoffe

Using building block of recycled Phenolic resin in Bio-epoxy matrix

- 3-Point bending test utilized for mechanical property investigation





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Further Steps

❖ Systematic variation of bio-additives / recyclates content

- Curing profile → Tailoring for different use-cases
- Thermal properties → Fulfil the requirements
- Mechanical properties → Static testing, dynamic testing (Fatigue Crack Propagation)

❖ Dispersing techniques

- Further time and energy consumption enhancement (for laminates)

❖ Laminate manufacturing and characterization

❖ Recycling methods

- Optimize microwave reactor and acidic process for higher efficiency
- Other mentioned techniques (High-pressure reactor and Super Critical Liquid, Solvolysis etc.)

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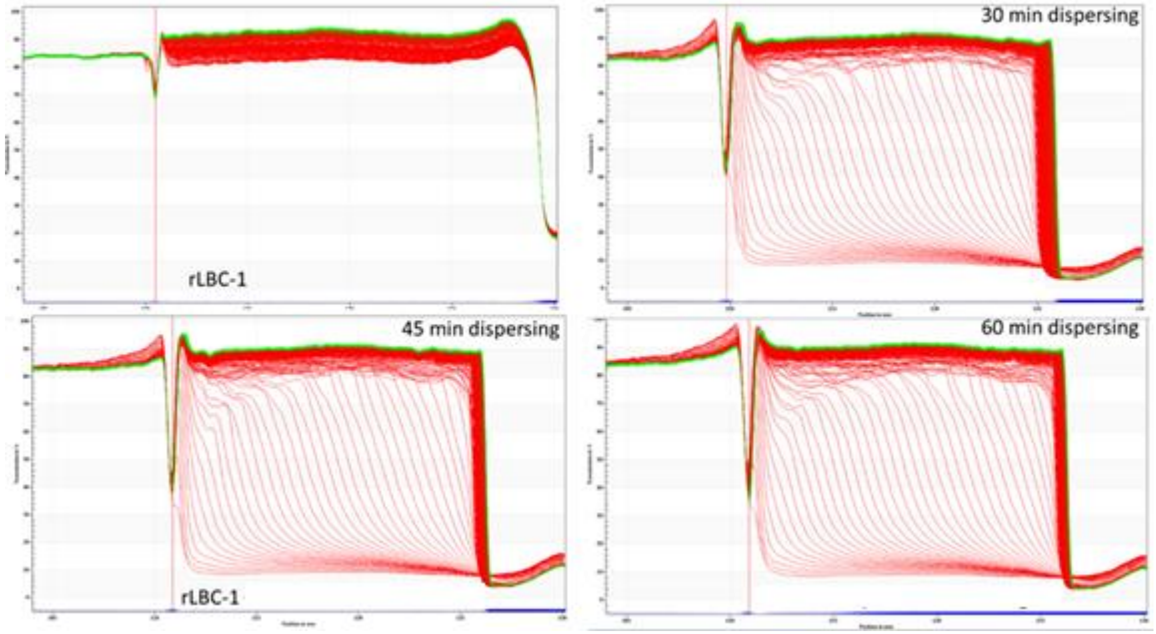
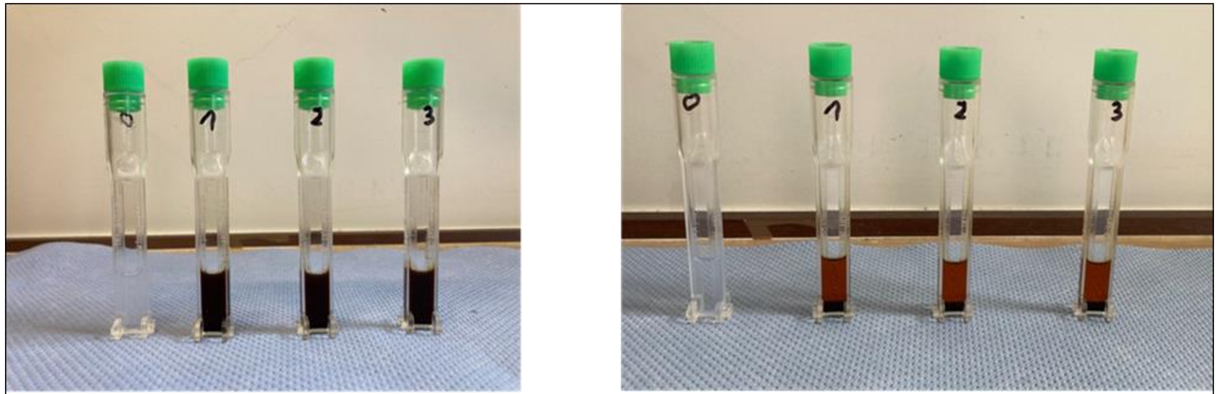
Ongoing Research: Dispersion Process and Nanoparticle Stability

Functionalized Lignin Nanoparticles dispersion in low-viscosity thermoset system.

Stability Test in Lumisizer (Centrifuge)



Resulting Dispersion



After Manufacturing in Dissolver

After Sedimentation in Lumisizer

Stable Dispersions reached after 30 Min. in Dissolver

Stable Dispersions after accelerated Sedimentation Test

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An MCDM based Decision Support System to enable circular strategies for composites

Dr. Marco Diani, Politecnico di Milano

3rd EURECOMP Workshop
Athens, Greece 19/03/2025

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101058756

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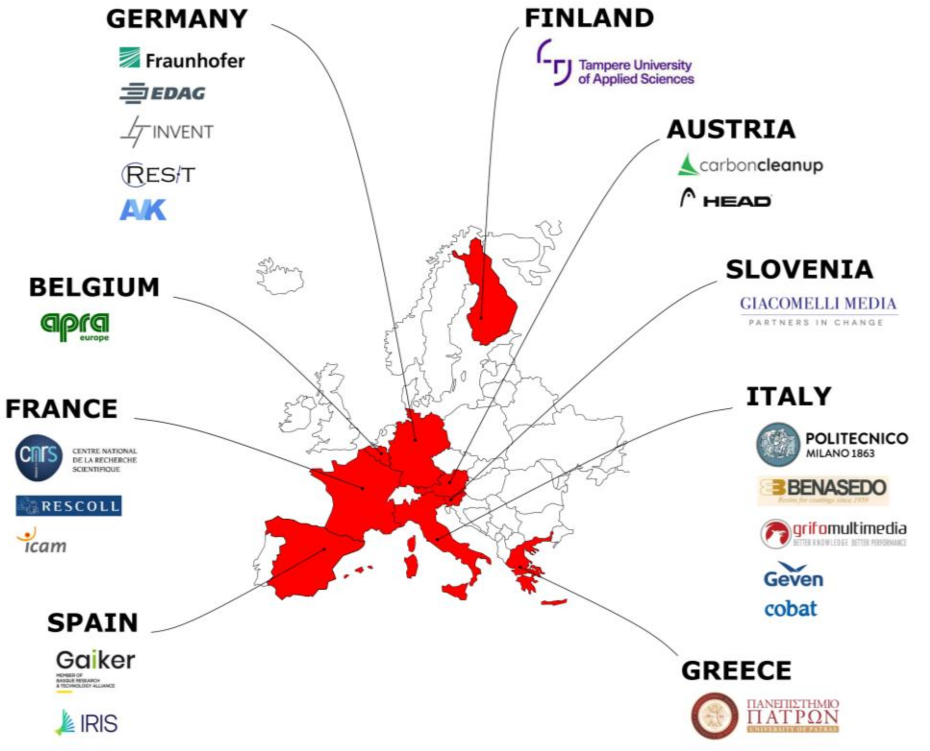
RE CREATE — REcycling technologies for Circular REuse and remanufacturing of fiber-reinforced composite mATErials

- Granting authority: **European Health and Digital Executive Agency** (G.A. no. 101058756)
- Topic: HORIZON-CL4-2021-RESILIENCE-01-01 Ensuring circularity of composite materials (Processes4Planet Partnership) (RIA)
- Grant: **€ 8.3 million**
- Duration: **4 years** started on 1st of June 2022
- Consortium: **21 partners**, from **9 EU countries**.



General objective: **develop a set of innovative technologies aimed at exploiting the potential of end-of-life complex fiber-reinforced composite waste as feedstock for profitable reuse of parts and materials in the manufacturing industry.**

This project has received funding from the European Union's Horizon Europe research and innovation programme under Grant Agreement No. 101058756

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Strategy and approach

Technical pillars

Strategy A1: reuse of current generation, EoL GFRC and CFRC parts.

Strategy A2: fiber liberation and reusable matrix recovery.

Strategy A3: design and demonstration of next-gen FRCs.

Systemic pillars

Strategy B1: circular economy and sustainability assessment and acceleration.

Strategy B2: educational and learning instruments through digital technologies.

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Technical pillars

Strategy A1: reuse of current generation, EoL GFRC and CFRC parts.

- laser-based recognition and inspection for sorting; high precision dismantling (laser-shock) and repair; T-assisted reshaping; design for disassembly based on reversible joints; AI-assisted decision support systems

Strategy A2: fiber liberation and reusable matrix recovery.

- catalyst-assisted green solvolysis, electrofragmentation

Strategy A3: design and demonstration of next-gen FRCs.

- green reversible thermoset resins as enabling materials for next-gen FRCs with easier repairability and enhanced reusability → recyclable-by-design composite materials and structures

Realization of nine **demonstrators** (TRL6)

- **reuse of EoL** GFRC/CFRC parts
- fiber and resin **recovery, recycle and reuse**

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Systemic pillars

Strategy B1: circular economy and sustainability assessment and acceleration.

- IoT, big data, data analytics, dedicated digital tools to enable the assessment and acceleration of the circular economy principles; integrated environmental and socio-economic sustainability assessment; definition of dedicated circular business models.

Strategy B2: educational and learning instruments through digital technologies.

- Co-design of learning resources; definition of suitable digital tools for learning; validation and replication of learning resources.

Dedicated software for circularity and sustainability assessment.

Massive Online Open Courses and digital twins.

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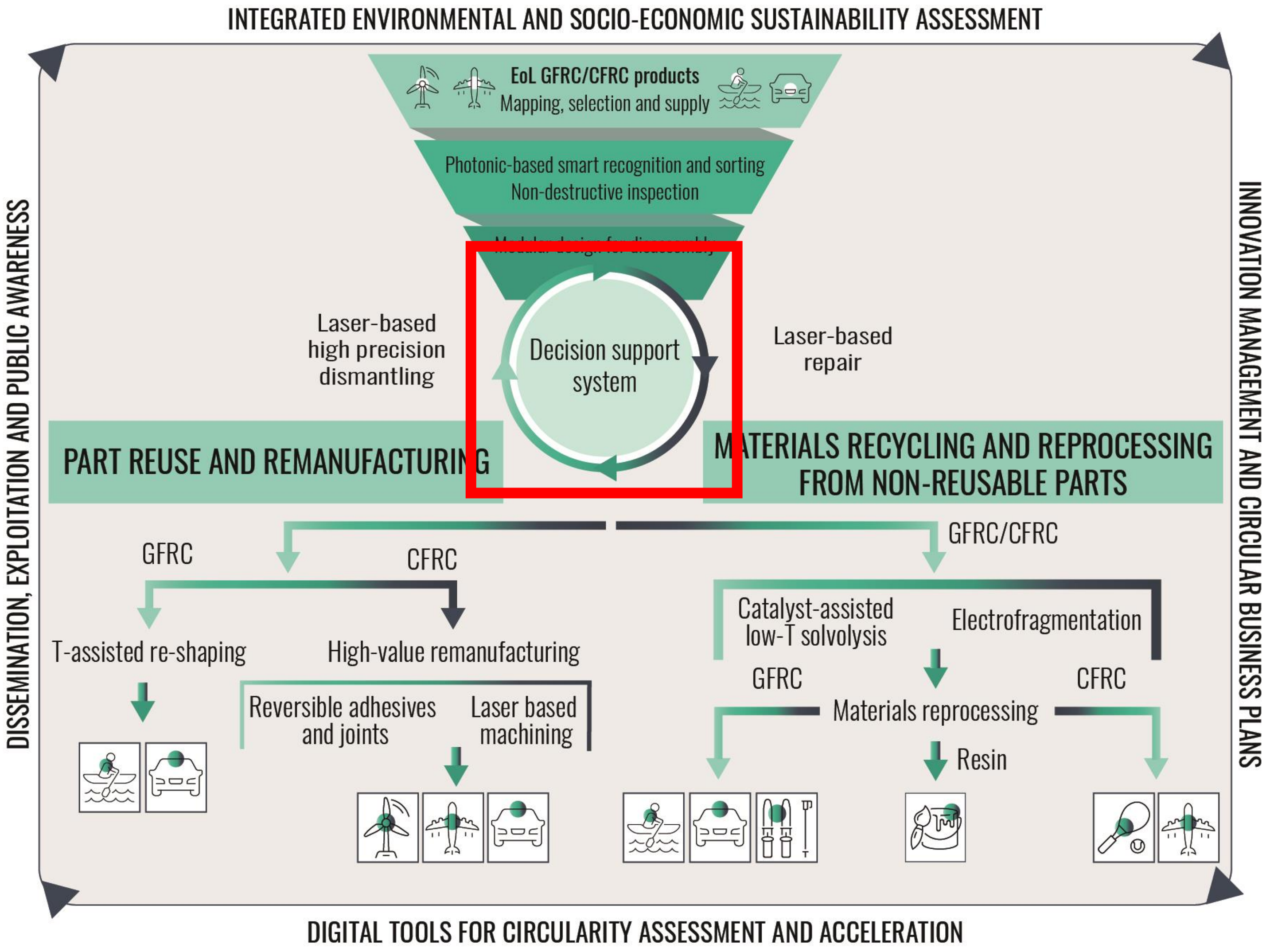
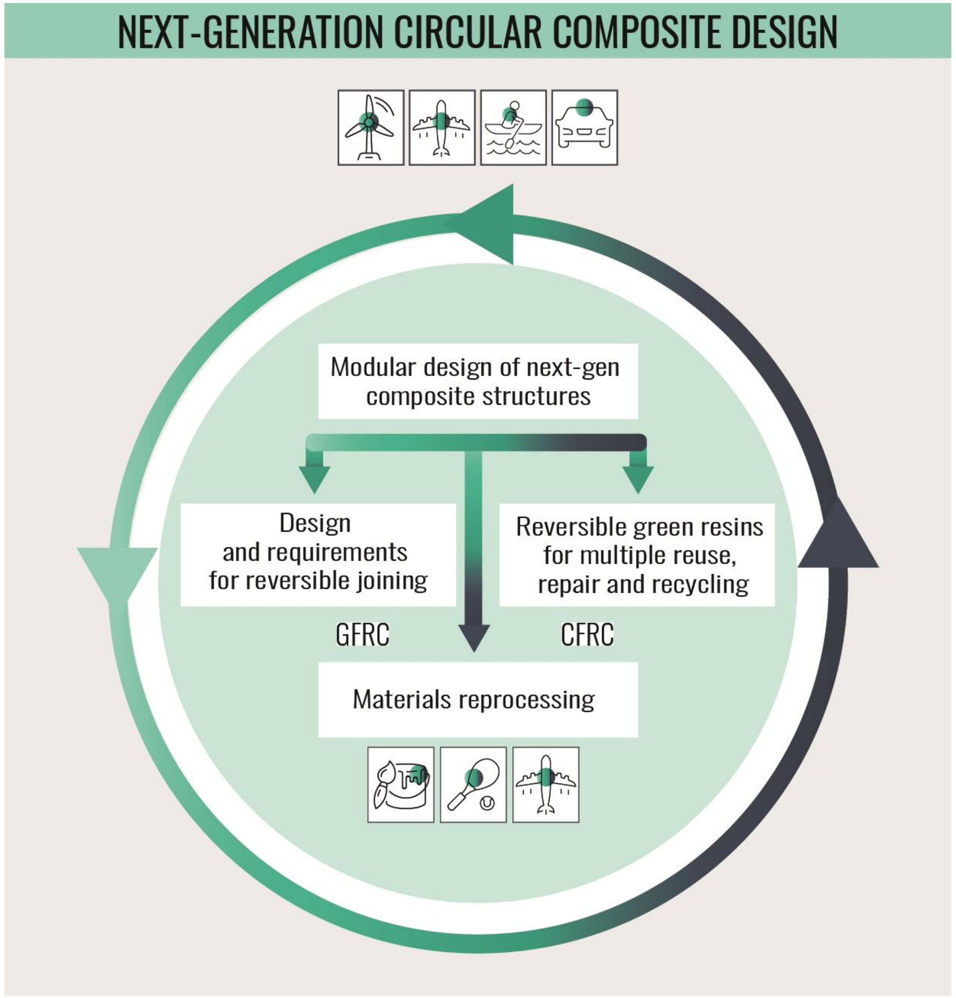
Technical pillars





