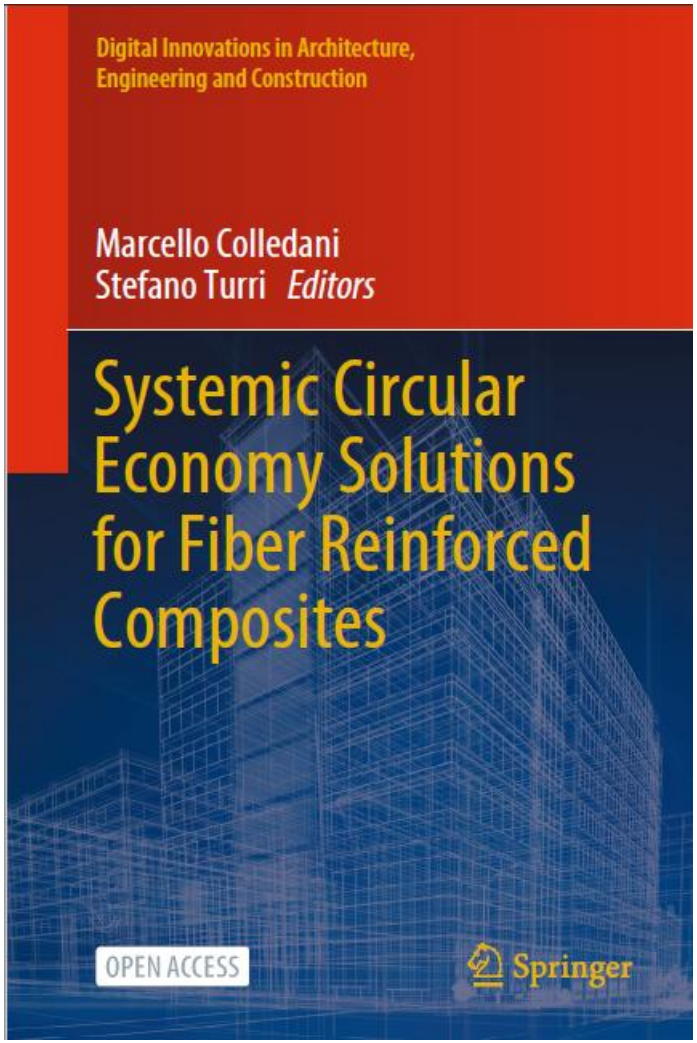
Circular options in composite materials



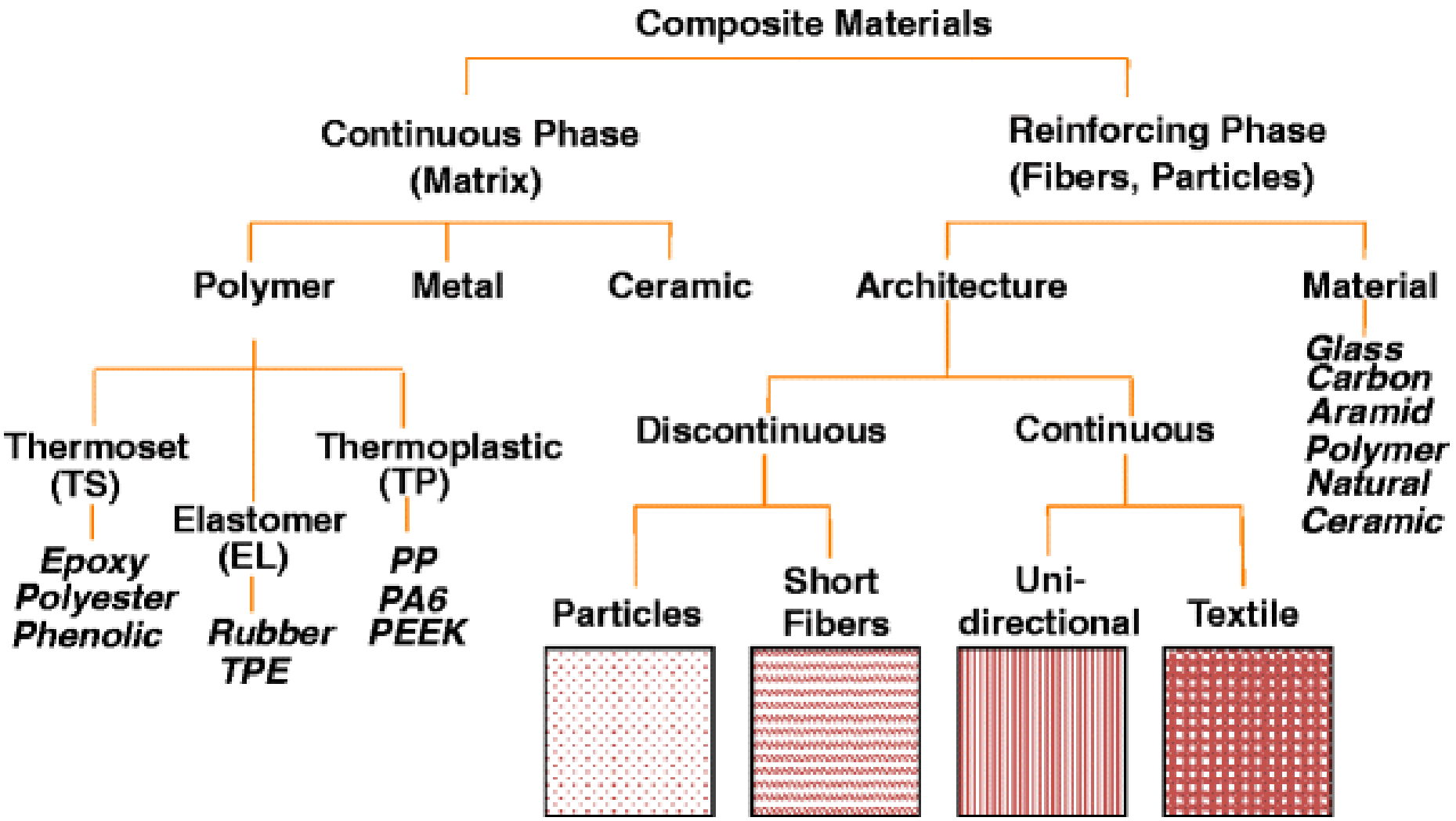
Source of the figure: https://www.ivv.fraunhofer.de/en/recycling-environment/recycling-of-plastic-composites.html

Main sources of information





Composites (reminder)



Source of figure: Applied Composite Materials volume 20, 107–128 (2013)

Composites (reminder)

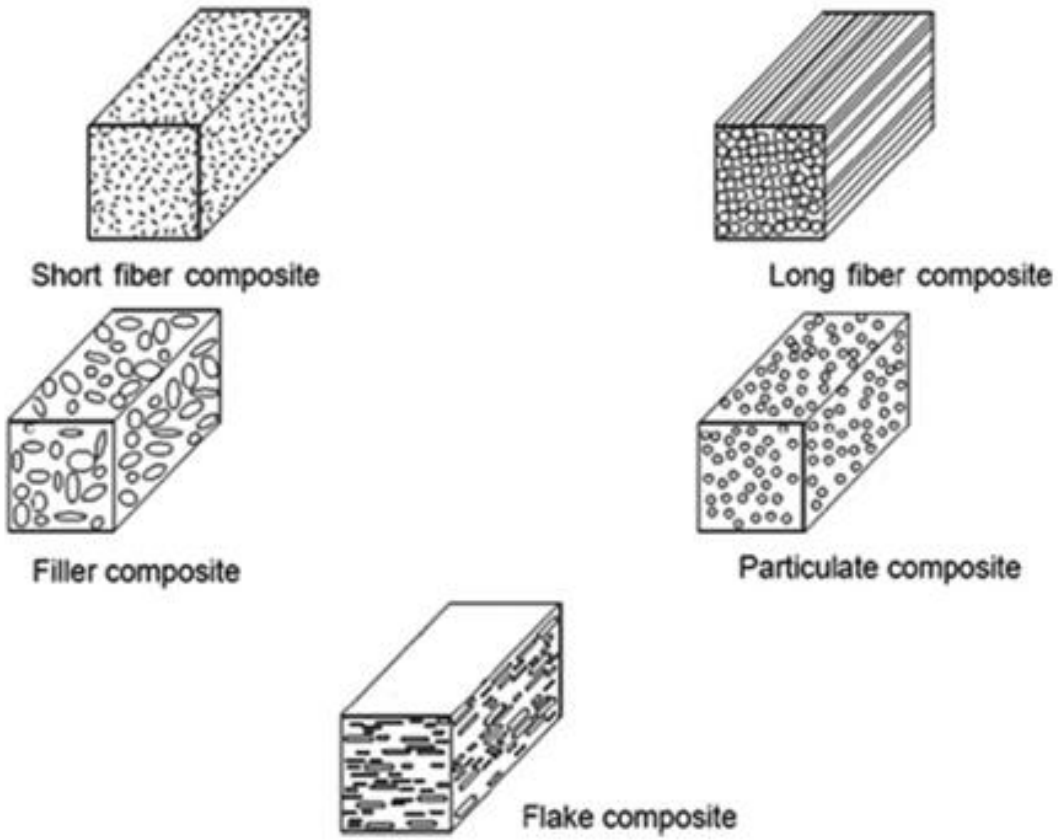
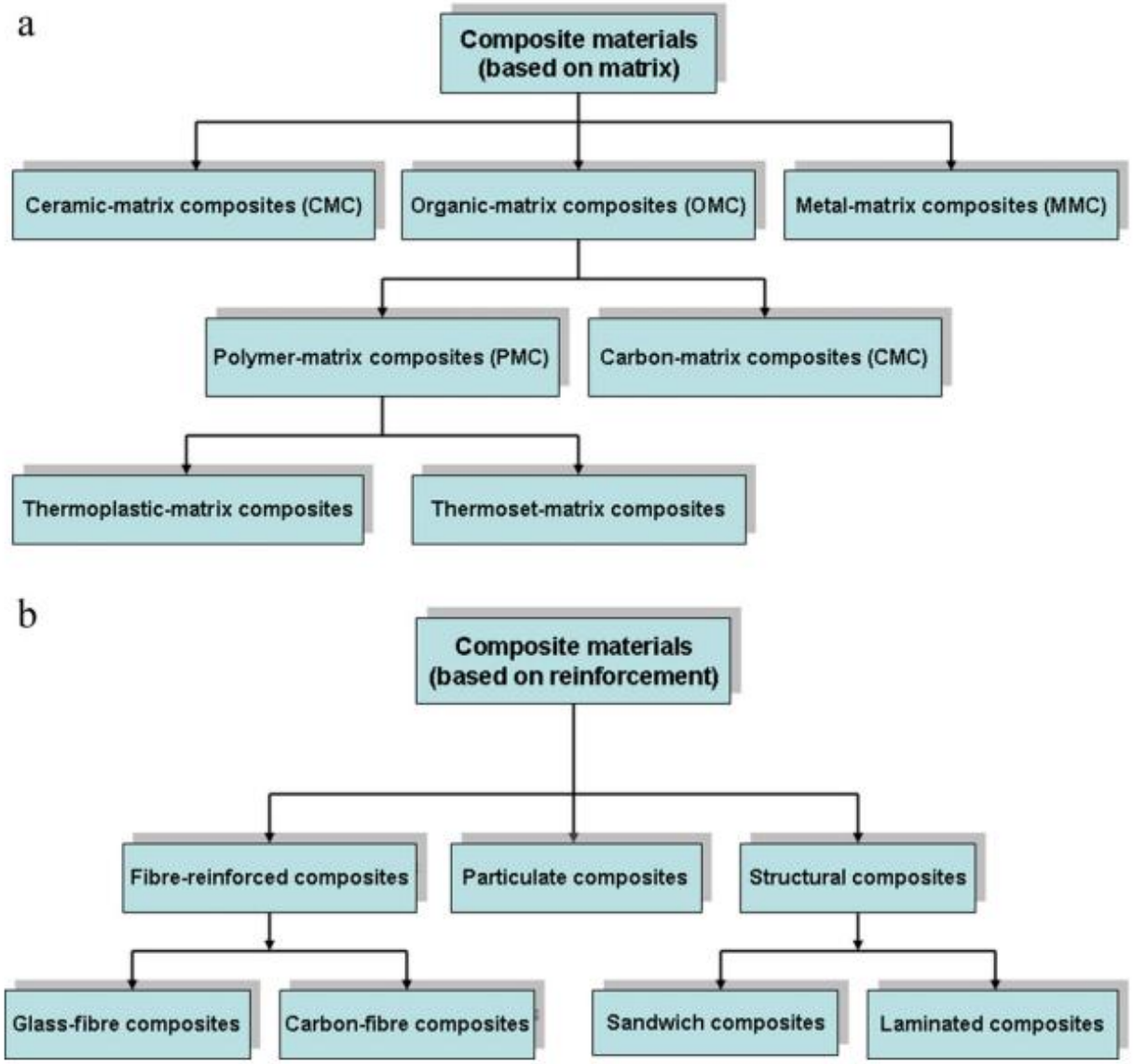


Fig. 2 Different fibers/matrix configuration in composite materials [5]

Source of figure: Applied Composite Materials volume 20, 107–128 (2013)

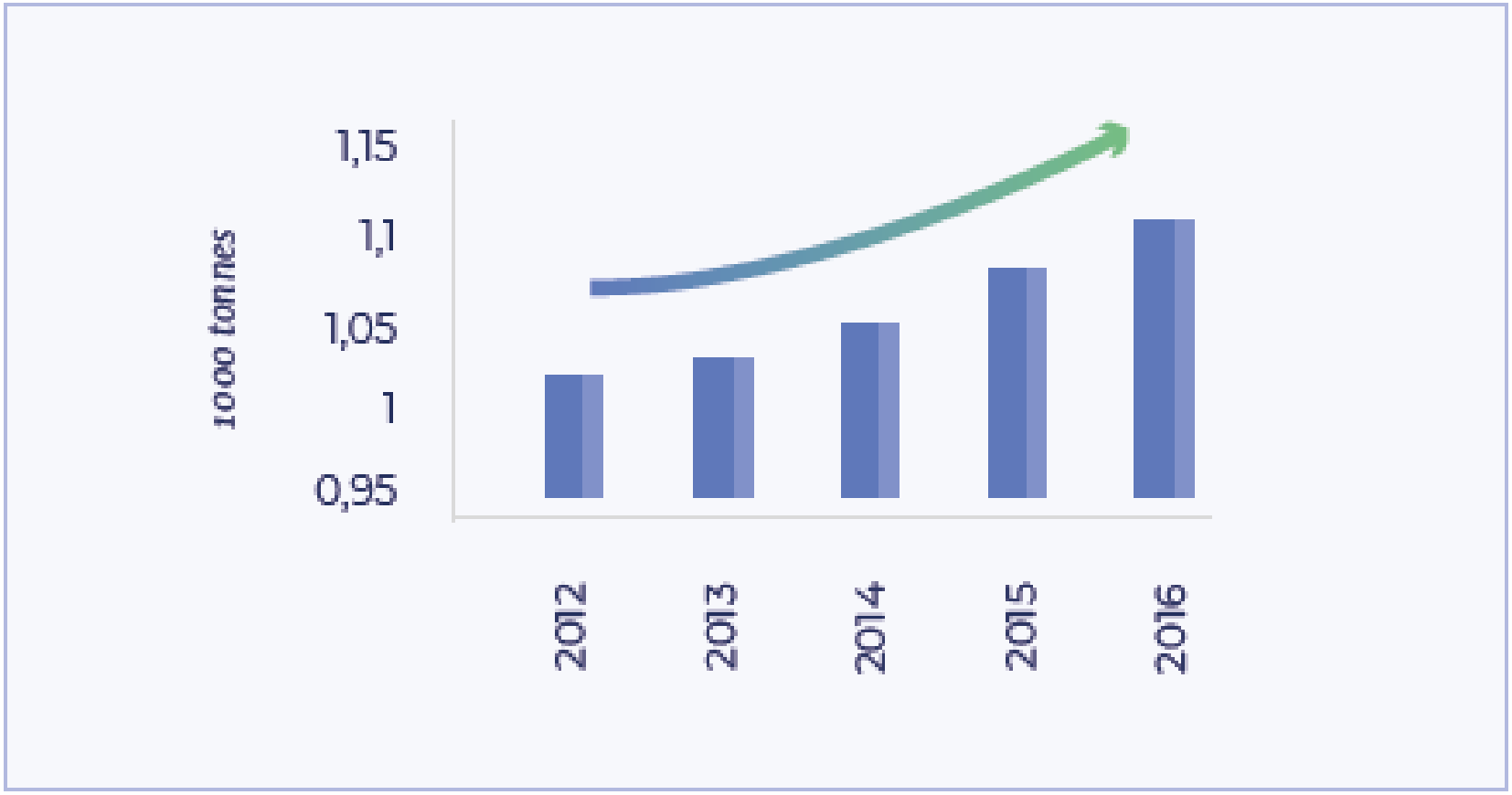
Composites: complex and heterogeneous systems



Classification of composite materials. (a) Based on matrix materials and (b) based on reinforcement materials

Source of figure: Chemical Engineering and Processing 51 (2012) 53–68

The starting points

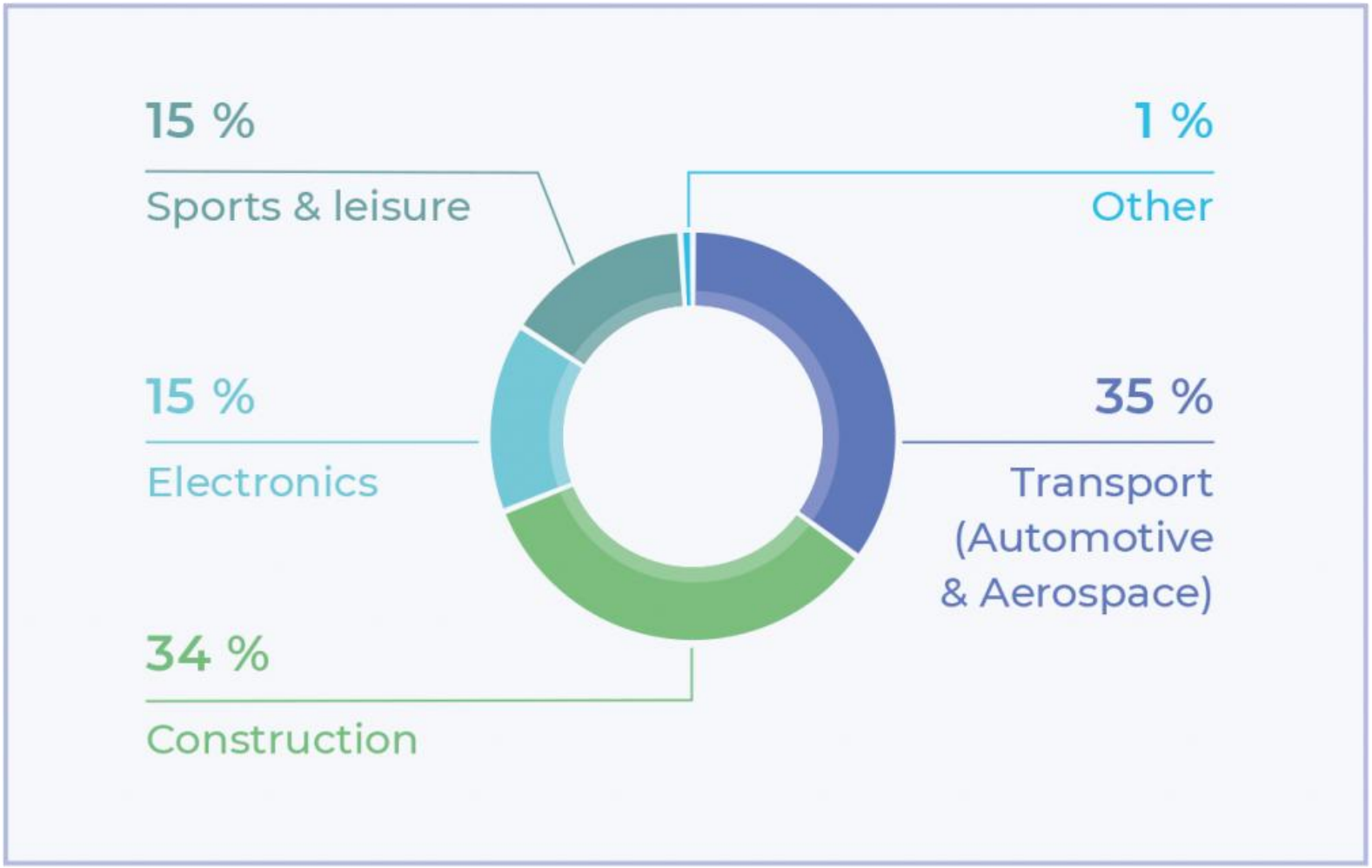


Polymer Composites production in Europe 2012-2016

Source of the figure: Suschem- Polymer composite circularity – White paper

The starting points

Use of composites for applications fields (Europe)



Source of the figure: Suschem- Polymer composite circularity – White paper

The starting points

- growing demand for composites (also hi-tech)
- carbon fibre reinforced polymers (CFRP) and glass fibre reinforced polymers (GFRP) are experiencing a **steady market growth**; average annual growth is estimated to be 4.5% and 10% in the next few years for the global GFRP and CFRP markets respectively.
- in Europe, production of polymer composites has been growing at an average rate of 2.5% over the last decade.
- increase in number of applications
- in EU, about 40,000 tonnes of composite waste are deposited in landfills annually and by the end of 2015, 304,000 tonnes of composite waste were estimated to have accumulated*
- as much as a 40% of the total production of composites ends up being **wasted**, either as scrap or defective parts, representing a major loss of resources and energy.

