Recycling of glass fibre thermoset composites by cold incorporation into a sustainable inorganic polymer matrix

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Current issue: Recycling challenges

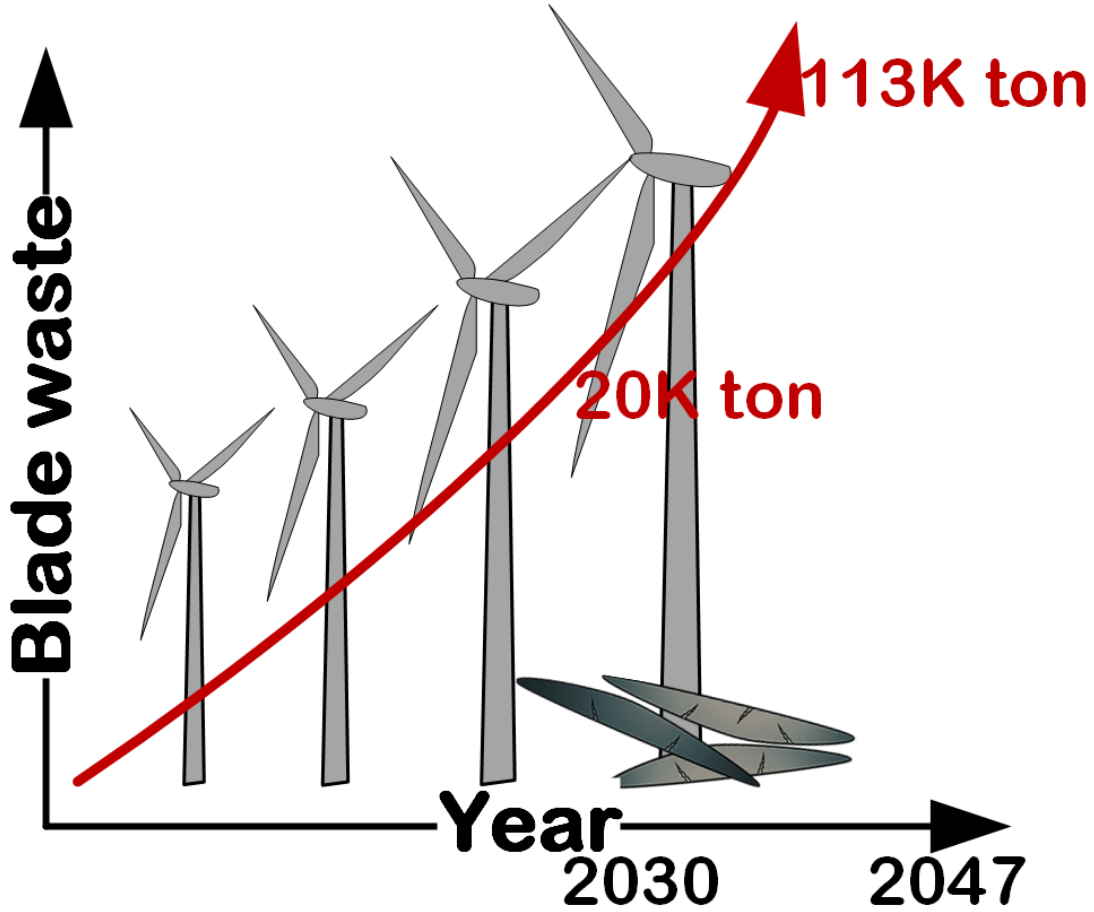
- Large volume

Table1: Dismantled wind turbines in Belgium (since 1987)

Dismantle reason	Percentage	Service years
Blade failure	3.2%	8
Decommissioned	25.8%	20
Repower	67.7%	16
Not recorded	3.2%	8

Repower: replacing old WT with newer and more efficient models
Data source: Windpower (updated to 6th June 2023)

Belgium dismantled WT shows an average lifetime of **17** years, shorten than typical design lifetime of **20-30** years

