CADE20006: Structures and Materials

University of BRISTOL

Theme:

Sustainable Materials and Manufacturing

Lecture 4: Sustainable manufacturing and composites

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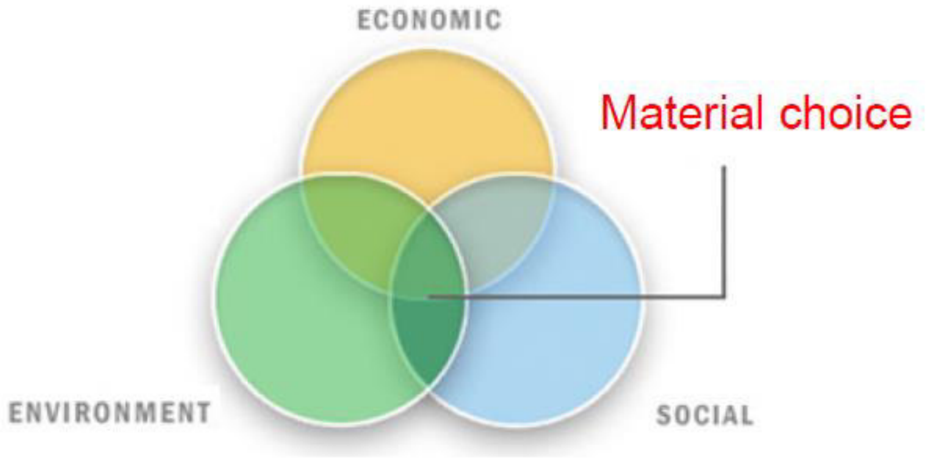
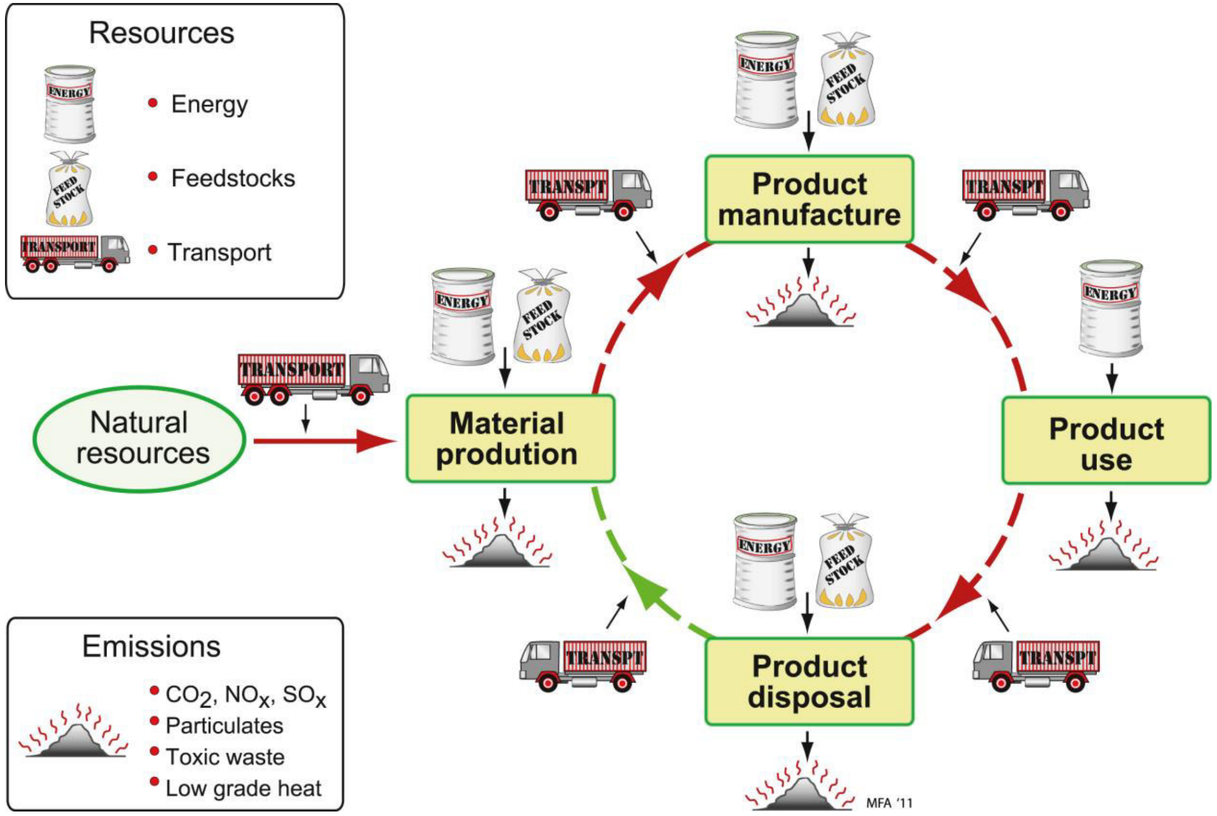
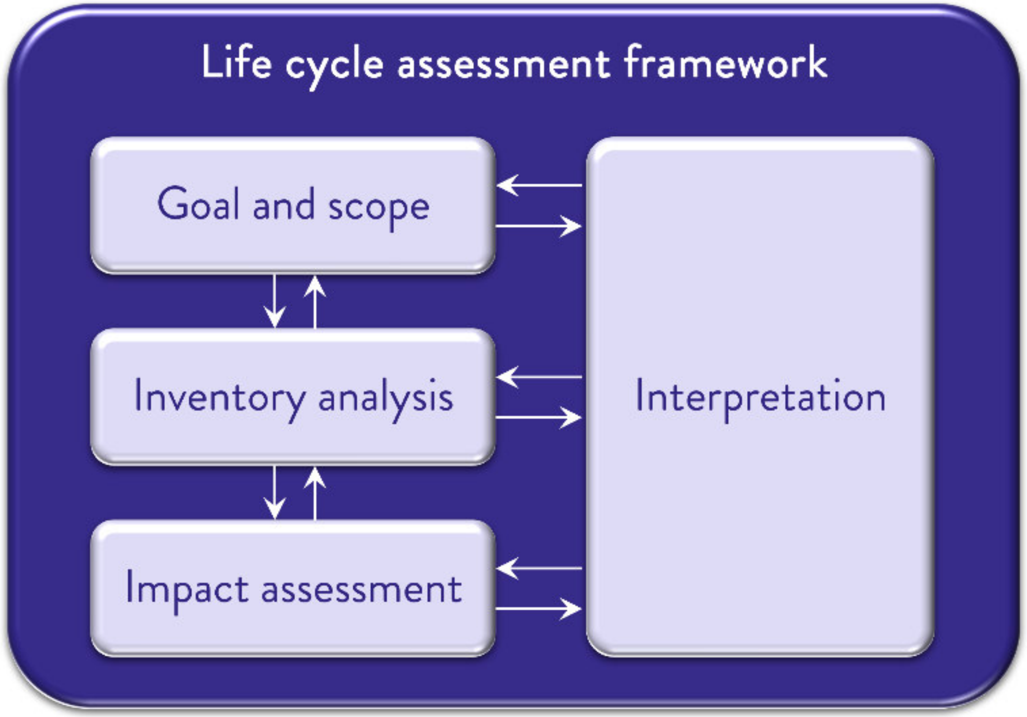
Sustainability themes

- Economic dimension
  - Energy use
  - Material consumption
  - Manufacturing costs
  - Profitability
- Environmental dimension
  - Impact on climate change
  - Source of energy
  - Impact on water quality through solid waste
- Social dimension
  - Working condition
  - Impact on worker's long term health