* National Composites Network (2006), *Best Practice Guide; End of Life Options for Composite Waste*

what will happen to all the composite waste that is generated either from production or end-of-life parts?

Circular options in composite materials



Source of figure: Chatziparaskeva, Georgia & Papamichael, Iliana & Voukkali, Irene & Loizia, Pantelitsa & Sourkouni, Georgia & Argirusis, Christos & Zorpas, Antonis. (2022). End-of-Life of Composite Materials in the Framework of the Circular Economy. Microplastics. 1. 377-392. 10.3390/microplastics1030028.

Main burdens for circularity in composite materials

- The complex and heterogeneous structure of a composite material makes it inherently hard to separate the different materials again.

- Firstly, there is the monetary and energy costs of recycling the materials, compared to creating virgin materials. For glass fibre for example, the price of virgin glass fibres is so low that no process currently available can provide recycled glass fibres with the same characteristics as virgin fibres at a competitive price.

- Secondly, the materials are always at a lower value level as they are decreased in quality due to the recycling process and lifetime wear, or reduced to their feedstock elements

- Thirdly, as the material is of lesser quality, it has fewer application purposes and is more difficult to use than virgin materials. For example, recycled fibres are short and of a fluffy nature, which makes it difficult to incorporate it into a new material due to reduced bonding between the fluffy fibres and the new matrix.

Main burdens for circularity in composite materials

- part of the difficulties of composite recycling lies in the reverse logistics whether this is to the original fibre producer or product manufacturer, or a recycling company.

- Considering these drawbacks, it might not make sense from a sustainable perspective to use and recycle composite materials in the current manner.

- This would suggest that there needs to be a change in how the composite materials are currently constructed, used, and/or recycled. A desirable recycling method would deliver materials of near-virgin quality against a cost cheaper than creating virgin fibres.



Relevance of reverse logistics

It is identified both in the academia and industry that the introduction of reverse logistics is essential to the transition towards a circular economy business model. It is considered one of the main modifications for the companies' circular economy business models.

During the reverse logistics management on a circular business model it is highly important to investigate the potential of each return product and decide regarding the reuse, recycle, remanufacture of the material, component and product itself. In addition, another necessary issue is to understand the sources and the frequencies of the returns, as well as their impending benefits.

This includes concerns regarding the returns' quality and their quantification, especially in the future. In this section, potential reverse logistics pathways for composite materials are presented, along with the quantification of the sources.

Complexity as a challenge

the same inherent properties that make composite materials so attractive make their disassembly challenging and costly.

- fibres are impregnated within the matrix, and then treated to provide rigidity, firmly bonding them together.
- they might also contain fillers and additives to modify some properties, making separating one material from the other arduous.
- circular practices, such as designing, repairing, reusing and repurposing, need to be reinforced and some high potential recycling technologies also need to be further developed.

Complexity as a challenge: rethink the design

SYNTHETIC CHEMISTRY

Rethinking chemistry for a circular economy

Chemical complexity complicates product recycling and manufacturing sustainability

By Klaus Kümmerer[1,2], James H. Clark[3], Vânia G. Zuin[3,4]

desired grade, structure, and function for an application. With today's diverse and inter-

products have a long lifetime, such as those used in the human-made environ-

REMINDER:

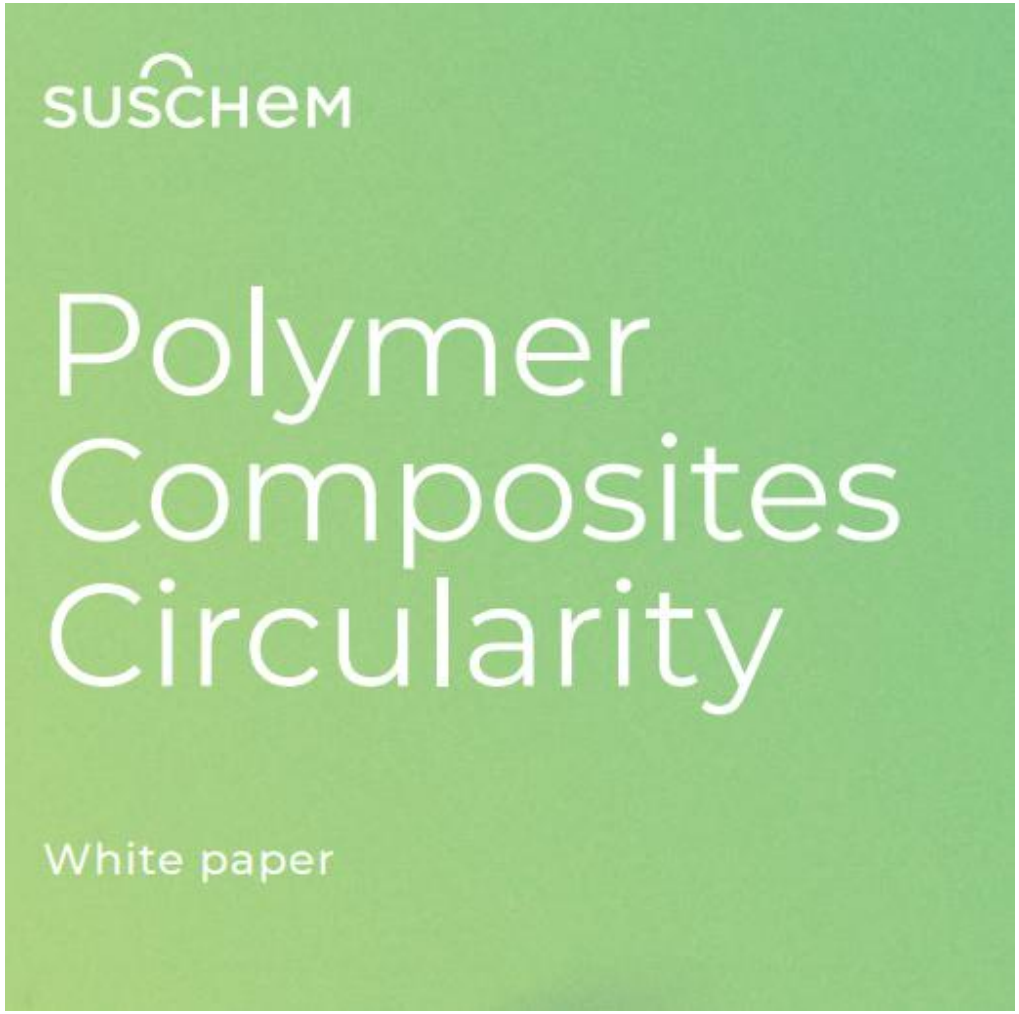
1. Keep **molecular complexity to the minimum** required for the desired performance, including end of life (complex molecules require more synthesis steps, may have additional undesirable properties, and can be more difficult to recycle).

2. Design **products for recycling**, including all additives and other components of the product.

3. **Reduce and simplify diversity and dynamics of substance, material, and product flow**s; e.g., use fewer chemicals overall (both number and quantity), design for less resource intensity, and adapt innovation speed of products to adaptation speed of recycling.

4. **Avoid complex** products (e.g., multiple components, materials).

Polymer composite circularity



SusChem is the European Technology Platform for Sustainable Chemistry.

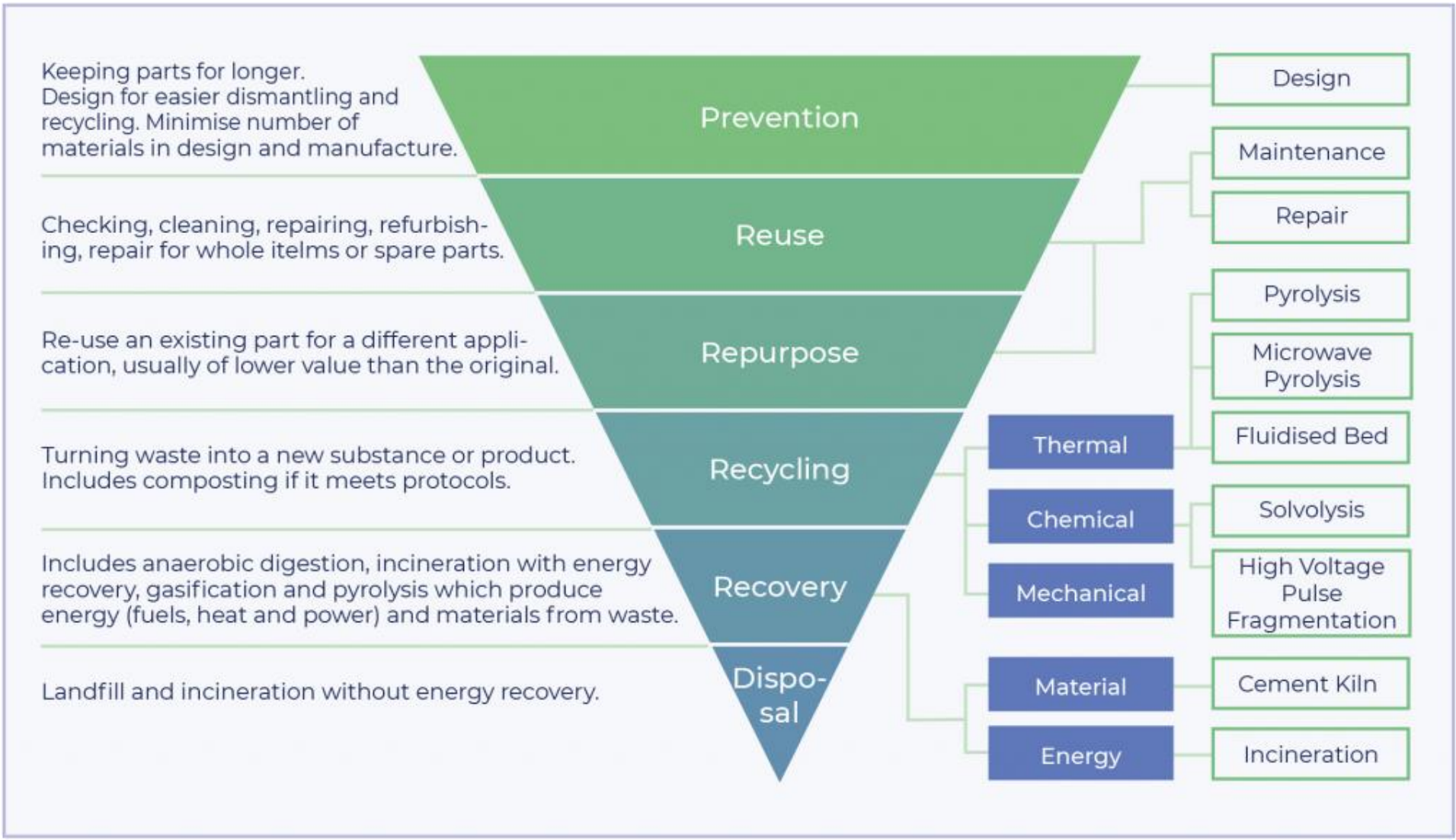
It is a forum that brings together industry, academia, policy makers and the wider society.

SusChem's vision is for a competitive and innovative Europe where sustainable chemistry and biotechnology together provide solutions for future generations.

SusChem's mission is to initiate and inspire European chemical and biochemical innovation to respond effectively to societal's challenges by providing sustainable solutions.

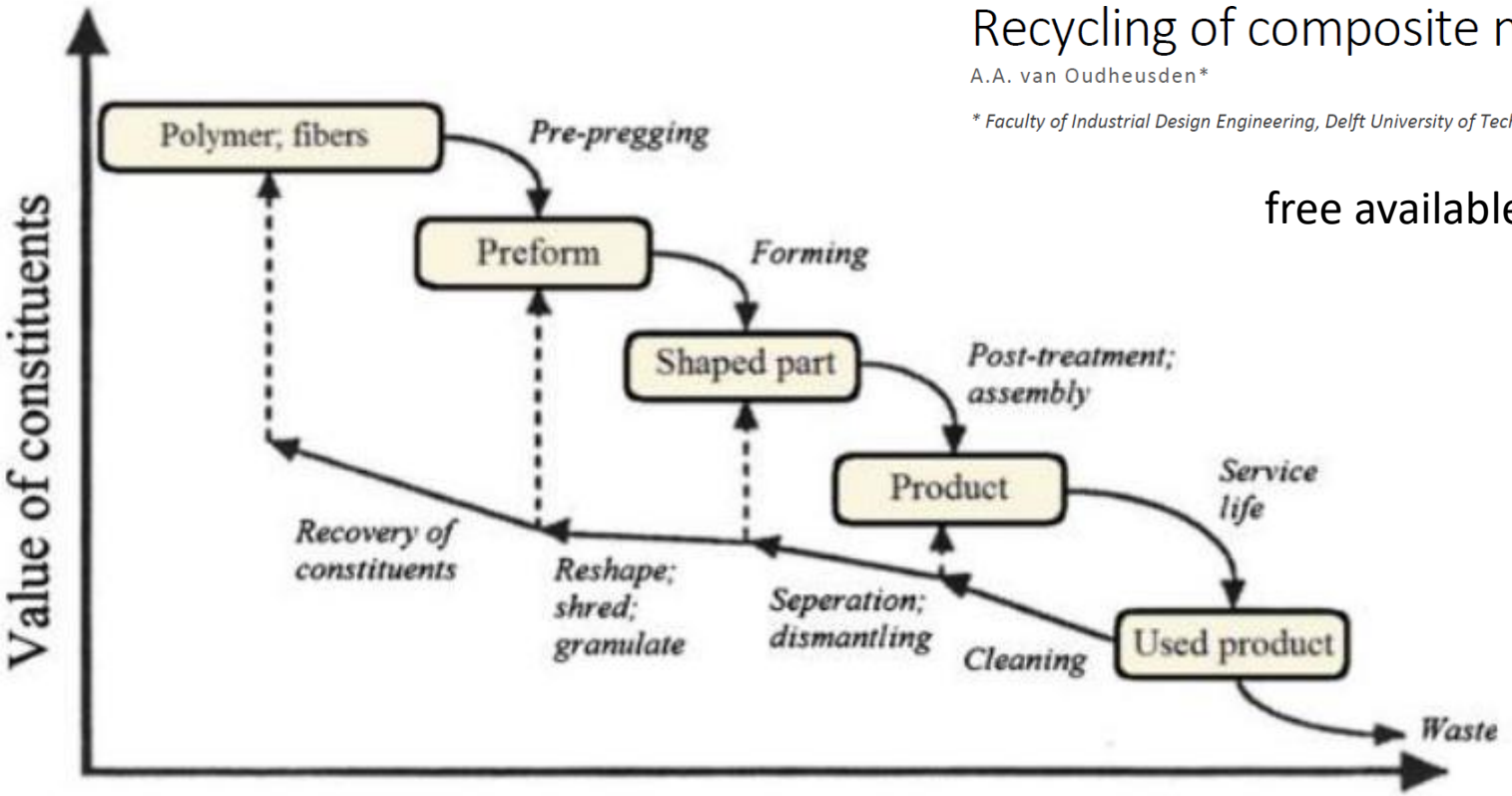
Source: Suschem/CEFIC- Polymer composite circularity – White paper, 2018

Circular options for composites



Source of the figure: Suschem- Polymer composite circularity – White paper

Recycling of composites



Recycling of composite materials

A.A. van Oudheusden*

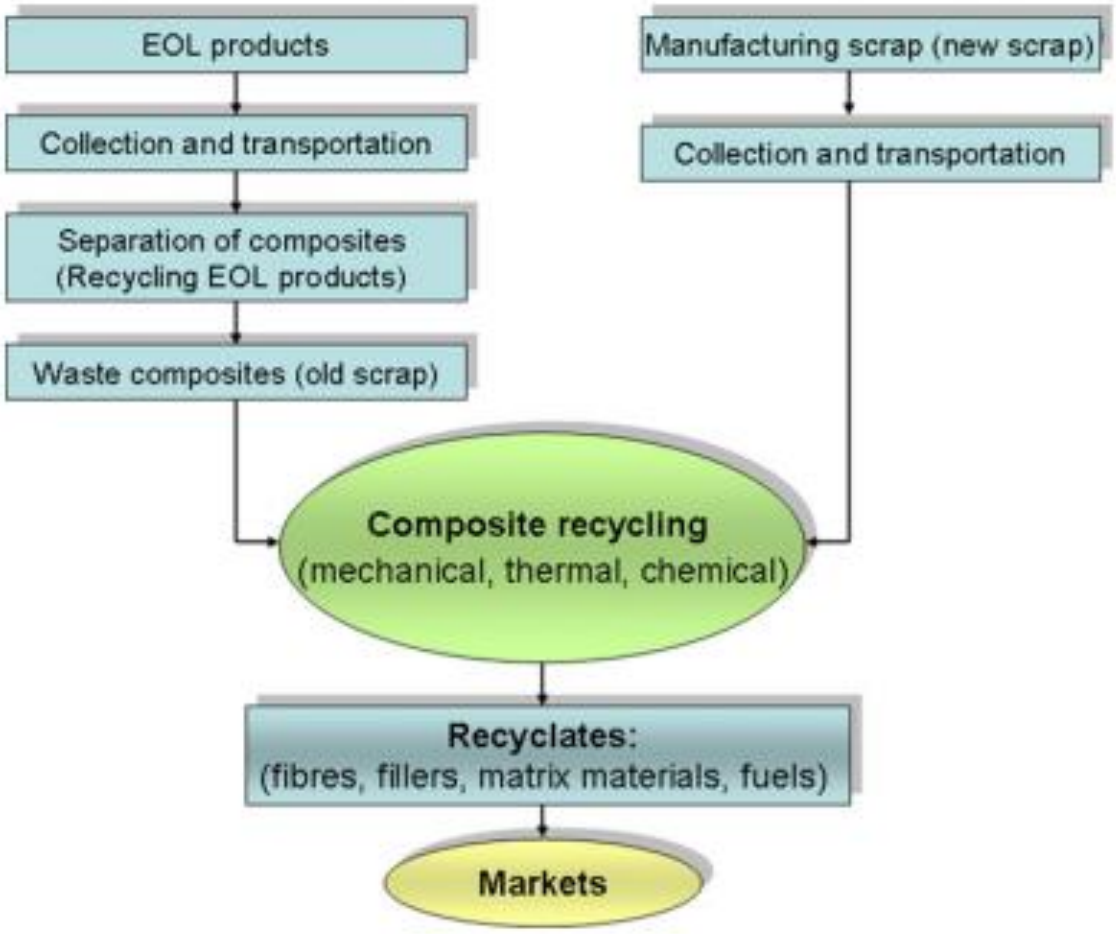
* Faculty of Industrial Design Engineering, Delft University of Technology, the Netherlands

free available

Change in value of the constituents with increasing life cycle (after Manson, 1994)

The value change of the different constituents is plotted over the lifecycle of the materials. When cycling back, it can be seen that the value loss, illustrated with the arrows with the dashed lines, becomes bigger with each step. When looking to retain higher mechanical performance over consecutive recycling loops, it is important to optimise the fibre reclaiming process and avoiding fibre damage both during product use and during the recycling process.