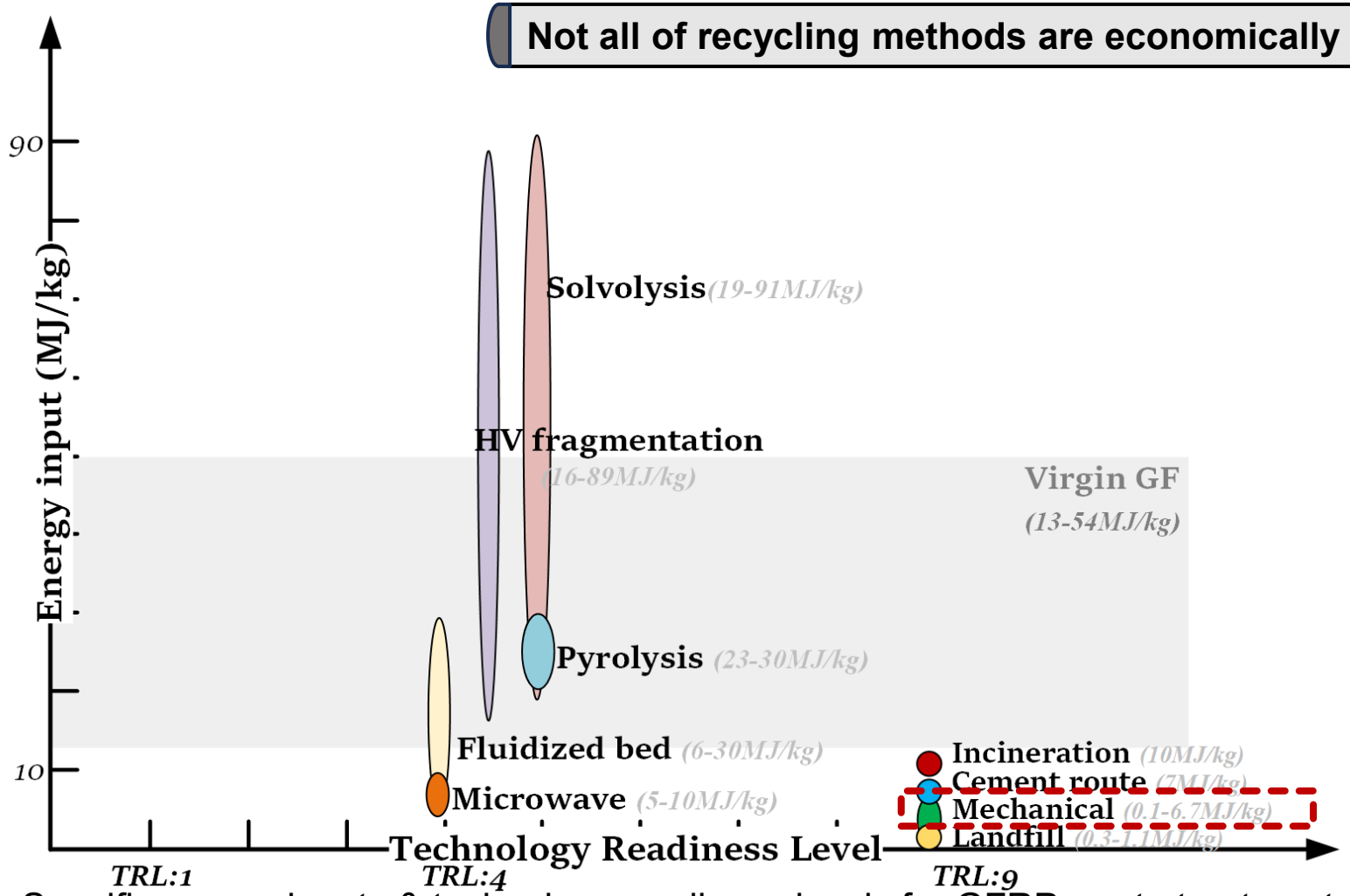


Estimated EoL blade waste: case of Belgium

Current issue: Recycling challenges

- Cost-effectiveness

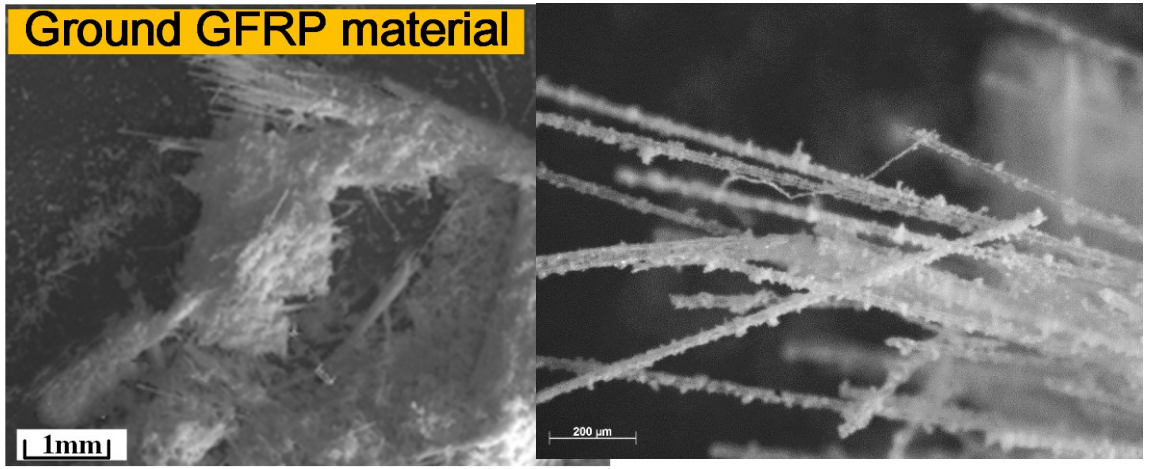
Not all of recycling methods are economically or scalable viable



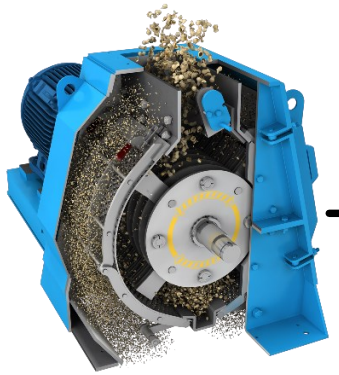
Specific energy inputs & technology readiness levels for GFRP waste treatments

Current issue: Recycling challenges

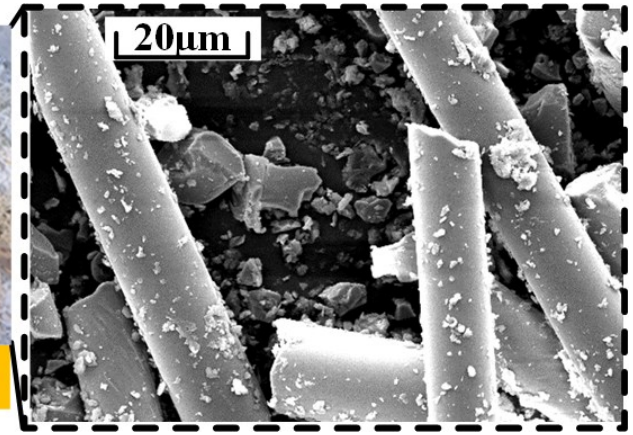
- Mechanical recycling barriers



a few microns to 10mm



Hammer milling
(or other high-speed grinding)



100 microns

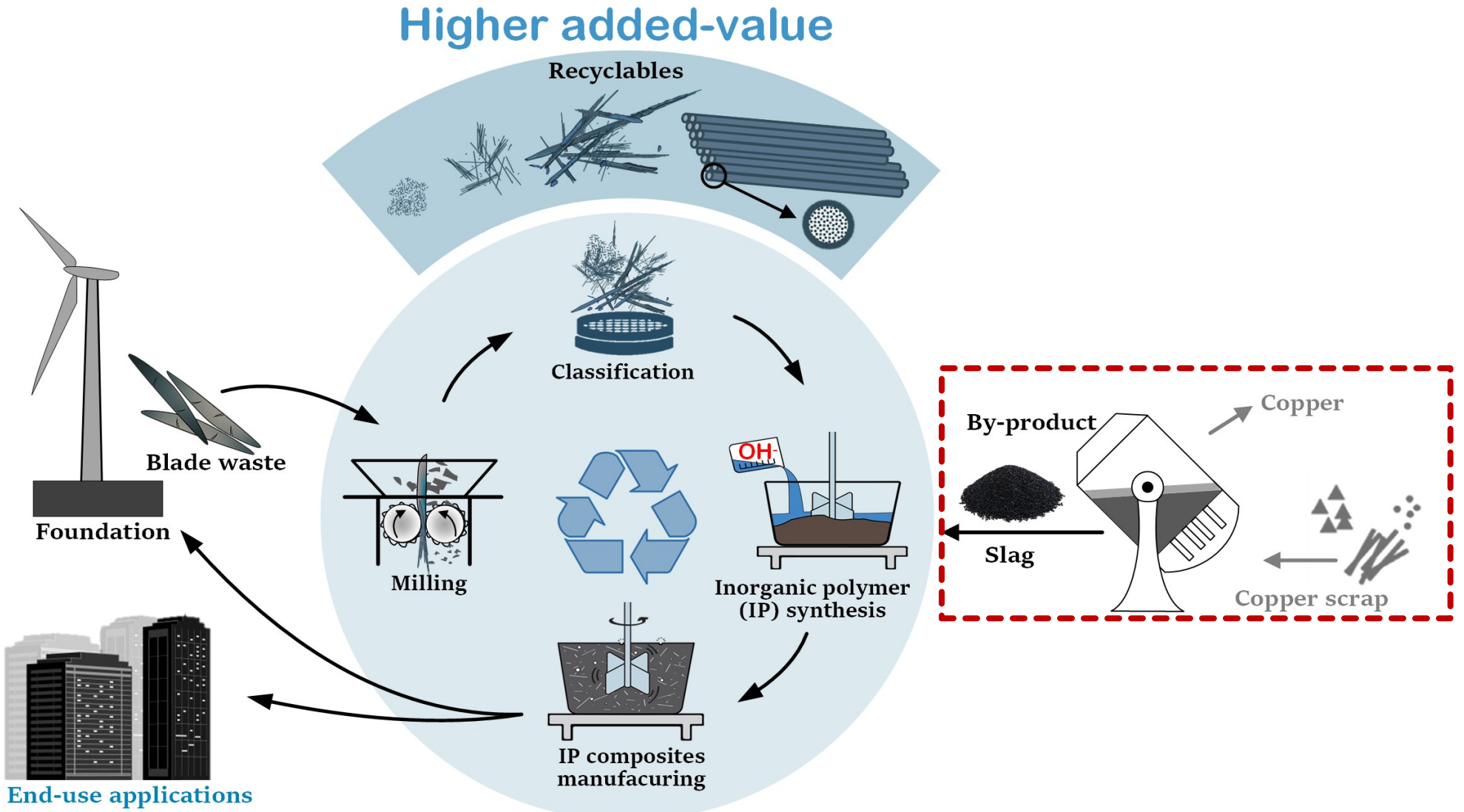
Cons (vs virgin GF):

- × Shorter length
- × Lower quality
- × Increased variations
- × Hindered bonding with new polymer
- × **Low added-value**

Virgin GF (1-3€/kg)

Filler (0.25€/kg)

Recycling GFRP composites: A double waste solution



Zhang Y et al. "Recycling and valorization of glass fibre thermoset composite waste by cold incorporation into a sustainable inorganic polymer matrix" - *Composites Part B: Engineering 223, p. 109120.*