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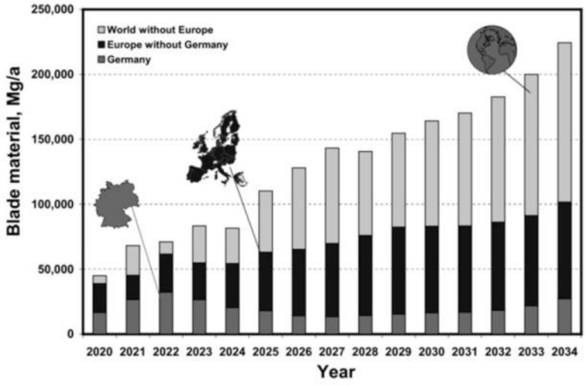
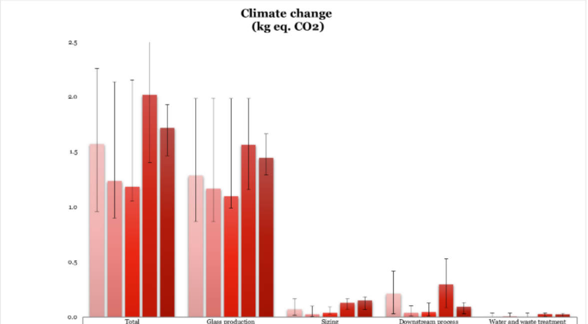
Circularity drivers for the composite sector

Increasing EoL waste in the composite sector

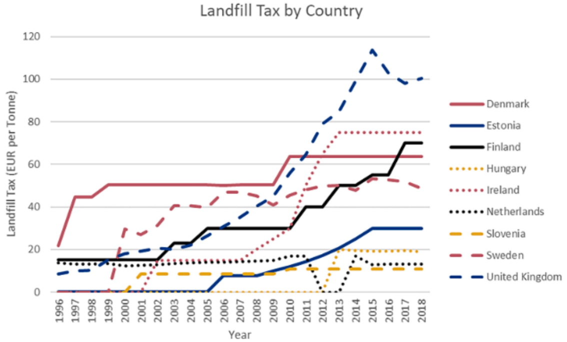


Energy intensive manufacturing of virgin materials



	Total	Glass production	Sizing	Downstream process	Water and waste treatment
Dry chopped strands	1.57	1.28	0.07	0.21	0.00
Wet chopped strands	1.24	1.17	0.02	0.04	0.01
Direct rovings	1.18	1.10	0.04	0.04	0.00
Assembled rovings	2.02	1.56	0.13	0.30	0.03
Mats	1.72	1.45	0.15	0.09	0.03

Ban on landfilling, increase in landfill tax



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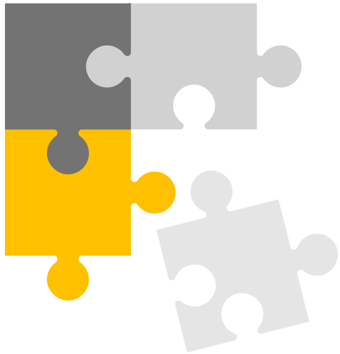
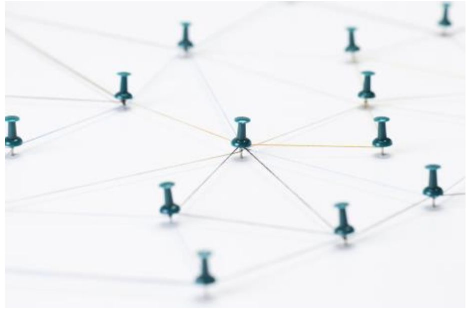
Barriers for circular solution implementation

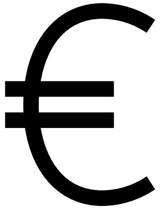
Information Asymmetry



Relatively low interaction between actors in the value chain



Economic unfeasibility due to linear approach



A Decision Support Tool?

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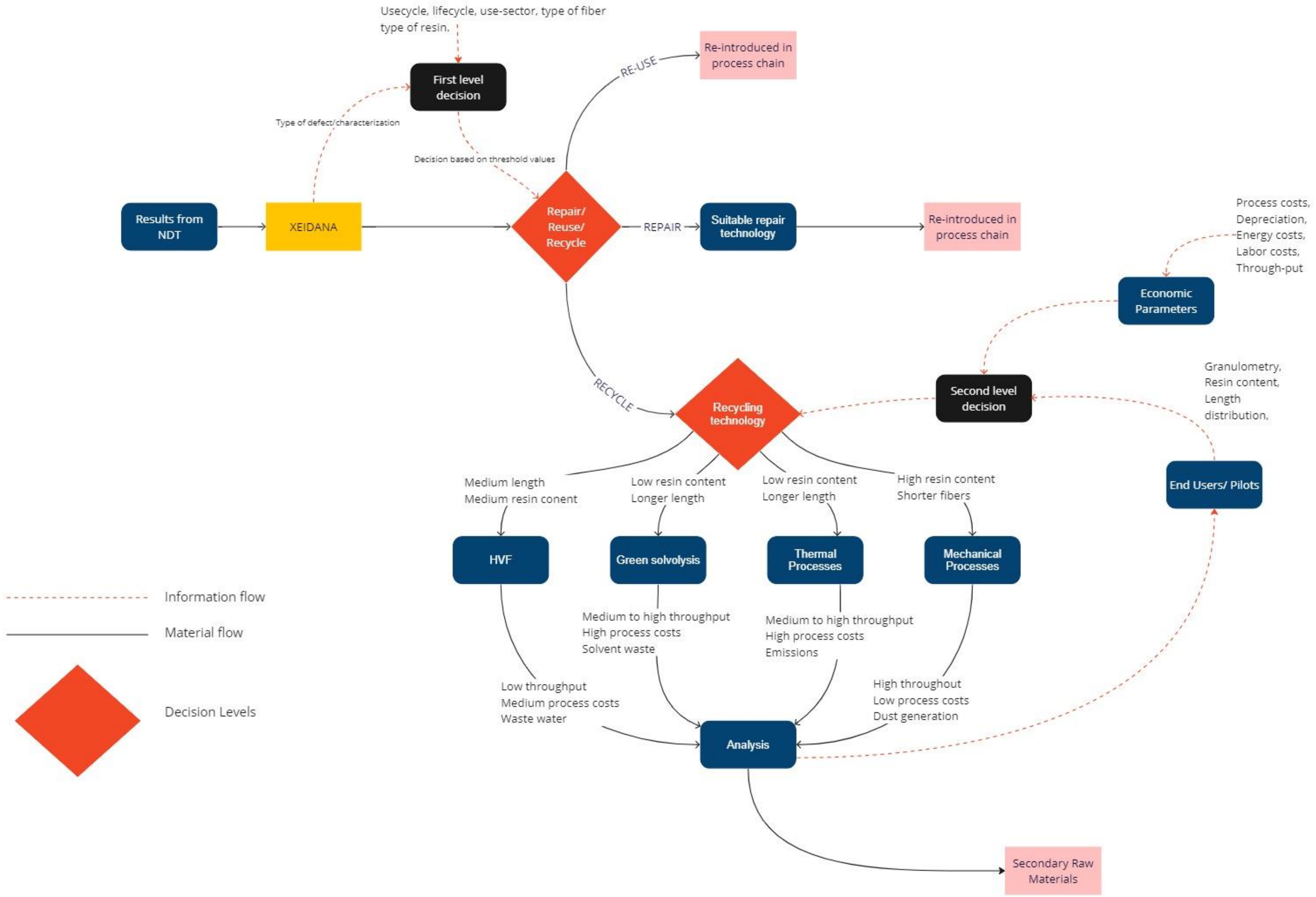
Architechture of the DSS



2 Step decision making

Decision Point 1: EoL Strategy Recommendation
The first decision point in the DSS suggests suitable strategies for managing End of Life parts effectively.

- **Decision Point 2: Recycling Technology Selection**

The second decision point evaluates recycling technologies based on economic, process, and technical parameters to rank choices.

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Criteria for decision making

		Decision Point 1		
S.no	Name of Criteria	Dependencies	Objective Function	Comments
1	Defect structurality	Defect geometry, modulus, surface energy	Minimize based on input	Also captures health of the component /damage of the piece
2	Service life rating	Age, sector	Threshold values	Affected by area of application
3	Appearance	Surface finish	Optimize	Demand-driven component
4	Joining Elements	Type of joining method	Threshold values	To check if it is fit to be re-usable

Decision Point 2				
S.no	Name of Criteria	Dependencies	Objective Function	Comments
5	Material Recovery	Input mass, output mass	Maximise	Accounts for losses during process
6	Environmental Score	Emissions also Co_2	Minimise	Sustainability component
7	Energy consumption	Real energy consumed	Optimise	Demand driven component
8	Average throughput	Processing capacity	Maximise	Process parameter
9	Market Value of recyclate	Granulometry, percentage of clean fibres (type) , resin monomers if any	Maximise	Demand driven component
10	Technological readiness	Easy of scalability	Maximise	
11	Tensile strength of rGF/CF	Tensile strength of recycled fibres	Optimise	Demand driven component
12	Cost of recycling	OC, and Auxillary costs	Minimise	Process parameter, demand driven component
13	Labour Requirement	Man hours per kilo	Minimise	Process parameter, demand driven component

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DSS - Logic

Criteria weights: best approach to assign weights to identified criteria:

- From Literature review ⇒ **BWM** (*Best-Worst Method*): efficiently ranks options by identifying best and worst criteria, facilitating rapid and balanced identification of the relative weights of criteria

Alternatives selection: best approach to select among alternatives (e.g., *Reuse*, *Repair*, *Recycle*, *Dispose* in Decision Point 1):

- From Literature review ⇒ **TOPSIS** (Technique for Order of Preference by Similarity to Ideal Solution)

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BWM - Overview

Steps in the best – worst method are as follows;

1. Define a list of criteria at the relevant decision point

   $C_i = \{ C_1 , C_2 \ldots\ldots\ldots C_n \}$

   Example Decision Point 1

Criteria Number = 4	Criterion 1	Criterion 2	Criterion 3	Criterion 4
Names of Criteria	Defect structurality	Service life rating	Appearance	Joining Elements

2. Select Best and Worst

Select the Best	Defect structurality

Select the Worst	Appearance

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BWM - continued

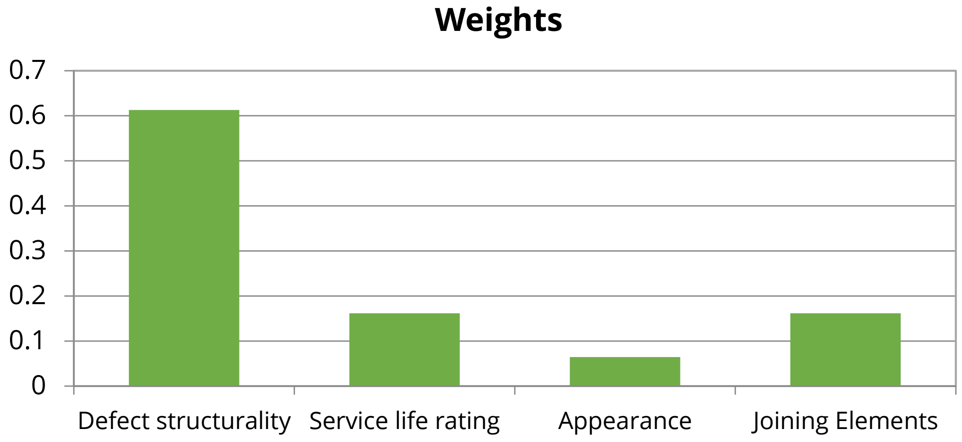
3. Relevance of best – to- others and others – to –worst with an integer between {1,2,3….9}

Best to Others	Defect structurality	Service life rating	Appearance	Joining Elements
Defect structurality	1	4	9	4

Others to the Worst	Appearance
Defect structurality	9
Service life rating	3
Appearance	1
Joining Elements	3

The meaning of the numbers 1-9:
1: Equal importance
2: Somewhat between Equal and Moderate
3: Moderately more important than
4: Somewhat between Moderate and Strong
5: Strongly more important than
6: Somewhat between Strong and Very strong
7: Very strongly important than
8: Somewhat between Very strong and Absolute
9: Absolutely more important than

4- The final weights are assigned if the consistency check is satisfied as follows



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TOPSIS

While BWM can be an effective method to assign weights to the different criteria, a TOPSIS logic is more suitable to carry-out comparison between decision alternatives

Criteria (N): C_1 C_2 … C_N

Alternatives (M): A_1, A_2, …, A_M

$$[x_{ij}] = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1N} \\ x_{21} & x_{22} & \cdots & x_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ x_{M1} & x_{M2} & \cdots & x_{MN} \end{bmatrix}$$

This is the decision-making matrix with M, alternatives and N criteria

$\boldsymbol{x_{ij}}$ is the value assigned to criterion $\boldsymbol{j}$ in alternative $\boldsymbol{i}$ (e.g., resin content, fibre length)

The object is to select the alternatives having the highest *Similarity*

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TOPSIS Method-Example (Dummy data)

Distance of each alternative from the best alternatives

(D^b_j) =

Alternatives (M)	
HVF	0,42
Green solvolysis	0,00
Thermal processes	0,24
Mechanical processes	0,24
Dispose	0,24

Distance of each alternative from the best alternatives $D_i^b = \sqrt{\sum_{j=1}^{N}(\chi_{i\,j} - \chi_j^b)^2}$

Distance of each alternative from the worst alternatives

(D^w_j) =

Alternatives (M)	
HVF	0,17
Green solvolysis	0,46
Thermal processes	0,27
Mechanical processes	0,27
Dispose	0,27

Distance of each alternative from the worst alternatives $D_i^w = \sqrt{\sum_{j=1}^{N}(\chi_{i\,j} - \chi_j^w)^2}$