Circular options for composites: recycling



Structure of recycling system for composite materials

Source of figure: Chemical Engineering and Processing 51 (2012) 53–68

The availability of the composite scrap: this is the source of composites for recycling, which can originate from EOL postconsumer products – “old scrap”, or can be the production waste during manufacturing process – “new scrap” or “prompt scrap”

Circular options for composites

Prevention

Design is a critical step in determining the degree of circularity of any product. In the first place, it should serve the purpose of extending the life of the product, either by matching it with the application requirements or pre-defining possible second life applications (i.e. defining future reuse or repurpose applications). In the second place, it should consider the EoL phase of the product, i.e. ensure recycling, which is closely dependent on the material selection and combination, design for dismantling considerations, and material separation properties. Finally, it should incorporate the use of recycled materials in new products.

Maintenance, treatment and repair are key to postponing EoL as much as possible and ensuring maximum value for both resins and fibres is retained along the useful life. Recent developments in this field include health monitoring of applications, health forecasting, products for online repair (while the part is operational), and self-healing materials (see following slide).

Reuse and repurpose

Design should consider incorporating spare composite parts or second life products in new products.

Treatment and repair of EoL and damaged parts, to be reused or repurposed for other applications.

Source: Suschem- Polymer composite circularity – White paper

Self-healing materials (supplement)

- The term "self-healing materials" commonly implies substances or systems of materials that are able to partially or fully restore their initial properties after being mechanically damaged and rapidly developed a trend in materials science.

- Restoring may refer to any initial characteristics such as shape, appearance, and various properties.

- An ideal self-healing material is supposed to automatically, without any external action, recover its characteristics and integrity in a minimum amount of time necessary after the suffering damage and repeat this countless times.



Self-healing materials (supplement)

Material Type	Characteristics	Application Areas
Microcapsules	Autonomous healing, rupture releases healing agent	Coatings, aerospace, automotive
Thermoplastics	Reversible bonding, phase transformations	Automotive, aerospace, consumer goods
Shape Memory Polymers	Respond to heat, light, mechanical stress	Medical devices, textiles, robotics
Light-Sensitive Materials	Photochemical reactions	Sensors, smart windows, coatings
Hydrogels	Absorb and retain water, flexibility	Medical devices, wound dressings, agriculture

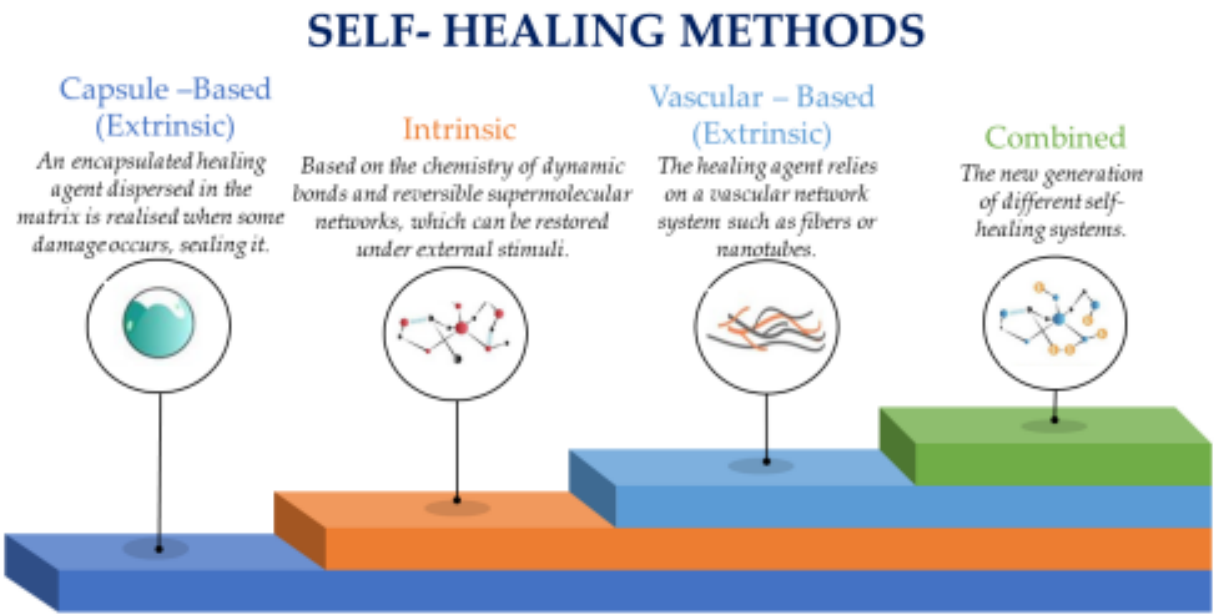


Figure 1. The self-healing methods.

Circular options for composites: recycling

Overview of recycling technologies for different types of composites.

Type of composites	Recycling methods	Technology features	Status of the technology
Thermoplastic–matrix composites	Remelting and remoulding	•No separation of matrix from the fibre	More studied for the manufacturing or process scrap.
		•Regrinding – compression or injection moulding/extrusion – compression moulding	Commercial operation? unknown
		•Product as pellets or flakes for moulding	
		•Fibre breakage – property degradation	
	Chemical recycling	•Dissolution of matrix	Not much studied
		•Fibre breakage – property degradation	
	Thermal processing	•Combustion or incineration for energy recovery (option for old scrap)	Not much studied or published
Thermoset–matrix composites	Mechanical recycling	•Comminution – grinding – milling	Commercial operation
		•Products: fibres and fillers	ERCOM (Germany)
		•Degradation of fibre properties	Phoenix Fibreglass (Canada)
	Thermal recycling	•Combustion/incineration with energy recovery	Promising technology
		•Fluidised-bed thermal process for fibre recovery	
		•Pyrolysis for fibre and matrix recovery	
			Hindered by the market for recycled fibres
	Chemical recycling	•Chemical dissolution of matrix	Only laboratory studies
		•Solvolysis (supercritical organic solvent)/hydrolysis (supercritical water)	Promising
		•Product of high quality fibres, potential recovery of resin	
		•Inflexibility of solvent and potential pollution	
Metal–matrix composites	Re-melting – casting	•Dir-cast scrap: direct remelting – casting	MMC is much more expensive than the alloys or reinforcements
		•Foundry scrap: direct remelting with (dry Ar) cleaning	Aiming at reuse of MMC
		•Dirty scrap: remelting – fluxing – degassing cleaning	
		•Very dirty scrap: metal recovery only – remelting and refining to separate reinforcement from Al (alloy)	

Source of figure: Chemical Engineering and Processing 51 (2012) 53–68

Circular options for composites

Recycling

Microwave pyrolysis is a thermo-chemical process in which the material is heated with microwaves, allowing better and easier control of the heating process and therefore reducing the induced damage and resulting in gas, oil and fibres recovery.

Mechanical grinding is the most commonly used technology due to its effectiveness, low cost and low energy requirement. It is, however, the least desirable recycling technology since it drastically decreases the value of the recycled materials. The recycled products, short fibres and ground matrix, can be used as fillers or reinforcement. Because of the deterioration of the mechanical properties, the incorporation level of filler material is extremely limited (less than 10%).

High voltage pulse (HVP) fragmentation (cfr. Electrofragmentation) is an electromechanical process that effectively separates matrices from fibres with the use of electricity. However, only short fibres can be recovered from the process and obtaining quality fibres requires high levels of energy, an issue that could be overcome by operating at higher rates. Compared to mechanical fragmentation, the quality of the fibres obtained is higher; fibres are longer and cleaner, and therefore less down-cycled.

Source of the figure: Suschem- Polymer composite circularity – White paper

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Processing using microwave energy

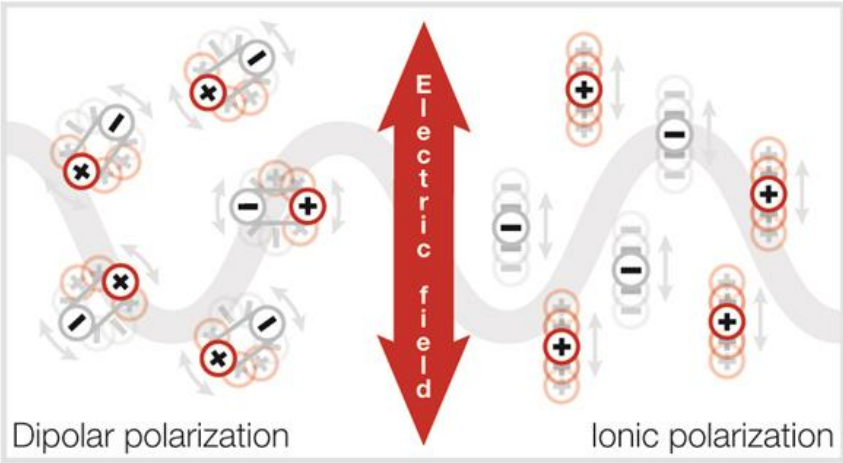
Microwave chemistry is based on the efficient heating of materials (in most cases solvents) by dielectric heating effects, by two major mechanisms:

1. Dipolar polarization

For a substance to be able to generate heat when irradiated with microwaves it must be a dipole. Since the microwave field is oscillating, the dipoles in the field align to the oscillating field. This alignment causes rotation, which results in friction and ultimately in heat energy.

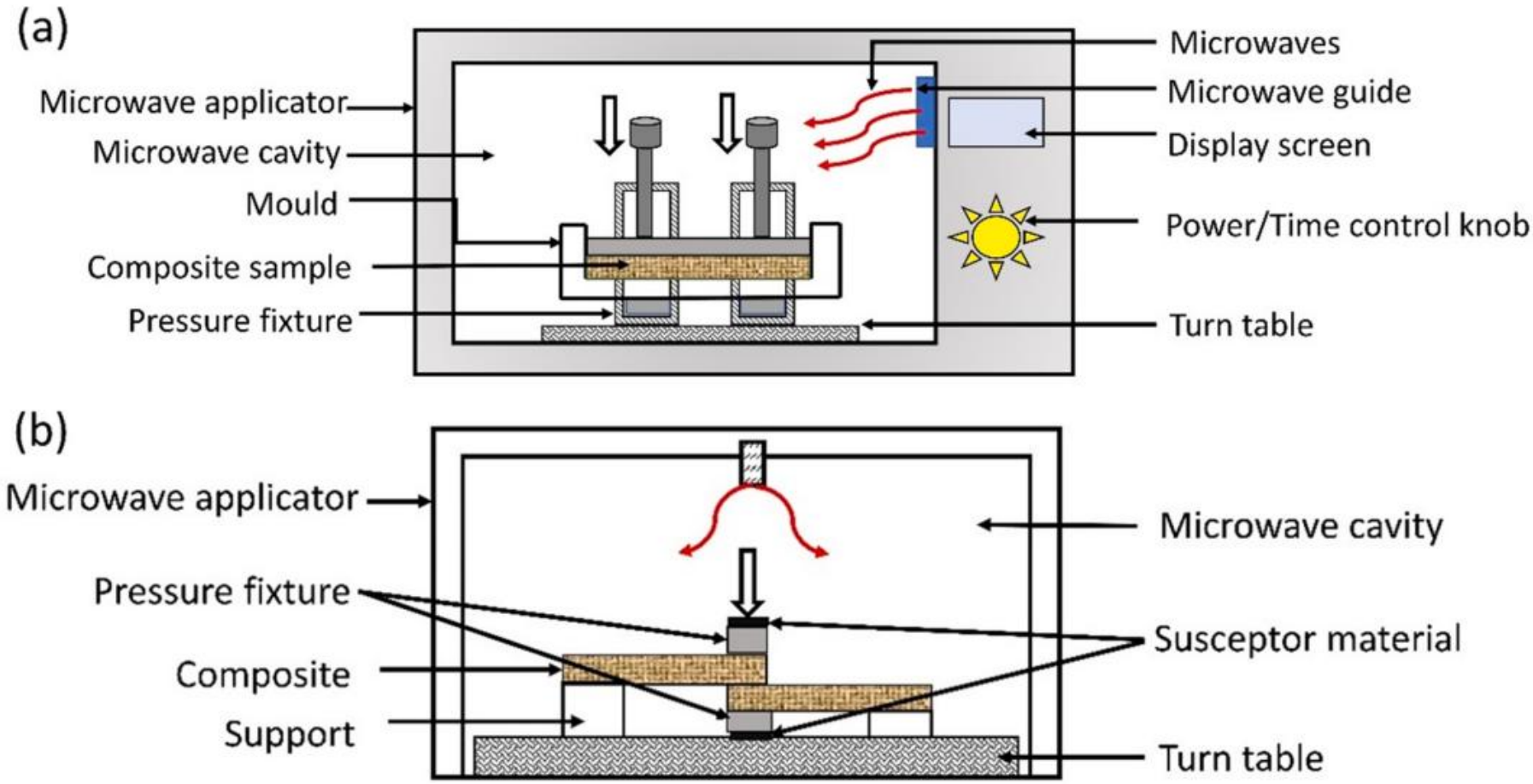
2. Ionic conduction

During ionic conduction, dissolved (completely) charged particles (usually ions) oscillate back and forth under the influence of microwave irradiation. This oscillation causes collisions of the charged particles with neighboring molecules or atoms, which are ultimately responsible for creating heat energy.



Electric energy is converted into kinetic energy, ultimately converted into heat

Processing using microwave energy



Setup diagrams for microwave processing of thermoplastic (a) Moulding, and (b) Joining.

Source of the table: Naik et al. Composites Part A 156 (2022) 106870

Challenges in processing using microwaves

Table 4
Challenges in processing of polymers and polymer-based composites.

Challenges	Remarks
Non-uniform power distribution	• This is because of non-uniform EM fields in the cavity. • Uneven temperature over the target material surface because of hot spots formation. • Hot spot formation can be reduced by; rotating the turntable, rotating the EM reflectors, use of multiple magnetrons, use of multiple frequency microwave.
Thermal conductivity and physical properties of the matrix material	• Processing of polymeric composites is a challenging task as it is a two-phase system and anisotropic in nature, where each constituent exhibit different thermal behaviour at same processing conditions. • Due to the material's low thermal conductivity, heat accumulates at the centre of the specimen, forming the hot spot. • Optimization of the processing parameters is required for wide variety of polymers found in market as they have different density, melt flow index, melting point, and so forth.
Modeling and simulation of composites	• Microwave curing is a complex phenomenon as the constituents present in the composites show different behaviour with increase in temperature.
Temperature measurement	• Difficult to control temperature of different phases in composite • Non-contact pyrometer, optical fiber probe and shielded thermocouples are different techniques used to measure the temperature profile inside the microwave's cavity.
Poor repeatability of the process	• Limit the use of process for industrial application.
Selection of susceptor	• Improper selection of susceptor leads to non-uniform heating of the composites. • It may also lead to burning and degradation in properties of the composite materials.
Microwave arcing	• Both the composite and the equipment may suffer significant localized damage. • Mainly seen with carbon fiber used as reinforcement. • Leads to severe health and safety concerns.
Economics	• Design and development of customized microwave cavity is costly and time consuming. • Compromise with part size.

Source of the table: Naik et al. Composites Part A 156 (2022) 106870

Circular options for composites

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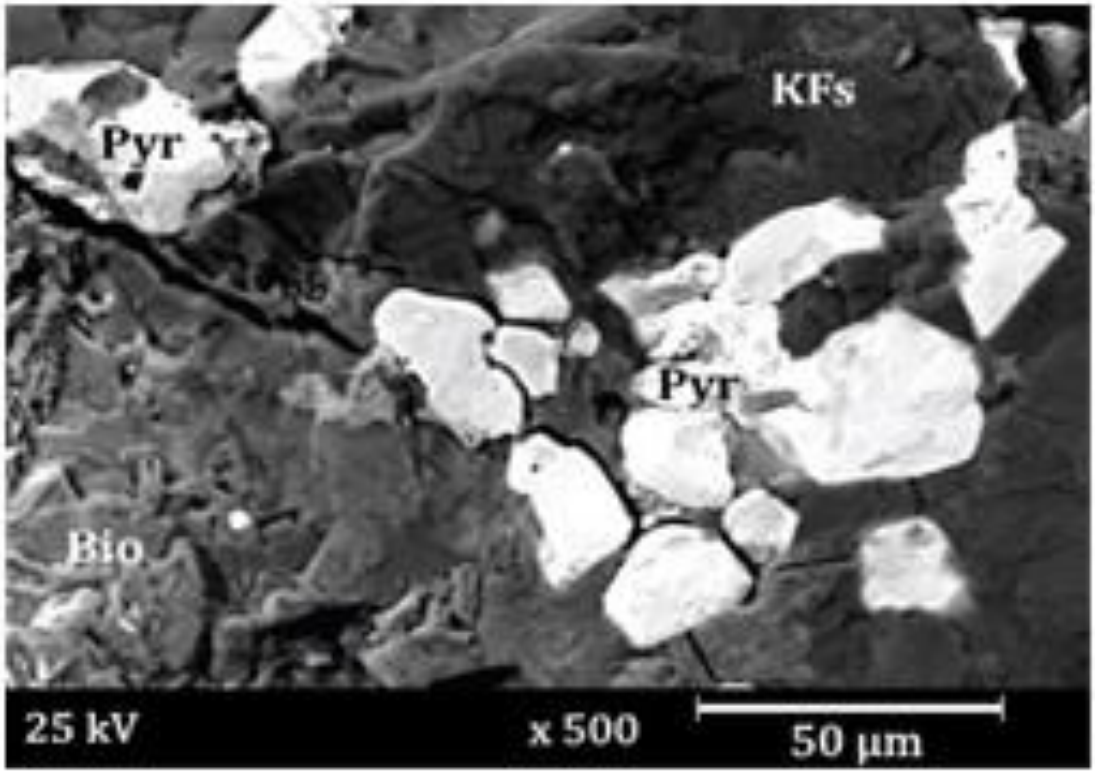
High voltage pulse (HVP) Fragmentation-Electrofragmentation





Source of the table: https://www.hiserproject.eu/files/and-demolition-waste_twd62vktrgt50r4632maip/