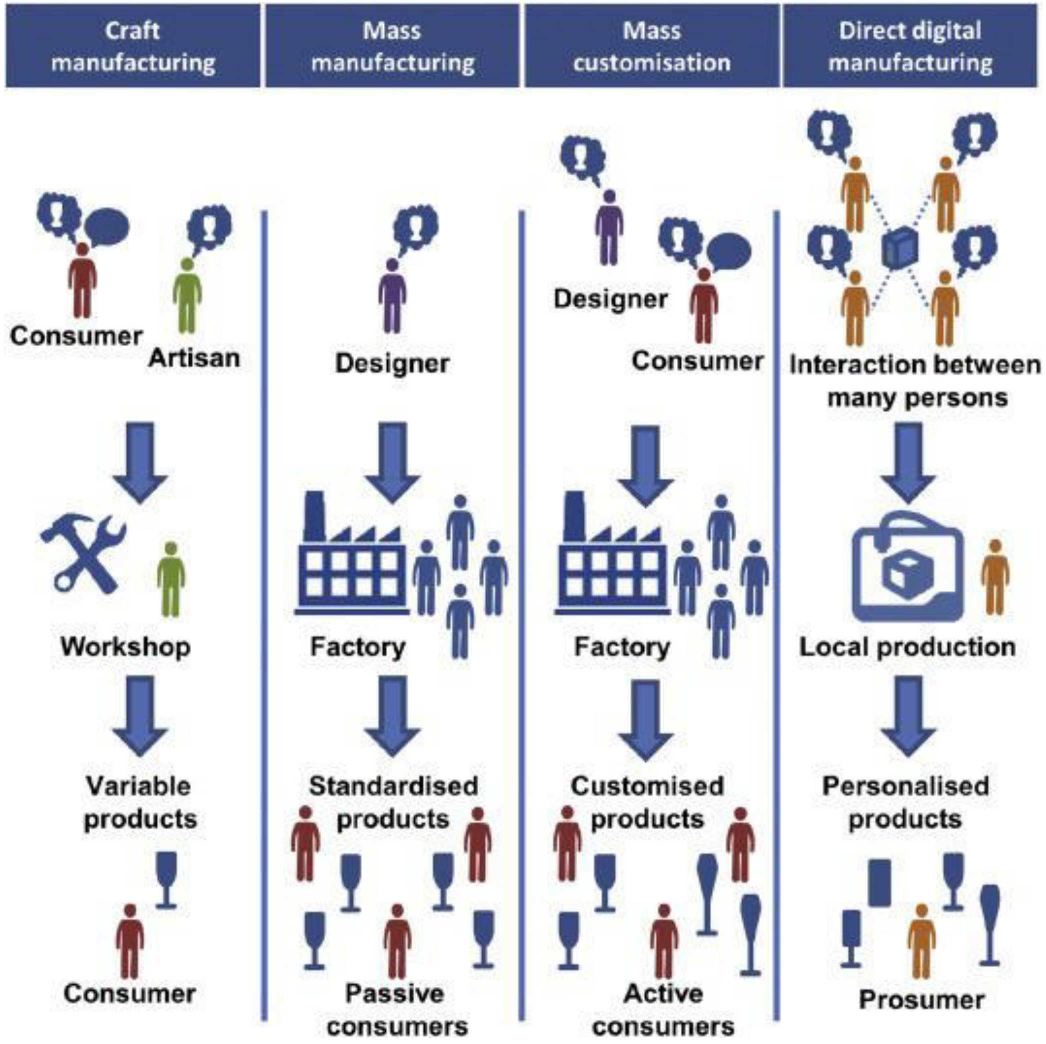


Previously… Life cycle assessment

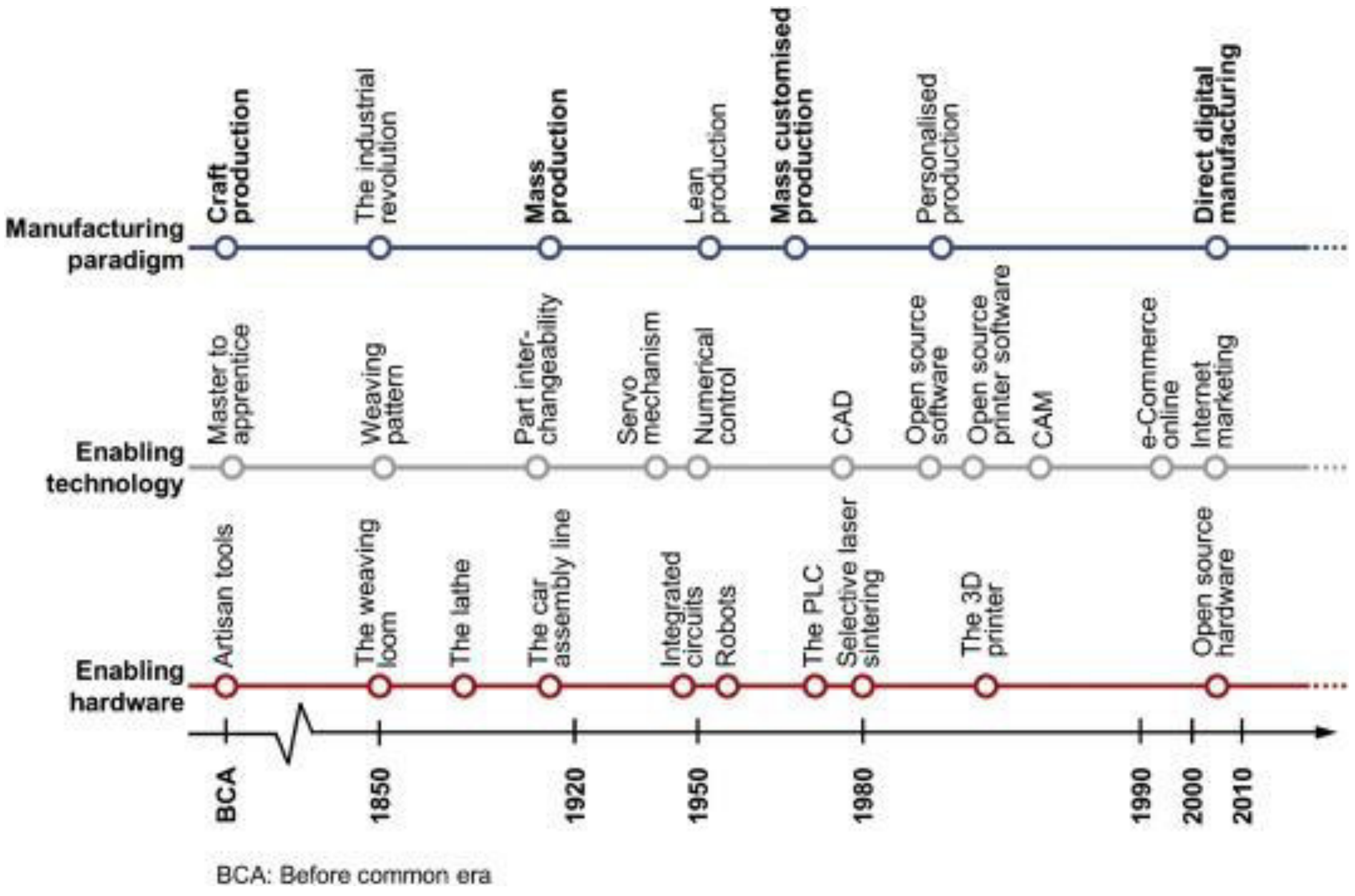




Manufacturing paradigms



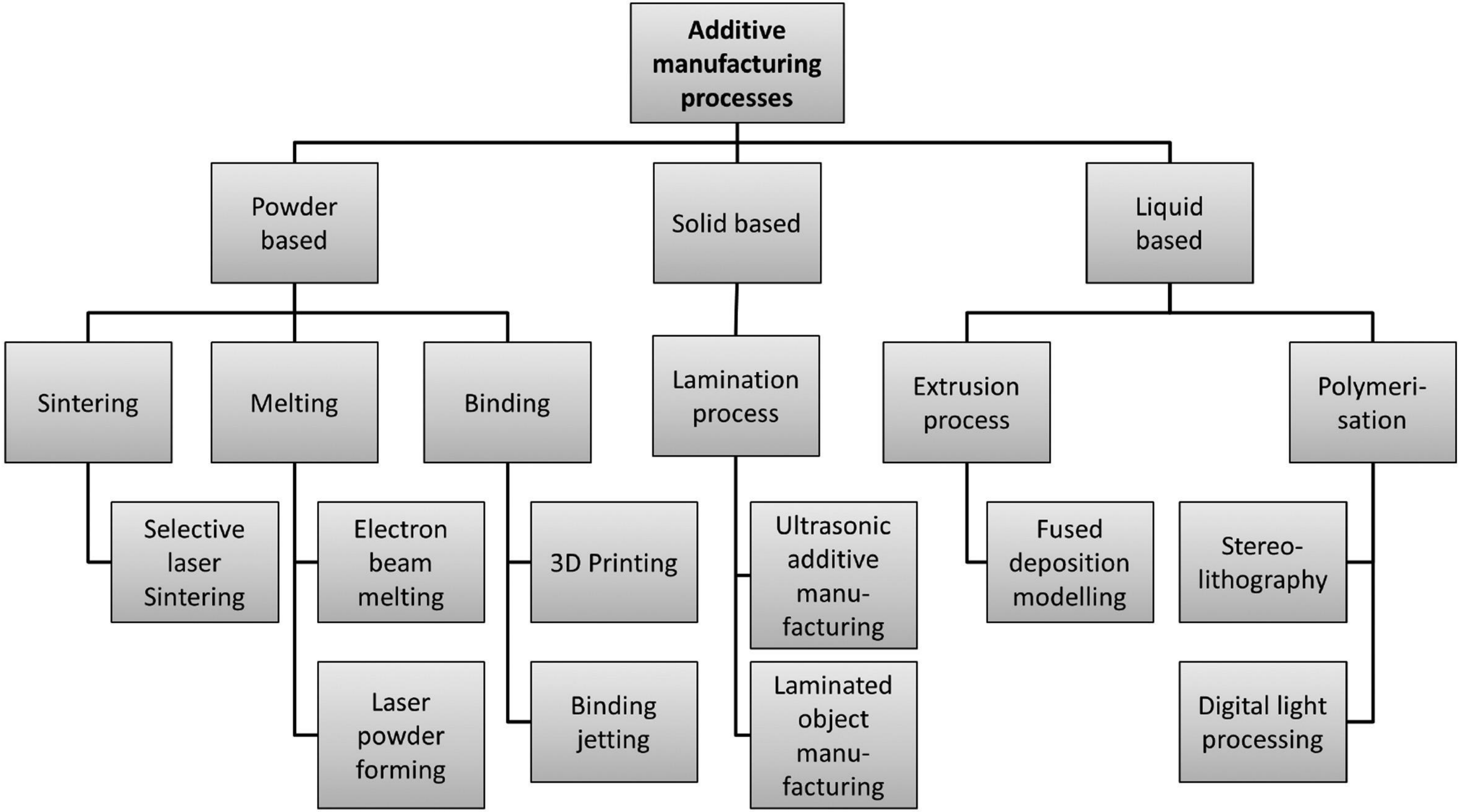
Enablers - digitalisation



Direct digital manufacturing and sustainability

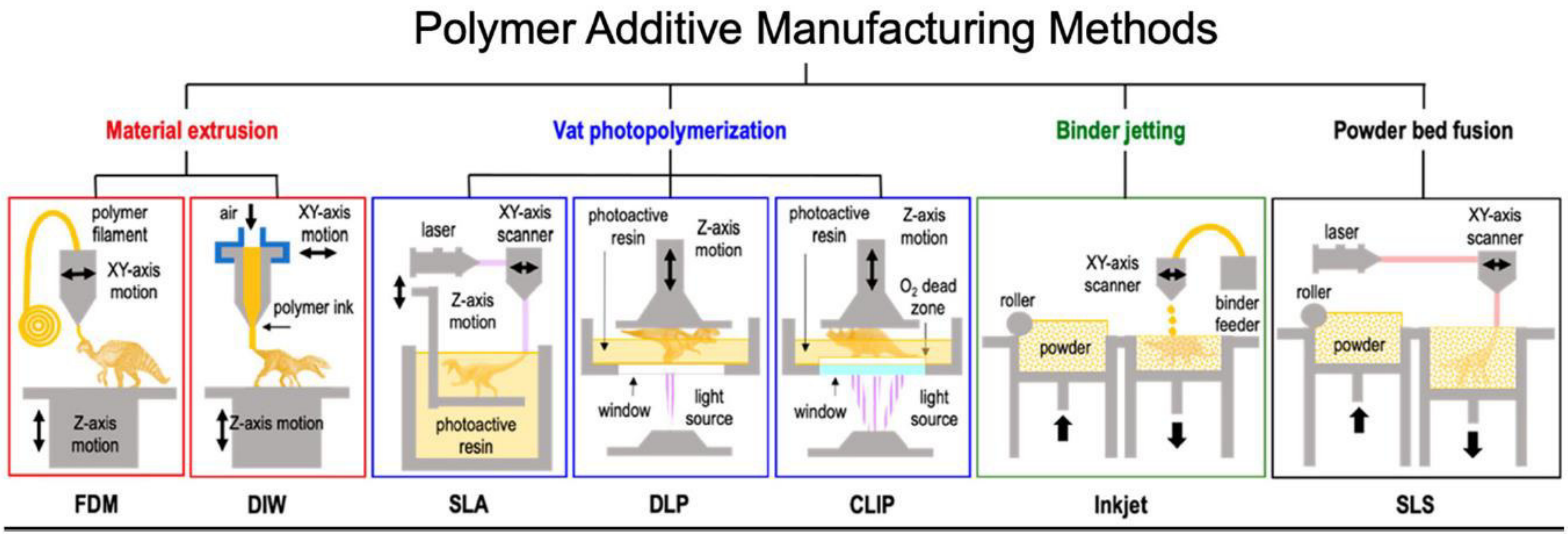
<table>
<tr><th>Economic</th><th>Environmental</th><th>Social</th></tr>
<tr><td colspan="2">•Higher material utilisation (+)
•Simpler, more efficient supply chains with less transportation efforts (+)
•Less material and energy losses due to less inventory (+)
•Less waste and better waste management through possibility of direct recycling (+)
•User oriented manufacturing, less over-production in stocks (+)
•No moulds etc. necessary (+)
•Higher specific energy demand (−)
•Quality issues are not finally solved, thus risk of bad parts and rework (−)</td><td rowspan="2">•equal possibilities to all participants in markets and societies (+)
•bridge technological, educational and cultural gaps between developing and developed countries (+)
•user oriented products, more customer satisfaction (+)
•potential benefits on human/worker health (+)
•unclear impact on an employment situation of industry (+/−)</td></tr>
<tr><td>•Potentially higher profit due to customer specific solutions (+)
•Profitability could be proved in selected cases (+/−)
•Longer manufacturing time (−)</td><td>•Ambivalent studies in terms of an environmental impact or eco-efficiency, (+/−)</td></tr>
</table>