Similarity to the worst condition

(S_j) =

Alternatives (M)	
HVF	0,29
Green solvolysis	1,00
Thermal processes	0,53
Mechanical processes	0,53
Dispose	0,53

Similarity to the worst condition $S_i = {D_i^w}/{(D_i^w + D_i^b)}$

$S_i \in [0, 1]$

$S_i = 1$ if and only if the alternative solution has the best condition

$S_i = 0$ if and only if the alternative solution has the worst condition

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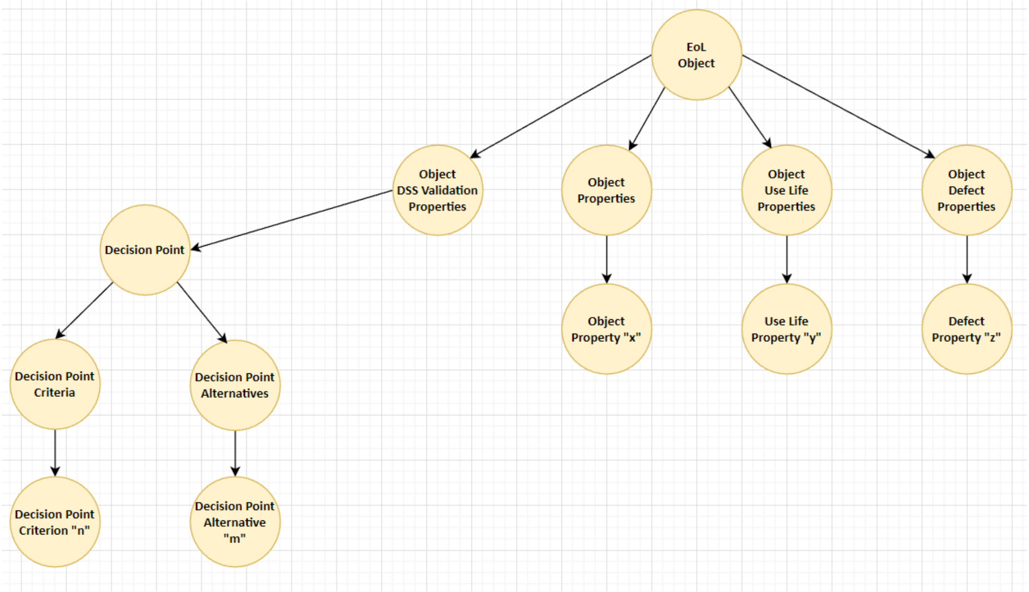
Data structure - DSS

Data elements identification: data structures the DSS has to manage & their relationships:

- 2 main data structures:
  - ***Decision Point*** : collects data elements related to a specific DSS Decision Point (e.g., criteria, alternatives)
  - ***EoL*** : collects data elements related to an EoL composite object to be evaluated using the DD (e.g., fiber type, matrix type, fiber %)
- Related data structures:
  - ***Criterion*** : data elements related to a specific criterion (e.g., name, weight)
  - ***Object Property*** : ....
  - ....



Elements structuring: a formal specification of the data elements:

- ***GraphQL*** : query language for APIs and data elements specs

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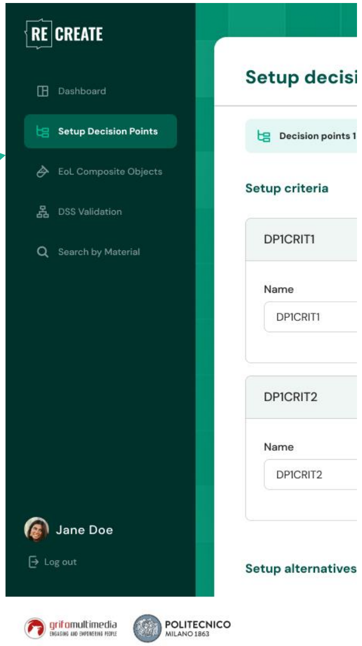
DSS UI Design and development

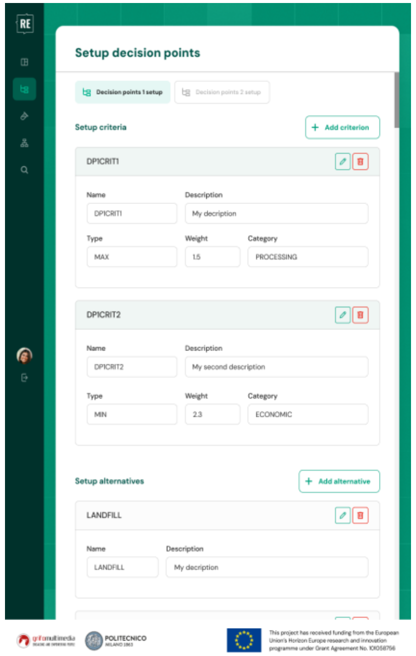
UI mock-up:

- *UI Design and development* - main aspects:
  - Navigation: a clear and logical system to move through the interface easily
  - Clarity and Simplicity: simple and intuitive design
  - Consistency: have a consistent design throughout the interface (e.g., fonts, colours, layout)
  - Responsive Design: ensure the UI adapts to different screen sizes and devices (e.g., laptops, tablets)

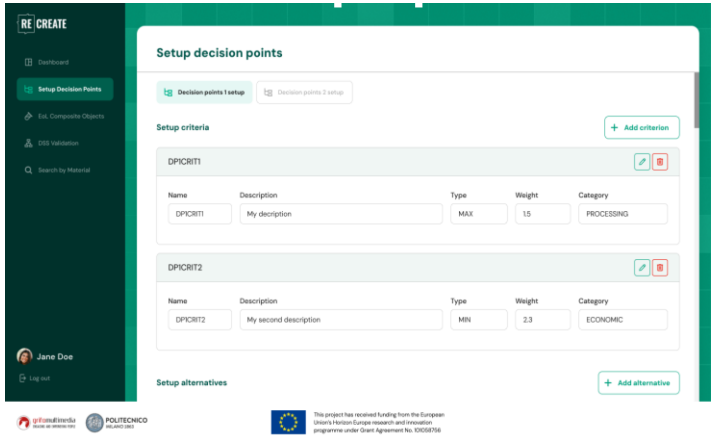
Navigation pane on the left



Tablet



Laptop



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Decision Point 1: Example 1

A EoL wind blade, with 8 defects, that has been in service for 20 years, held together by irreversible adhesives.

EoL Element Descriptive elements

Element description = EOL Wind blade

Composite Type =
- ○ Carbon fiber reinforced composite (CFRC)
- ◉ Glass fiber reinforced composite (GFRC)

Structural part: A component that bears heavy loads or contributes to the stability of a structure (e.g., wind turbine blade, automotive frame)

EoL Element characteristics

Height (mm) =	284
Width (mm) =	241
Thickness (mm) =	2

Defect structurality data

Please specify the following data for each defect

Defect Area	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	A_5 (mm^2)	A_6 (mm^2)	A_7 (mm^2)	A_8 (mm^2)
	611,85	721	410	503	1580	2688	505	607
Defect Depth	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)	d_7 (mm)	d_8 (mm)
	0,7	1,1	1,1	1,2	1	1	1,5	1,7

Appearance data

Moderately damaged

Appearance Description: Deep visible cracks, one or many

Service life rating data

Input sector: Wind energy

Insert EoL Element Age (years): 20 √

Joining Elements data

Joint Type: Irreversible

Mechanism: Irreversible Adhesive √

DSS Indication

Higher values indicate the most suitable solution

Repair	0,05
Reuse	0,00
Recycle	1,00
Dispose	0,17

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Decision Point 1: Example 2

A EoL wind blade, with 8 defects, that has been in service for 20 years, held together by irreversible adhesives.

EoL Element Descriptive elements

Element description = EOL Wind blade

Composite Type =
- ○ Carbon fiber reinforced composite (CFRC)
- ● Glass fiber reinforced composite (GFRC)

Structural part — A component that bears heavy loads or contributes to the stability of a structure (e.g., wind turbine blade, automotive frame)

EoL Element characteristics

Height (mm) =	284
Width (mm) =	241
Thickness (mm) =	2

Appearance data

Moderately damaged — **Appearance Description:** Deep visible cracks, one or many

Defect structurality data

Please specify the following data for each defect

Defect Area	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	A_5 (mm^2)	A_6 (mm^2)	A_7 (mm^2)	A_8 (mm^2)
	611,85	721	410	503				

Defect Depth	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)	d_7 (mm)	d_8 (mm)
	0,7	1,1	1,1	1,2				

Joining Elements data

Joint Type Irreversible — **Mechanism** Irreversible Adhesive √

Service life rating data

Input sector Wind energy — **Insert EoL Element Age (years)** 5 √

DSS Indication

Higher values indicate the most suitable solution

Repair	0,81
Reuse	0,00
Recycle	0,21
Dispose	0,17

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Decision Point 1: Example 3

A EoL wind blade, with 4 defects, that has been in service for 10 years, held together by irreversible adhesives.

EoL Element Descriptive elements

Element description = EOL Wind blade

Composite Type =

- (selected) Carbon fiber reinforced composite (CFRC)
- Glass fiber reinforced composite (GFRC)

Non-structural part: A component that does not bear significant loads or affect structural stability (e.g., table-top, seat, wall panel)

EoL Element characteristics

Height (mm) =	284
Width (mm) =	50
Thickness (mm) =	2

Defect structurality data

Please specify the following data for each defect

Defect Area	A_1 (mm^2)	A_2 (mm^2)	A_3 (mm^2)	A_4 (mm^2)	A_5 (mm^2)	A_6 (mm^2)	A_7 (mm^2)	A_8 (mm^2)
	210	721	410					
Defect Depth	d_1 (mm)	d_2 (mm)	d_3 (mm)	d_4 (mm)	d_5 (mm)	d_6 (mm)	d_7 (mm)	d_8 (mm)
	0,5	1	1					

Appearance data

Scuffed

Appearance Description: Micro-cracks, abrasions

Service life rating data

Input sector: Sports Equipment

Insert EoL Element Age (years): 2 √

Joining Elements data

Joint Type: Reversible

Mechanism: Reversible Adhesives √

DSS Indication

Higher values indicate the most suitable solution

Repair	0,25
Reuse	0,82
Recycle	0,00
Dispose	0,00

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Decision Point 2: Some examples

500kg of GFRP that coming from EoL wind blade

EoL Element Descriptive elements

Element description = Pieces of EoL wind blade

Composite Type =
- ◯ Carbon fiber reinforced composite (CFRC)
- ◉ Glass fiber reinforced composite (GFRC)

Fiber Type = E-Glass

EoL Element characteristics

Weight (Kg) =	500
Fiber ratio (% by weight) =	50%

OK

DSS Indication

Higher values indicate the most suitable solution

High Voltage Fragmentation (HVF)	0,39
Green solvolysis	0,53
Thermal processes	0,39
Mechanical processes	0,56

Expected tensile strength

Process	High Voltage Fragmentation	Green solvolysis	Thermal processes	Mechanical processes
Tensile Strength (MPa)	2067	3100,5	2067	1722,5

Expected granulometry

Process	High Voltage Fragmentation	Green solvolysis	Thermal processes	Mechanical processes
Granulomtery	Granulates with medium fibers	Uncut fibers	Uncut fibers	Granulates
Dimensions (mm)	1,4 - 15	>20	>20	0,6 - 5

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RE

Find out more about RECREATE by subscribing to our newsletter!!

Questions?

Dr. Marco Diani
marco.diani@polimi.it

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Thank you for your attention!

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BWM - continued

4. The consistency is checking using an input- based Consistency ratio matrix which depends on both the number of criteria and the scale of assigned preferences

	Number of Criteria						
Scales	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1898	0.2206	0.2527	0.2577	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

5. The consistency ratio CR is calculated based on assigned preferences and if CR<0,2681 in our example, the assigned preferences are acceptable

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TOPSIS - continued

Steps are as follows:

1. Start from identifying alternatives

For decision point 1 : Re-use , Repair, Recycle or Dispose

For decision point 2 : Mechanical, HVF, Thermal and Solvolysis

2. Criteria for the relevant decision-making points

3. Constructing the decision matrix as seen in the previous slide

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TOPSIS Method (continued)

4. Normalize the Decision Matrix
   - Normalize the values to eliminate the scale differences between criteria
   - Use normalization techniques such as min-max normalization or vector normalization

5. Calculate the Weighted Normalized Matrix
   - Multiply the normalized values by the assigned weights for each criterion

6. Determine the *Positive* and *Negative Ideal Solutions*
   - Calculate the ideal solution, which represents the best performance for each criterion
   - Calculate the negative ideal solution, which represents the worst performance for each criterion

7. Calculate the distances ($\boldsymbol{D_i^B}$, $\boldsymbol{D_i^W}$) of each alternative from the *Positive* and *Negative Ideal Solutions*

8. Calculate the *Similarity* ($\boldsymbol{S_i}$) of each alternative to the *Negative Ideal Solutions*

$$\boldsymbol{S_i} = \frac{\boldsymbol{D_i^W}}{\boldsymbol{D_i^W} + \boldsymbol{D_i^B}}$$

9. Select the alternative having the highest *Similarity*

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This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement no. 101096858

REFRESH

GEES RECYCLING

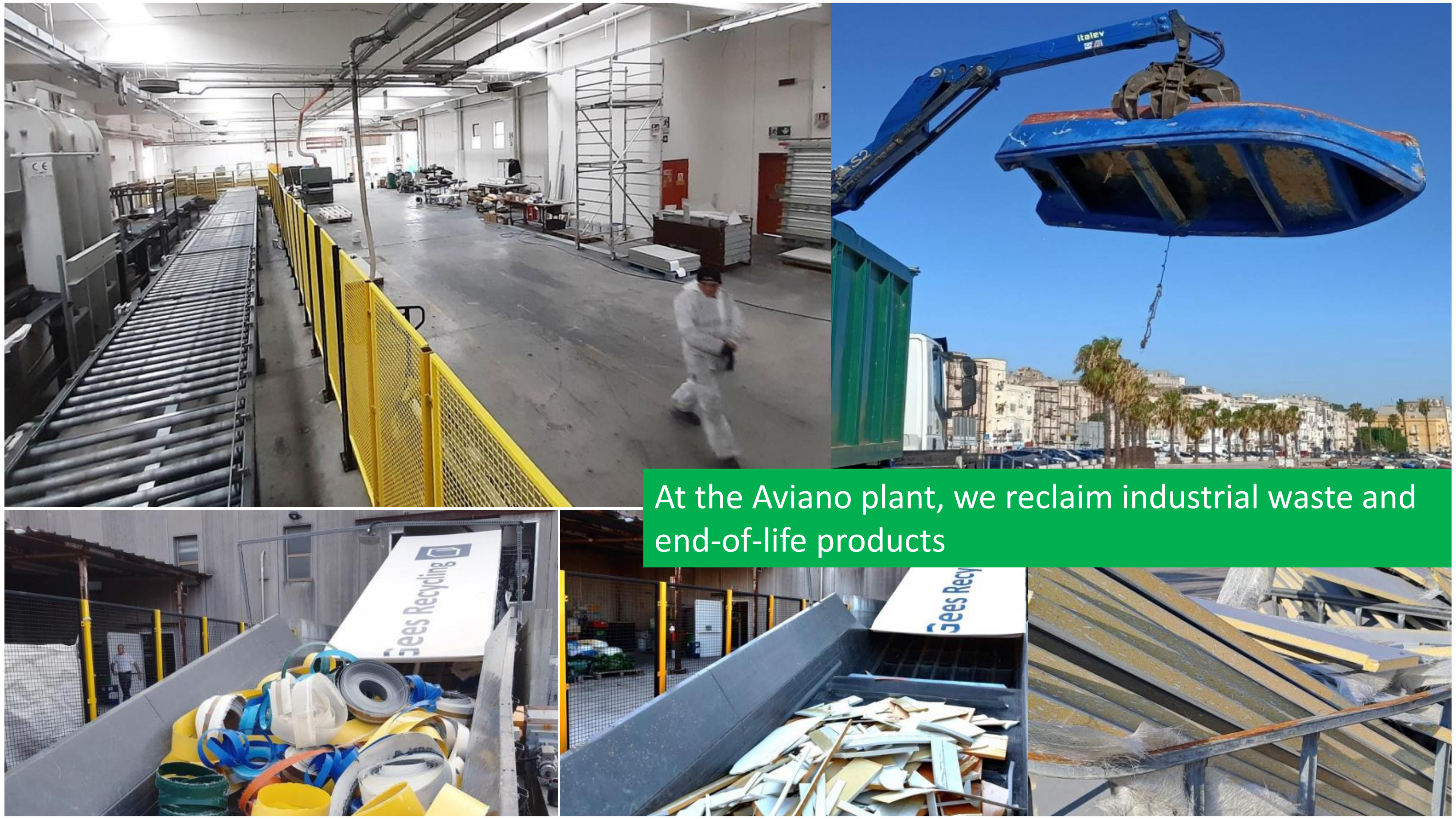
EuReComp

The 3rd EuReComp Workshop – March 19, 2025

Wind blades recycling :
Our experience in circular economy

Giorgio Betteto . R&D Gees Recycling Srl Italy

Gees Recycling has developed a mechanical recycling process for composites of any kind , rigid foams , core materials and other waste like x-linked thermoplastics



At the Aviano plant, we reclaim industrial waste and end-of-life products

Horizon Europe
101096858

We are authorised industrial recyclers with >1800 t/y processed

In operation with our EU and World Patents since 2015, Industrial operation since 2018

Gees is one of the few realities in Europe where is possible to send truckloads of composite waste to have them transformed in new products.