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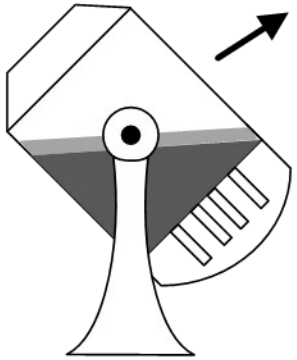
A double waste solution: Cement alternative – 1,Inorganic polymer

Copper scrap

Brittle:
compressive strength-20~50MPa
flexural strength-3~5MPa

Worldwide: 50 MT/year
In Flanders:376 kT/year, 8.5% of cement consumption

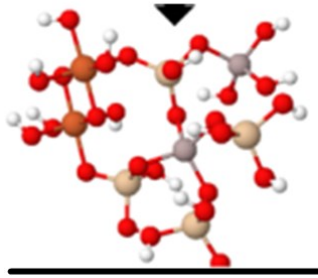


Copper

By-product

Non-ferrous metallurgical slag

Alkaline Activators



FeO_x-CaO-Al_2O_3-SiO_2
Geopolymerization

Inorganic polymer (IP)

Pros (vs cement):
- ✓ 10-30% Cheaper
- ✓ Less 17-47% CO_2
- ✓ Fire resistant
- ✓ Acid resistant

The synthetic IP lacks sufficient tensile strength and needs reinforcements for structural use

A double waste solution: reinforcements alternatives – 2,rGFP

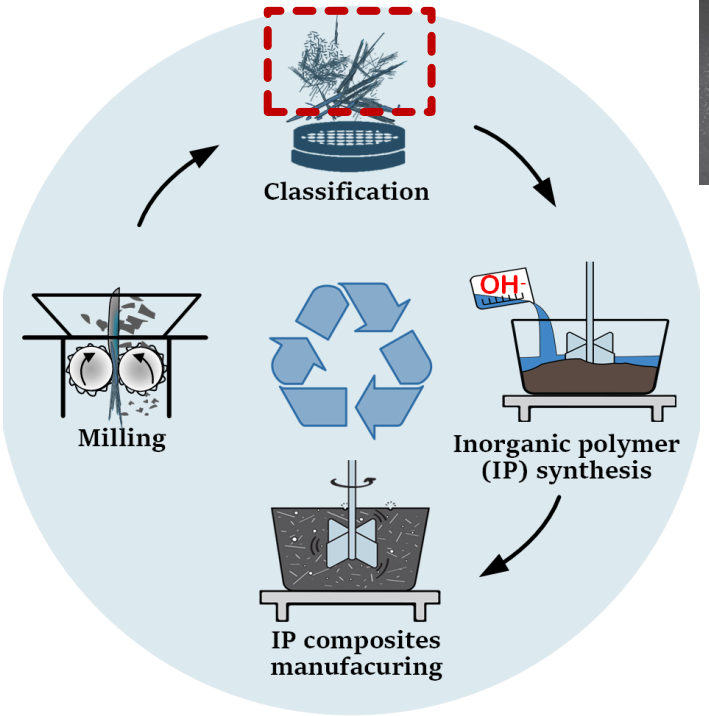
Typical virgin GF-reinforcement products:

Ground GF
(0.25€/kg)

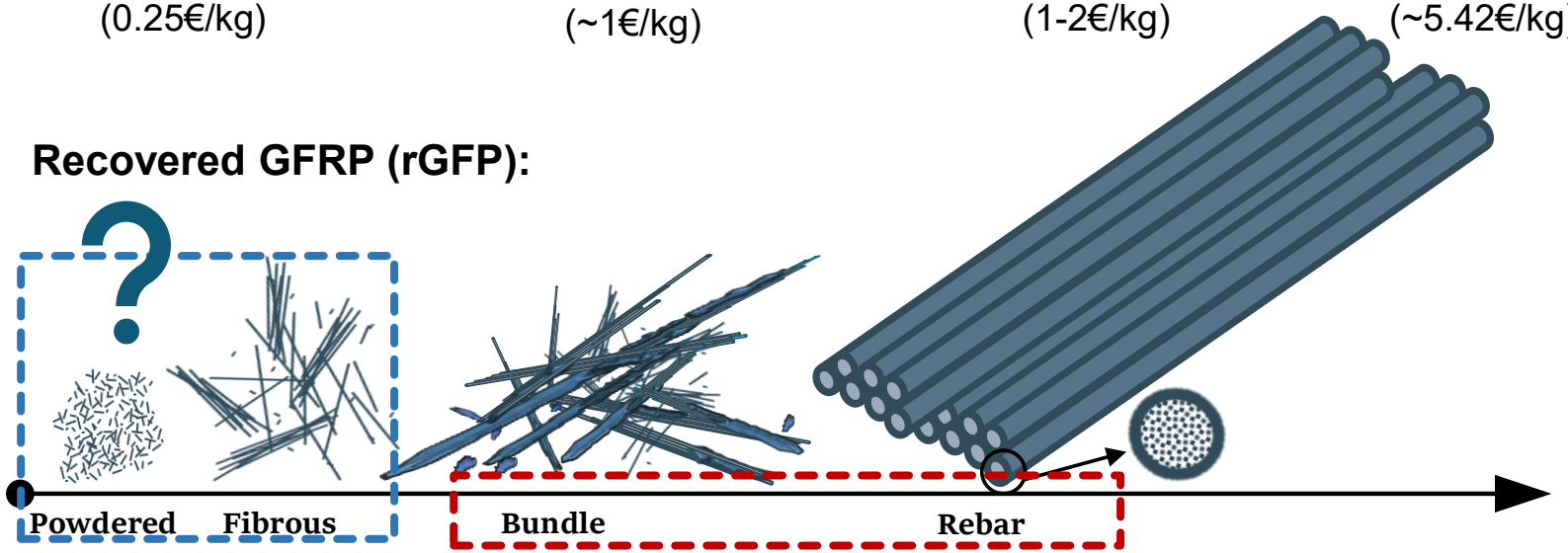
Chopped GF stands
(~1€/kg)

Chopped long GF stands
(1-2€/kg)

GFRP rebar
(~5.42€/kg)

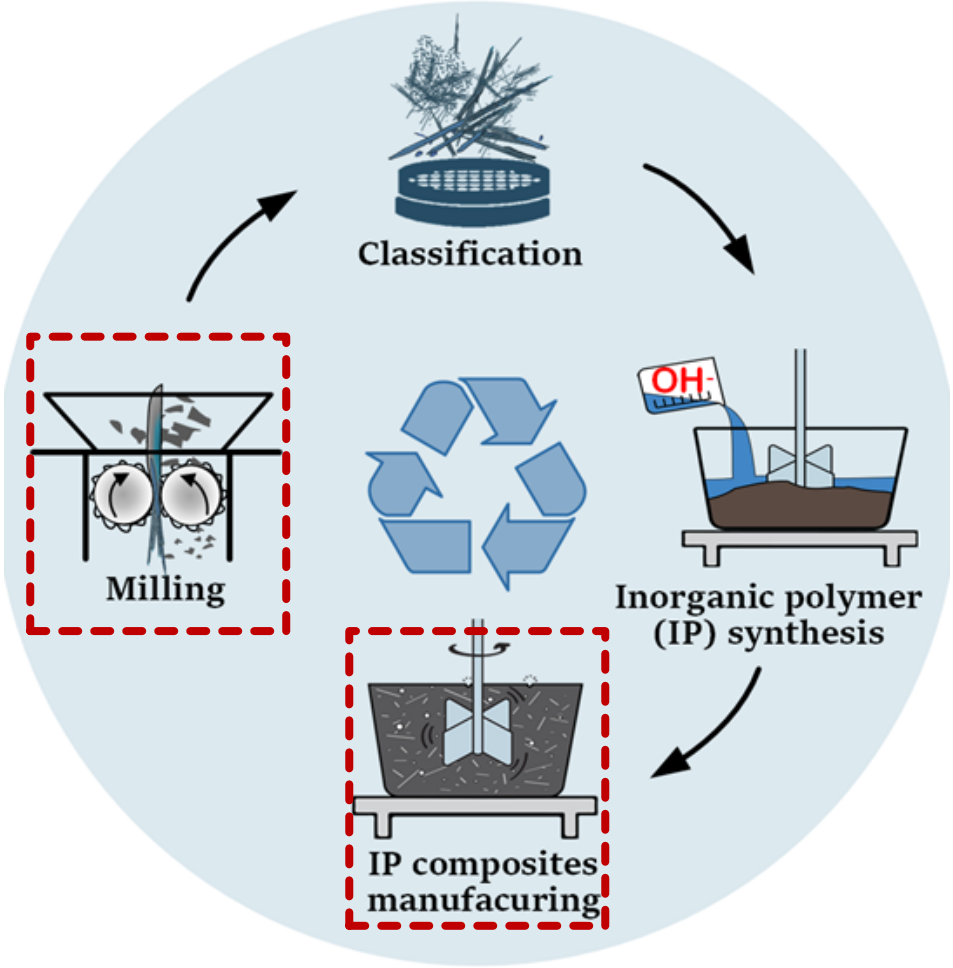


Recovered GFRP (rGFP):