Electrodynamic fragmentation

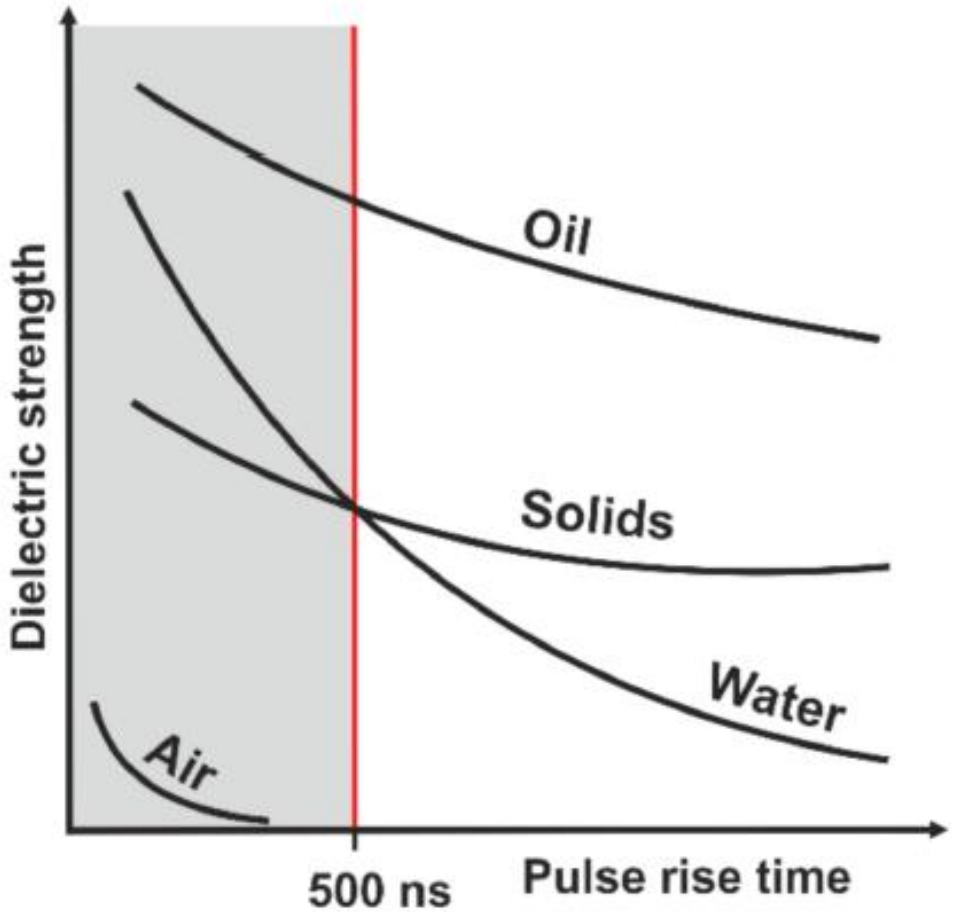
- electrodynamic fragmentation is a technique using pulsed power discharges to separate bulky multi-phase material selectively along grain boundaries.
- the discharge has to take place underwater to enable the solid material to be penetrated. thus, the whole approach is a “wet process”.
- the potential of this pulsed power processing approach was demonstrated for the recycling of waste concrete
- the method itself was first investigated and described at the University of Tomsk in the late 1940s.
- The technology of electrodynamic fragmentation is based on the physical principle that ultra-short electrical pulses (< 500 ns) prefer passing through solids. If, for example, a composite is placed under water between two electrodes and a high voltage is applied (approx. 200 kV), sparks are discharged which tend to pass through the solid along grain surfaces or phase boundaries, thus weakening it mechanically.

Electrodynamic fragmentation

- the efficiency of the method is the higher the more electrical discharges are generated over time
- whether an electrical discharge can penetrate a material or not depends on the dielectric strength* of the given material.
- the dielectric strength of a material is not a constant but varies in dependency with the slew rate (= **slew rate** is defined as the change of voltage or current, or any other electrical or electromagnetic quantity, per unit of time) and therefore the length of a discharge.
- at a pulse rise time lower than 500 nanoseconds, the dielectric strength of water is higher than that of solid material.

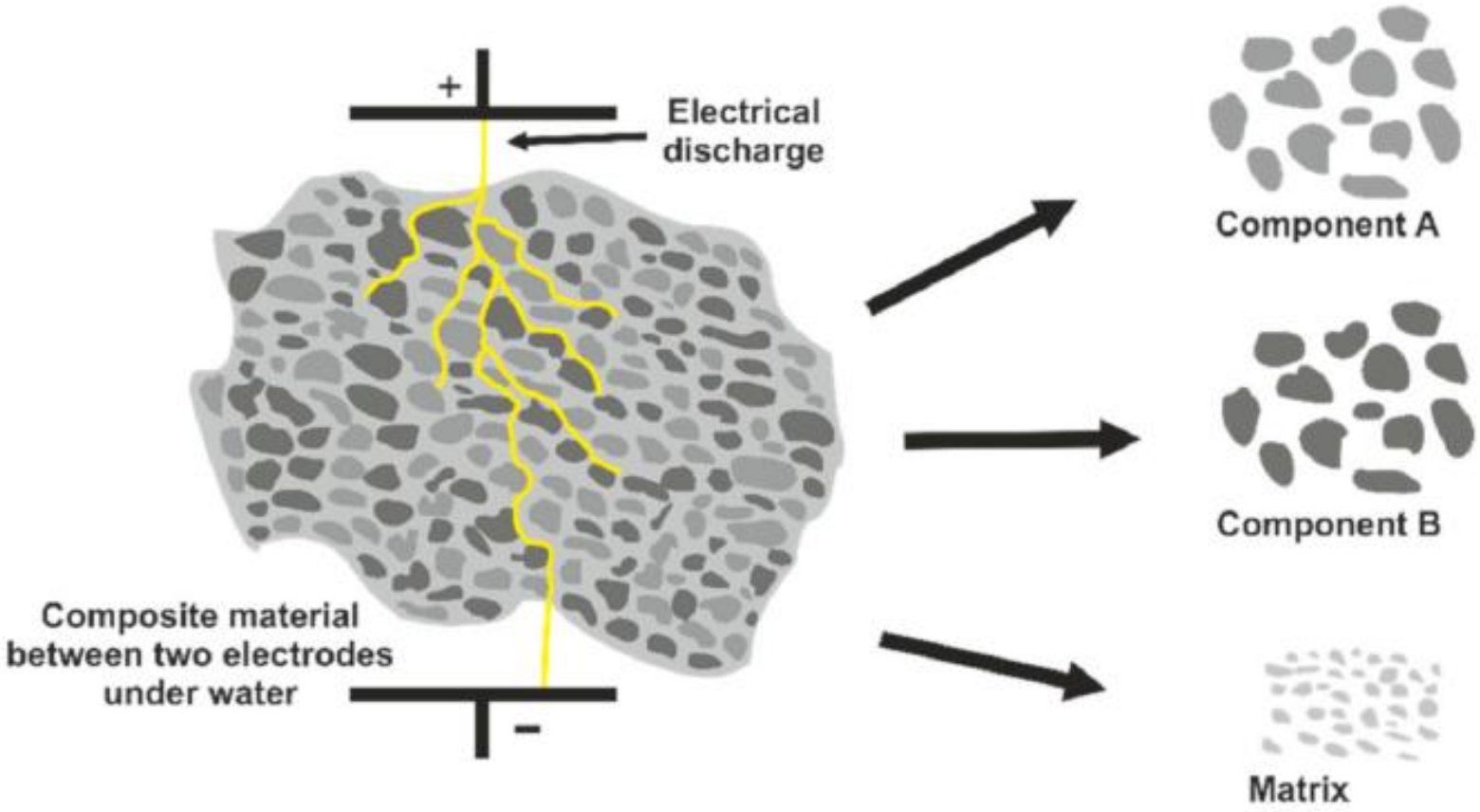
* Dielectric strength is measured as the maximum voltage required to produce a dielectric breakdown through a material. It is expressed as Volts per unit thickness. For a plastic material the dielectric strength varies from 1 to 1000 MV/m.

Electrodynamic fragmentation



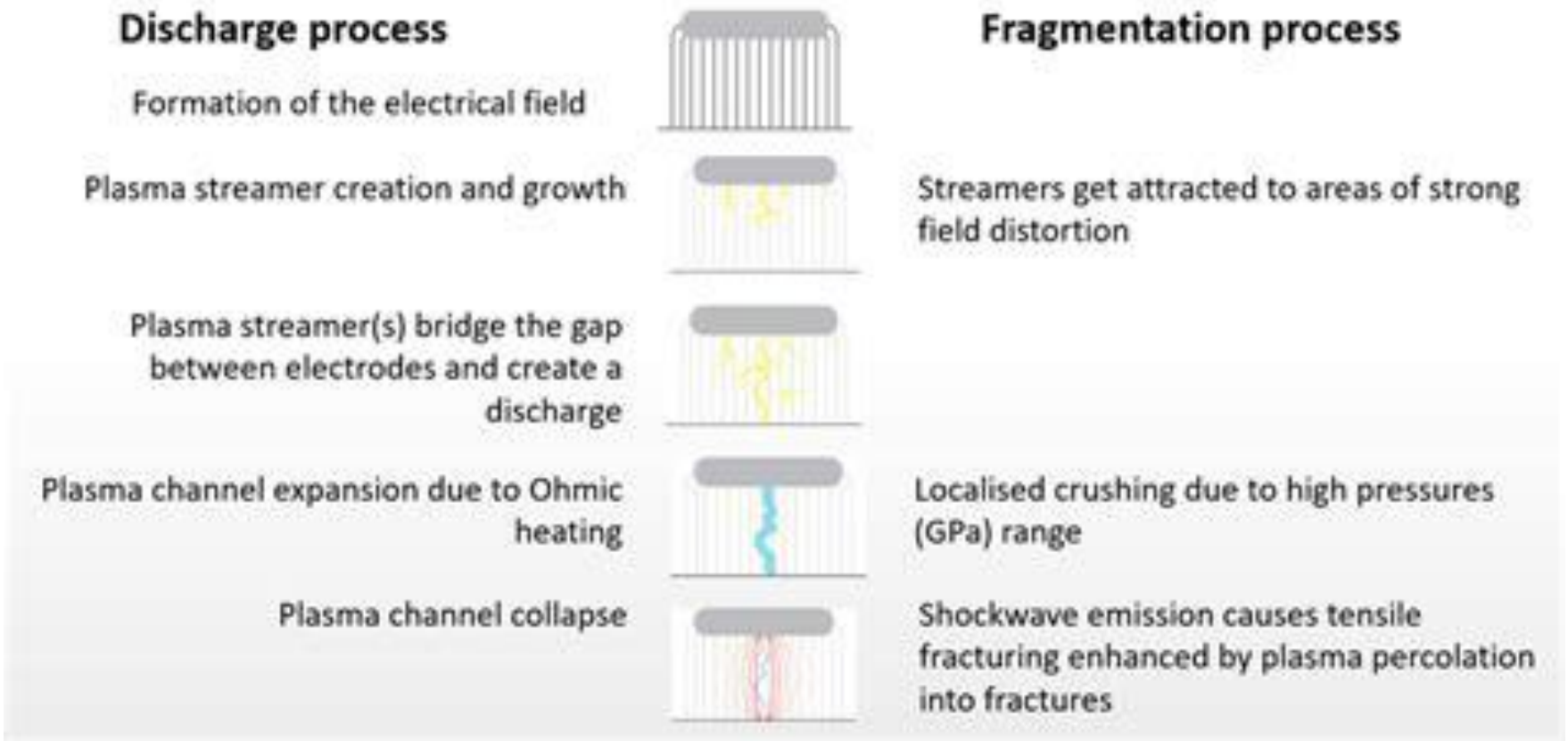
Dielectric strength of different materials as a function of the pulse rise time
Source of the figure: Processes **2021**, 9, 228

Electrodynamic fragmentation



Principle of electrodynamic fragmentation of a composite material
Source of the figure: Processes **2021**, 9, 228

Electrodynamic fragmentation



Source of the figure: https://www.researchgate.net/

Circular options for composites

Recycling

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Source of the figure: Suschem- Polymer composite circularity – White paper

Mechanical recycling for composites

In the mechanical grinding process, there are three main steps to be distinguished

	1. Shredding	2. Grinding/milling	3. Classifying
Process	Reduce waste materials into pieces	Grind pieces into fragments	Separating the fragments into resin-rich powders and fibrous fragments
Particle size [a]	50 – 100 mm	10 mm – 50 µm	-
Equipment	Slow speed cutting or crushing mill	High speed cutting or hammer mill	Cyclones and sieves

[a] at the end of the step

The recyclate of the mechanical grinding are mixtures of resin, fibre and filler. In this, two main fractions can be distinguished: fine and coarse. The finer fractions are powders with a higher resin and filler proportion compared to the original composite, whereas the coarser fractions are more fibrous with a higher fibre content

Recycling of composite materials

A.A. van Oudheusden*

* Faculty of Industrial Design Engineering, Delft University of Technology, the Netherlands

Mechanical recycling for composites

ADVANTAGES

- There are both environmental and economic advantages for mechanical recycling. As it does not use any chemicals, it does not produce any atmospheric or water pollution.

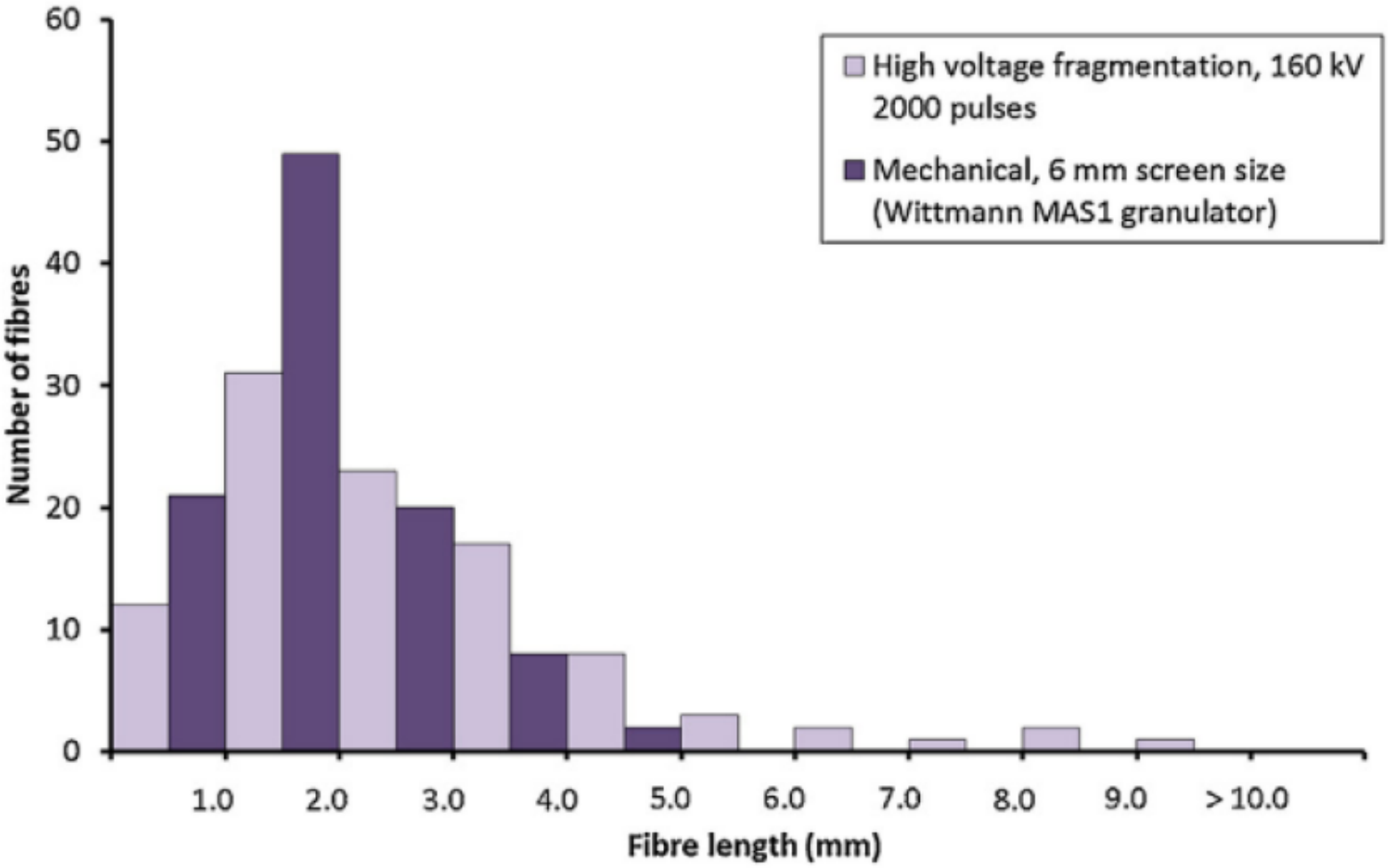
- Also, no high-end technical and expensive equipment is needed compared to the other methods, and it allows for processing of larger amounts of waste at higher throughputs.

DISADVANTAGES

- A big drawback however is that the recovered recyclate is of inferior quality compared to the virgin product, as previously mentioned. This makes it difficult to find market applications for the recyclate, as it is hardly competitive with virgin raw materials.

- Additionally, a continuous flow of waste is required for setting up and running a mechanical recycling plant and for producing products from the recyclates. This makes mechanical recycling not a viable solution if there is only a minimum amount of waste. With the expected composite waste volume from for example end of life windmills, the required waste volume will not be hard to achieve. However, without a viable application for the recyclate, going through the whole process might not be justified or even sustainable.

Comparison of approaches



Fibre length comparison between fibres recovered from mechanical and HVF methods

Circular options for composites

Recycling

Solvolysis is a chemical treatment which offers many possibilities due to a wide range of solvent, temperature and pressure options. Compared to thermal technologies, solvolysis requires lower temperatures to degrade the resins, resulting in a lower degradation of fibres. Solvolysis with super-critical water (see following slide) seems to be the most promising technology since both fibres and resins can be retrieved without major impacts on their mechanical properties. However, common solvolysis incorporates salts or other modifying components that damage fibres and can be highly polluting. Solvolysis is easily scalable but investment and running costs are high and it is still at a low Technology Readiness Level (TRL).

Pyrolysis (decomposition of a molecule by high temperature within a nonreactive atmosphere) is a thermal recycling process which allows the recovery of fibre, and matrix in the form of ash. It allows for the lowest value loss from industrial-scale technologies, but it is still more of a down-cycling method than recycling and still requires high investment and running costs. Matrices are turned into powder or oil, potentially useable as additives and fillers, and the fibre surface is often damaged due to the high temperatures resulting in a decrease in mechanical properties. Some improvements, such as combining the process with robotic precision cutting, could increase the quality of the recycled material.