Wind blades : an interesting feedstock

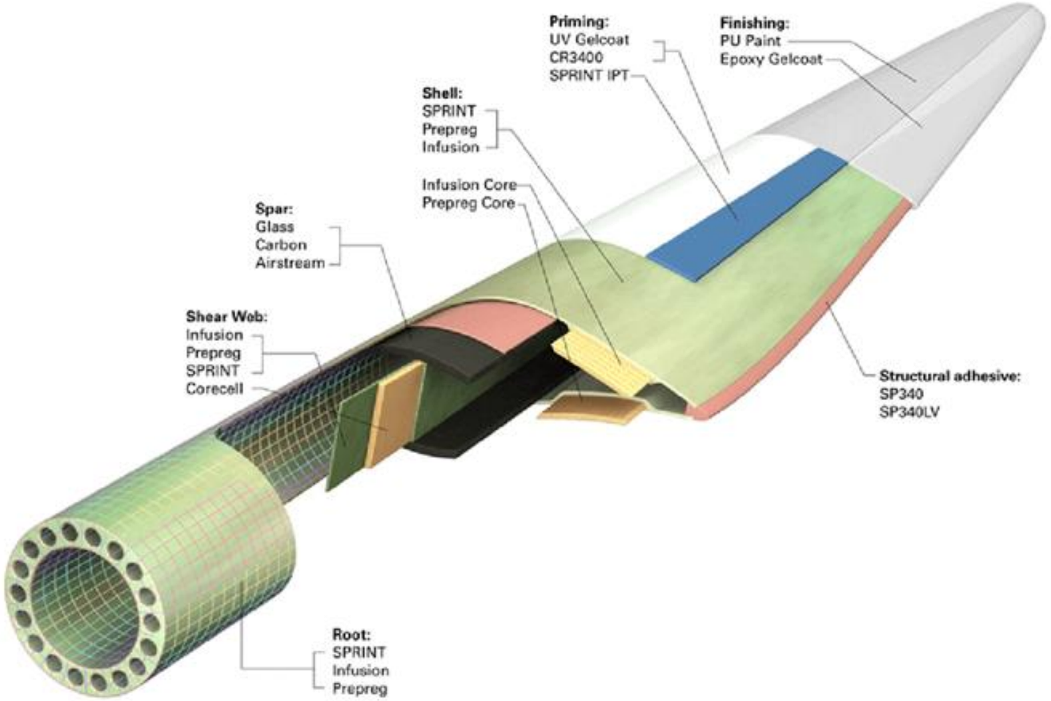


Figure 2 - Composition of a wind blade - Mischavewsky et al.

Green : fiberglass-epoxy, yellow and red : core material , Black : carbon fibre-epoxy, white : gelcoat

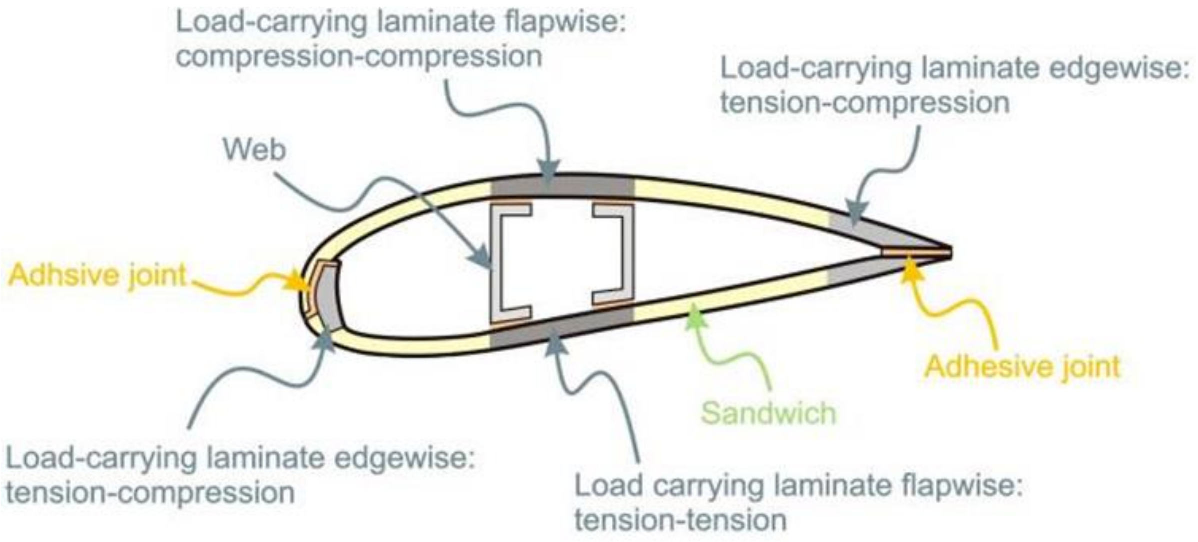


Figure 2 - Section of wind blade - Mischanewsky et al.

Wind blades : In practice the root and wing are two different products

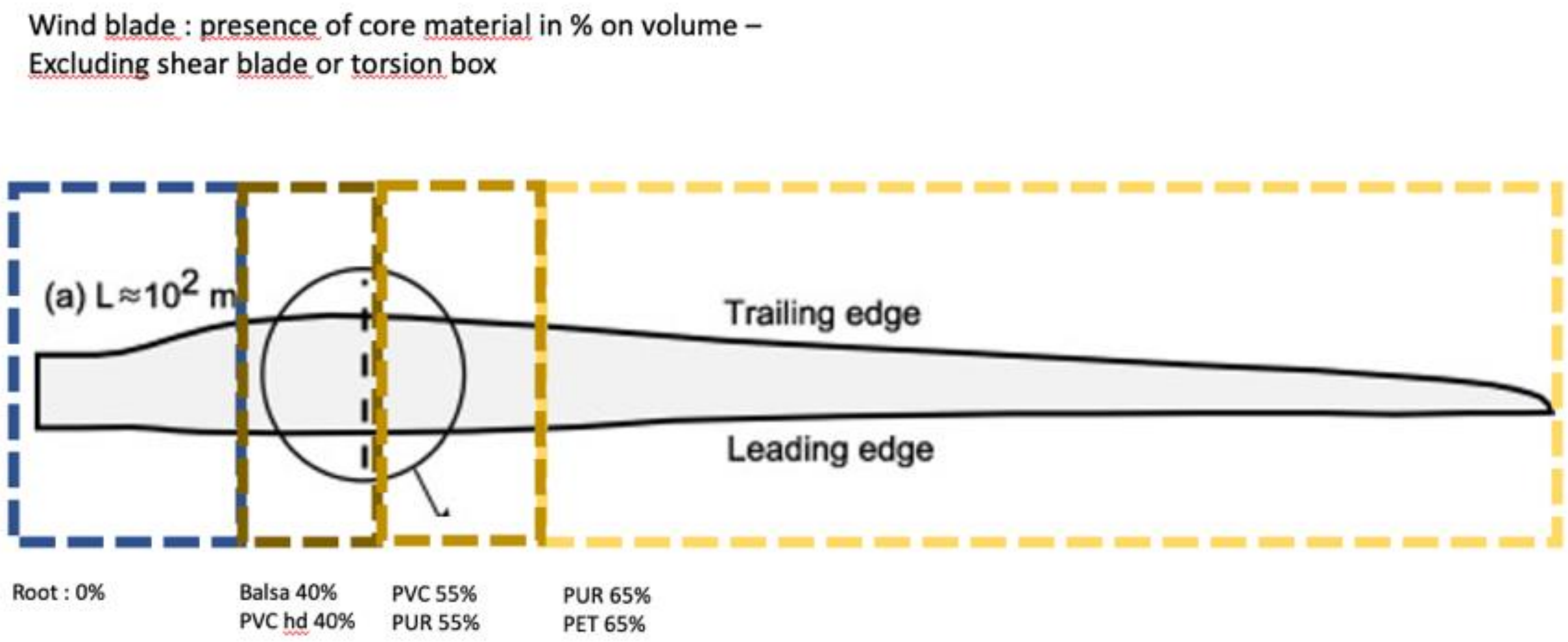


Figure 5 - Core material in blades - Giorgio Betteto

Presence of Carbon fiber in sparcaps

The core material makes the difference – also in recycling of blade

Figure 4 - Shredded and granulated blades - Gees Recycling

Left : Coarse shredding   Centre : heaviest fraction   Right : lightest fraction

Core Material makes

- Much less interesting – if not forbidden the use in cement kilns .
- Lower the production output by >70% in any thermochemical process like pyrolysis or solvolysis – Reactors have fixed volumetry , here the density is ¼
- Complicate (much) the process , with unwanted gases , byproducts and residues , that will change on type of CM.

GEES RECYCLING

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Something not found in literature…

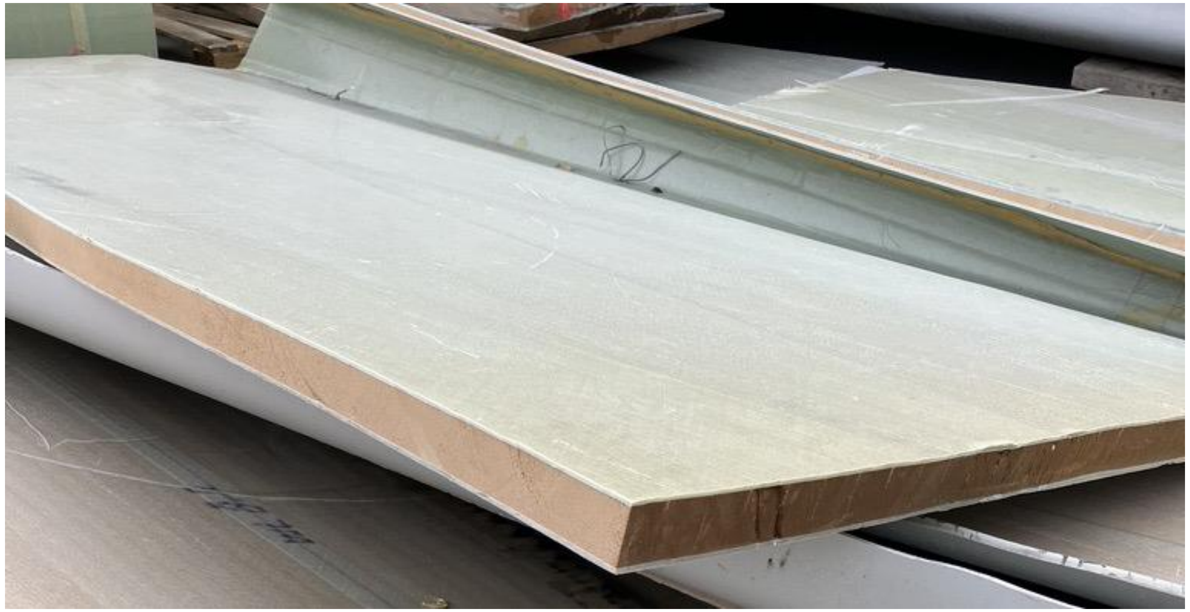


Figure 6 - Low density parts of blades - Giorgio Betteto

By volume , the core material presence in blades is significant , particularly after shredding:

Blades composition	Example Vestas V42 36 Meters						
			Specific weight after shredding				
weight of blade kg	1280		Fiberglass epoxy specific weight /S	Balsa Specific weight	Core Material specific weight		
			0,8	0,18	0,09		
Part	Material	Density	Lenght M	Weight Kg	Volume Shredded in Liters	% of volume	% of weight
Root (Blue)	Fiberglass Epoxy	1,5	5	510	637,50	**23,35%**	39,84%
Transition (brown)	Fiberglass epoxy	1,5	4	290	362,50	**13,28%**	22,66%
	Balsa / Core M	0,18	4	45	250,00	**9,16%**	3,52%
Wing connection (Light brown)	Fiberglass epoxy	1,5	27	340	425,00	**15,56%**	26,56%
	Core Material	0,09	27	95	1055,56	**38,66%**	7,42%
			Total	1280	2730,56	**100,00%**	100,00%

Table 1 - Composition of blade in volume - Gees Recycling from Wind Blade examination

These data are from our analysis , is very hard to get data from blade makers

Our idea :

- Use the least interesting parts of blades , the less adapt to other recycling processes
- Transform in new materials using the RFM mechanical recycling – that was developed for composite waste regardless of resin , fiber or rigid foam type
- Exploit the low density as a value insted than a obstacle