Additive manufacturing



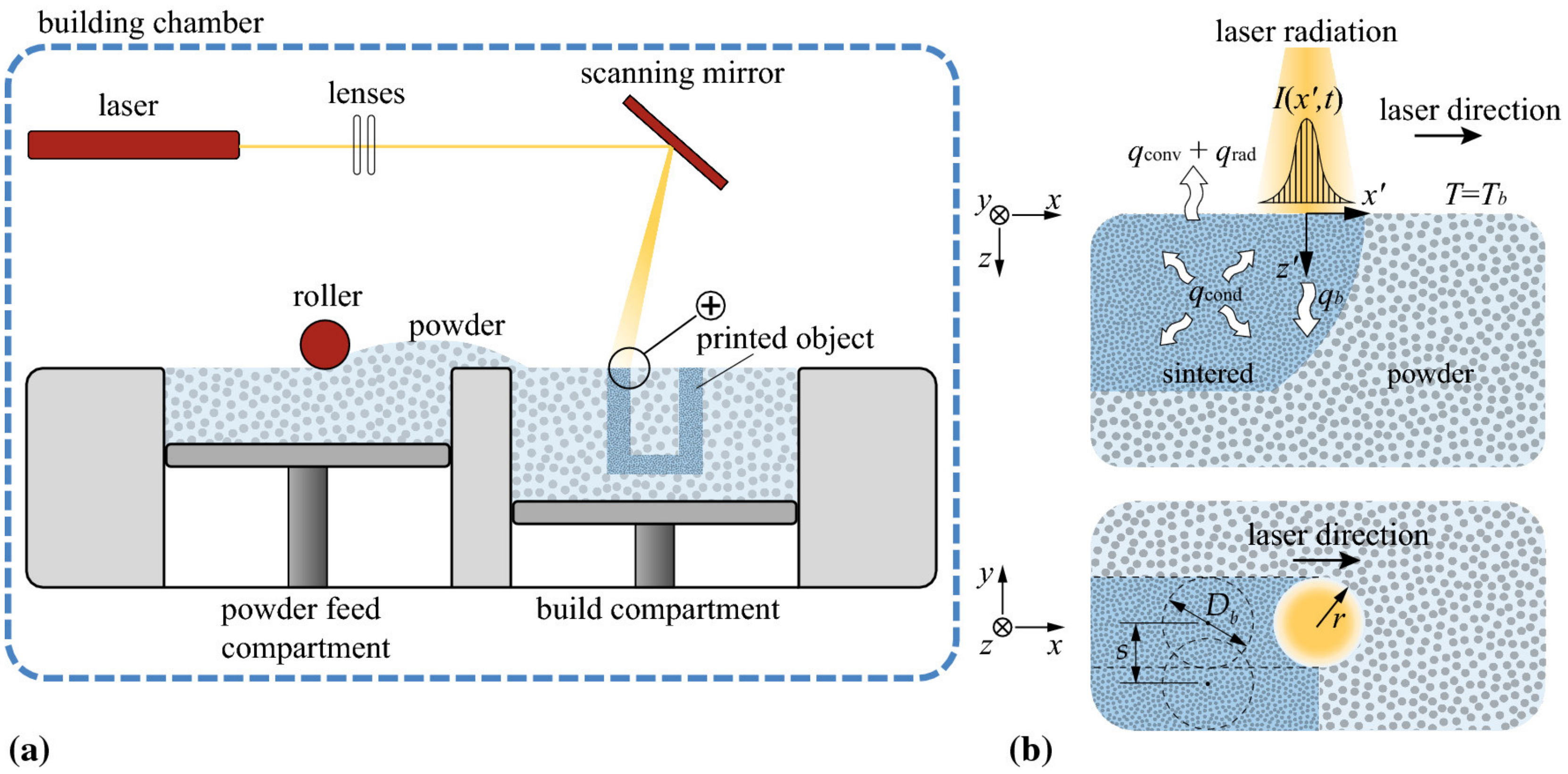
AM and sustainability

- AM promises to reduce material waste in manufacturing through light-weighting of objects via latticing and topology optimization.
- Such lattices cannot be produced by traditional manufacturing techniques such as injection molding or subtractive manufacturing.
- Challenge: the liquid waste resin from vat photopolymerization needs to be disposed
- the sustainability of AM materials relies on
  - the reduction of waste production and raw material consumption,
  - the reuse of parts that do not need to be reprocessed, and
  - the collection and recycling of materials
- AM predicted to reduce CO_2 emissions by 130.5–525.5 million tons and energy demands by up to 9.30×10^{18} J



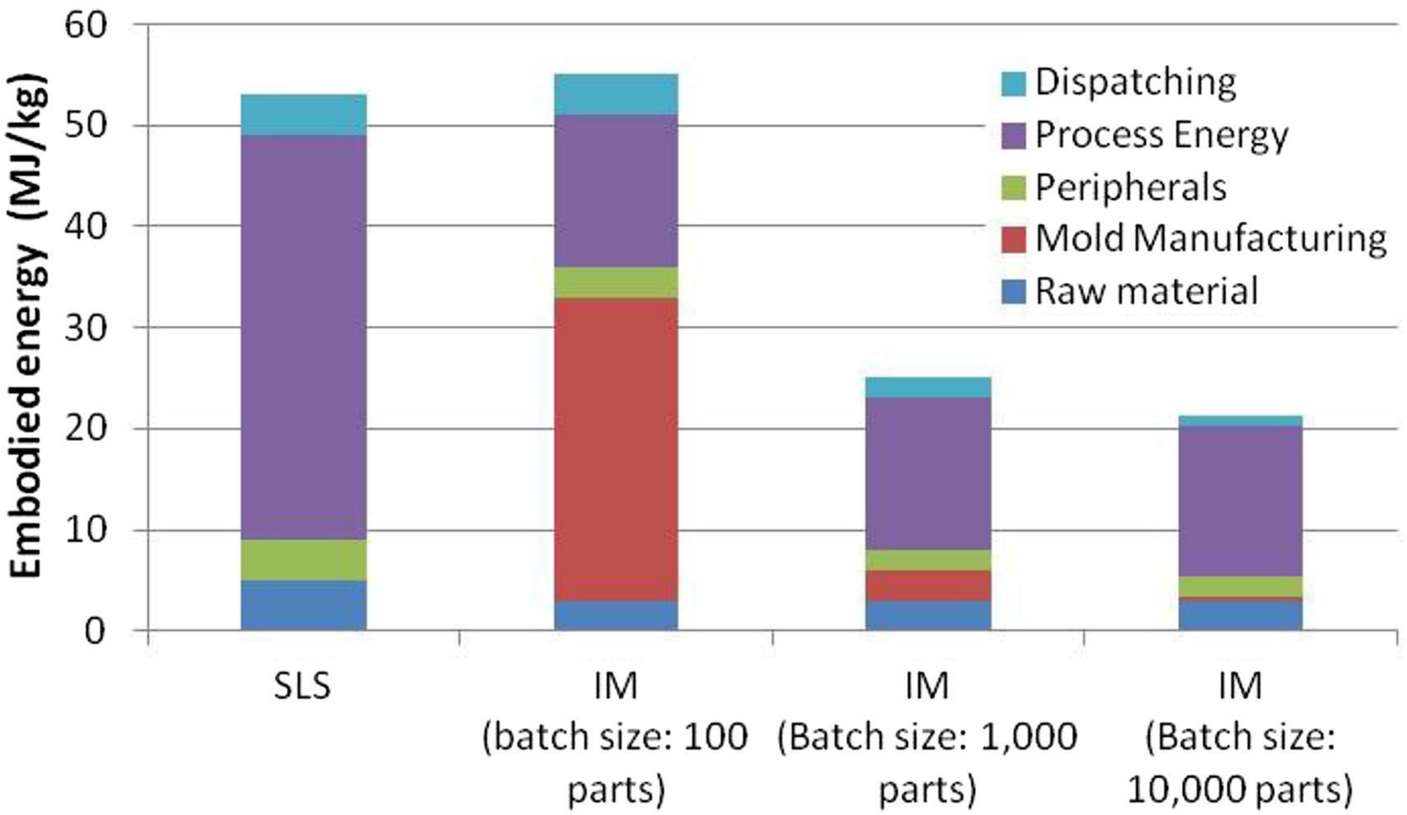
Chyr and DeSimone DOI: 10.1039/d2gc03474c

Selective Laser Sintering

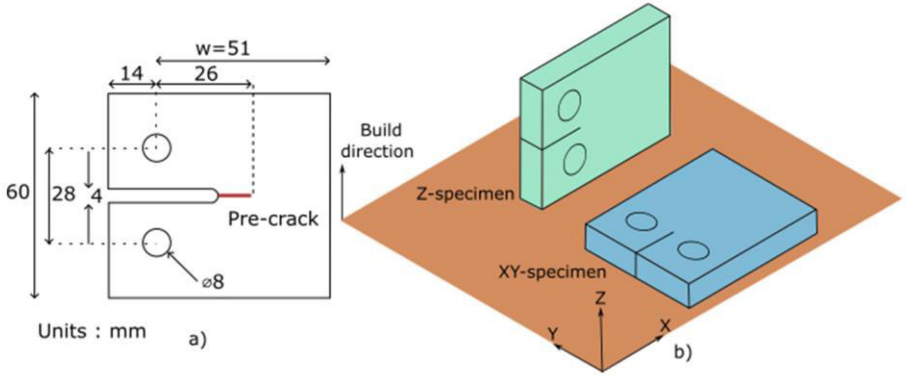


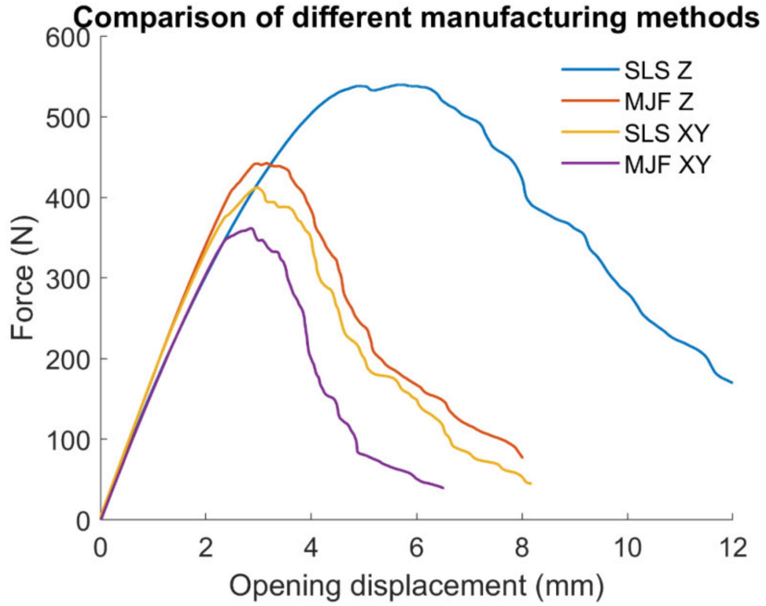
Brighenti et al., https://doi.org/10.1007/s10853-020-05254-6