Source: Suschem- Polymer composite circularity – White paper

Circular options for composites

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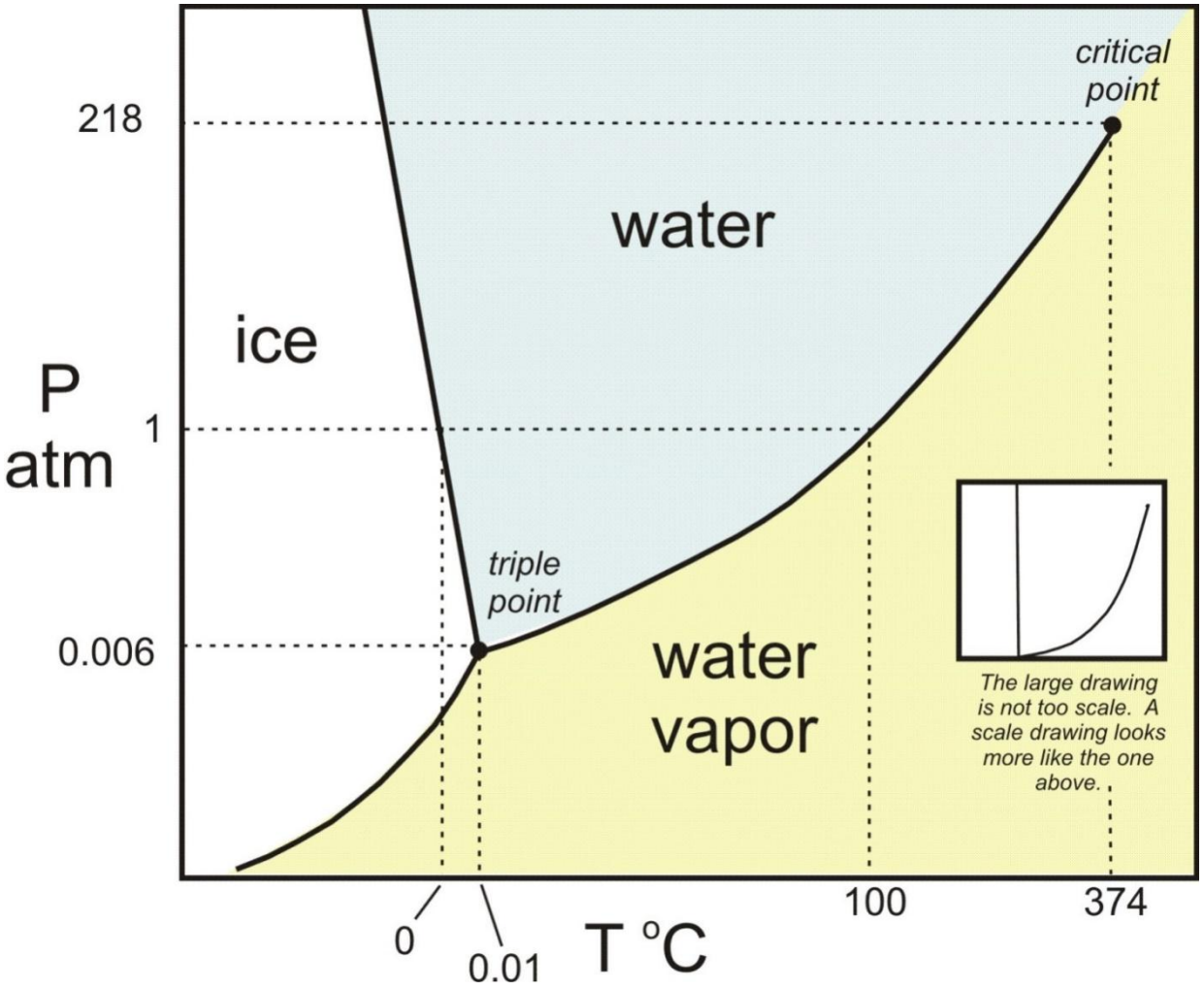
Supercritical water



Critical point

The temperature and pressure at which the liquid and vapour intensive properties (density, heat capacity, etc.) become equal. It is the highest temperature (critical temperature) and pressure (critical pressure) at which both a gaseous and a liquid phase of a given compound can coexist.

IUPAC Goldbook: http://goldbook.iupac.org/C01396.html

Circular options for composites

Recycling

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Source: Suschem- Polymer composite circularity – White paper

Circular options for composites

Recovery

Cement kiln allows recovery of material and energy. Although it is very promising in terms of cost effectiveness and efficacy, this process is one of the most downgrading route of all these the technologies described here and, therefore, should be used only when the value of the composite materials no longer suits any other application.

Incineration is mainly used to recover energy. It is the least desirable technology since it results in major loss of material. The same process as the for the cement kiln route applies here.

Disposal

Landfilling translates into an absolute loss of resources.

Source: Suschem

Cement coprocessing the end-of-life composite materials

Position paper

June 2023

Cement co-processing is a sustainable solution for recycling end-of-life composite materials.

Executive summary

This paper summarises the position developed by WindEurope, EuCIA, CEMBUREAU, EBI, Cefic UP/VE, Cefic Epoxy Europe, and Glass Fibre Europe on the benefits of cement co-processing for end-of-life composite materials used in construction, wind, marine, infrastructure and industrial markets and how the EU regulatory framework can help to scale it up. Co-processing offers a sustainable and circular solution for recycling the end-of-life glass fibre reinforced composite materials. As partners, these organisations want to promote sustainable recycling approaches and encourage composite use sectors beyond the wind and boating industry to sustainable recycle their end-of-life composite materials.

Source: https://eucia.eu/wp-content/uploads/2023/07/230623-Joint-position-Co-processing-Composites.pdf

Cement coprocessing the end-of-life composite materials

During coprocessing the end-of-life composite materials are simultaneously used as both a source of energy and a source of mineral raw material:

- The glass fibre mineral fraction is recycled in the cement clinker composition, preventing the extraction and use of equivalent quantities of mineral raw material input for cement manufacturing.

- The polymer fraction is used as alternative fuel in cement kiln, saving the extraction and use of more than equivalent quantities of fossil sources of energy (e.g., coal, pet coke, etc.) and their associated greenhouse gas (GHG) emissions.

- This is a win-win solution that:
- 1) Allows for a sustainable recycling solution for end-of-life composite materials from decommissioned assets, vessels, and composites manufacturing processes.
- 2) Supports the sustainable development and decarbonisation of the European construction market.
- 3) Increases the overall circularity of end-of-life composite materials.

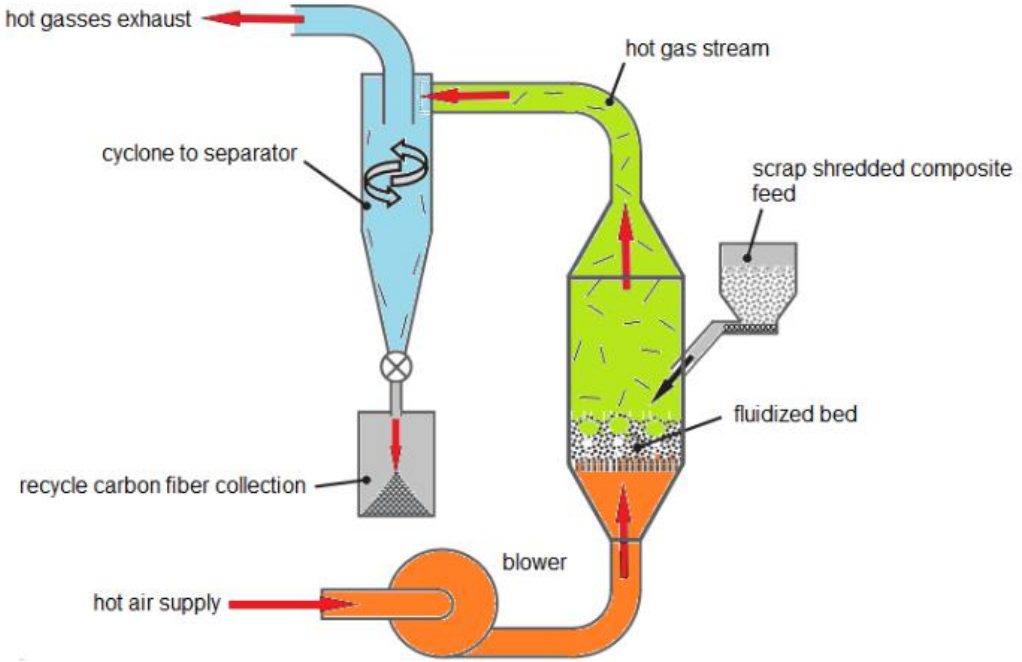
Source: https://eucia.eu/

Circular options for composites

Fluidised bed (granular systems of solid-particles subjected to a vertical upward flow of fluid) is a thermal method which only allows the fibre to be recovered and, compared to pyrolysis, with lower quality since the fibre surface seems to be more damaged. The unique characteristic of this process is that it can treat **mixed and contaminated material** (e.g. painted surfaces or foam cores), and therefore could be particularly suitable for EoL waste.

Hybrid technology most commonly consists of a combination of thermochemical recycling technology (solvolysis or pyrolysis) and mechanical grinding. This process allows improved quality for the recycled material by retrieving the matrix in the first place.

Carbon fibers recovery from CFRP recycling process and their usage: A review - Scientific Figure on ResearchGate.
Available from: https://www.researchgate.net/figure/Fluidized-bed-process-9_fig2_350166065 [accessed 17 Nov 2024]



Circular options for composites

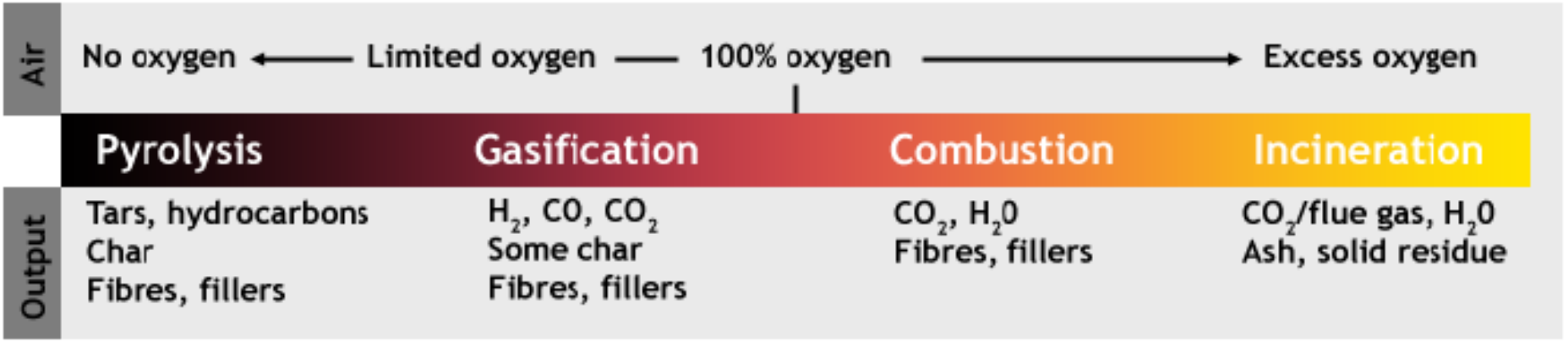


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Figure 17: The difference between pyrolysis, gasification, and combustion. Image constructed using EnerSol Technologies Inc. (2008) and Williams (2005)

Comparison of approaches

	Definition	Energy	Output	Types [f]
Incineration	Burning it completely Temperature: > 850 °C [a] or > 1100 °C [b]	Exotherm Retrieved energy is roughly equal to the calorific value of the resins (approx. 30 MJ/kg for most resins [e])	Energy recovery and ash	- Grate firing - Rotary kiln incinerator
Combustion	Controlled burning Temperature: 450-600 °C [c]		Fibre + filler recycling and energy recovery	- Fluidised bed combustion
Co-processing	Burning and incorporating the residue into the cement Temperature: 1050-2000 °C		Energy recovery and ashes + minerals that can be used as cement clinker feedstock	- Co-processing in cement kiln
Pyrolysis	Thermal decomposition of polymers (in inert atmosphere) Temperature: 300-800 °C [d]	Endotherm Energy costs are 23-30 MJ/kg (5-10 MJ/kg for microwave pyrolysis)	Solids (50-75%): fibres, fillers and carbon char Liquids (10-50%): mix of organic compounds Gas (5-15%): mix of CO_2, CO and hydro-carbons	- Chain conveyor - Rotary kiln - Microwave - Superheated steam - Catalytic - Gasification

[a] general waste (European Parliament and Council, 2000)
[b] in case of > 1% of halogenated organic substances (European Parliament and Council, 2000)
[c] depending on resin type and atmosphere; typically, 450 °C for polyester and 550 °C for epoxy (Yang et al., 2012)
[d] A higher temperature of 1000 °C can be applied but resulting fibre products will be seriously more degraded (Yang et al., 2012)
[e] polyester, vinyl ester, phenolic, and epoxy resin have a calorific value of approximately 30,000 kJ/kg, urea formaldehyde has a calorific value of 15,700 kJ/kg (Pickering, 2005).
[f] The most common types that will be discussed in this report

Overview of the thermal processing methods used for composite materials (European Parliament and Council, 2000; Job et al., 2016; Pickering, 2005; Yang et al., 2012)

Comparison of approaches

- pyrolysis and solvolysis seem to be the most promising technologies since they allow recover of both matrix and fibre and involve the lowest value loss.
- especially in the case of CFRP, both technologies have demonstrated the recovery of fibres without major loss of their reinforcement capacity.
- fibres recovered by solvolysis are cleaner and less damaged than those recovered by pyrolysis.
- the quality of the recovered material ultimately relies on the temperature of the process, acidity of the solvents, and the disposition of the fibres (e.g. it is harder to remove resins which are reinforced with woven fibres).

Comparison of approaches

	Availability (Mativenga et al., 2016)	Application	
Mechanical grinding	Operating at commercial scale with wide range of potential applications available	Mechanical recycling is mostly used for glass fibre composites due to the relatively low values of the recycled products. It is suitable more for the waste sheet moulding or bulk moulding compounds, but may be difficult for the laminated compounds such as in wind turbine blades (Papadakis, Ramírez, & Reynolds, 2009; Yang et al., 2012)	
High voltage fragmentation	Laboratory and pilot scale machine available, e.g. SELFRAG		
Incineration and co-processing	Commercially available, several companies perform incineration of composite scrap (Bax et al., 2015)	Mainly glass fibres composites are incinerated/ co-processed. It is used for production of energy and recycling of ash in significantly lower value applications (Bax et al., 2015)	Thermal recycling processes have the advantage of being able to tolerate more contaminated scrap materials, making it suitable for processing mixed post-consumer waste (Pickering, 2005)
Combustion	Fluidised bed process investigated at pilot scale	Thermal and chemical processes are mostly used for carbon fibre composites. Any thermal or chemical process strips the sizing off the fibres, which makes these type of processes unsuitable for glass fibres unless post-treated (Job et al., 2016).	
Conventional pyrolysis	Industry scale process available at commercial level, currently operated by companies (e.g. ELG, UK and CFK Valley Stade, Germany)		
Alternative pyrolysis	Microwave pyrolysis has limited availability, even at pilot scale		
Solvolysis	Research done on lab scale, focus on carbon fibre composites		No (commercial) application yet

Comparison of approaches

	Energy	Output	Recyclate application	(Dis)advantages	WMH level & TRL
Mechanical					
Mechanical grinding	Energy costs: 0.1-4.8 MJ/kg [1]	- Resin-rich powders [2] - Fibrous fractions [2]	Resin powders: filler [3] Fibres: filler, moulding compounds, injection moulding [4]	+ Suitable for post-consumer waste + No atmospheric/water pollution [5] (Ribeiro et al., 2016) + Low investment, fast processing, large volumes [5] - Highly inferior recyclate, low market appeal [5,6] - Continuous waste flow required waste [7]	WMH: Recycling [8,9,10] TRL: 8-9 for GF [8,10] 6-7 for CF [8,10]
High voltage fragmentation	Energy costs: 17.1-89.1 MJ/kg [4]	- Resin pieces [8] - Fibres [8]	Resin: not mentioned Fibres: filler, moulding compounds, injection moulding [4]	+ Suitable for post-consumer waste + Quite good matrix and fibre separation [8] + Relatively low-cost [8] + Fibre quality better compared to mechanical grinding [4,9] - Quite energy-intensive [4] - Moderate fibre quality compared to virgin fibres [8] - Resin residue on fibres [8]	WMH: Recycling [8,9] TRL: 5-6 [8]
Thermal					
Incineration	Exotherm Energy gain: approx. 30 MJ/kg [11]	- Energy from resin matrix [12] - Ash and solid residue (fibres and fillers) [13]	Ash: aggregates, construction applications, landfill [14]	+ Suitable for post-consumer waste + Energy recovery of matrix [12] - Near-worthless output [12,15] - Potential health, safety and performance issues due to roaming fibre fragments [16,17]	WMH: Recovery [8,9,10] TRL: 9 [8,10]
Combustion	Exotherm Energy gain: approx. 30 MJ/kg gain [11]	- Energy from resin matrix [6] - Fibres [11]	Fibres: moulding compounds [18], non-woven fibre fabrics [11]	+ Suitable for post-consumer waste + Very tolerant of mixed and contaminated materials [11] + No need to remove metal inserts [11] - Reduced fibre quality and fibres are short and fluffy [6,11] - No resin recovered, difficulty in replicating lab results [8]	WMH: Recycling [8,9,10] TRL: 4 [8,10]
Co-processing	Exotherm Energy gain: Approx. 30 MJ/kg gain [11]	- Energy from resin matrix [7] - Solid residue (fibre ashes, mineral fillers) [7]	Solid residue: incorporated in cement clinker [1,11]	+ Suitable for post-consumer waste + Treats mixed waste [1] + Lower carbon emissions of cement processing [7] + Decreases costs of waste management [7] + No residues left behind [7] + Saves on virgin materials [7]	WMH: Recovery [8,9] TRL: 9 [8]

[1] (Job et al., 2016), [2] (Pickering, 2005), [3] (Oliveux et al., 2015), [4] (Mativenga et al., 2016), [5] (Ribeiro et al., 2016), [6] (Yang et al., 2012), [7] (Vijay et al., 2016), [8] (Bax et al., 2015), [9] (Devic et al., 2018), [10] (Rybicka et al., 2016), [11] (Pickering, 2005), [12] (Larsen, 2009), [13] (Crowder & Richards, 2003), [14] (Williams, 2005), [15] (Halliwell, 2006), [16] (Hedlund-Åström, 2005), [17] (Limburg & Quicker, 2016)

Data overview of all composite recycling methods previously discussed

Comparison of approaches

				- Loss of all composite material value - Potential production of hazardous dust [16,17] - Effects on cement product uncertain [15]	
Pyrolysis ***Types:*** ***- classic*** ***- fluidised bed*** ***- microwave*** ***- superheated steam*** ***- catalytic*** ***- gasification***	Endotherm Energy costs: Classic: 23-30 MJ/kg [1] Microwave: 5-10 MJ/kg [1] Other: N/A *operating scale too small*	- Char, oil and gas from resin matrix [2,3] - Fibres, fillers, inserts [2,3]	Resin products: energy source [3], chemical feedstock [18] Solid residue: filler [19] Fibres: moulding compounds, non-woven fibre fabrics [1]	General + Suitable for post-consumer waste + Flexible, able to treat mixed and contaminated waste [1] + Recovers both fibre and resin feedstock [2] - Refining of resin products difficult, only feasible on large scale [2] Classic: - Takes a long time due to inefficient heating [20] Fluidized bed: + More effective heating [1] - More fibre damage [1] Microwave: + More effective heating [21] + Lower CO_2 emission [21]	WMH: Recycling [8,9,10] TRL: 4-8 depending on type [8,10] *Classic:* *8 for CF [1]* *6-7 for GF [10]*
Chemical					
Solvolysis ***Types:*** ***- HTP*** ***- LTP***	Energy costs: 21-91 MJ/kg[1]	- Monomers or petro-chemical feedstock and gases from depolymerised matrix [6] - Fibres [1,6]	Feedstock: new resin [6], fuels [22], polymers [22], thermo-plastics[1], adhesives[1], etc. Fibres: thermoplastic composites, moulding compounds, non-woven fibre fabrics [1]	General: + Lower temperatures compared to pyrolysis [1] + Higher reclaim of chemicals from resin [1] + Cleaner fibres with no char [1] + Suitable to treat waste with known characteristics (e.g. production waste) [6] - Difficult to treat mixed/ post-consumer scrap [6] - Reactors can become expensive [1,3] - Recycled fibre can be more expensive than virgin [23] - Environmental and health issues through solvents & toxics [1,6] - High energy consumption [23] LTP: + Better control of reactions [3] + No secondary reactions, leading to higher recovery [3] - The strong (mostly) acid conditions can be dangerous [3]	WMH: Recycling [8,9,10] TRL: 3-4 [8,10]