Valorization key: maximizing the length and integrity of rGFP

Recycling GFRP composites: Goals and targets



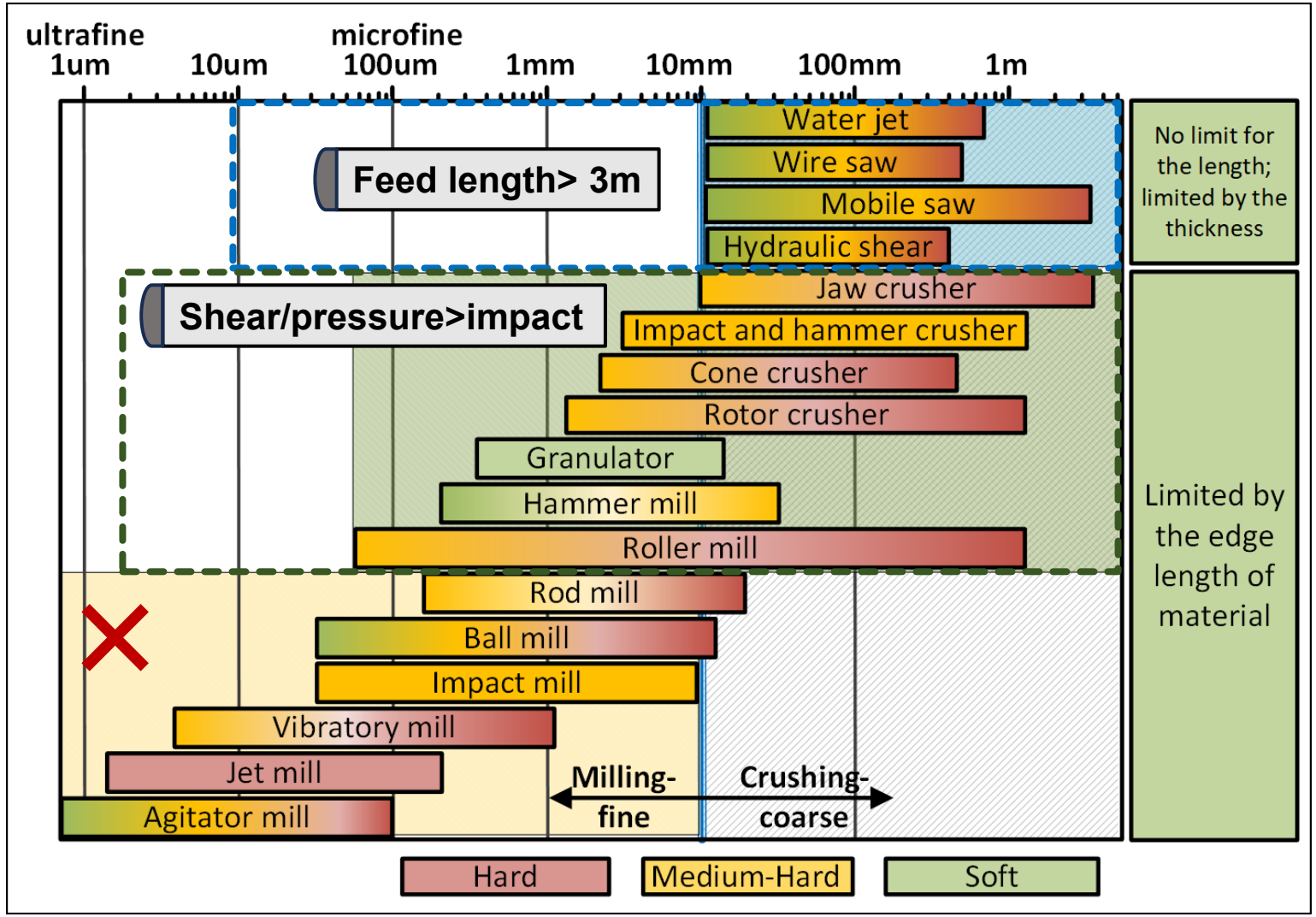
1-Develop a mechanical recycling route
- **for longer and higher-integrity rGFP**

2-Effectiveness-cost Investigation:
1. **Assess the weight fractions of rGFP**
2. **Compare the performance of rGFP vs. vGF**
3. **Evaluate the environment impact**
4. **Assess the economic viability**

1-Develop a mechanical recycling route

Blade pieces (length~6-12m, thickness~80mm):
brittle and abrasive
medium-hard to hard comminution

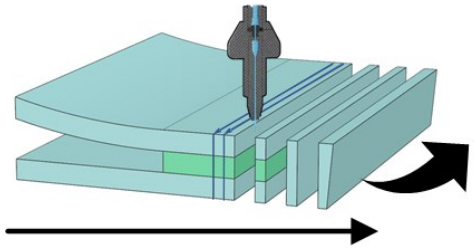
(Waterjet) & (shear and roller mill)



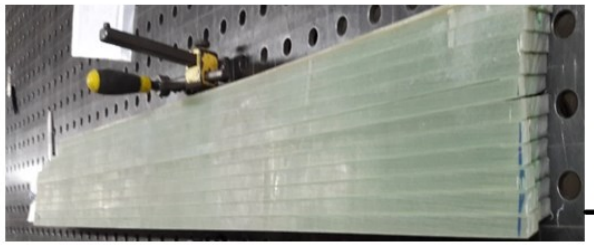
Shredder classification based on the size and hardness of feed material