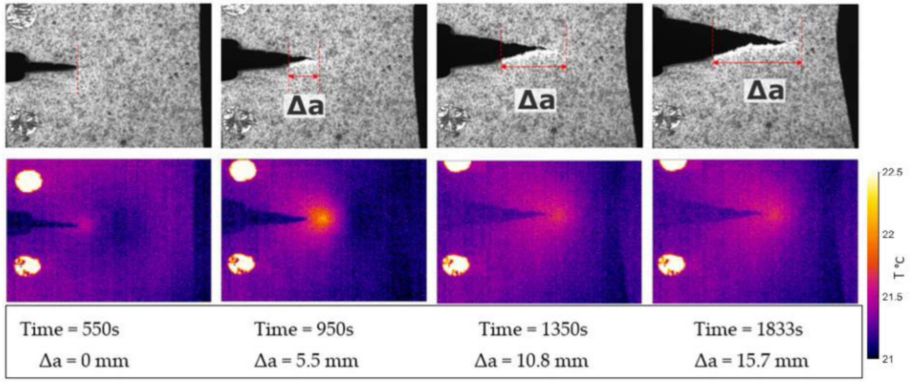
Energy and manufacturing method

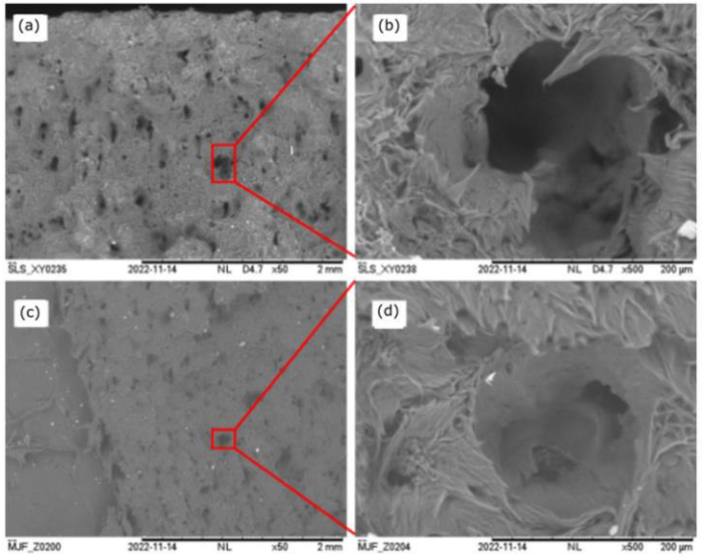


AM in research at BCI







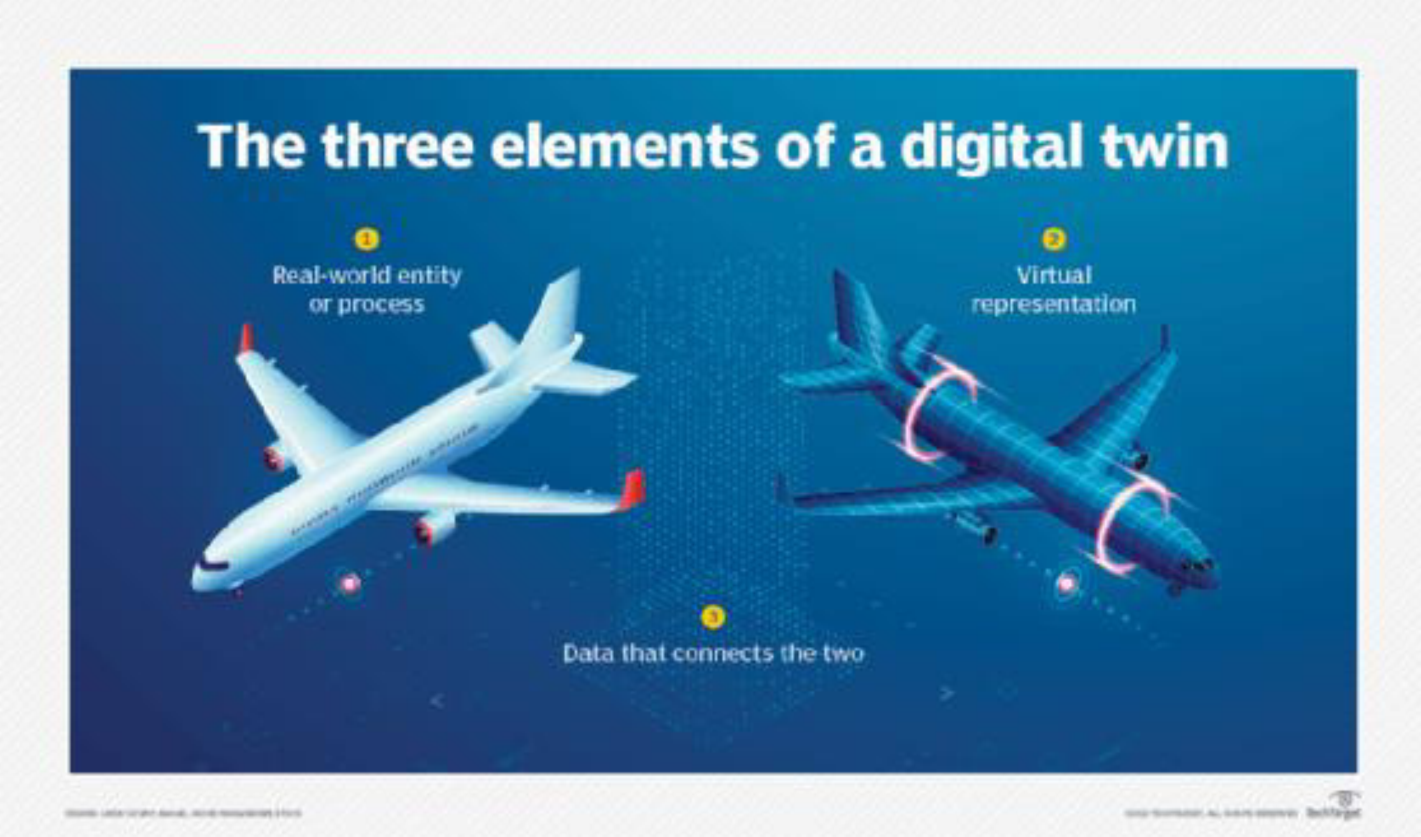


Sustainable manufacturing

- Digital manufacturing is the connection of computers and computer aided design (CAD) models with production so that products and processes can be visualized and analyzed to improve efficiency before production begins
- Digital manufacturing provides the key for AM to move beyond just rapid prototyping to also provide on-demand inventory, local production of goods, flexible manufacturing plants, and access to previously impossible geometries for products.
- The ability to access product models and manufacture a product quickly means that AM can bring more production back to local communities and avoid overseas shipping

Other digitalization tools

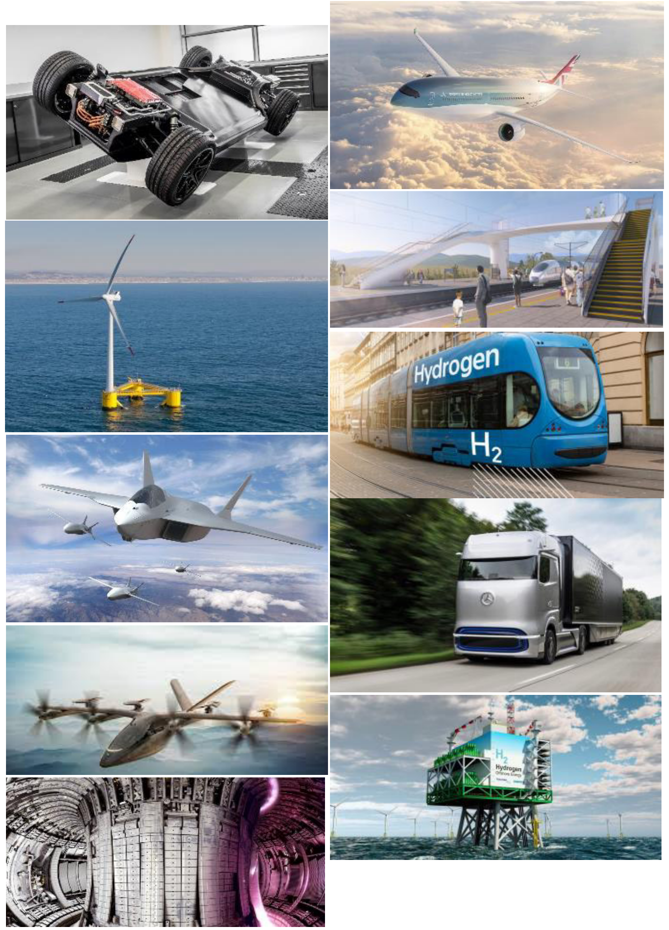
- IoT sensors
- Artificial Intelligence tools
- Digital Twins
- Data driven engineering
- Cloud based platforms
- Automation