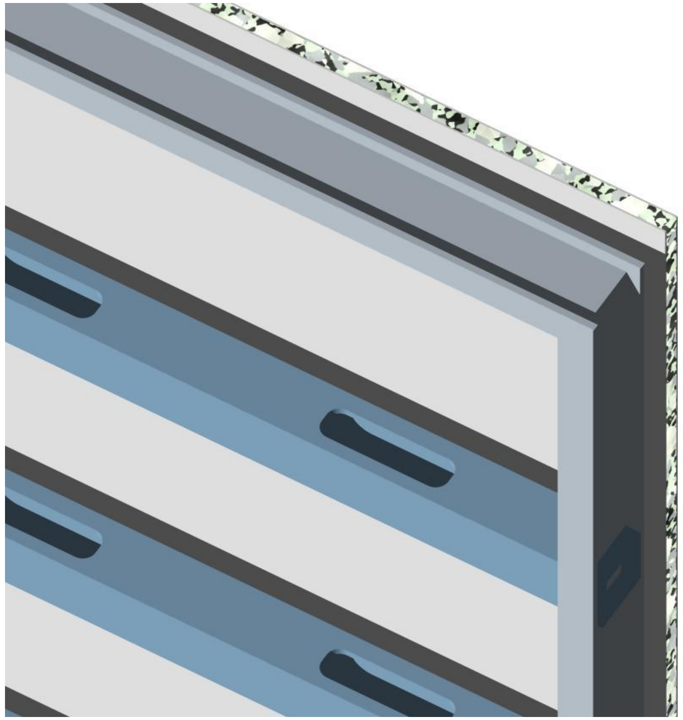
Demonstration of results

From JEC World2025 https://www.youtube.com/watch?v=26hVxI4Wnhs

Second part : Circular economy

Formwork panels – widely used in any reinforced concrete structure , including wind parks onshore and floating wind

Second part : Circular economy – From project to results



Formwork panels – Fully composite made – Panel from wind blades with fiberglass laminate
Reinforcing in pultruded composite with recycled content . Competitive and durable

Circular economy - Formwork

Advantages :

- Cost competitive
- No water absorption, no rust , no rot, electrical insulants
- Lighter than steel and aluminum
- RFID embedded for easy remote id
- Less prone to theft
- Recycled content >85% very good for Green public procurement
- LCA lowest by far of all products on market
- 100% recyclable

Second part : Circular economy

Equipment Shelter

Standard dimensions 2,4 X 2 X 2,4 – 3 X 2,4 X 2,4

Outer panel in RFM recycled from wind blades

Insulation inside

Fixed structure in
Composite pultruded with recycled content

Absolutely resistent to water, weather , corrosion
Not conductive

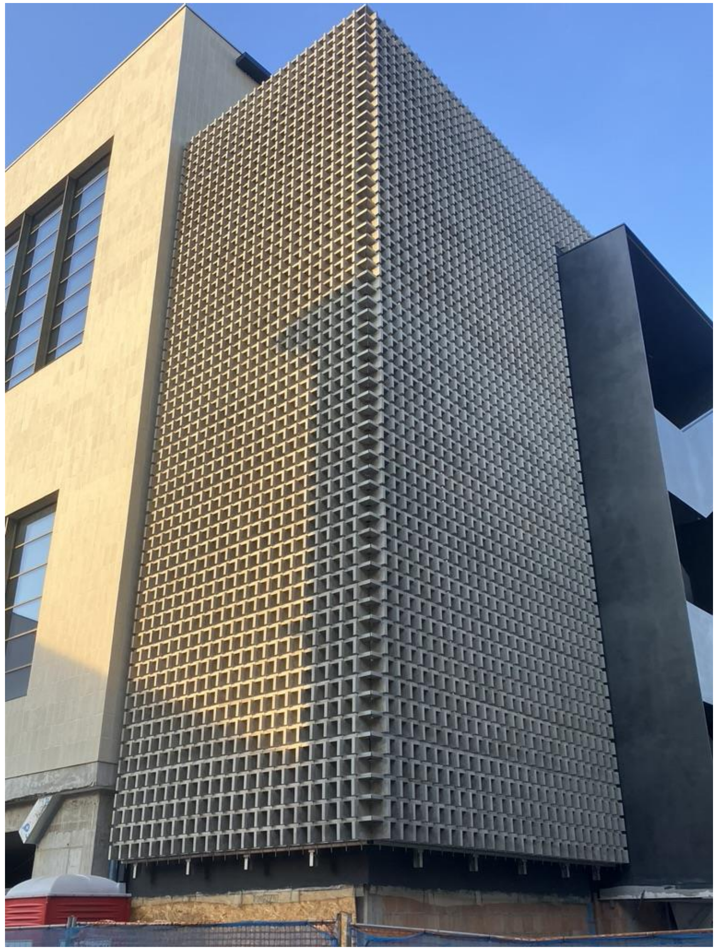
Circular economy

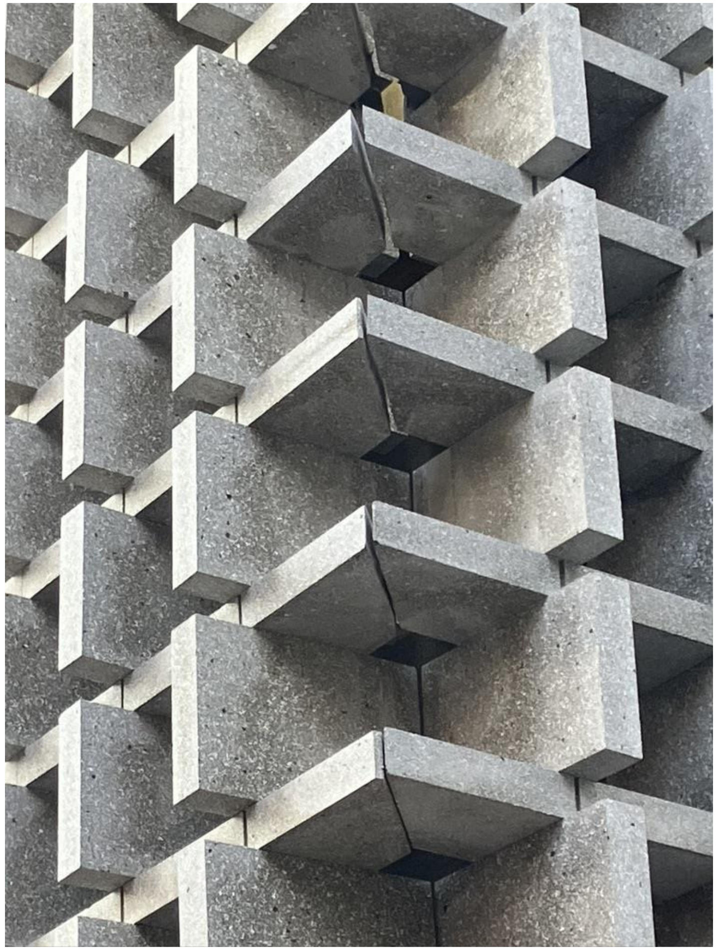
Equipment Shelter

Fully composite - >90% Recycled content

Circular economy - Building components

Recycled composites for shading facades and architectural components
40% lighter than ceramics
70% lighter than concrete
96% Recycled content





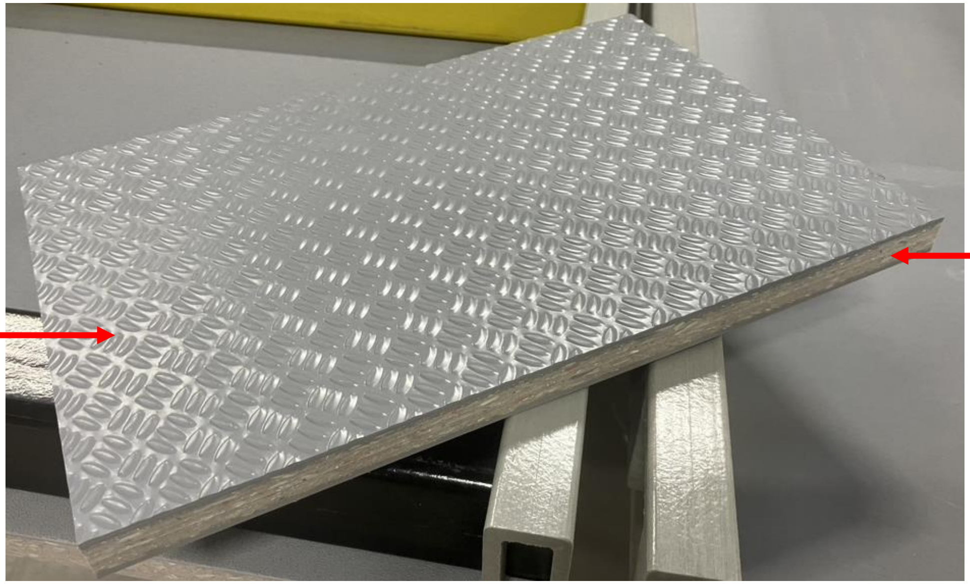
REFRESH : Synergy and cooperation as key factor

Gjenkraft

Recycled GF from pyrolysis

Glass fiber Mat

Fiberglass Laminate



GEES RECYCLING

Recycled wind blade panel as core

TOWARD A GREENER AND BLUER MORROW
ENECOLAB

Energy from dust and powders to feed the processes

Circular economy

ENECOLAB
process : energy
from dusts and
powders to feed
the recycling
Processes
https://www.youtube.com/watch?v=x_xtKuVrH-Q

Open to any question and request

Thanks

Giorgio Betteto
geesretracking@gmail.com

REPOXYBLE – Depolymerizable bio-based multifunctional closed loop recyclable epoxy systems for energy efficient structures

Athanasios Kotzakolios
University of Patras

3rd EURECOMP Workshop

March 19°

Athens, Greece

REPOXYBLE - Depolymerizable bio-based multifunctional closed loop recyclable epoxy systems for energy efficient structures
Funded by the European Union. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union. Neither the European Union nor the granting authority can be held responsible for them.

repoxyble
BIO-BASED MULTIFUNCTIONAL RECYCLABLE COMPOSITES

REPOXYBLE goals & objectives

REPOXYBLE aims to contribute to the developement of a new generation of multifunctional, safe and sustainable by design polymers.

O1 — **New chemistries** for fast curing resins, new bio-based composites and novel production techniques with advanced functionalities with potential to extended use in extreme conditions (high temperatures)

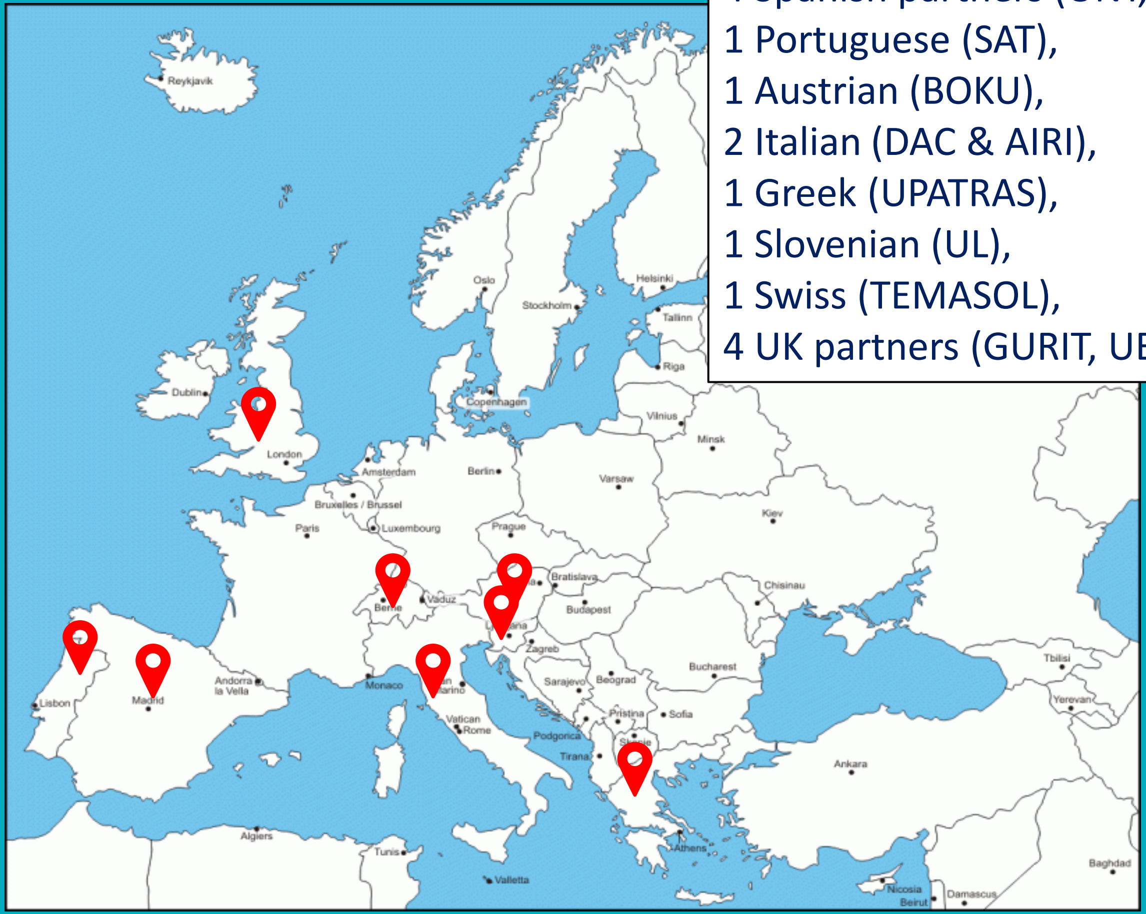
O2 — Integrate **multifunctional composites** with enhanced thermal and electrical conductivity for thermal management and in-situ strain sensing

O3 — **Closed loop energy efficient recycling system**

O4 — Energy efficient lightweight composites with **positive environmental impact over their entire life cycle**

O5 — **Economic feasibility in different market applications, business models and circular value chains** for lightweight bio-based components, improving **time to market**

Repoxyble consortium



4 Spanish partners (ONY, AVA, GAIKER, UDG),
1 Portuguese (SAT),
1 Austrian (BOKU),
2 Italian (DAC & AIRI),
1 Greek (UPATRAS),
1 Slovenian (UL),
1 Swiss (TEMASOL),
4 UK partners (GURIT, UBAH, RIVERS, AEROGEL CORE)

Project management

avanzare

Technology development

MATERIAL LIFECYCLE VALUE CHAIN

- Polymer synthesis building blocks
- Resin formulation, additives
- Composite design and manufacturing
- Material characterization
- Energy Efficient Manufacturing
- Chemical recycling
- Automotive and Aerospace end users

Horizontal aspects: safety, sustainability, legal, dissemination, exploitation

SSbD & MATERIAL VALUE CHAIN SUPPORT

- Diss & Comm Multicriteria Decision analysis
- Safety and risk assessment
- SSbD, legal criteria
- IPR management Exploitation strategies
- Data collection & management

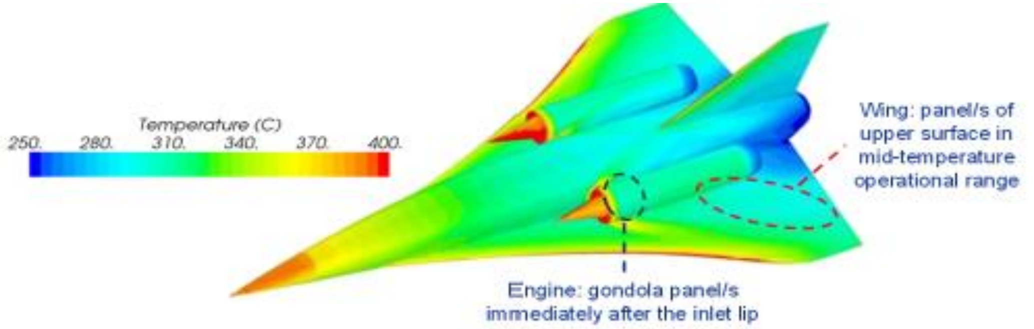
BIO-BASED MULTIFUNCTIONAL RECYCLABLE COMPOSITES