1-Develop a mechanical recycling route

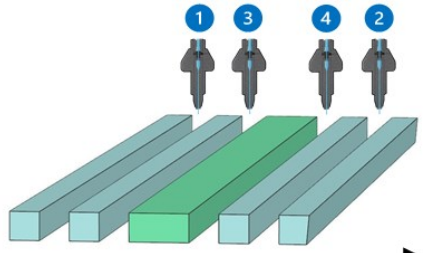
Process1:mainly waterjet



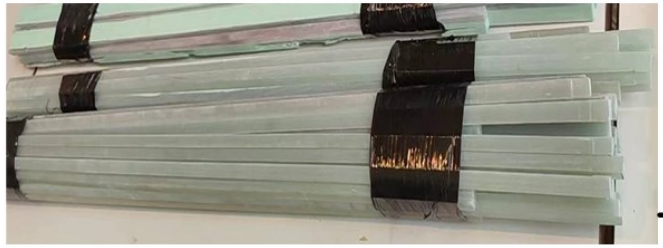
Waterjet cutting



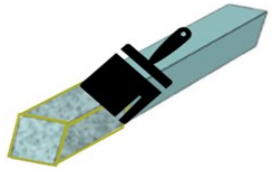
GFRP flats



Waterjet cutting



Square bars



Sand coating

Process2:mainly shear& roller mill

GFRP waste leftover

Hydraulic shearing

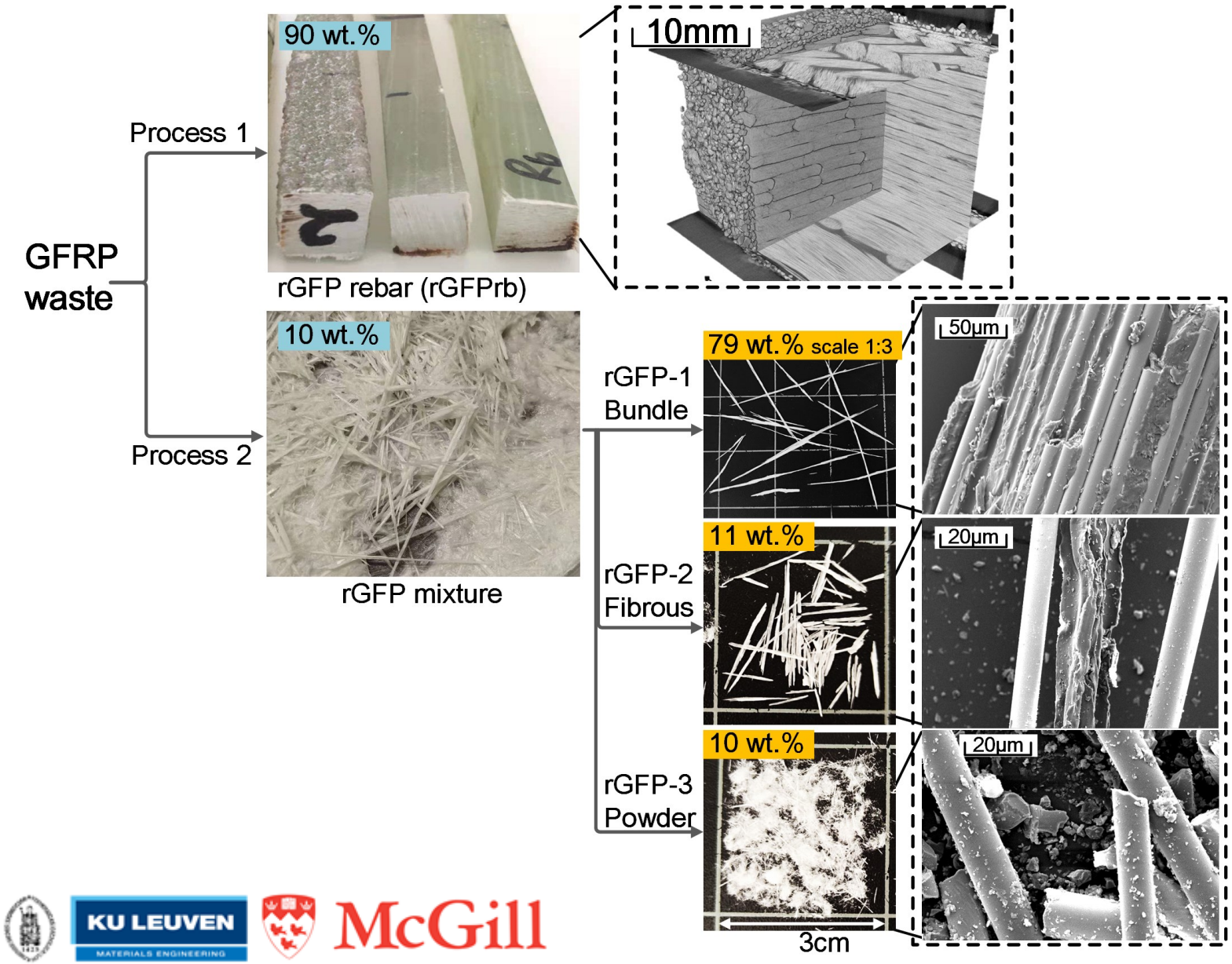
Feed strips

Roller milling

Loosened strips

Fragmentizing

2-Effectiveness Investigation: 1-rGFP properties



	rGFP mixture	Virgin Chopped GF
rGFP-rebar	Can be several meters long	Length range: 6-38mm
rGFP-1 Bundle	Avg=32mm Max=80mm 1.47g/cm^3	
rGFP-2 Fibrous	Avg=7mm Max=56mm 1.38g/cm^3	
rGFP-3 Fine	Avg=0.7mm Max=1.4mm 1.62g/cm^3	

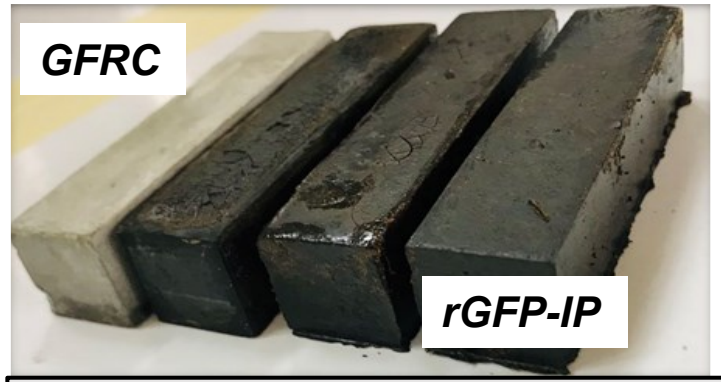
2-Effectiveness Investigation: 2-rGFP v.s. virgin GF

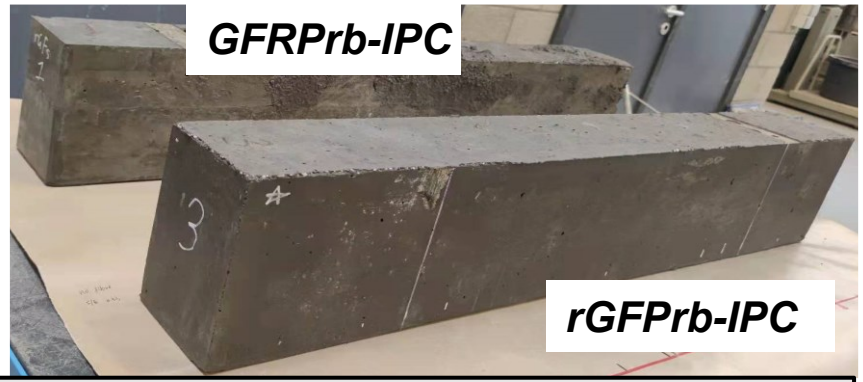
Beam weights for equivalent deflections	
Beam (loaded in bending) ——strength limited design	
Function and constraints	**Material indices**
Shape and length specified; section area free	$\frac{\rho}{\sigma_f^{2/3}}$
ρ-Composite's bulk density *σf -Flexural strength*	

Two benchmarks to consider the size effect

Reference 1:
Glass fibre-concrete premix(GFRC) (ACI-549.3-22)

Reference 2:
Virgin GFRP rebar-inorganic polymer concrete (GFPrb-IPC) (ACI-440.1R-15)





Performance data obtained from experiments and ACI report (ACI-549.3-22)

For example:
Material a: rGFP-IP
Material b: vGF-cement

Substitute factor (a measure to reference) :
λ=Mass(a)/mass(b)=$\rho_d/\rho_b*(\sigma_{fb}/\sigma_{fa})^{2/3}$

		GFRC [1]	rGFP1-IP	rGFP2-IP	rGFP3-IP	*GFPrb-IPC* [2]	rGFPrb-IPC
Properties*	ρ	*2.06*	2.50	2.50	2.55	*2.54*	2.54
	σ_f	*10*	26.70	17.20	10.10	*24.16*	23.4
		The performance of rGRP-IP/IPC in relation to the reference material					
Substitute factor λ		*1*	1.58	1.18	0.81	*1*	0.98
		1 kg of rGFR in IP composite can substitute xkg VGF/GFPrb					
Substitute factor λ'		-	1.25	0.93	0.64	-	0.98