[1] (Job et al., 2016), [2] (Pickering, 2005), [3] (Oliveux et al., 2015), [6] (Yang et al., 2012), [8] (Bax et al., 2015), [9] (Devic et al., 2018), [10] (Rybicka et al., 2016), [11] (Pickering, 2005), [15] (Halliwell, 2006), [16] (Hedlund-Åström, 2005), [17] (Limburg & Quicker, 2016), [18] (Cunliffe & Williams, 2003), [19] (Cucurás et al., 1991), [20] (Chen et al., 2015), [21] (Kim et al., 2017), [22] (Rush, 2007), [23] (Eurecomp, 2013)

Data overview of all composite recycling methods previously discussed

Recyclates

	Fibres				Resin	
	Carbon fibre		Glass fibre			
	Fibre length	Mechanical properties	Fibre length	Mechanical properties	Residual on fibre	Products
Virgin	Any length	*High strength fibre:* Tensile strength: 4.65e3 MPa [1] Stiffness: 225 - 245 GPa [1] *High modulus fibre:* Tensile strength: 2.4e3 MPa [1] Stiffness: 370 - 390 GPa [1]	Any length	*E-glass fibre:* Tensile strength: 2.00e3 MPa [1] Stiffness: 75 - 85 GPa [1] *C-glass fibre:* Tensile strength: 3.25e3 MPa [1] Stiffness: 60 - 70 GPa [1] *S-glass fibre:* Tensile strength: 4.75e3 MPa [1] Stiffness: 86 - 93 GPa [1]	0% resin content Clean surface	Virgin resin material
Mechanical						
Grinding	N/A	N/A	0.8-3.1 mm [2] mean: 2 mm [2]	*Not measurable*	49-59 % resin content [2]	Resin-rich powder [3]
High voltage fragmentation	N/A	N/A	0.5-9 mm [2] mean: 2 mm [2]	*Not measurable*	32-37 % resin content [2]	Resin chunks [4]
Thermal						
Incineration	*No fibres are retrieved*					Energy, ash [5,6]
Combustion	6-10 mm [3,7]	Tensile strength: *550 °C:* –20 % [3,7] Stiffness: retained [3,7]	6-10 mm [3,7]	Tensile strength: *450 °C:* –50 % [3,7] *650 °C:* –90 % [3,7] Stiffness: retained [3,7]	Very little [3]	Energy [7]
Co-processing	*No fibres are retrieved*					Energy [8]
Conventional pyrolysis *Types:* *- classic* *- fluidised bed*	Fibre length can be retained [9] Commercially available: 3 –90 mm in various length categories [10]	*Classic* Tensile strength: –4 % to –85 % [11] *Possible to achieve 90% to near-virgin properties using blending* [12] *Fluidised bed* Tensile strength: –25 % [12] Stiffness: retained [12]	No data found	*Classic* Tensile strength: –52 % to –64 % [11] *Fluidised bed* Tensile strength: *450 °C:* –50 % [13] *550 °C:* –80 % [13]	None, but there is a char on the fibres [11,12] and the sizing is stripped off the fibres [12]	Oil, gas, char [11,12]

[1] CES Edupack (Granta Design Limited, 2018), [2] (Mativenga et al., 2016), [3] (Pickering, 2005), [4] (Bax et al., 2015), [5] (Larsen, 2009), [6] (Crowder & Richards, 2003), [7] (Yang et al., 2012), [8] (Vijay et al., 2016), [9] (Pimenta & Pinho, 2011), [10] (ELGCF, 2017), [11] (Oliveux et al., 2015), [12] (Job et al., 2016), [13] (Pickering et al., 2000)

Data overview of the recyclate of all composite recycling methods previously discussed (N/A = method generally not applied for this type)

Recyclates

Alternative pyrolysis *Types:* *- microwave* *- superheated steam* *- catalytic* *- gasification*	No data found	*Microwave* Tensile strength: ca. –20% [14] Stiffness: –13 % [14] *Superheated steam* Tensile strength: *550 °C:* –10 % to –15 % [15] Stiffness: mild decrease [15] *Catalytic* Tensile strength: –1 % to –17 % [3] *Gasification (comb. w. pyrolysis)* Tensile strength: –28 % [16] Stiffness: –10 % [16]	*Microwave* Length varied between 0.1 mm to original scrap size length [17] Using scrap sized 7-30 mm lead to 0.1-31 mm fibre length, with roughly 52 wt% of the fibres being <15.7 mm in length [17]	*Microwave* Tensile strength: *360 °C:* –25 % [17] *440 °C:* –27 % [17] *Gasification* Tensile strength: *500 °C:* > –50 % [18] (similar to effects of heat treatment)	None, but there is a char on the fibres [11,12] and the sizing is stripped off the fibres [12]	Oil, gas, char [11,12]
Chemical						
Solvolysis *Types:* *- HTP* *- LTP*	No data found	Generally 90% or near-virgin properties [11,12] *Supercritical water w. alkaline catalyst* Tensile strength: –2 % to –10 % [19] *Supercritical alcohol* Tensile strength: *350 °C:* –1 % to –15 % [20]	N/A	N/A	*SC water with alkaline catalyst* <10 % resin content [19] *SC alcohol (350 °C)* 2% resin content [20]	Gases [11], chemical feedstock elements; mainly phenol as well as other phenolic compounds [7]

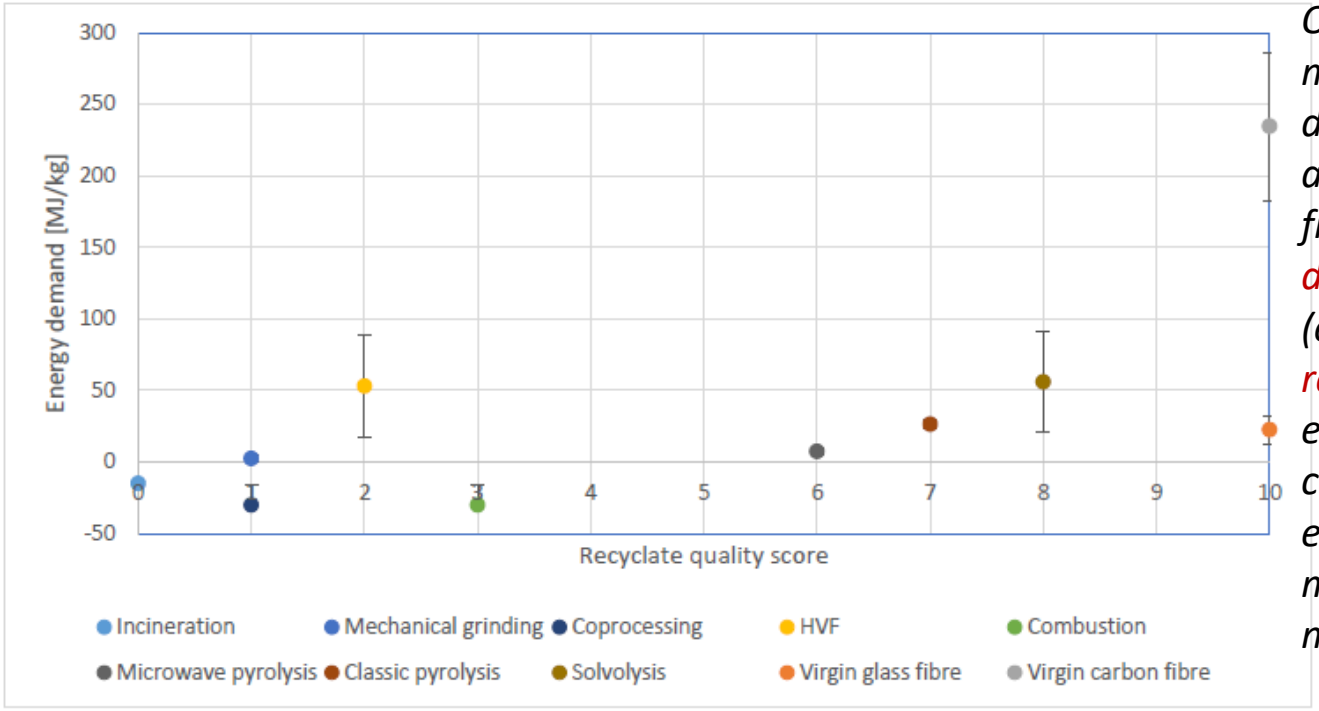
[3] (Pickering, 2005), [7] (Yang et al., 2012), [11] (Oliveux et al., 2015), [12] (Job et al., 2016), [13] (Pickering et al., 2000), [14] (Lester et al., 2004), [15] (Kim et al., 2017), [16] (López et al., 2013), [17] (Åkesson et al., 2012), [18] (ReFiber ApS, 2004), [19] (Piñero-Hernanz, Dodds, et al., 2008), [20] (Piñero-Hernanz, García-Serna, et al., 2008)

Data overview of the recyclate of all composite recycling methods previously discussed (N/A = method generally not applied for this type)

Recyclates

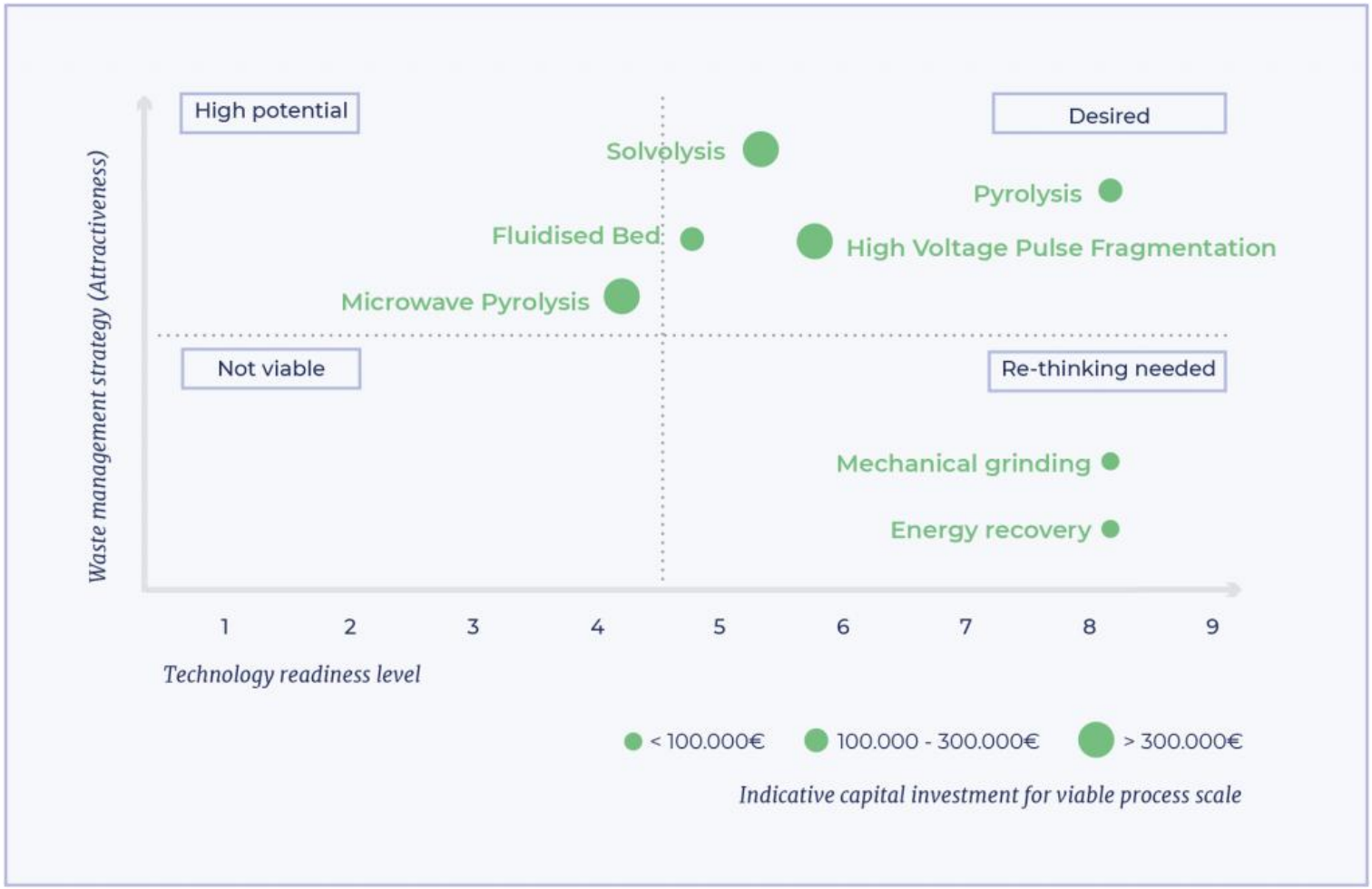
Fibre type	Resin type	Direct reprocessing	Mechanical recycling	Cement kiln	Thermal treatment	Chemical treatment
Glass	Thermoset		x	x		
	Thermoplastic	x	x			
Carbon	Thermoset		x		x	x
	Thermoplastic	x	x		x	x

Summary of the recycling solutions according to the type of processed composite waste



Offset of energy costs and material quality for the discussed recycling methods and the production of virgin fibres. Negative energy demand means an energy gain (e.g. exotherm process). The recyclate quality score was estimated using the following categories: virgin (10) – excellent (9-8) – good (7-6) – moderate (5-4) – poor (3-1) – no recyclate (0)

Maturity levels



The maturity levels of all the analysed recycling technologies used to recycle FRPC are plotted against their potential to extract value, providing an indicator of overall desirability;
Source: Suschem

Maturity levels (TRL)

European Commission

Technology Readiness Levels

TRL 0: **Idea**. Unproven concept, no testing has been performed.

TRL 1: **Basic research.** Principles postulated and observed but no experimental proof available.

TRL 2: **Technology formulation**. Concept and application have been formulated.

TRL 3: **Applied research**. First laboratory tests completed; proof of concept.

TRL 4: **Small scale prototype** built in a laboratory environment ("ugly" prototype).

TRL 5: **Large scale prototype** tested in intended environment.

TRL 6: **Prototype system** tested in intended environment close to expected performance.

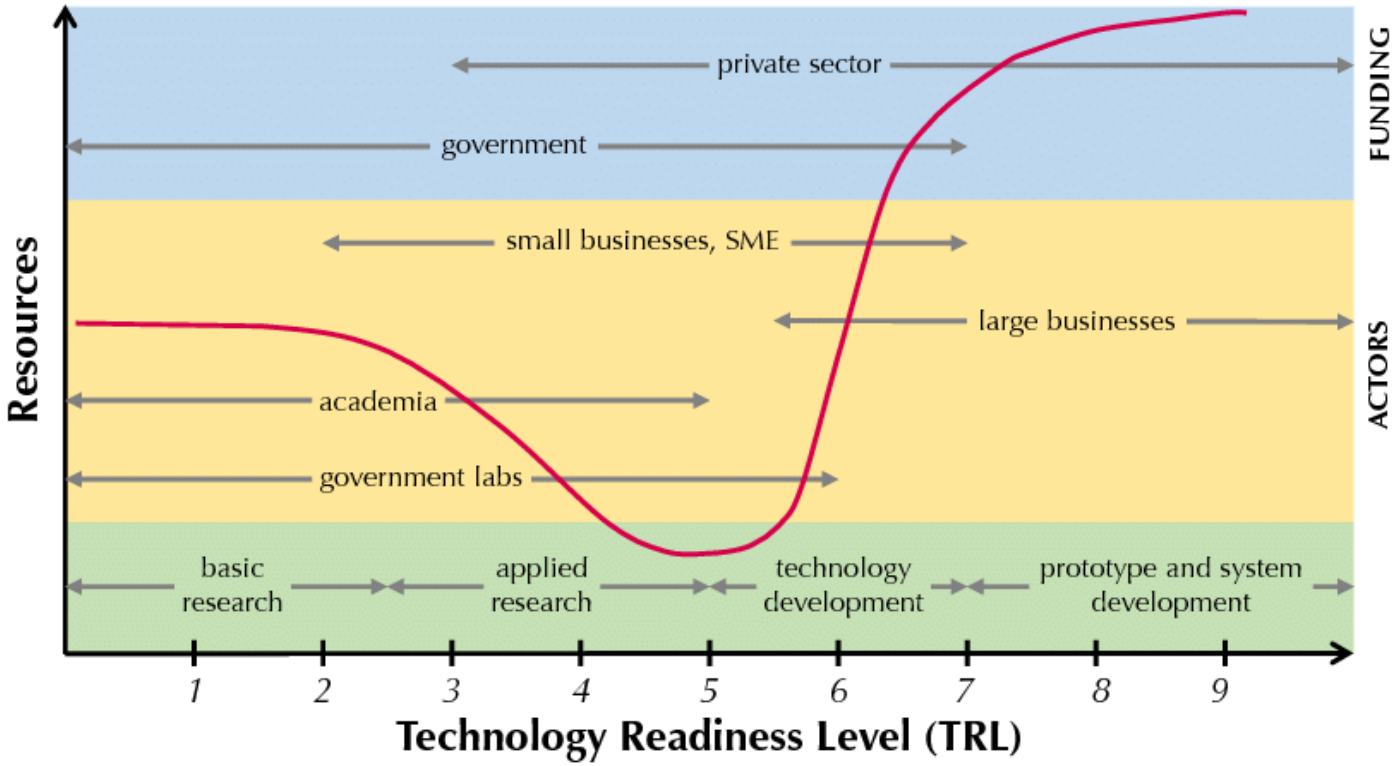
TRL 7: **Demonstration system** operating in operational environment at pre-commercial scale.

TRL 8: **First of a kind commercial system**. Manufacturing issues solved.

TRL 9: **Full commercial application**, technology available for consumers.

Source: European Commission

Technology maturity levels (TRL)



Availability of resources for new product development at various TRLs. The gap in the middle is sometimes referred to as "The Valley of Death“ (The Valley of Death is known as a metaphor for the lack of resources and expertise that impedes new ideas in their transition from lab to market. This gap also hinders innovation and adoption of new technologies for improved energy efficiency in buildings).

Source: Hensen, J. et al. (2015). Using building simulation for moving innovations across the “Valley of Death”. REHVA Journal. 52. 58-62.

Main challenges in circularity

- The **major barriers** that prevent the adoption and upscaling of composites circularity technologies and practices can be classified in three main categories:

1. technical: related to the design of materials, applications and the maturity and capacity of the related technologies

2. financial/market: refer to the constraints in the market or along the value chain both from supply and demand sides

3. policy: refers to existing, or non-existent, local, national or European regulations or guidelines that hinder the circularity of composite materials.

Technical challenges in circularity

- The inherent resilient nature of composites, together with the large variety of applications, and subsequent requirements in terms of chemical composition, manufacturing processes and recycling technologies translate into a wide variety of materials, technologies and techniques employed in the sector. This creates an extremely complex and fragmented environment for a smooth and effective circular system to take place in.

- the inherent nature of FRP/FRC makes it very challenging to separate fibres and matrix. Retrieving fibres in their full length is very difficult and usually recycling results in significant downgrading of the retrieved material, either due to damage to the fibres, reduction of size, or both.