REPOXYBLE case studies

Two key case studies:

- **Aerospace:**

High technical requirements (e.g. lightweight, high temperature resistence)



- **Automobile**

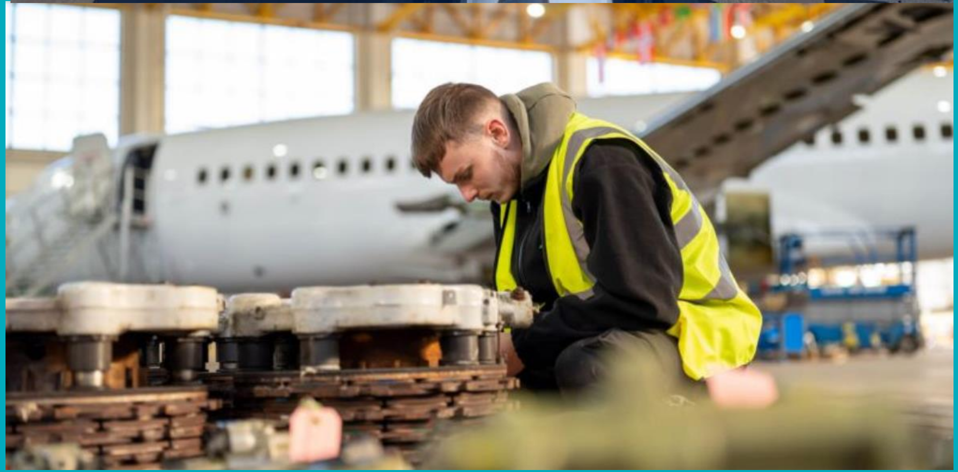
High sustainability (e.g. Recyclability, high bio-based content)

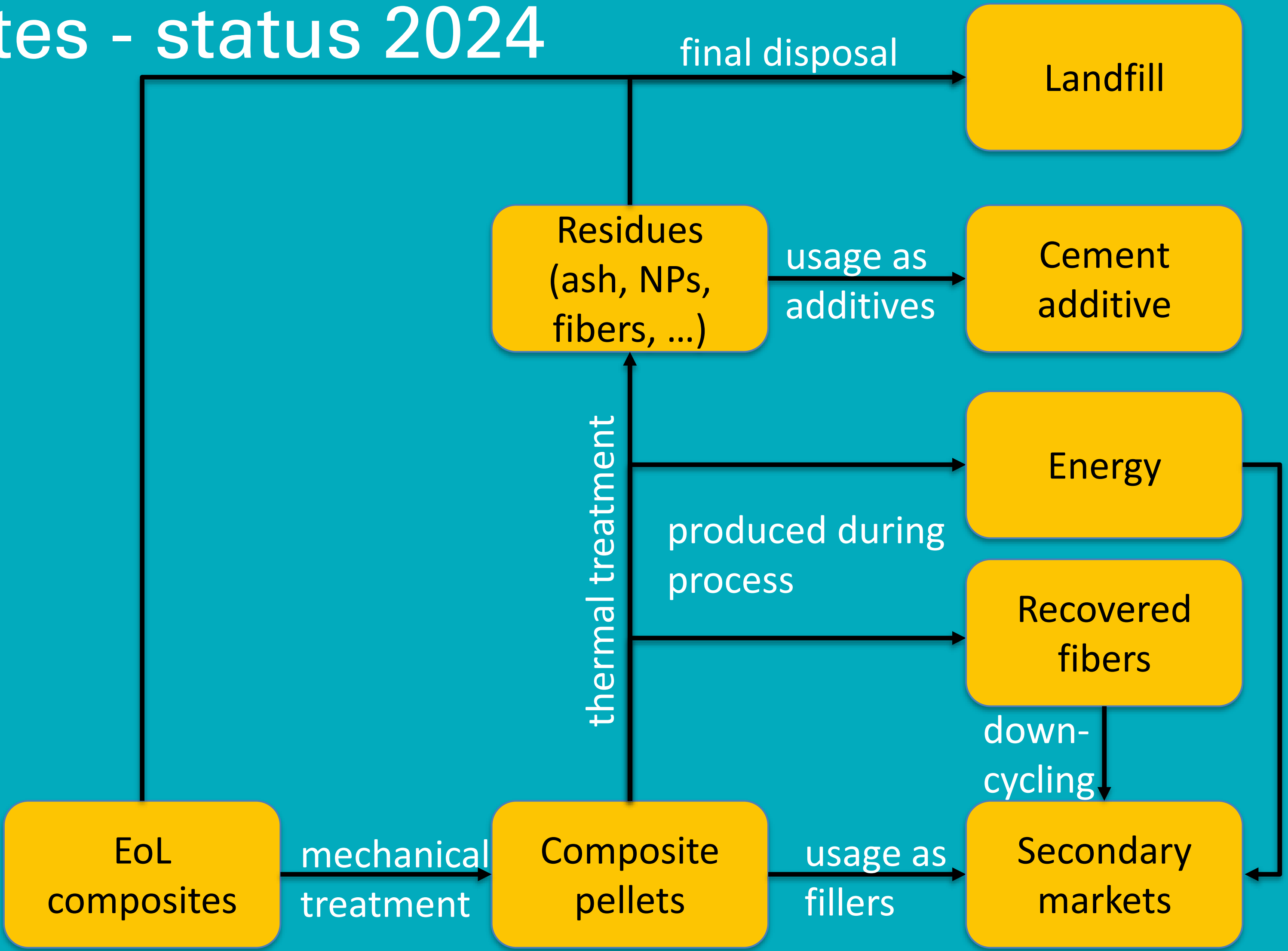
repoxyble BIO-BASED MULTIFUNCTIONAL RECYCLABLE COMPOSITES

State of composite (recycling)

- **323.000 tonnes** of composite material **produced** in EU in 2017, trend rising
- **Key sectors**: Energy; Food & Water; Transportation; Home, Leisure, Information & ICT; Construction
- Main methods of disposal: **Thermal treatment, landfilling**
- Main problem: **Heterogenity of composites; no industrial-scale recycling route (closed loop) available**

Recycling of composites - status 2024





repoxyble
BIO-BASED MULTIFUNCTIONAL RECYCLABLE COMPOSITES

Recycling options for composites

Mechanical Recycling:
Milling, Grinding, Shredding, etc.

TRL

TRL $\geq$ 9

Thermal recycling:
Pyrolysis, Fluidized Bed, Joule heating, etc.

TRL < 6

Chemical Recycling:
Solvolysis (Hydrolysis, Glycolysis, Aminolysis, Supercritical)

Electrical Recycling:
Pulse discharge, electrical driven heterocatalytic decoposition, etc.

TRL < 4

Biological Recycling:
Microbial, fungal, etc.

Mechanical Recycling:

Milling, Grinding, Shredding,etc.

Pros	Cons
Already established (TRL ≥ 9)	No clear separation of base materials
High throughput	Damage to Fibers
Market for product established	Limited application of products

Thermal Recycling:

Pyrolysis, Fluidized Bed, Joule heating, etc.

Pros	Cons
Already established (TRL ≥ 9)	Energy intensive
Products for multiple uses (gas, fluids, solids)	May damage e.g. fibres
Volume reduction of waste material	Not all base materials can be recovered
Markets for products established	Problematic emissions
High throughput	

Chemical Recycling:

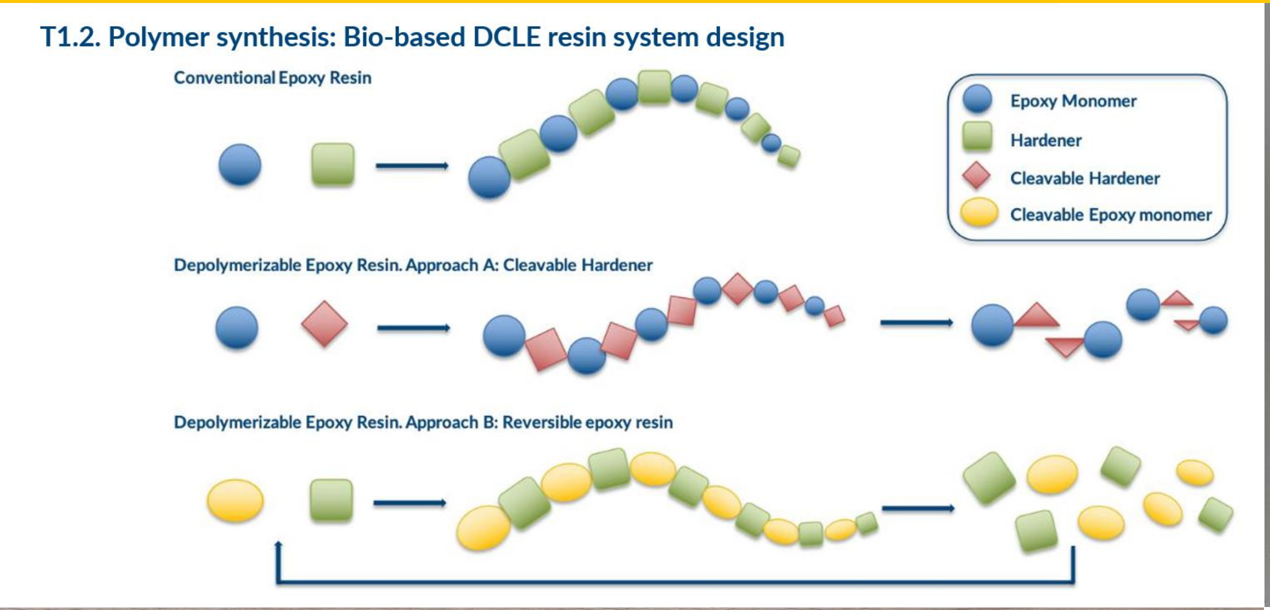
Solvolysis (Hydrolysis, Aminolysis, Supercritical)

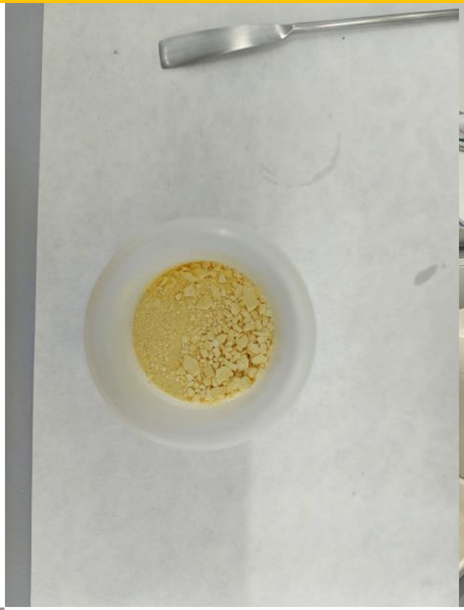
Pros	Cons
High recovery rate (lab scale)	Moderate TRL (< 6)
Enables recovery of most base materials	Usage of hazardous substances
„Good quality“ of recycled material	Market for recycled products not established on larger scale
Depending on method, not energy intensive	

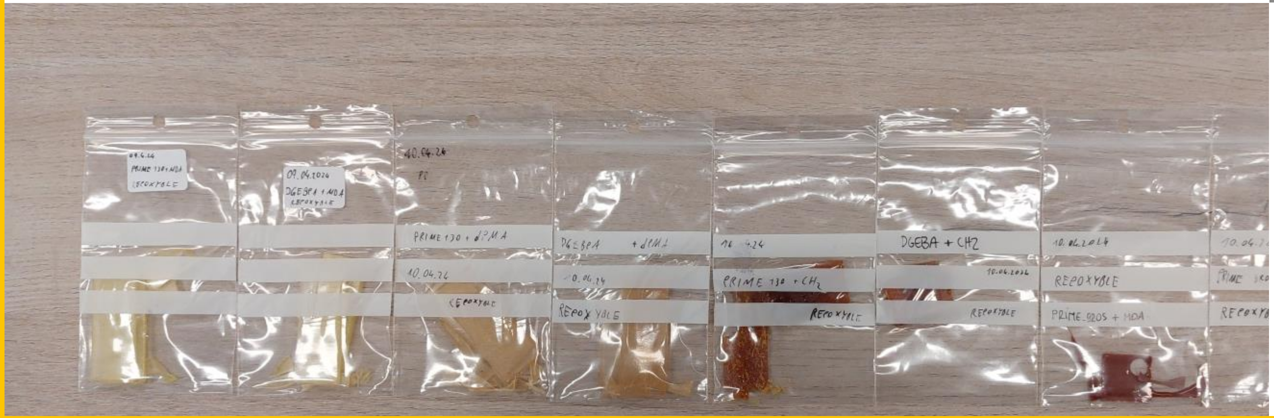
👉Conclusion from recycling comparison

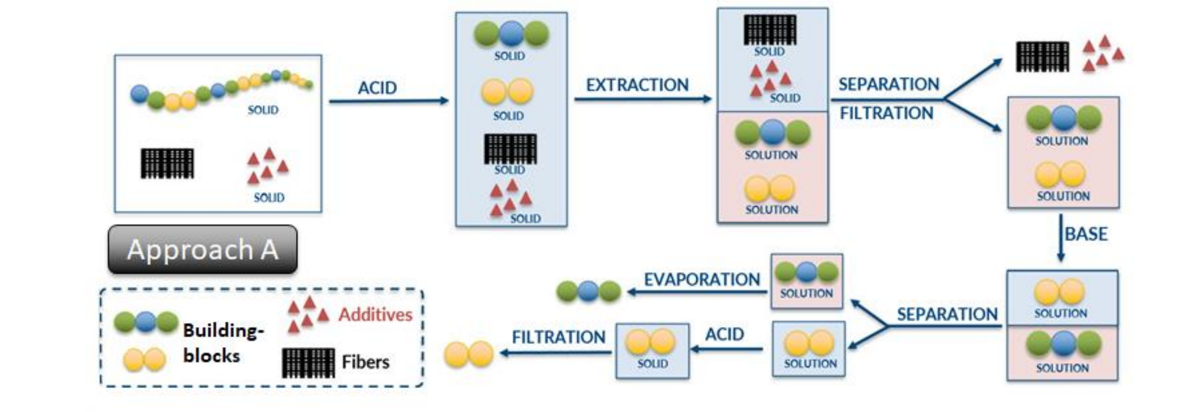
- **Chemical recycling** can recover all base materials
- Pyrolysis for recovery of carbon fibers as secondary option
- Mechanical (pre)treatment as last resort as fibers are irreversibly damaged
- Cement and or use as filler as last product option

DCLE system in REPOXYBLE (developed by ONYRIQ)









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Depolymerisation results- concentrated acids

Tab. Ability of acids to depolymerize different epoxide systems in 120h of exposure. Y = depolymerized completely, N = depolymerisation not achieved, I = incomplete depolymerisation

Depolymerization possible? (Y/N/I)					
Resin	**Hardener**	**Acid 1**	**Acid 2**	**Acid 3**	**Acid 4**
Prime 130	CH2	Y	Y	Y	I
Prime 130	CH5	Y	I	Y	N
Prime 130	CH6	Y	I	Y	I
Prime 130	MDA	Y	N	Y	N
Prime 130	dPMA	Y	I	Y	N
DGEBPA	CH2	Y	I	Y	N
DGEBPA	MDA	Y	N	Y	I
DGEBPA	dPMA	Y	N	Y	N
AMPROBIO	CH5	Y	N	Y	I
AMPROBIO	CH6	Y	N	Y	Y
AMPROBIO	MDA	Y	N	Y	N

REPOXYBLE achievements

- Developed:
  - **all the building blocks**
  - **resins formulations** and the recycling process
  - Working on the composite **IR-based curing process**
  - materials and techniques for **multifunctional properties**:
    electrical conductivity, thermal dissipation, and structural self-monitoring

- Next
  - Full characterization and testing, upscale and first prototypes.