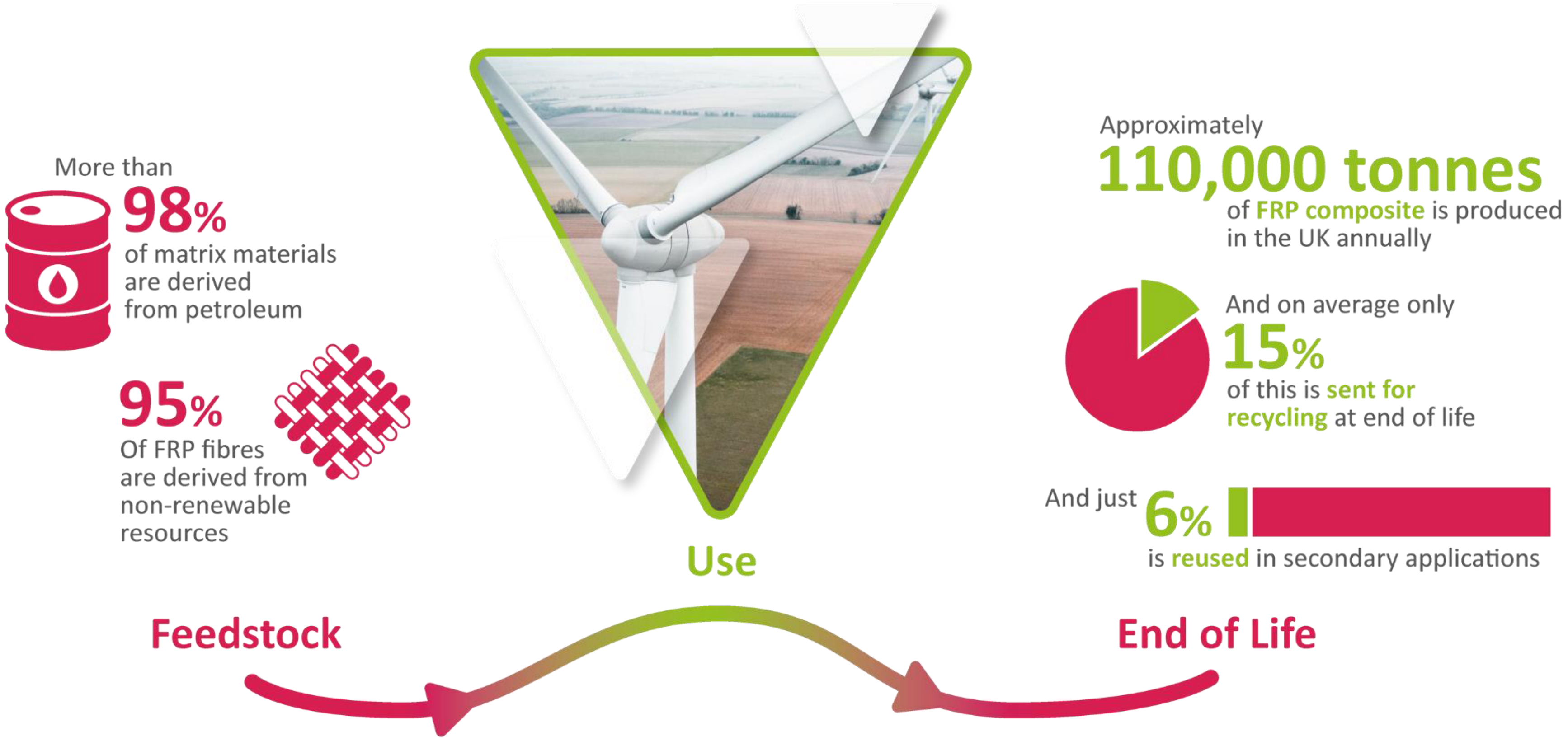
Composites and sustainability

Composites Enabling Net Zero Transformation

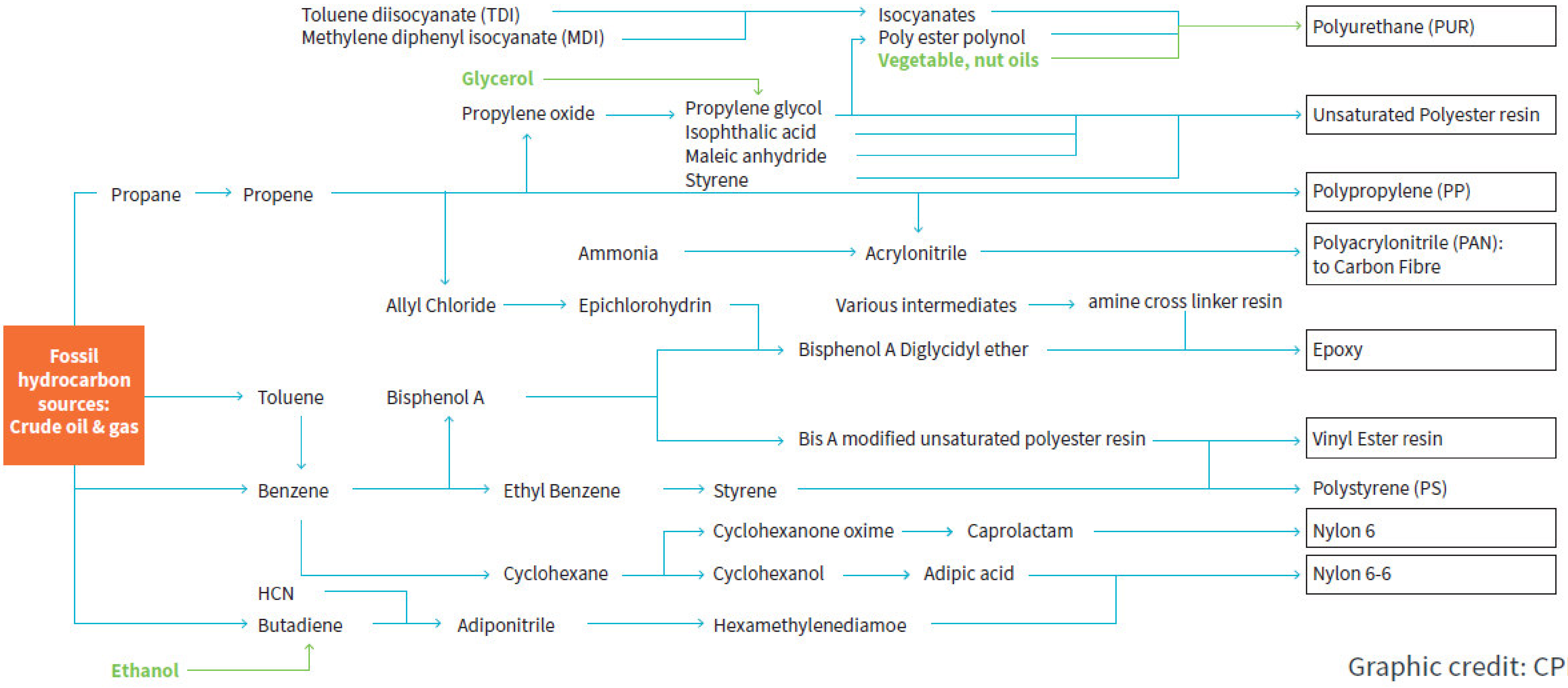
- Light-weighting to accelerate electric mobility
- Storage and distribution technology to enable hydrogen
- Performance step-change to scale wind energy
- Zero emission aircraft to achieve ‘jet zero’
- Energy efficient infrastructure and buildings
- Advanced multifunctional structures for defence
- High temperature, lightweight materials to unlock nuclear
- Accelerate growth in new frontiers such as space



Sustainability challenge for Composite Materials



Resin systems and their feedstock



Graphic credit: CPI

Bio-derived resins

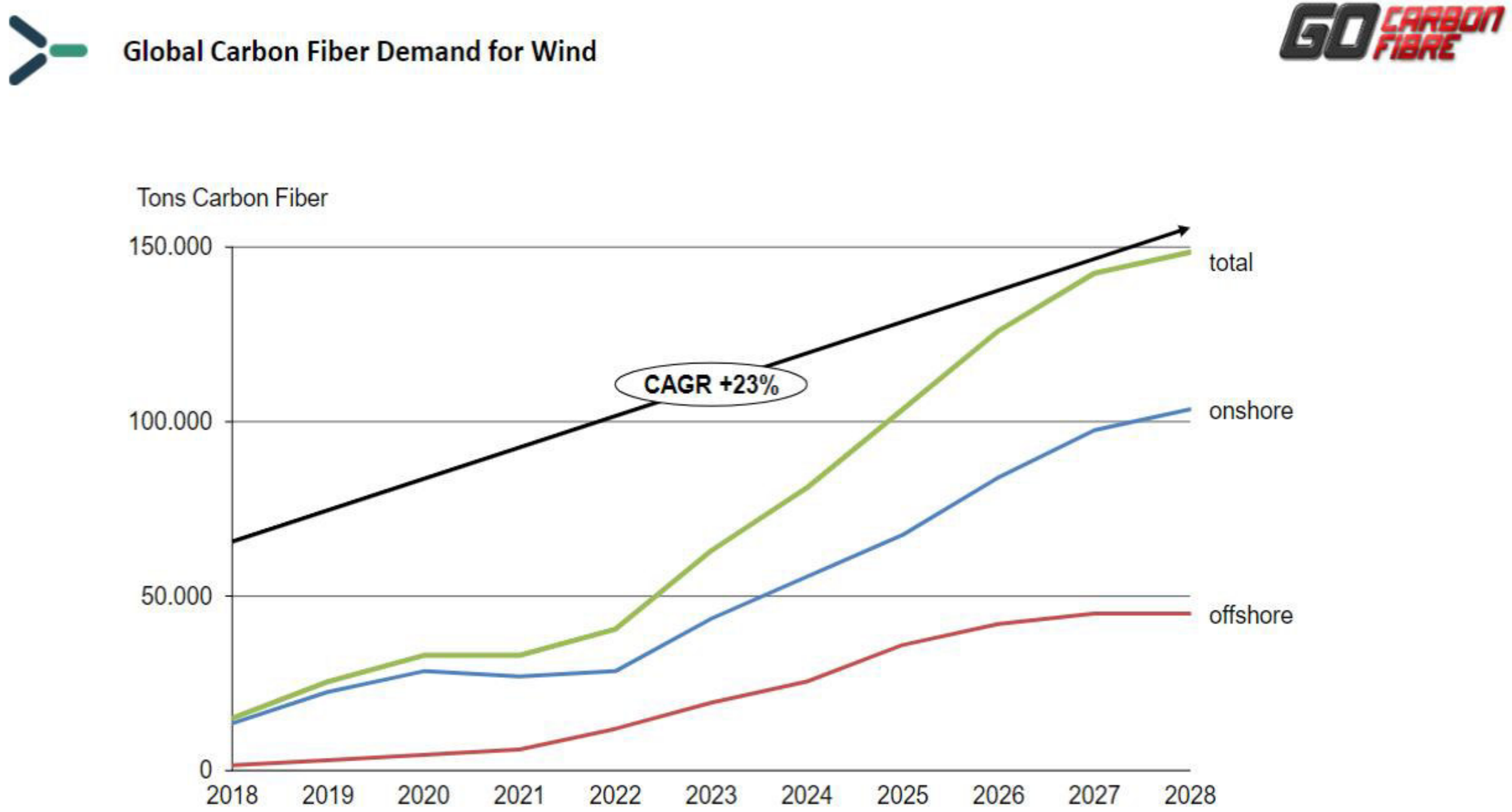
Most bio-derived resins are derived from biomass feedstocks.

• **Plant oils:** Plant oils are long chain fatty acids. Their unsaturated sites are ideal for functionalisation but their levels will vary depending on the crop, for example, epoxidation into monomers for epoxy resin synthesis

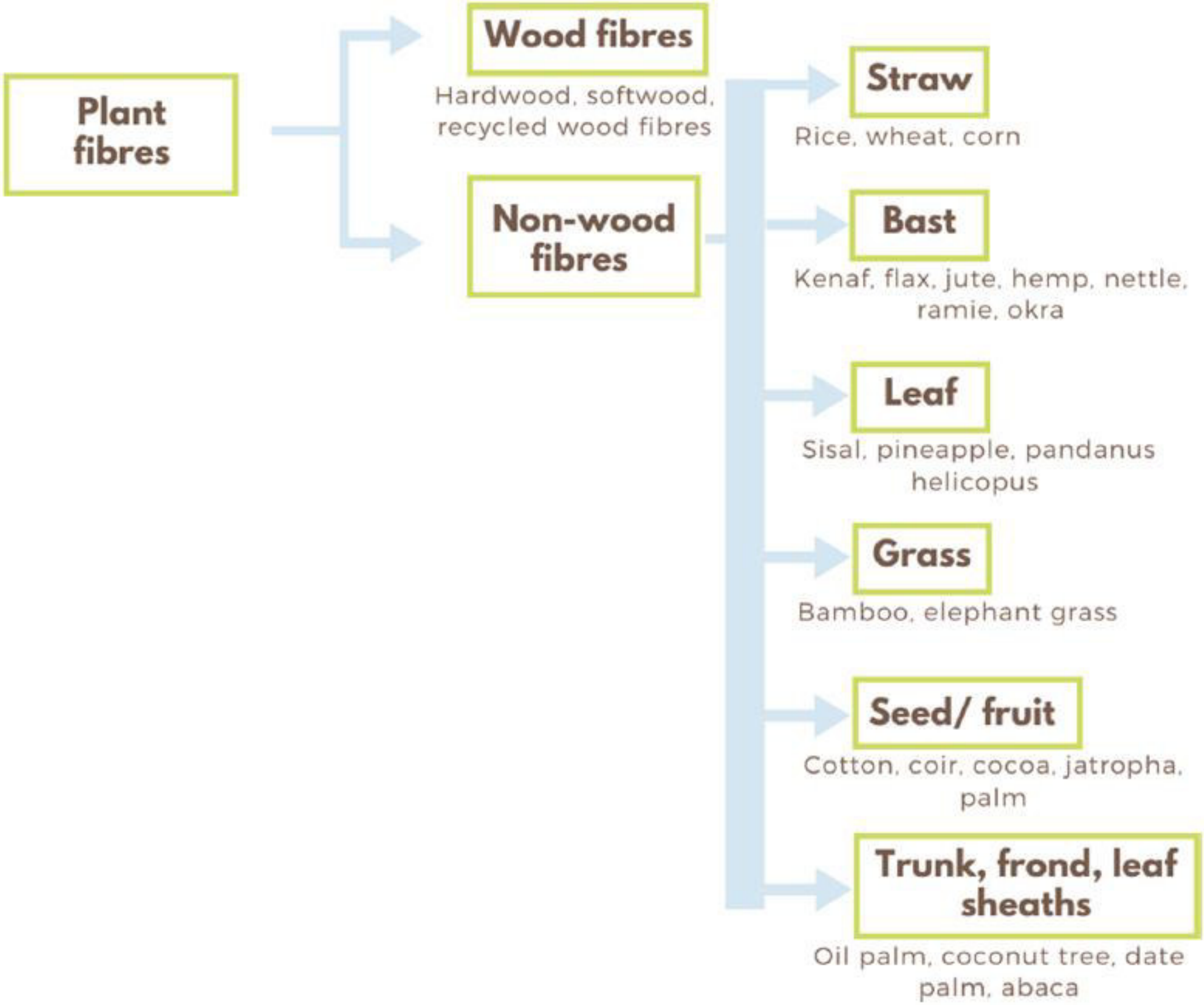
• **Lignocellulosics and plant-based polysaccharides:** Starch and lignocellulose are the two main types for polymer production. Lignocellulosic biomass contains cellulose (34–54%), hemicellulose (19–34%), and lignin (11–30%).65 Lignin is of interest as a polyaromatic structure as it provides a good baseline to mimic the aromatic structures used in petrochemical-based materials