- Regarding resins, thermoplastics, although inherently more recyclable, are relatively new engineering materials and their circular economy practices are in their infancy compared to thermosets.

- the often very large dimensions and increasing complexity of FRP parts, together with the lack of consideration for dismantling and separation issues during the design phase, increase the challenges of retrieving material without incurring major downgrading.

Technical challenges in circularity

- The current trend is to make parts more complex and produce an increasing number of materials, which will only further compromise dismantling and therefore recycling quality.

- the increasing diversity of **material combinations** also hinders the alignment of initiatives in terms of up-scaling, recycling and reusing strategies and technologies (e.g. joining of FRP and metals that is often applied in the automotive sector).

- Current recycling processes are highly energy intensive (e.g. 23-30 MJ/kg on average for conventional pyrolysis or 63-91 MJ/kg for solvolysis), require long cycle times (e.g. from 30 to 60 minutes for solvolysis) and are therefore very costly – ultimately generating a counterproductive environmental impact as well.

- Treating higher volumes of composite waste can substantially reduce running costs. For instance, mechanical grinding energy requirement can be decreased up to 0.27 MJ/kg with a recycling rate of 150 kg/hr, from 2.03 MJ/kg at a rate of 10 kg/hr.

Financial/market challenges in circularity

- Across the board in Europe, currently there is limited implementation of circular practices, technologies and private initiatives regarding composites in the market.
- while many recycling technologies and improved materials (easier to repair, recycle, reuse, etc.) are developed at a research level, few of them are reaching market maturity, and even less to full scale up.

- **Factors imparing a circular implementation:**

  - lack of information dissemination across Europe, between sectors and between academia and industry;
  - lack of systematic business model analysis
  - lack of initiative and investments for upscaling capacity for mature material and process technologies
  - fragmentation of private initiatives towards circularity, mainly on developing recycling capacities,
  - lack of alignment in technologies creates a persistent gap between new material's recycling properties and adequate and mature recycling technologies (development of material properties happens at a greater speed than recycling technologies)

Financial/market challenges in circularity: high costs of recycling

- Commercialising such recycling technologies or upscaling high-capacity recycling plants requires high capital investment, as well as the necessity of having a constant, homogeneous, and sufficient supply of composite waste. The absence of such a supply creates a highly unstable and unattractive market for private investors.

- lack of both public and private financial support or other incentives, together with the lack of dissemination of results in the academic sector, does not help to overcome these barriers.

- High costs of recycling processes also translate into high prices for secondary (recycled) material, while at the same time, prices of imported virgin materials (for GF especially) are declining, further decreasing the demand for recycled materials and the financial appeal of the recycling market.

- lack of understanding of the value and quality of recycled composite materials also prevents more widespread use. The market still expects secondary raw materials to be significantly cheaper than virgin, despite having similar or equal properties.

- landfilling remain still cheaper than dismantling and recycling large components such as wind turbine blades and boat parts.

Financial/market challenges in circularity

- systematic circular initiatives regarding composites do not seem to be visible yet
- initiatives include reusing and repurposing strategies, but also development of practical initiatives, such as implementing small recycling pilot plants for industrial composite waste

Policy challenges in circularity

- new materials require a process of certification before entering some sectors (e.g. fire-retardant specifications for rolling stock parts, failure specifications for aerospace parts).
- fragmented regulatory environment that obstructs waste streams, making sourcing and transporting composite waste very challenging.
- The lengthy certification processes delay the commercialisation of new, potentially more sustainable materials, such as bio-based thermoplastics that are easier to recycle
- lack of harmonised standards for design and material use in production further complicates sorting and recycling of composite waste as different materials require different recycling technologies.
- lack of understanding of the value of composite waste and recycled material and technological advances translates into unrealistically strict regulations concerning the reuse and repurposing of these parts.

Example: the use of recycled materials in certain applications, such as boats or airplanes, is in some cases not allowed, although the current properties of many of the recycled materials meet the necessary safety requirements. This translates into a complete absence of specific regulations around composite waste

Opportunities in circularity

- Europe possesses the necessary know-how, capital and human resources to develop and refine the required technology to achieve circularity in this field.
- This is evident from the fact that R&D initiatives and projects are fruitful, yielding positive results in terms of quality at low TRLs (projects such as EXHUME, MAI Recycling, KARMA2020, etc.).
- Industrial organisations, universities and RTOs are doing fundamental research in the recycling field, developing different niche technologies (e.g. ELG Carbon Fibre, UK; CFK Valley Recycling, Germany) and improved materials.
- New recycling processes and materials can bring unique properties to composites, allowing a total recovery of resins with minor loss of value (e.g. Arkema developed a resin that can be totally de-polymerised; Recyclamine by Connora Technologies, US/EU; ELG Carbon Fibre, UK).
- the growing demand for fibres in Europe, across sectors, together with the increasing use of thermoplastics (especially bio-based) bring a unique market opportunity for the recycling industry to scale-up.
- Carbon fibres are costly and energy intensive to produce – primary energy production of carbon fibres is about 183-704 MJ/kg13), and therefore enhancing their recyclability brings new opportunities for cost-effective production.

Opportunities in circularity

- growing interest in bio-based composites brings a particularly interesting opportunity for enhancing circularity since this not only increases the recyclability of composites, but allows the channelling of other types of waste streams into fibres and resins.
  - Example: initiatives are ongoing in Europe focused on transforming organic waste, such as feather waste from the poultry industry, food waste or pulp wood, into polymer composites.
- Also, the growing light-weighting priorities, and the increasing demand for lighter materials and their potential applications, increase the opportunity for market adoption of recycled materials.
- polymer composites themselves, due to their long-term durability, represent a great opportunity to exploit and establish reusing and repurposing strategies; parts containing composite materials offer a great potential to be refurbished in diverse applications due to their durability, corrosion resistance and light weight.

A case study: fibreglass-reinforced composites



Source of figure: https://designedconscious.com/plastics-in-the-ocean/sustainability-news-stories/is-fiberglass-recyclable-who-is-recycling-fiberglass/

A case study: fibreglass-reinforced composites

- Glass fibers are a very versatile class of materials used extensively as a reinforcement fiber for polymeric resins such as epoxy and unsaturated polyester.

- The stiffness of glass fiber is lower than that of other reinforcement fibers, but it possesses the distinct advantage of combining a very high strength with low density and, most of all, a very reasonable cost.

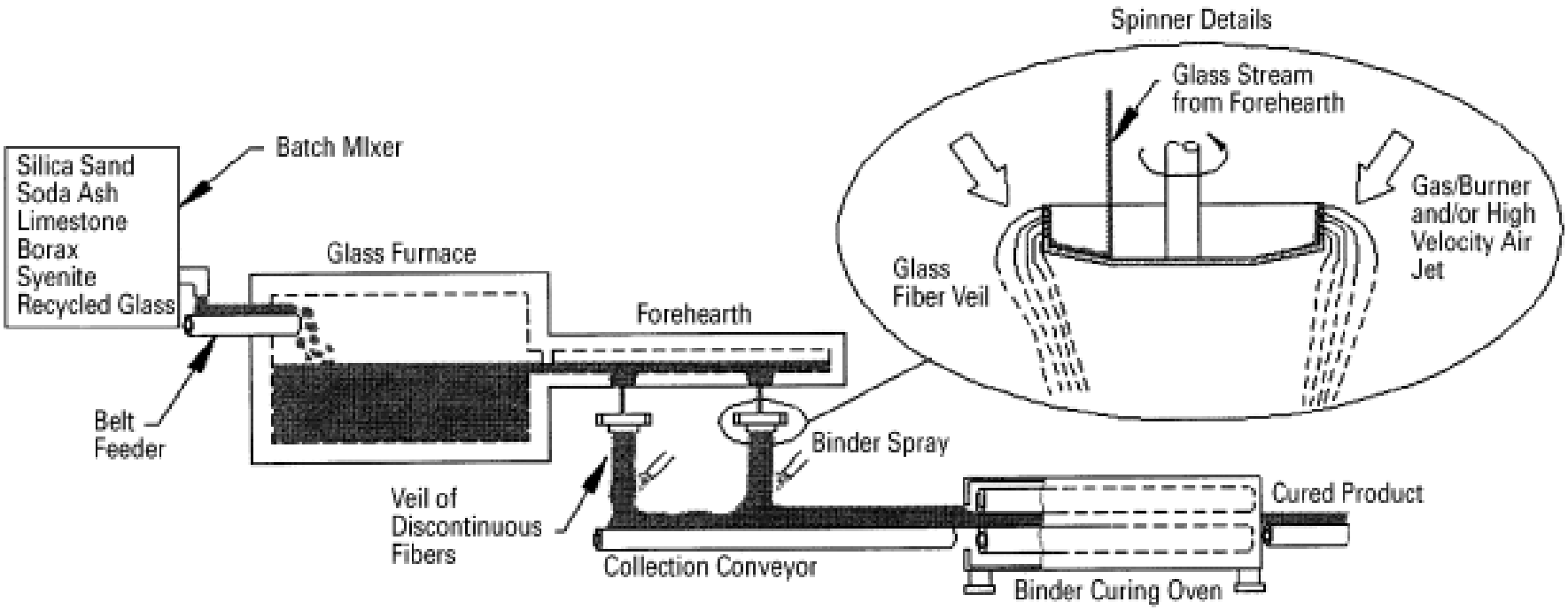
- Glass-Fiber Reinforced Plastic is a combination of glass fibers, resin and reinforced plastic, making it a very strong and extremely durable material.

- There are over forty thousand applications of reinforced fiberglass, and about five million metric tons of fiberglass are manufactured annually.



A case study: fibreglass-reinforced composites

Manufacturing of glass fibres



Source of the figure: https://www.sciencedirect.com/topics/nursing-and-health-professions/glass-fiber

A case study: fibreglass-reinforced composites

Applications of glass-fibers composite

Industries

- Construction
- Consumer Recreation
- Industrial / Corrosion
- Marine
- Transportation
- Wind Energy / Power

Processes


Closed Molding


Compression Molding


Filament Winding


Open Molding


Pultrusion

Source of the figure: https://www.compositesone.com/product/fiberglass-reinforcements/

A case study: fibreglass-reinforced composites



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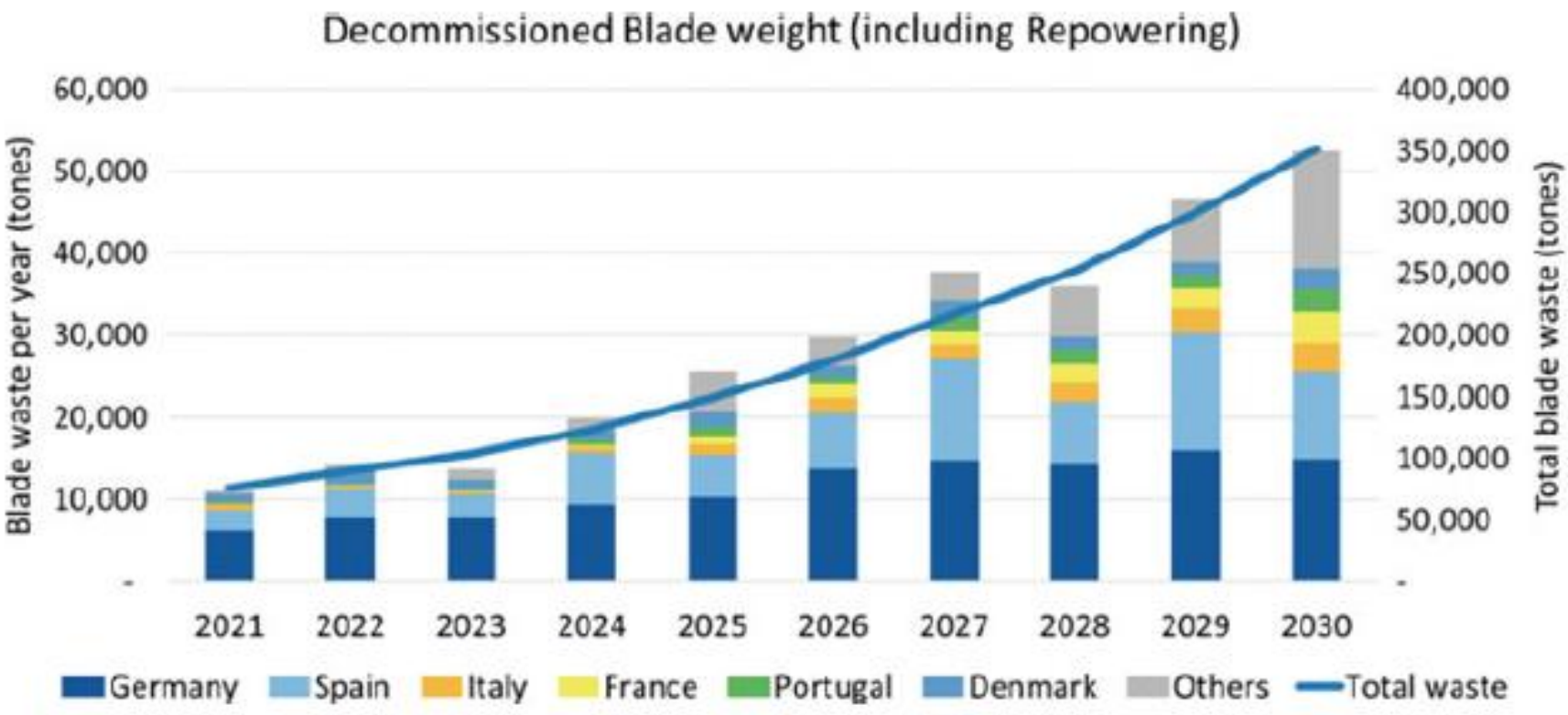
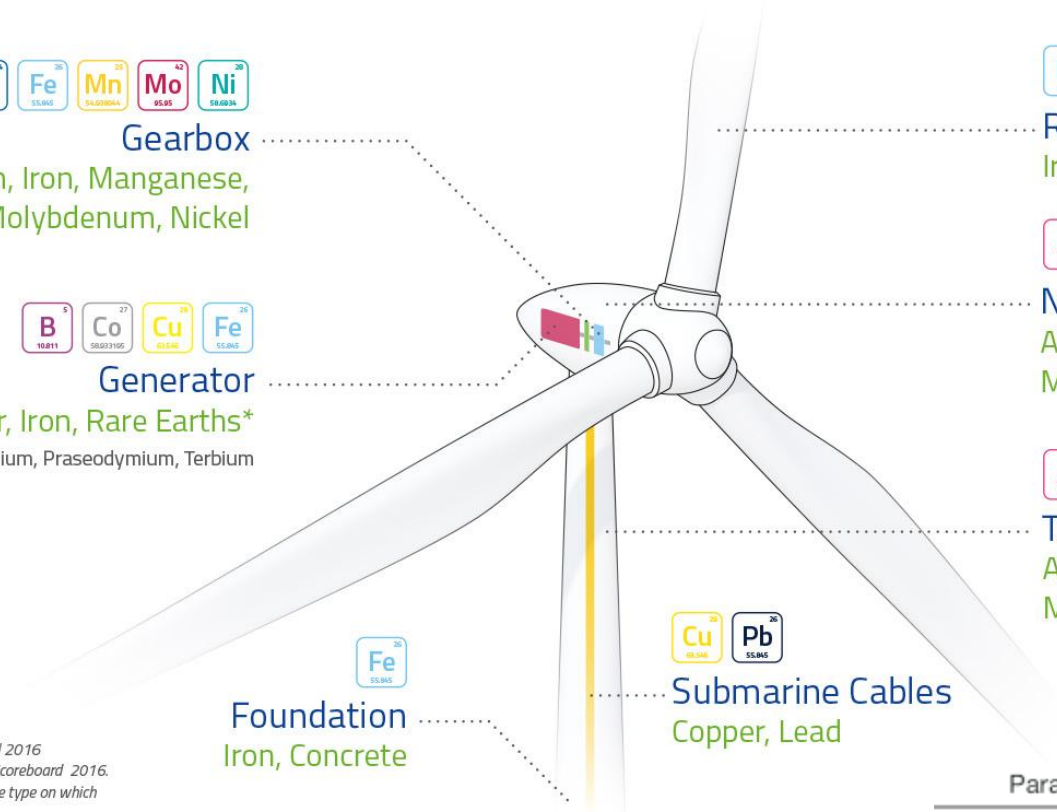


Expected amount of End-of-Life wind blades in tons per year in different European Countries

A case study: fibreglass-reinforced composites



Gearbox
Chromium, Iron, Manganese, Molybdenum, Nickel

Generator
Boron, Cobalt, Copper, Iron, Rare Earths*
*Dysposium, Neodymium, Praseodymium, Terbium

Foundation
Iron, Concrete

Rotor Blades
Iron

Nacelle
Aluminium, Chromium, Copper, Iron, Manganese, Molybdenum, Nickel

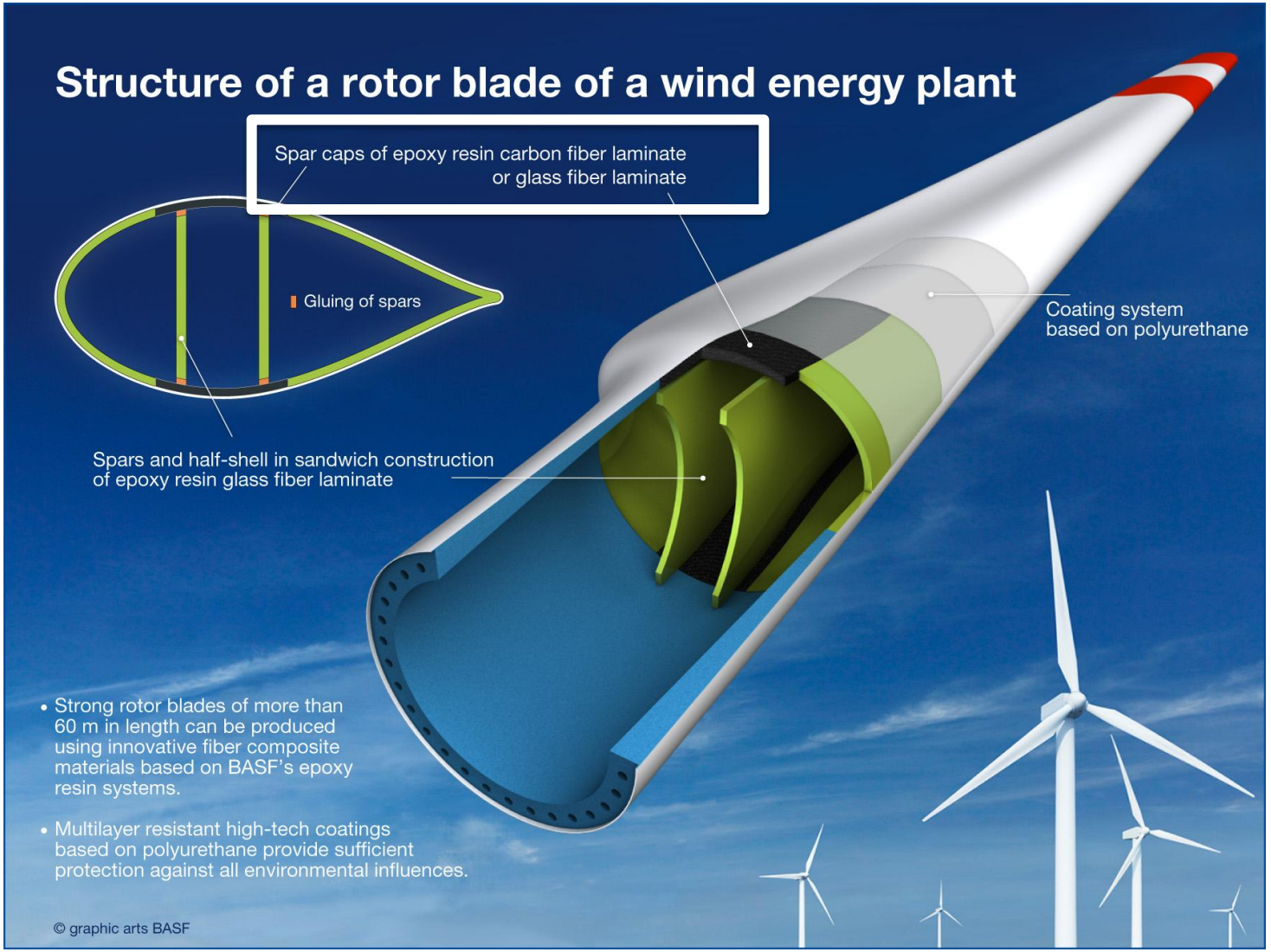
Tower
Aluminium, Chromium, Copper, Iron, Manganese, Molybdenum, Nickel

Submarine Cables
Copper, Lead

Sources: European Commission Materials Information System (MIS) Wind Energy, April 2016 and European Commission Raw Materials Scoreboard 2016. The source does not specify the wind turbine type on which the above information is based.