Key challenge: successfully recycle the epoxy system into valuable primary and secondary materials with high potential for several markets

REPOXYBLE - Outlook

- **Next Steps:**
  - Achieve complete depolymerization
  - Recyling of composite with additives (NPs + Graphene)
  - Validate and optimize the chemical recycling scheme
  - Upscale by factor 10

- **Barriers & Opportunities:**
  - Bio-based content as gatekeeper for technical application
  - Complete depolymerization mandatory
  - Legal challenges: inclusion of polymers into REACH
  - SSbD in evaluation phase → opportunity to give input

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BIO-BASED MULTIFUNCTIONAL RECYCLABLE COMPOSITES

Thank you for participating!

We will keep you updated on

www.repoxyble.eu

LinkedIn: REPOXYBLE project

REPOXYBLE - Depolymerizable bio-based multifunctional closed loop recyclable epoxy systems for energy efficient structures
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13th Venice Training School

Innovating with Purpose:
A Hands-on Journey into Functional, Safe and Sustainable Advanced Materials

REPOXYBLE is one of the co-organizing EU-funded projects for this year's edition!

The school is one of the key events on safe & sustainable advanced materials, taking an in-depth look at the application of Safe-and-Sustainable-by-Design (SSbD) in early, mid and late stages of innovation, and what it takes to put theory into practice

SAVE THE DATE:

09-13 June 2025

Auditorium Santa Margherita of Università Ca’Foscari, Venice, Italy

SARDINIA 2025

20th International Symposium on Waste Management, Resource Recovery and Sustainable Landfilling

SAVE THE DATE:

13-17 October 2025

Forte Village Resort in Santa Margherita di Pula, Sardinia, Italy

REPOXYBLE is organizing the workshop "Circular plastics and advanced composites"

The REPOXYBLE partners from the BOKU University will provide a focus on the barriers and drivers of circular business concepts, in line with the Safe and Sustainable by Design (SSbD) principles.

The workshop will be held in cooperation with partners from the project RETURN (Multi-Risk sciEnce for resilienT commUnities undeR a changiNg climate).

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BLADES2BUILD

Recycle, repurpose and reuse end-of-life wind blade composites – a coupled pre- and co-processing demonstration plant

Holcim Circular Economy Strategy : from Construction Demolition Waste to End-of-Life Wind Turbine Blades recycling

3rd EURECOMP Workshop

March 2025

Funded by the European Union

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HOLCIM - Global Leader In Sustainable Construction

65,000
Employees

Net Zero
1.5°C-aligned 2030 & 2050 targets validated by SBTi

2807
Operating sites around the world

50+ Markets around the World

26.4 BN CHF
Net Sales

4%
reduction in our CO_2 per net sales

100+ pilots with Startups
In our open innovation ecosystem

#1
R&D organization in our industry

5 worldwide R&D hubs

Funded by the European Union

HOLCIM - Global Leader In Sustainable Construction

Funded by
the European Union

Project to drive decarbonization

Funded by
the European Union

Holcim sustainability target – Strategy 2025

ECOPact	Circular Economy	Construction Demolition Materials	Green Capex
25%	**45**	**10**	**0.5**
TO NET SALES GROWTH	MILLION TONS	MILLION TONS	BILLION CHF

Freshwater withdrawal	Diversity	Climate	Sustainable Financing
-25%	**+40%**	**520**	**> 40%**
LITERS / TON OF CEMENT	MORE WOMEN IN SENIOR MANAGEMENT	KG CO_2 NET / TON OF CEMENT	LINKED TO CLIMATE, WATER & SAFETY GOALS

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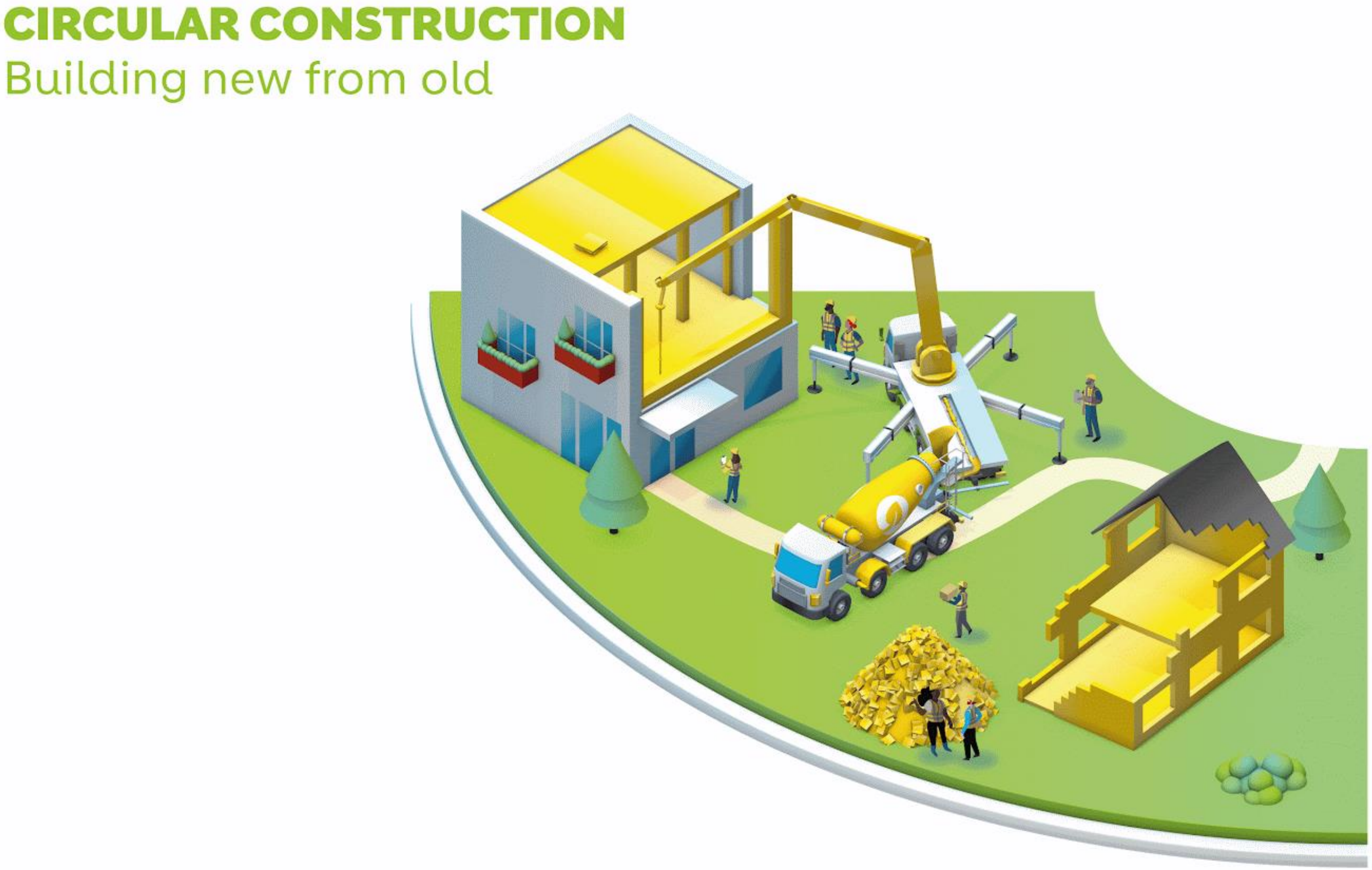
Focus on circularity



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Circular construction - Ecocycle

ECOCYCLE® INSIDE LABEL

OVERALL QUALIFICATION CRITERIA

Two main qualification criteria to be fulfilled for using ECOCycle® inside label

- Product contains at least **10% of recycled construction demolition materials by total mass**

+

- Recycled CDM usage in given plant should be **certified by a third party** (SGS, etc.)

ECOCycle

10% recycled construction demolition materials

Note: The label shows the minimum content (10%). The actual percentage of CDM for products with ECOCycle® inside can be displayed instead.

Note: Please refer to the specific guidelines for each business line in the next slide.

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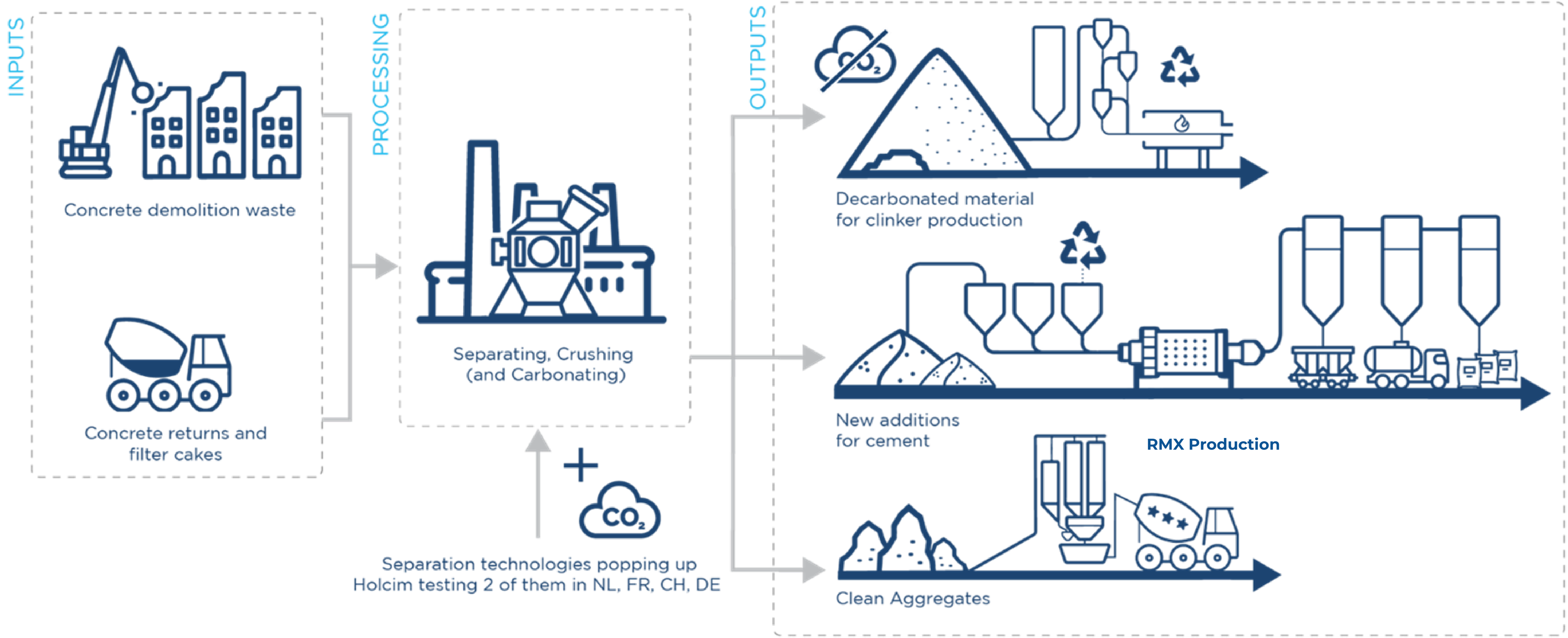
Circular construction - Ecocycle



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Wind Power: Hottest Job in US | US Offshore Wind Woes | Mega Wind Turbines | How Blades Get Reused | Landfill Pileup

Fragments of wind turbine blades await burial at the Casper Regional Landfill in Wyoming. *Photographer: Benjamin Rasmussen for Bloomberg Green*

Green | Energy & Science

Wind Turbine Blades Can't Be Recycled, So They're Piling Up in Landfills

Companies are searching for ways to deal with the tens of thousands of blades that have reached the end of their lives.

Funded by the European Union

BLADES2BUILD - CIRCULAR CONSTRUCTION MATERIALS FROM BLADES -
Positioning Holcim as a Partner for the Energy Transition

Rationale : Blue Sky Innovation

- **'Wind Turbine Can't be recycled**, so they're piling up in Landfills' was the headline of an article in Bloomberg in 2020 showing the problematic
- GE Vernova proposed to collaborate together. MoU was signed in March 2021
- **Horizon Project** Proposal was presented and approved in 2022.
- Project started in January 2023 ~**2 Mio € for HIC**
- It allows us to have a contact with Energy Developers and Wind Industry
- Geocycle developed a solution in Germany, but very difficult to multiply

Objectives + Scope

- Create **Circular Construction Materials** from Wind Blades Waste (CDM)
- Recycled Agg. for **Mortar** and **Concrete** are the lead application among others
- **Reevaluation** of Cement Co Processing is also included in the project

Strategy Fit - Basic Market Potential

- Circular Construction - Potential to be ECOCycle
- Holcim as a partner in the Energy Transition