• **Sugars from waste biomass:** Cellulose can be converted into glucose and key platform chemicals such as 2,5-furan dicarboxylic acid and hydroxymethylfurfural (HMF); 66 hemicellulose can be converted into C5 sugars which then give C5 furans including furfural and furfuryl alcohol.

Carbon fibre demand

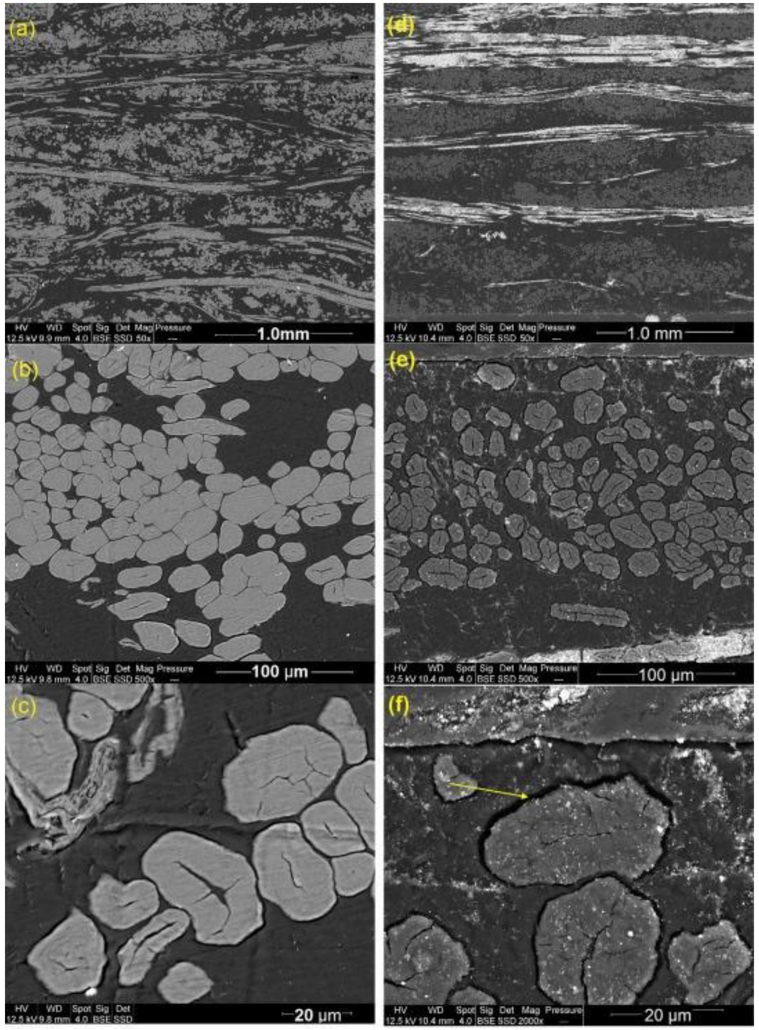


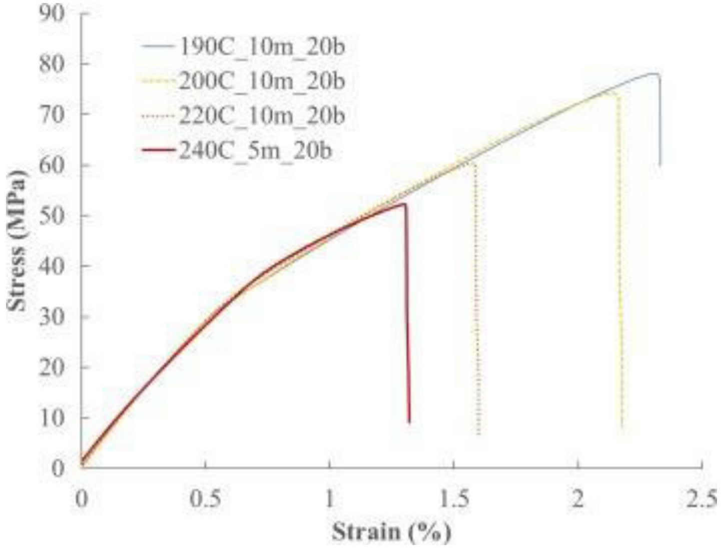
Fibres



Plant fibres
Wood fibres
Hardwood, softwood, recycled wood fibres
Non-wood fibres
Straw
Rice, wheat, corn
Bast
Kenaf, flax, jute, hemp, nettle, ramie, okra
Leaf
Sisal, pineapple, pandanus helicopus
Grass
Bamboo, elephant grass
Seed/ fruit
Cotton, coir, cocoa, jatropha, palm
Trunk, frond, leaf sheaths
Oil palm, coconut tree, date palm, abaca

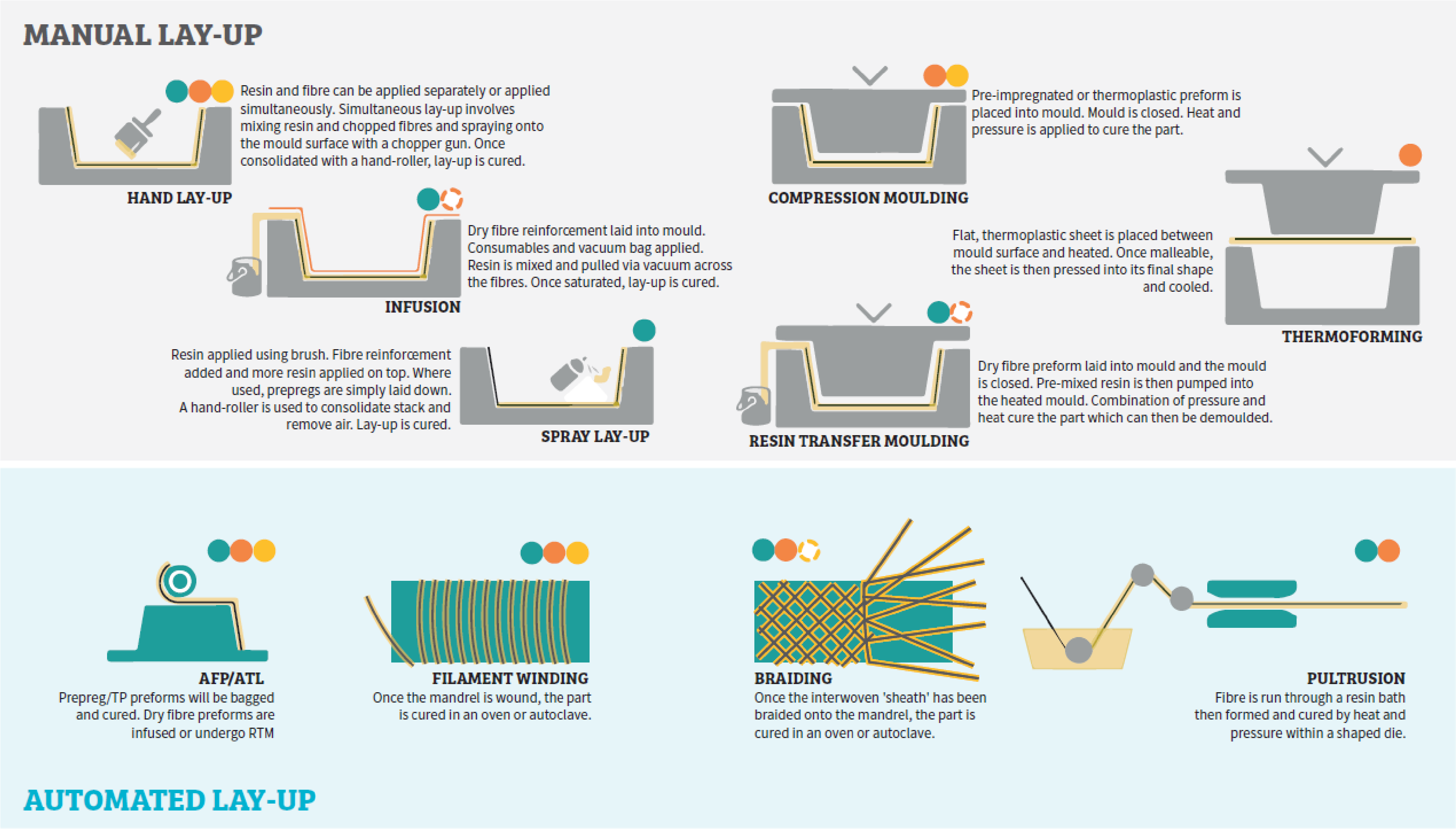
Flax thermoplastic manufacturing





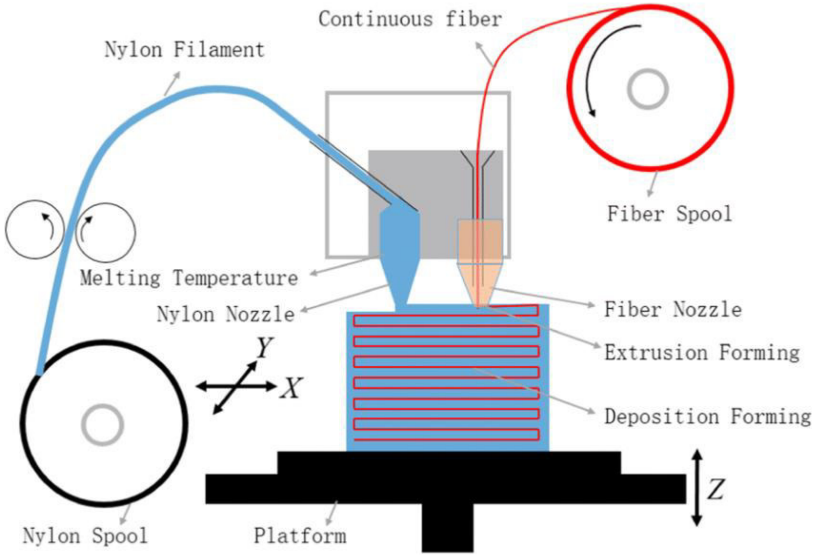
https://doi.org/10.1016/j.compositesa.2019.105493