Parameter	Weight (kg)
Blade	98
Hub arm	64
Rotor hub	16
Rotor axis	36
Rotor blade control unit	50
Additional unit	30
Total	294

A case study: fibreglass-reinforced composites



A case study: fibreglass-reinforced composites

- The wind energy industry is one of the fastest-growing application sectors of composites, where reinforcement fibers are used in the manufacturing of light rotor blades.

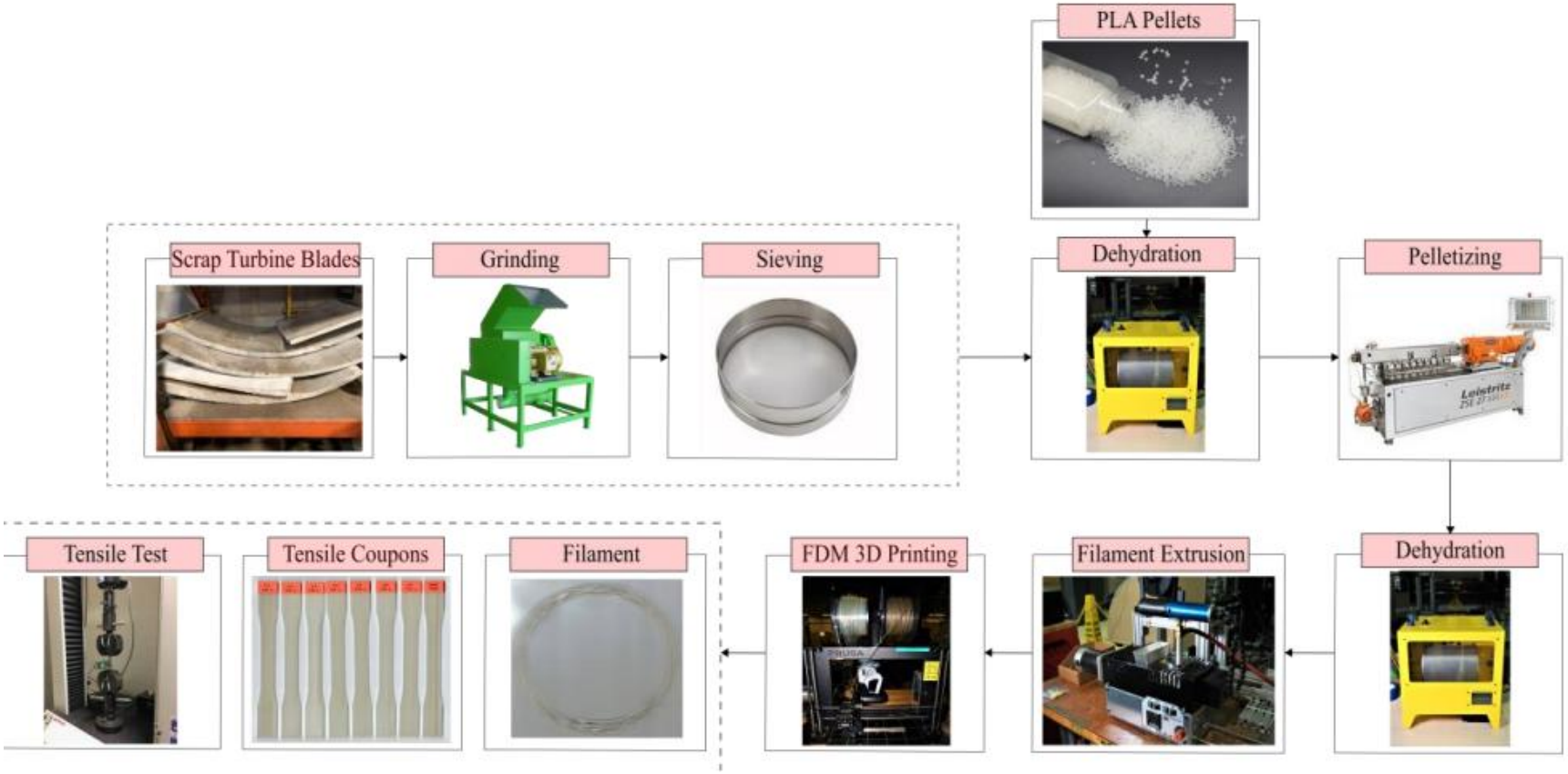
- Considering the limited lifetime (20-25 years) of turbine blades, a growing number of wind turbines will start to be decommissioned. Turbine blades are generally landfilled at their end-of-life, which highly impacts the environment.

- Case study proposed: a systematic scheme combining mechanical recycling and 3D printing to recycle the valuable constituents of the scrap blades and reuse them in a Fused Filament Fabrication (FFF) process with the aim of improving the mechanical performance of 3D printed components.

- Mechanical grinding integrated with a double sieving mechanism is utilized to recover the reinforcement fibers.

Source: Recycling of Fiberglass Wind Turbine Blades into Reinforced Filaments for use in Additive Manufacturing, Composites Part B: Engineering, https://doi.org/10.1016/j.compositesb.2019.107101

A case study: fibreglass-reinforced composites



The proposed methodology for recycling of wind turbine blade

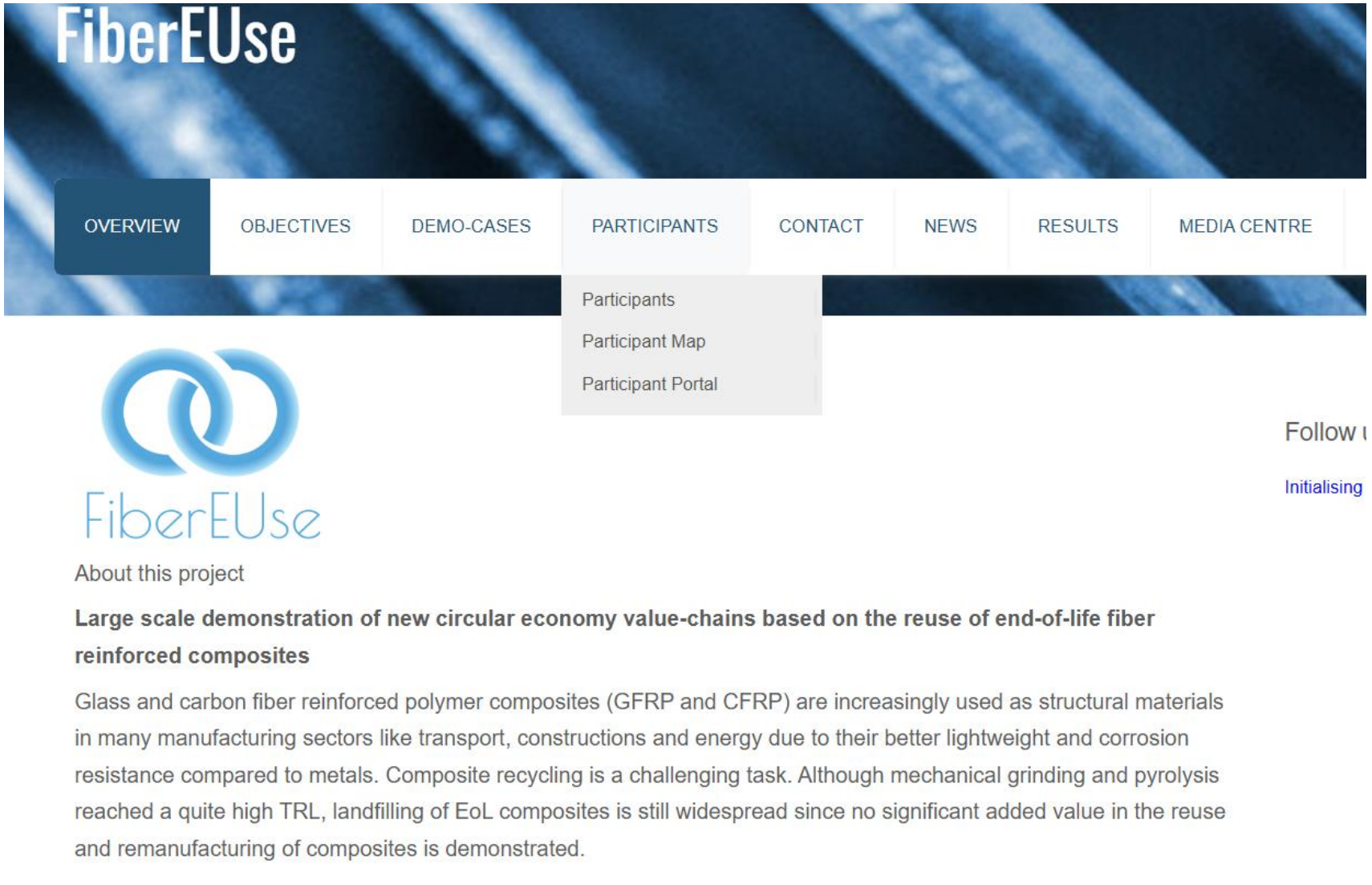
Source: Recycling of Fiberglass Wind Turbine Blades into Reinforced Filaments for use in Additive Manufacturing, Composites Part B: Engineering, https://doi.org/10.1016/j.compositesb.2019.107101

A case study: fibreglass-reinforced composites

1. A mechanical recycling method combining grinding and a double sieving process is performed to recover the glass fibers from the scrap blades.
2. The mixture of the PLA pellets and the fibers are placed in a dehydrator machine for a drying process of 4 hours at 60°C. This dehydrations process reduces the moisture content of the pellets that could generate voids during the extrusion process.
3. To generate the Recycled Glass Fiber Reinforced Filament (RGFRF) for FFF, the raw materials obtained in step 2 are first fed into a twin-screw extruder connected to a pelletizer to produce glass fiber reinforced pellets. Following the initial extrusion, the pellets are redried and fed into a single screw extruder to produce RGFRF. The extruder screw speed, the die temperature as well as the winder speed are tuned to attain a filament with consistent
4. Tensile properties of a single filament made out of pure PLA, as a baseline, and reinforced filaments are compared. In addition, tensile coupons are manufactured as per ASTM D638 type I out of pure PLA filament and RGFRF. Tensile testing is performed on the coupons and the resulting mechanical properties are compared to evaluate the performance of the newly developed filament.

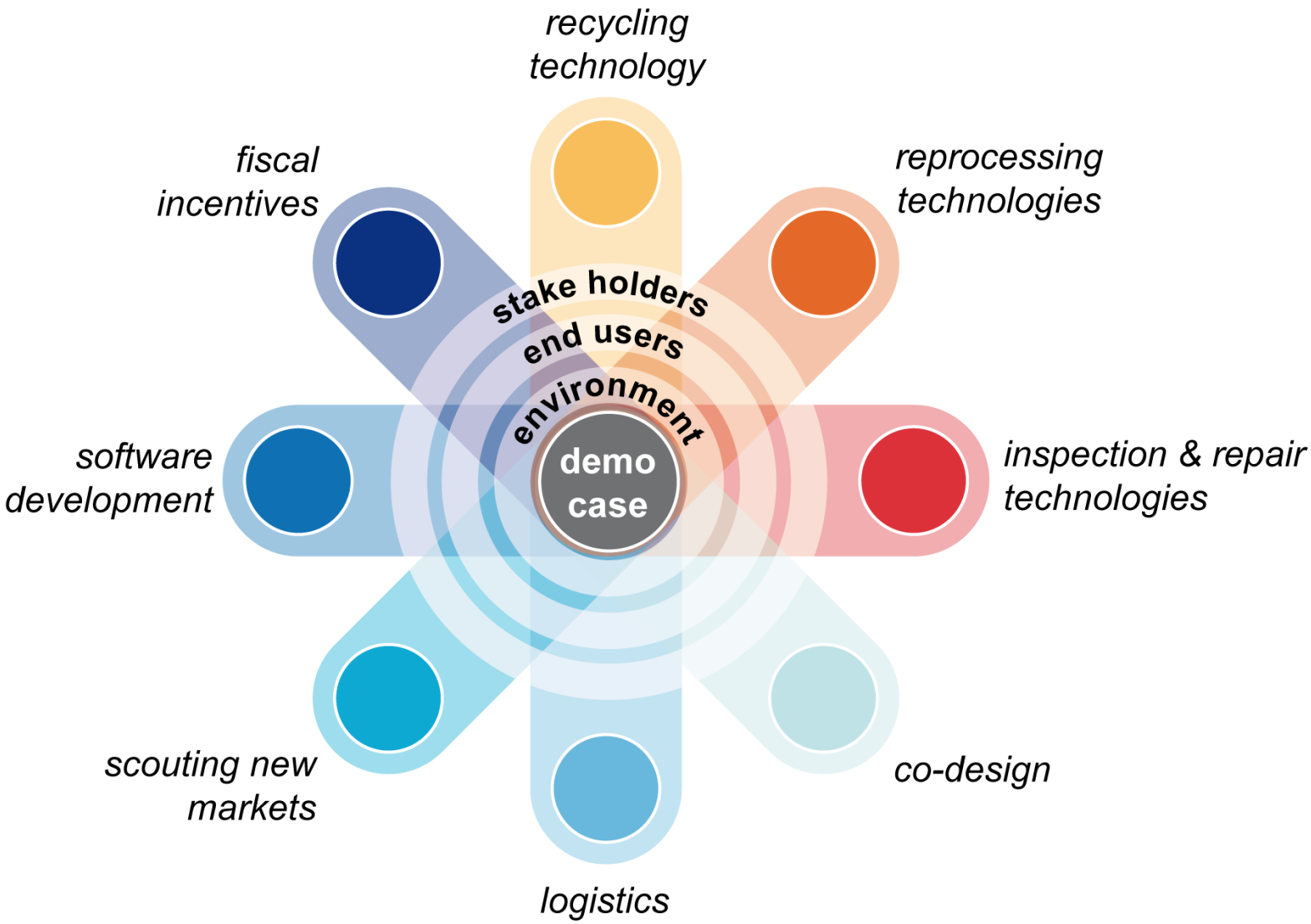
Source: Recycling of Fiberglass Wind Turbine Blades into Reinforced Filaments for use in Additive Manufacturing, Composites Part B: Engineering, https://doi.org/10.1016/j.compositesb.2019.107101

FiberEUuse



Source: https://fibereuse.eu/

FiberEUuse



Source: https://fibereuse.eu/

FiberEUuse: a case study

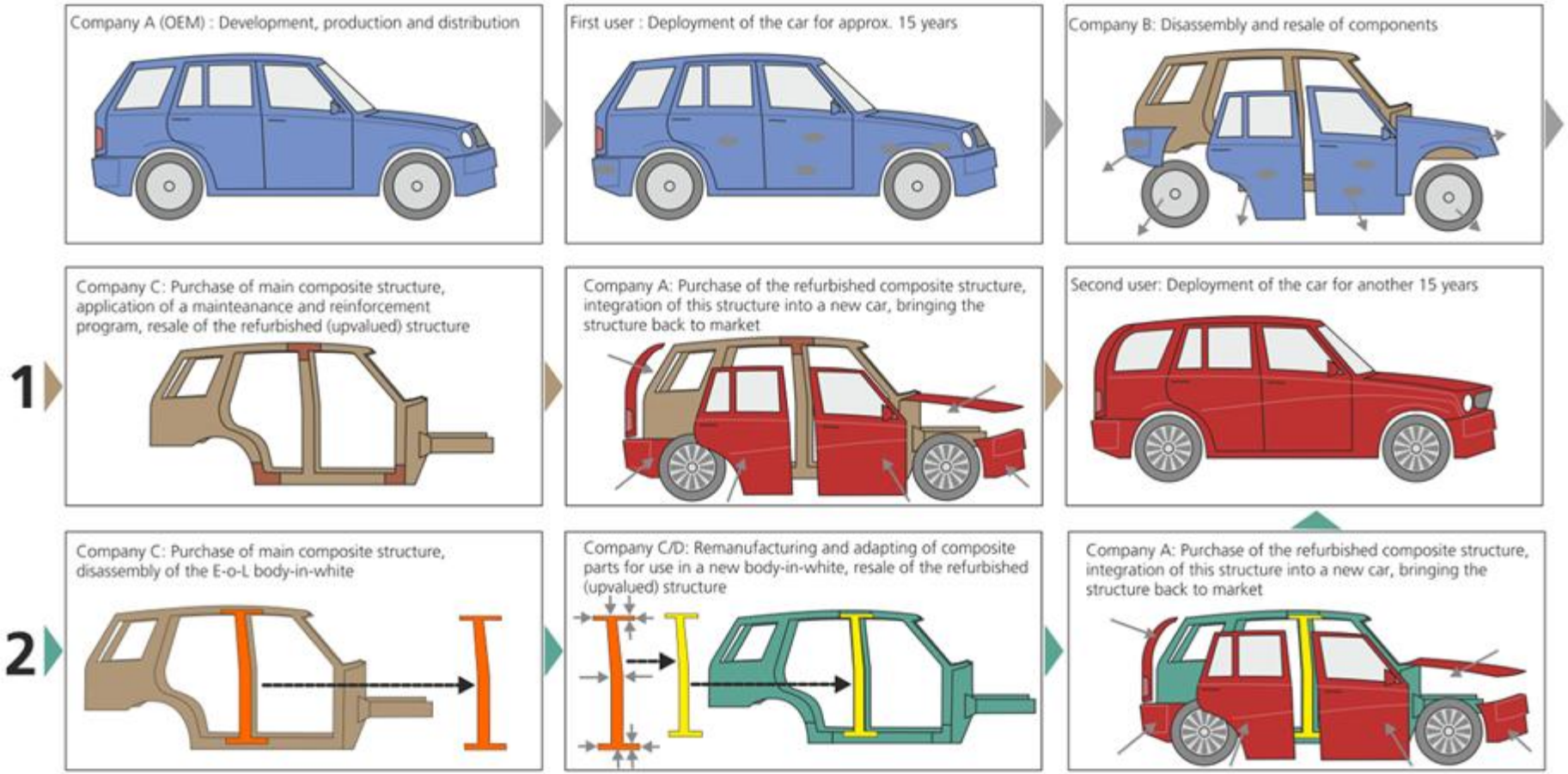


Figure 1.3.7: Two approaches for remanufacturing and reuse of composite structures in the automotive sector.

Source: https://fibereuse.eu/