Project Information

Blades2Build
Grant agreement ID: 101096437

DOI
10.3030/101096437

Start date
1 January 2023

End date
31 December 2025

Funded under
Climate, Energy and Mobility

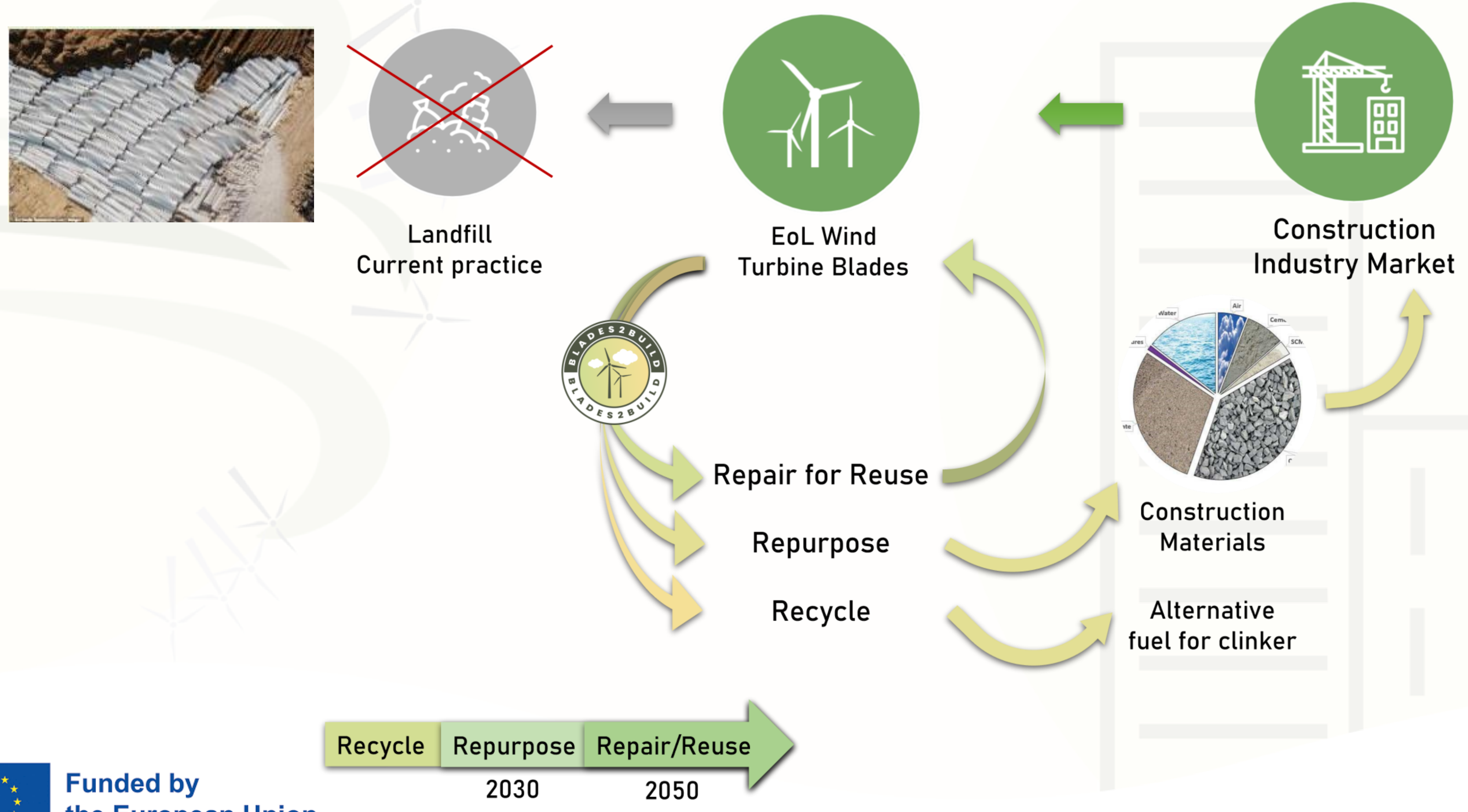
Total cost
€ 15 490 034

EU contribution
€ 12 362 239,68

Coordinated by
DANMARKS TEKNISKE UNIVERSITET
Denmark

Funded by the European Union

Blades 2 Build -Concept



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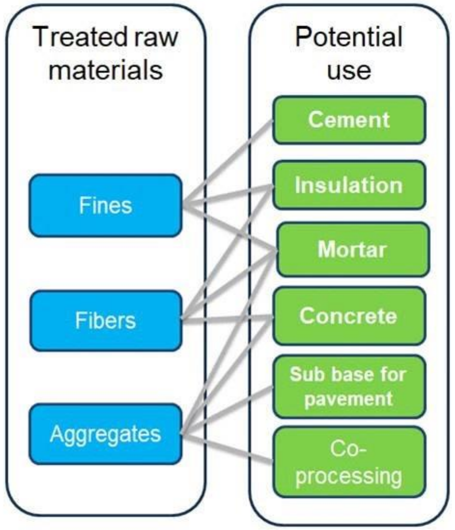
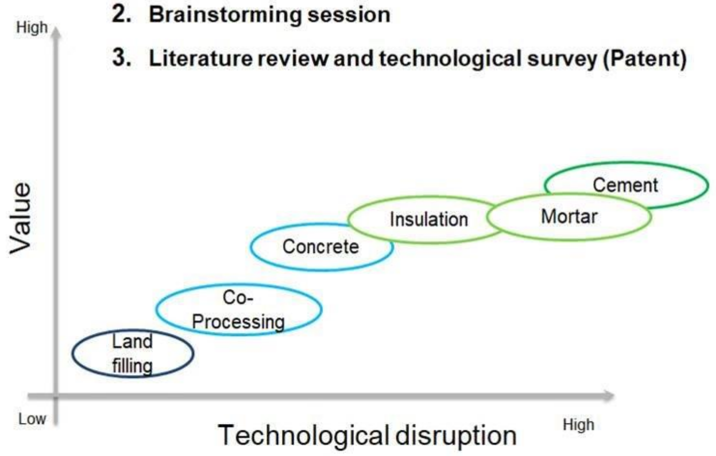
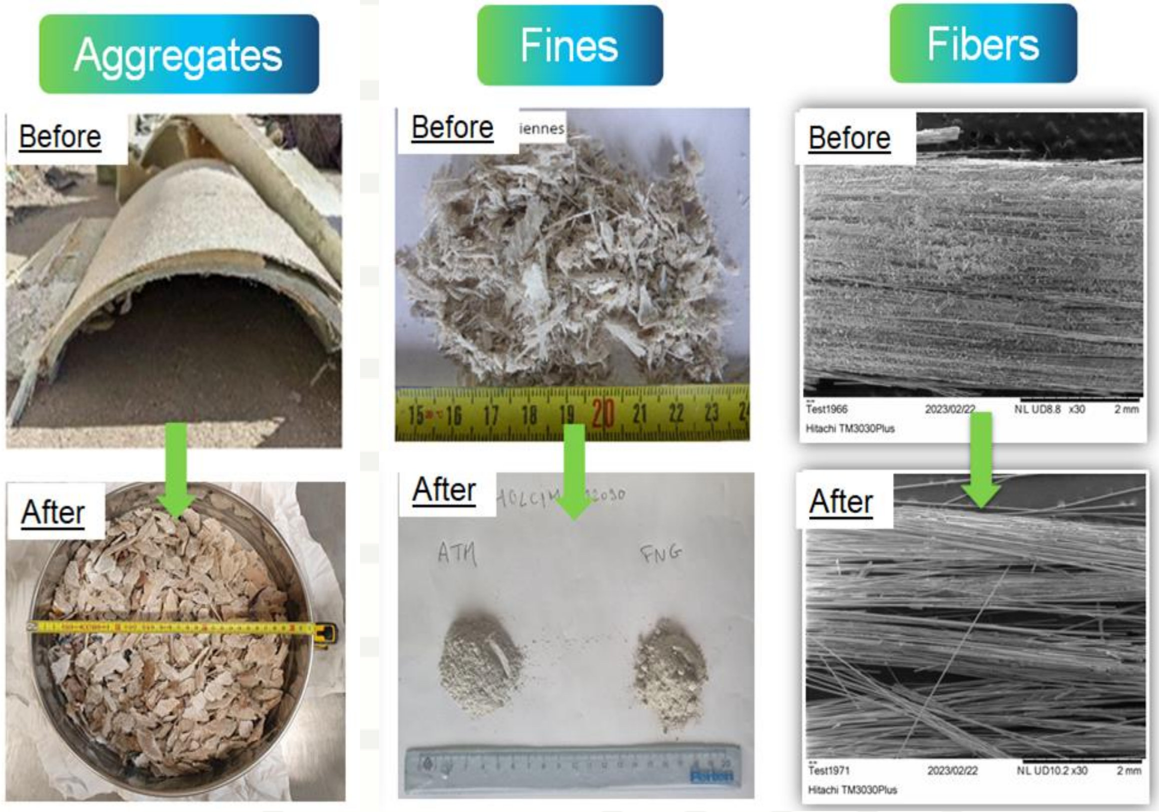
BLADES2BUILD - Repurpose of WTB and potential solutions





Approach:

1. **Interview** with operators , interviewee: R&D programs / Industrial clients
2. **Brainstorming session**
3. **Literature review and technological survey (Patent)**



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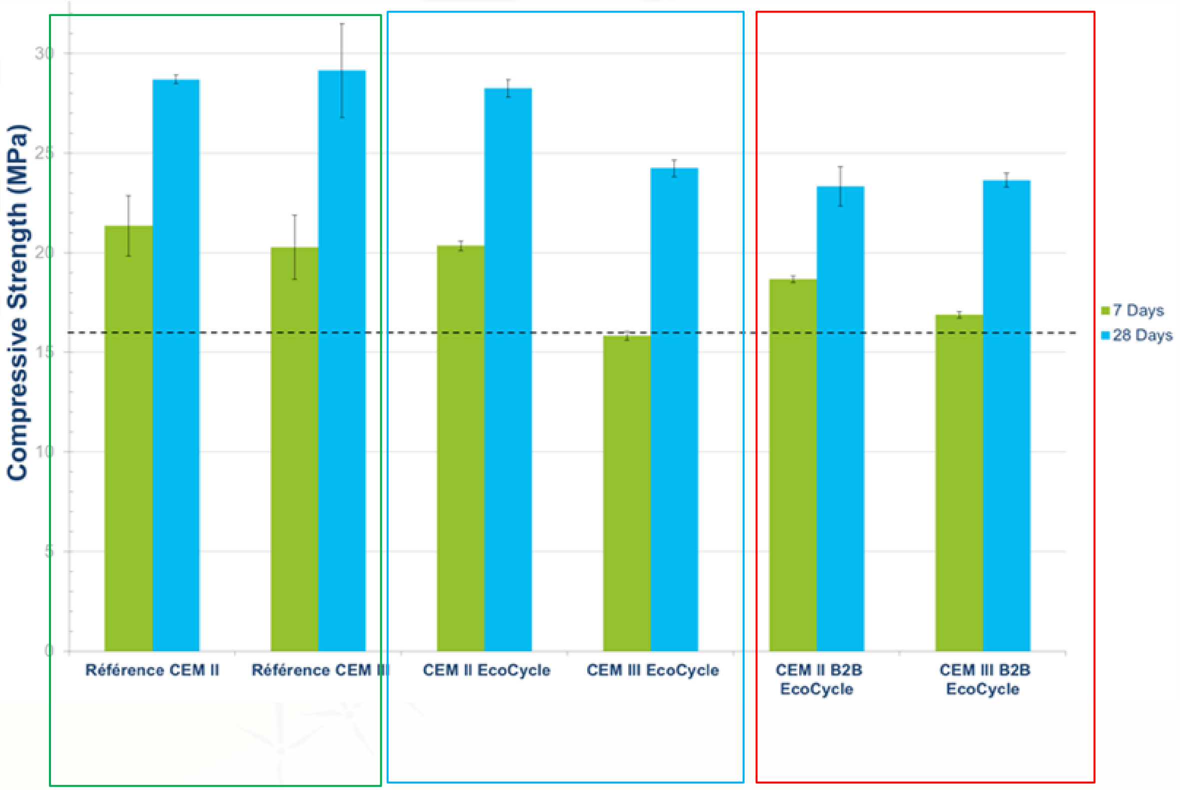
Results - As aggregates in Concrete

Mechanical strength: Slight impact on 28 days behavior



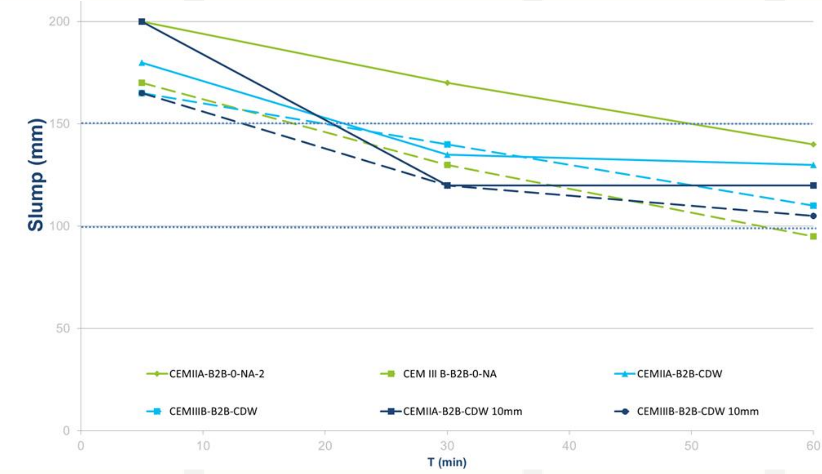
Natural AGG

Recycled AGG

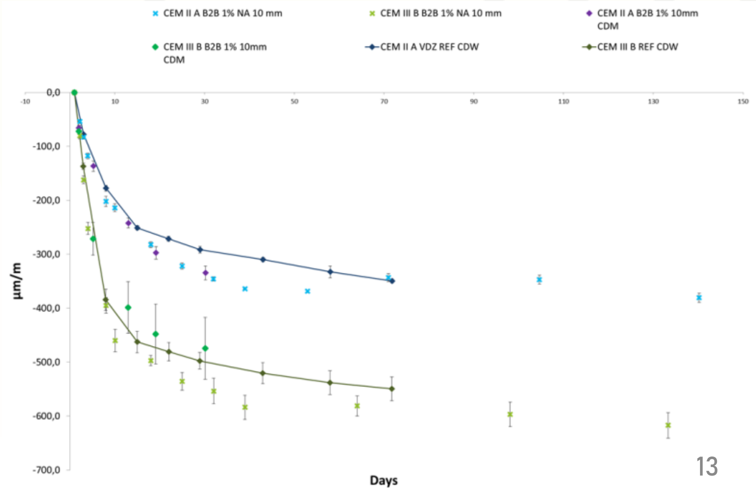
Recycled AGG +WTB waste

ECOCycle
10% recycled construction demolition materials

Workability: No impact



Shrinkage: No impact (good sign for Silica Alkali Reaction)



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Pilots coming - Concrete

- 100 m² of pavement (before June 2025)
- 3 walls – 3m³ each (before end 2025)

ACCIONA DEMOPARK - ALGETE

General view of the Demopark (June 2012)

- 28 m² of pavement for a windfarm access road (March-April 2025)

INDUSTRIAL PROCESS

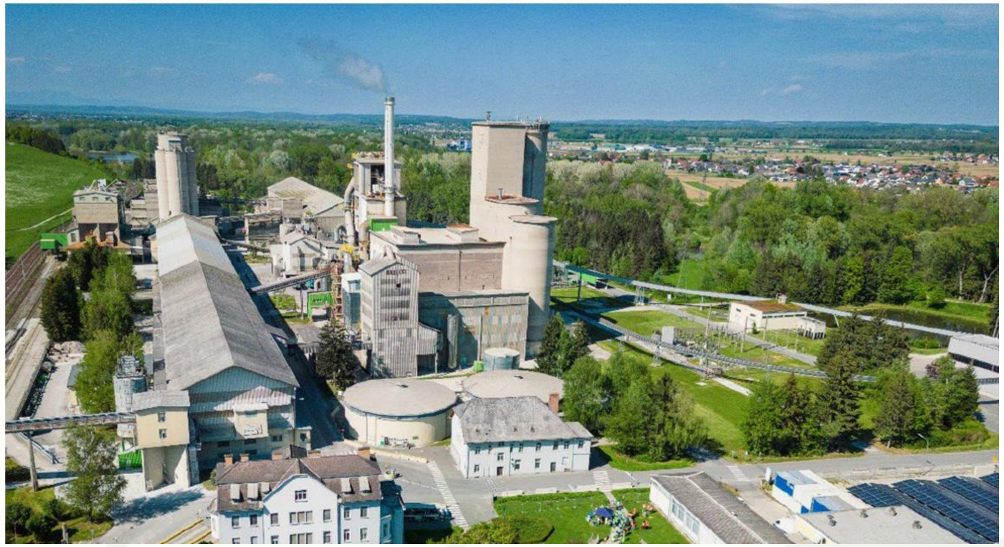
Pilots coming - Cement

GEOCYCLE

- Past case: Lägerdorf (GE) => data shared, LCA on going
- Potential: Saint-Pierre-La-Cour (FR) => pilot to start

- Estimated at 15-18kt/year starting from 2026-2027. SPLC cement plants capable of absorbing up to 10kt/year

Cement co-processing avoids up to 1 tonne of CO_2 emissions per tonne processed



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Thank you!

Quentin.favre-victoire@holcim.com

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HIC – Holcim Innovation Center

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