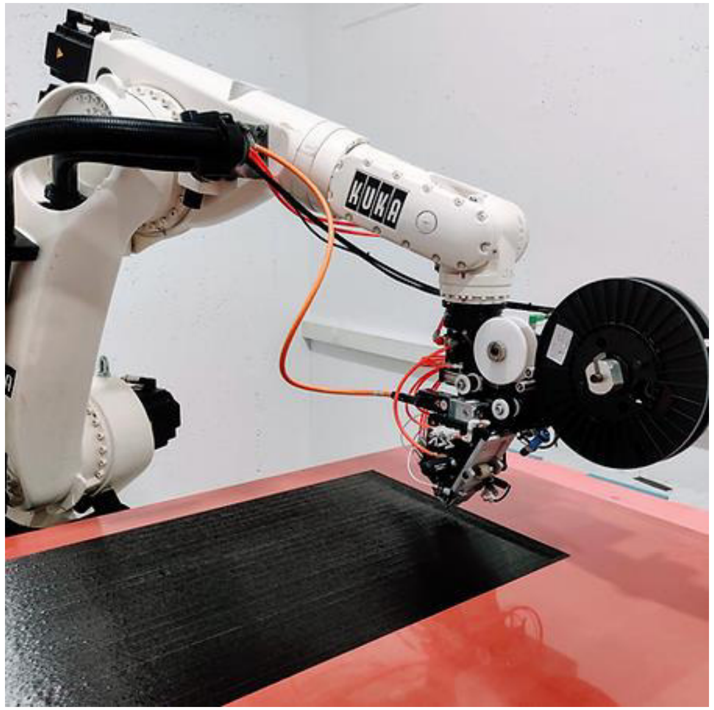
Manufacturing methods of composites



Sustainable Manufacturing in composites

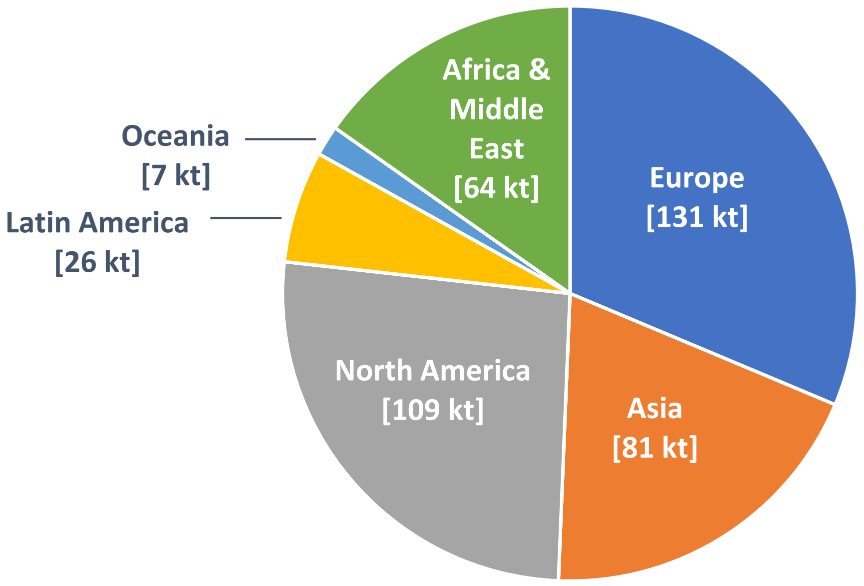
- Fast curing resins / low temperature curing resins
- UV curing
- Out-of-autoclave cure
- Automated fibre placement
- Additive manufacturing



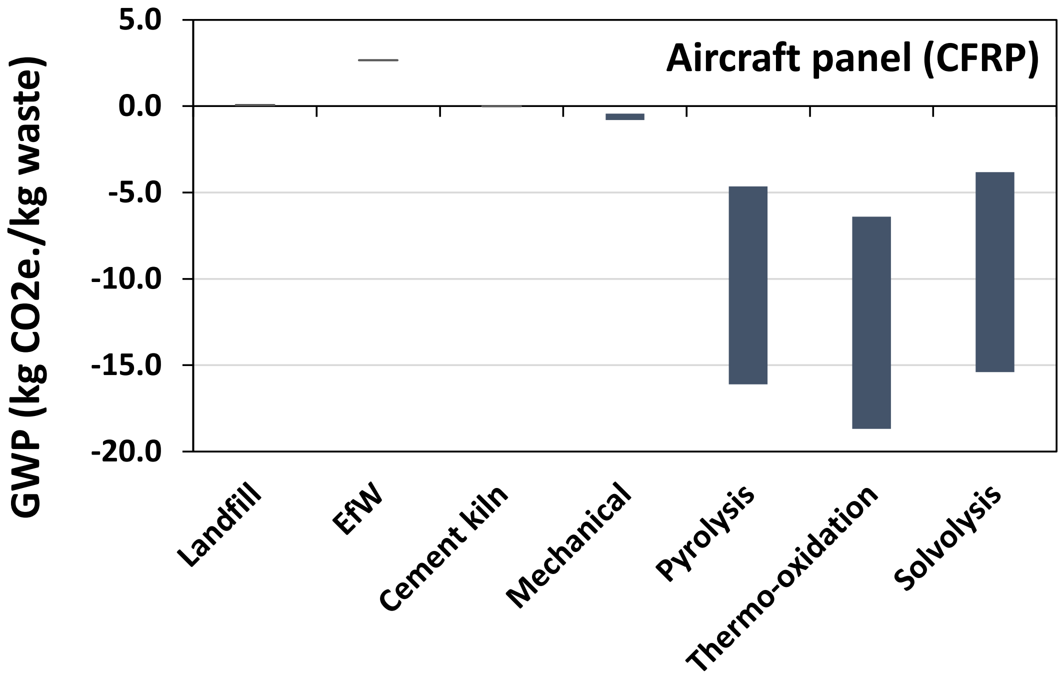


End of life

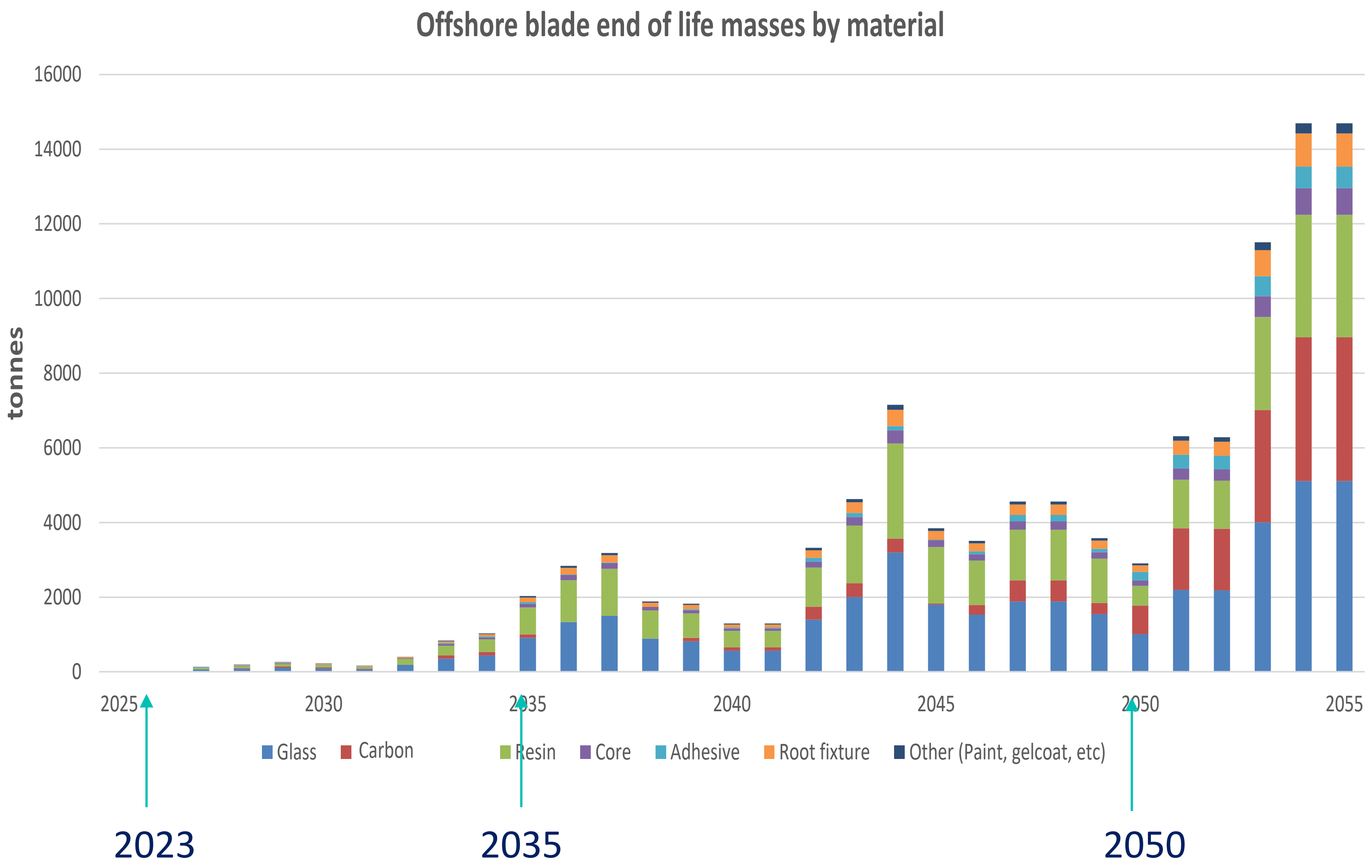
- Increasing quantities of composite End-of-Life waste e.g. by 2030, it is estimated that 11000 aircraft will be retired



2050 Cumulative Aerospace CFRP waste



End of life blades



Recycling of composites

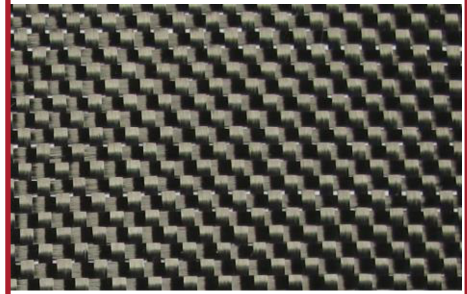
CHALLENGE

- Large structures w/ thick laminates
- Mixed waste streams with different polymer and fibre types
- Often low value recycled product
- Immature and unknown waste stream to established waste processers

PROBLEM

- No convergence on best technology for composite waste
- Not stress tested again real world EoL waste
- Industry doesn’t know which solution to back
- Need useful data to help make informed decision

Recycling and the circular economy

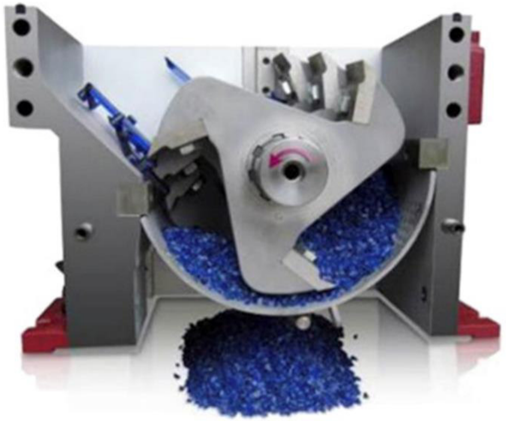


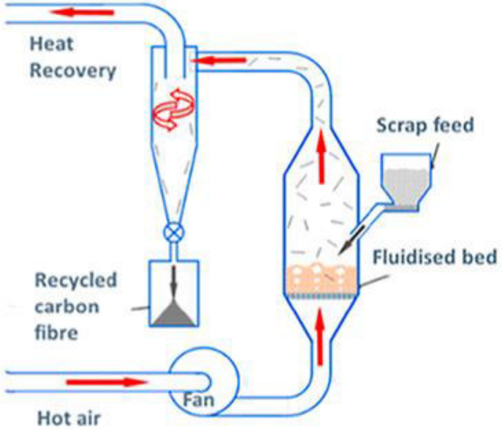
Engineering challenge: How to separate the fibres and the resin?