2-Effectiveness Investigation: 3-Environmental impact

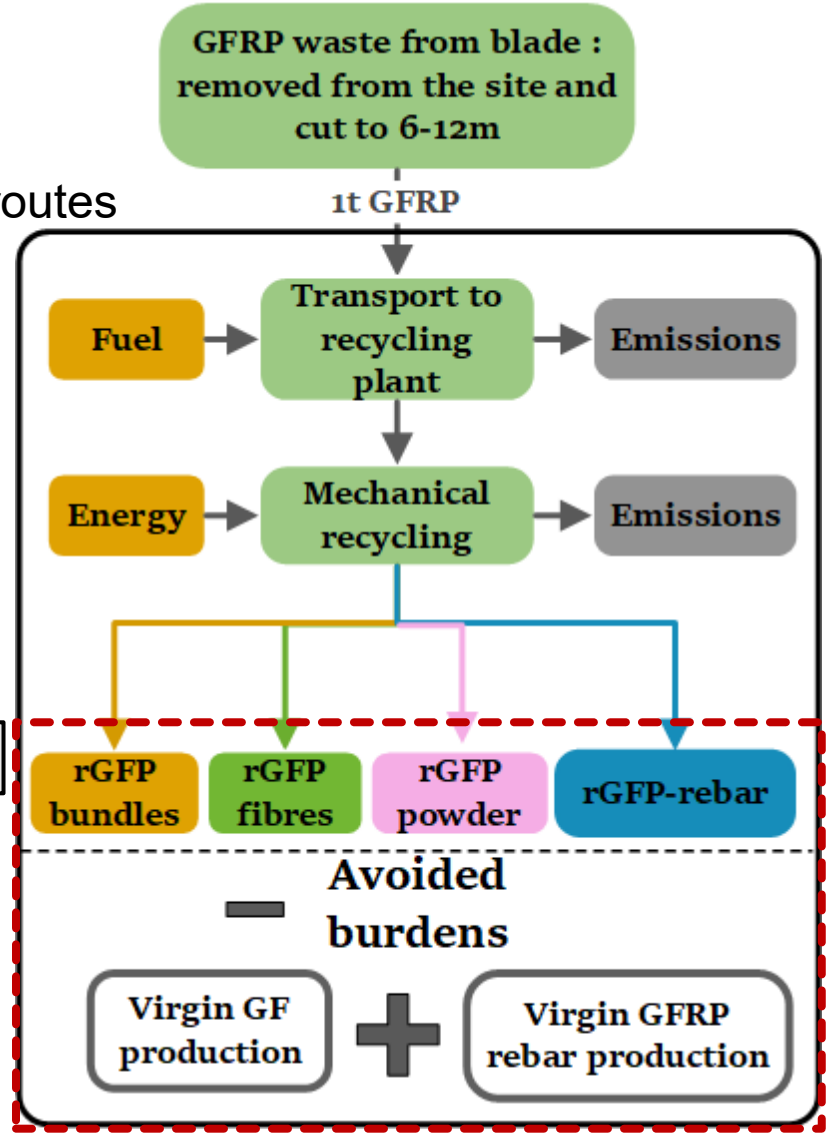
- Life cycle analysis (LCA)
  - Functional unit:1 ton of waste GFRP entered in the treatment routes
  - Database: Ecoinvent3.5 and literature reference
  - Impact method: EF v2.0
  - Analyzed impact: Global warming potential (GWP)

  - Versus conventional waste treatment methods:
    Landfill
    Incineration with energy recovery
    Co-processing in cement-kiln

Use of substitution factors

Scale-up the routes: process parameters adjusted

- Lab-scale:**2.5kg_waste/h**
- Pilot-scale:**11.8kg_waste/h**
- Industry-scale:**152.7kg_waste/h**



System boundary for the proposed mechanical route

2-Cost Investigation: 4-Cost

- Life cycle cost analysis (LCC) :

Evaluates GFRP waste disposal routes from two perspectives of key stakeholders

- 1-Waste owner: Average cost per mass unit of waste (Cw)
  - The gate fee to be paid to the government or industry for waste disposal
- 2-Recycling plant: Average cost per mass unit of recovered rebar (Cr)
  - The lowest selling price of rGFRP rebar for the recycling plant

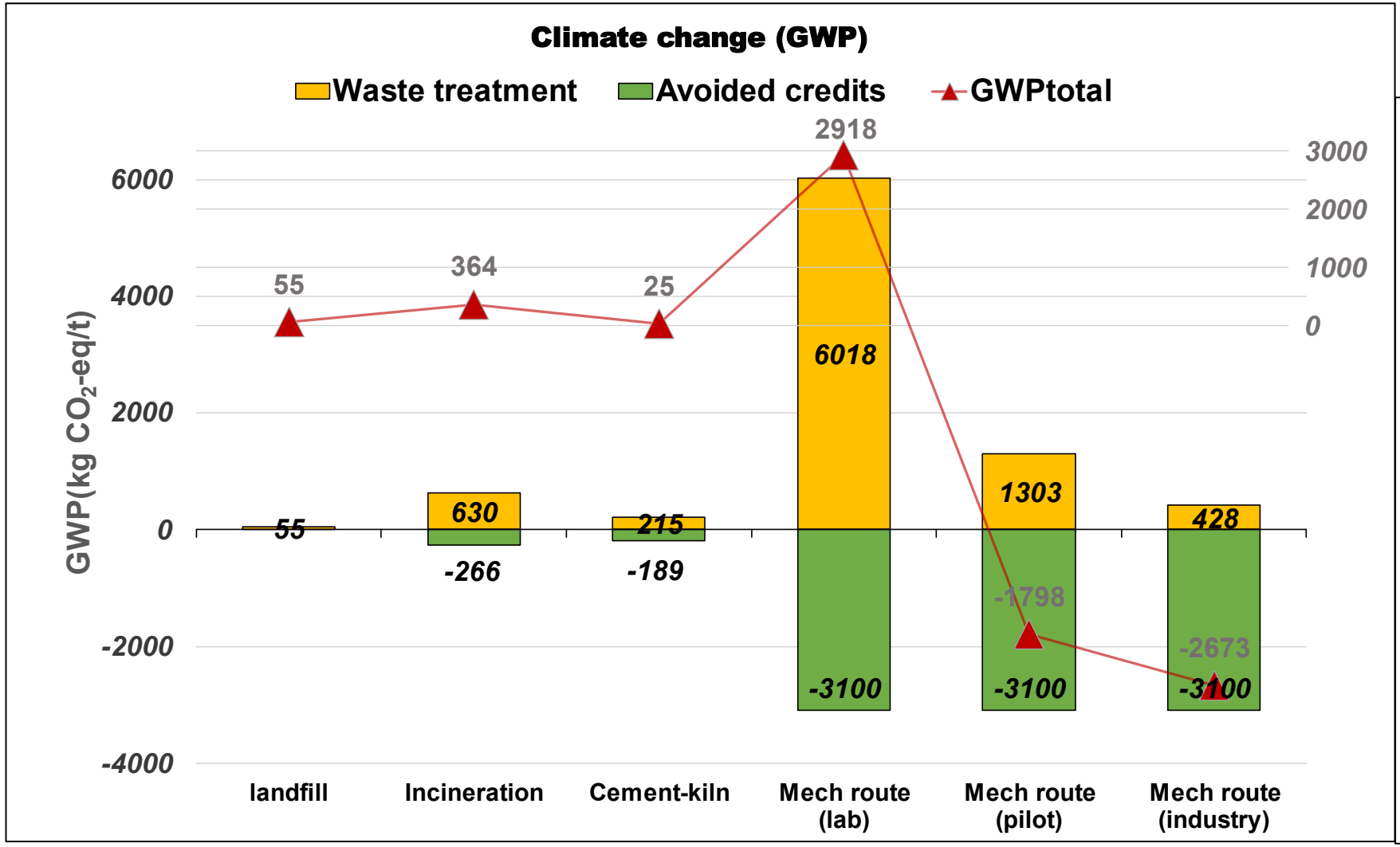
$$\mathrm{Cw} = \frac{REV(at\ NPV{=}0)}{Waste\ input\ capacity} \quad (1) \qquad Cr = \frac{REV(at\ NPV{=}0) - \sum Revenue\ of\ by{-}products(rGFP\ mixture)}{Recovered\ rebar\ capacity} \quad (2)$$

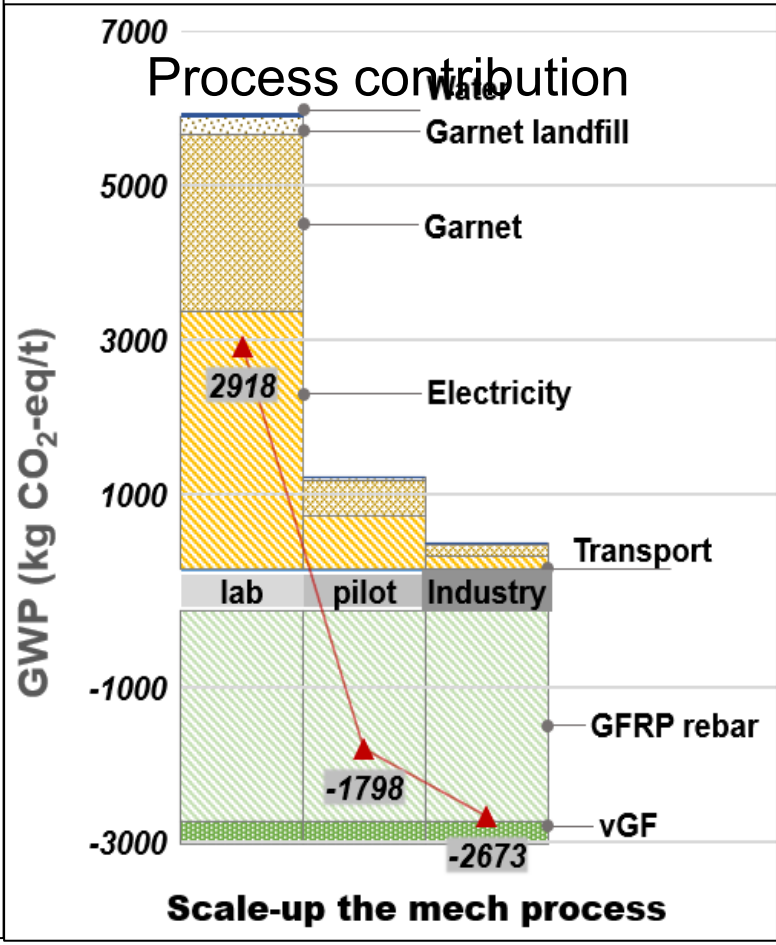
$$(Net\ present\ value)\ \ NPV = -INV + \sum_{t=1}^{10} \frac{(REV-TC)\times(1-a)+D}{(1+r)^t} \quad (3)$$

Investment (INV): 160 000 € of capacity less than 100t_GFRP waste/year
220 000 € of capacity of 900t_GFRP waste/year

Assume: The operating time of recycling plant (10 years)
a-tax rate=25%
r-internal rate of return=10%
REV: Annual Revenue of process
D:Depreciation (D=INV/H)
TC: Total annual cost (TC=D+ Cost(raw material, utility, labour and maintenance)

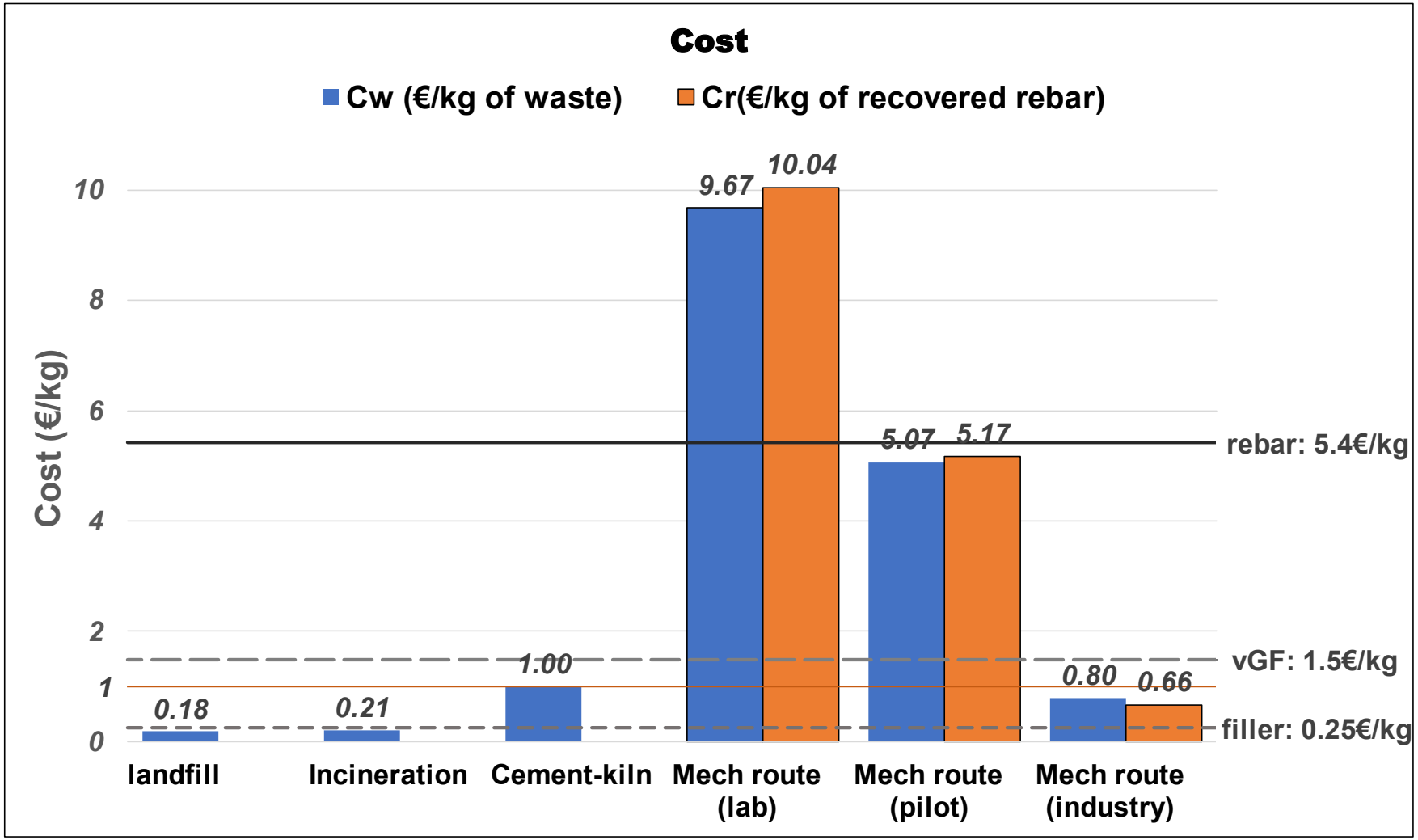
Environmental impact-GWP

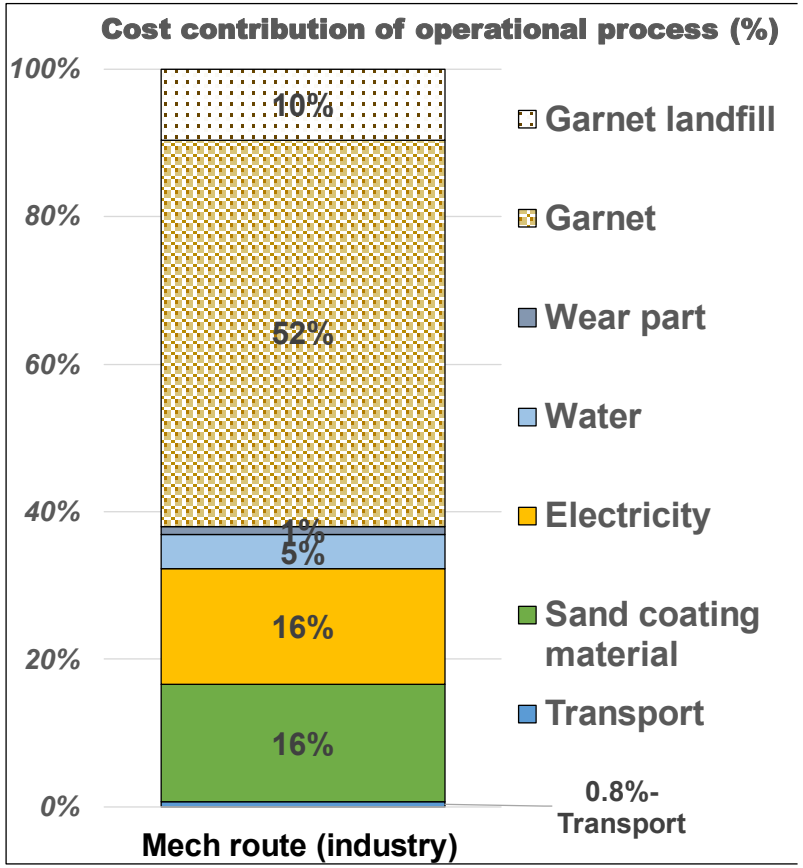




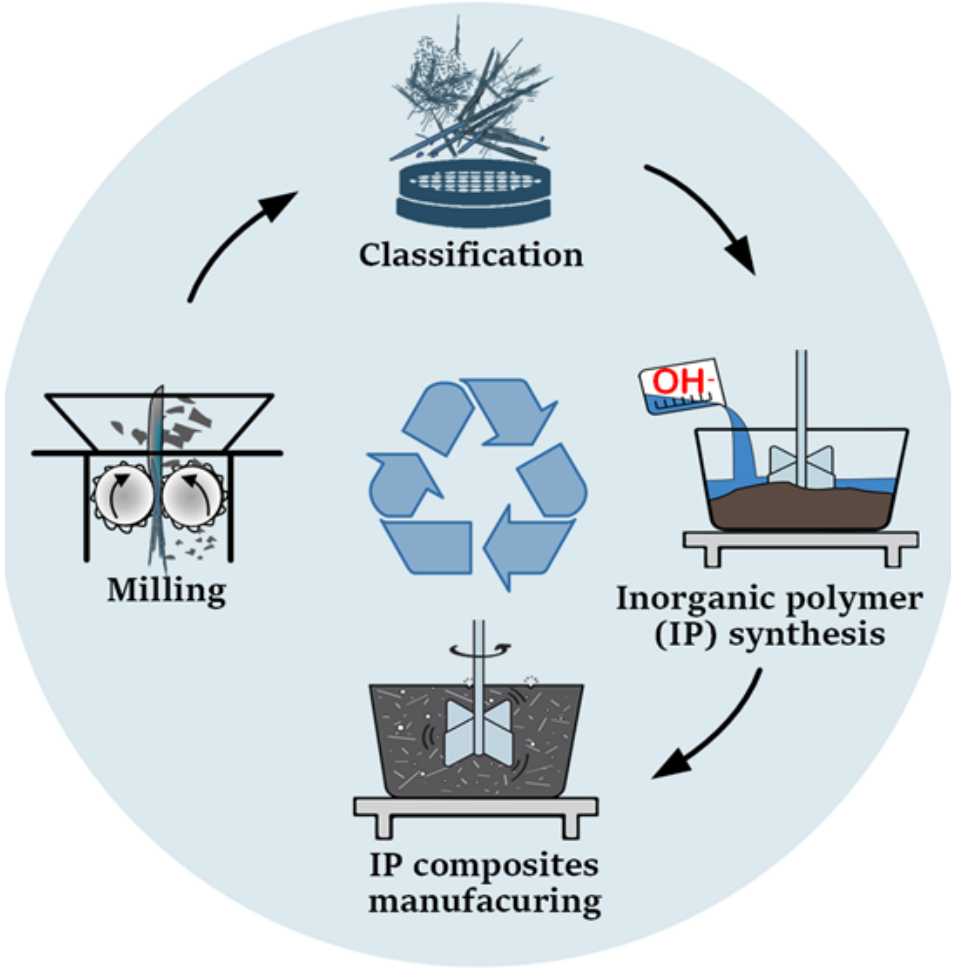
For 75mm-GFRP, increasing waterjet speed from 0.1m/min to 0.3m/min at pilot scale, to 0.6m/min at industry level

Cost


Cost
Cw (€/kg of waste)
Cr(€/kg of recovered rebar)
Cost (€/kg)
10
8
6
4
2
1
0
0.18
0.21
1.00
9.67
10.04
5.07
5.17
0.80
0.66
rebar: 5.4€/kg
vGF: 1.5€/kg
filler: 0.25€/kg
landfill
Incineration
Cement-kiln
Mech route (lab)
Mech route (pilot)
Mech route (industry)


Cost contribution of operational process (%)
100%
80%
60%
40%
20%
0%
10%
52%
1%
5%
16%
16%
Garnet landfill
Garnet
Wear part
Water
Electricity
Sand coating material
Transport
0.8%-Transport
Mech route (industry)

Key takeaway



Technical feasibility

- recovers concentrated long reinforcements (90wt% of rebar)
- no need to separate the resin residues

Environmental benefit & Cost-effectiveness

- If waterjet cutting speed is increased to 0.6m/min (for 75mm GFRP)

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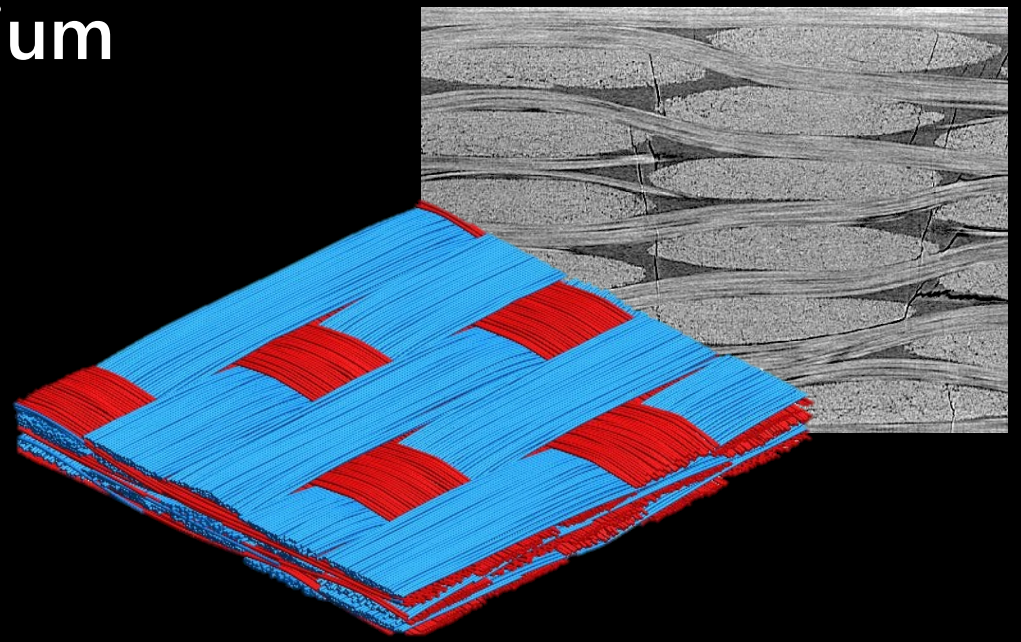
Abstract submission deadline 31 Mar 2024



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