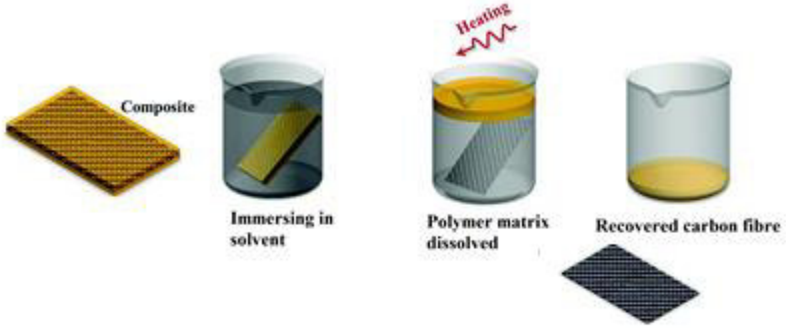
How do we extract fibres from EOL composites

Fibre recovery

- **Mechanical**
  - Milling
- **Thermal**
  - Pyrolysis
  - Fluidised bed
- **Chemical**
  - Solvolysis
  - Depolymerisation







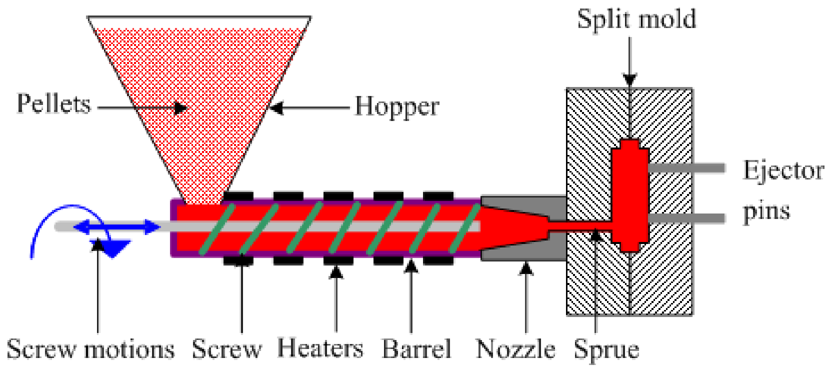
Manufacturing of recycled composites

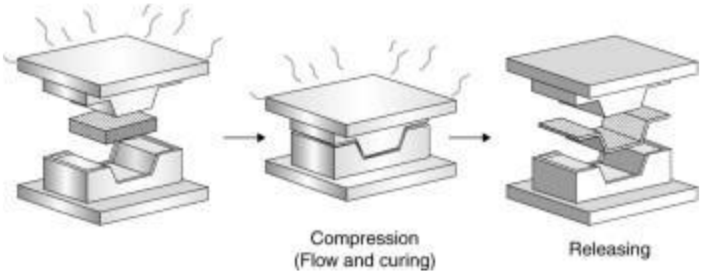
Reclaimed fibres

Pelletised carbon fibres

Non woven fibre mat

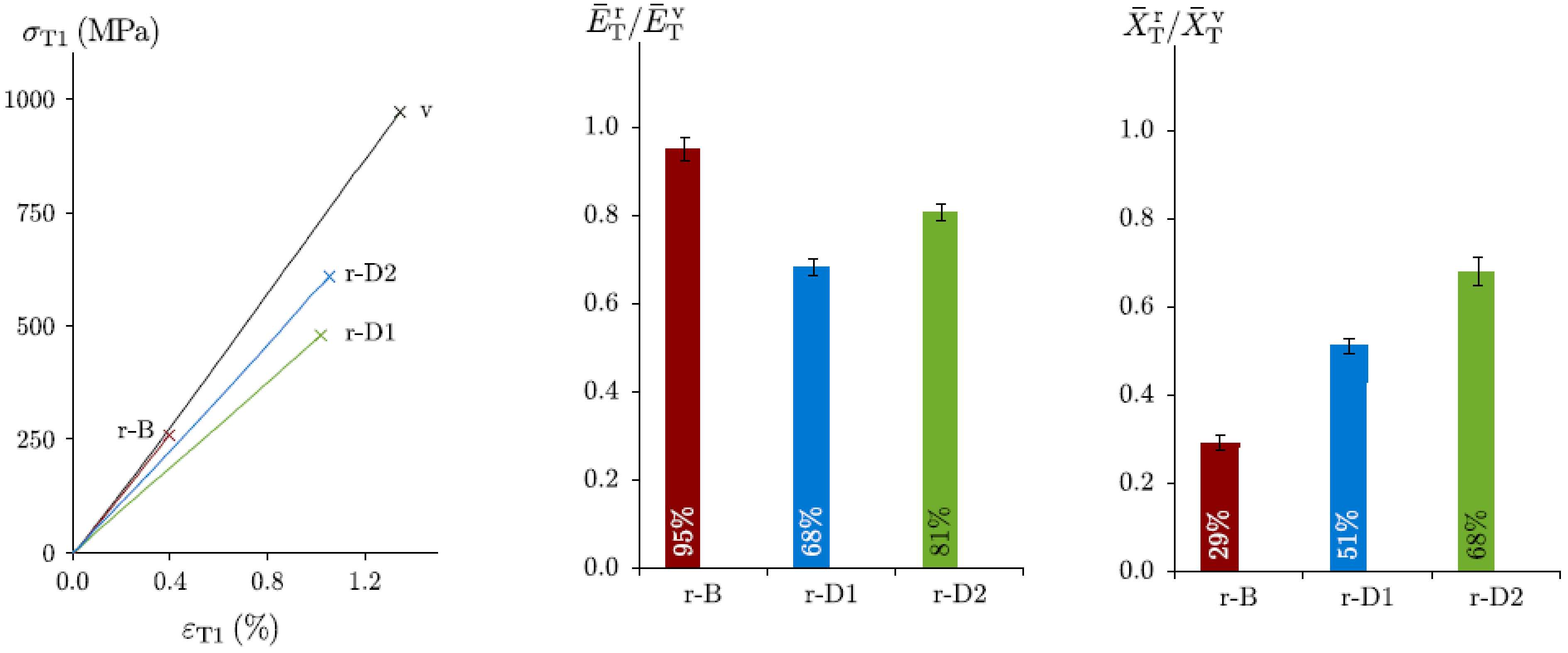
Injection moulding





Compression moulding

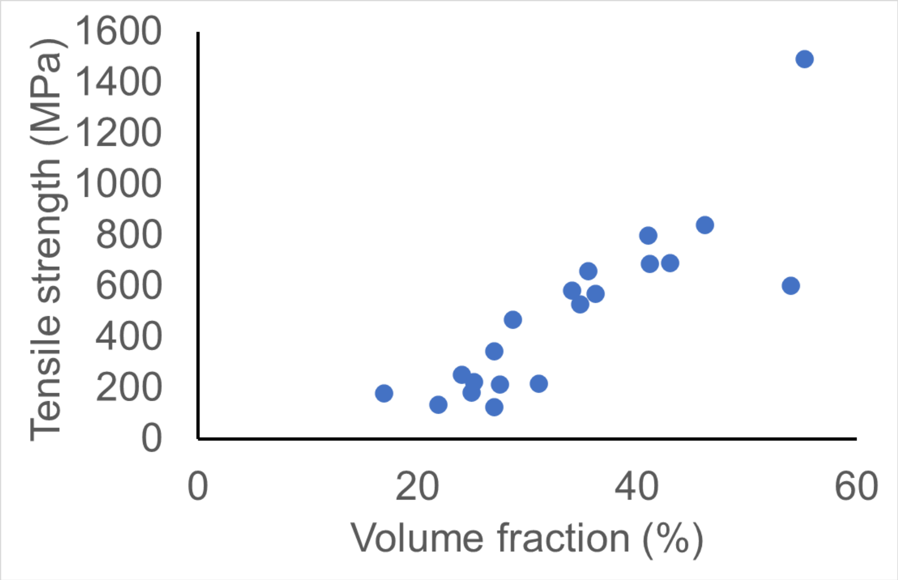
Mechanical properties of recycled composites

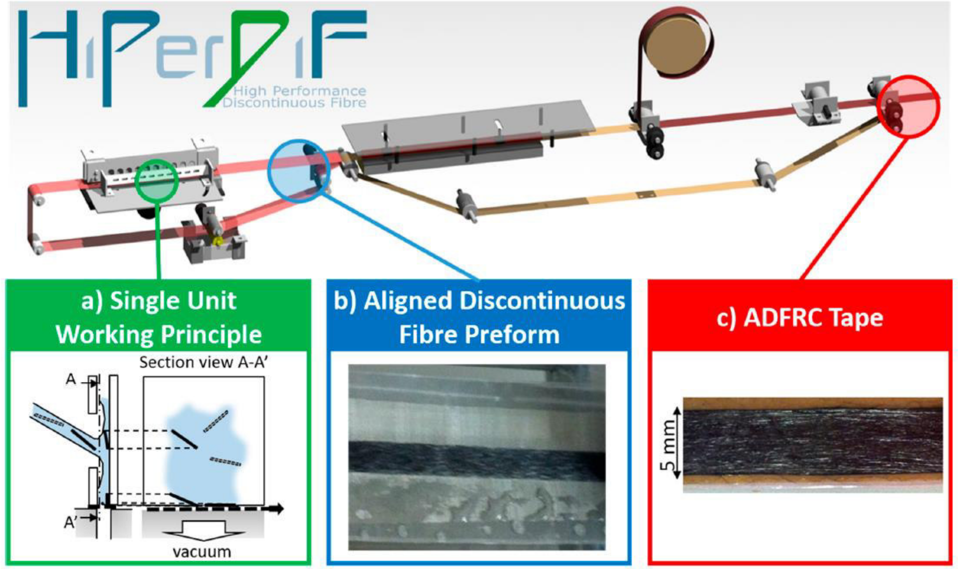


Pimenta S, Pinho ST. The effect of recycling on the mechanical response of carbon fibres and their composites. Composite Structures. 2012 Dec 1;94(12):3669-84.

Factors affecting the mechanical property

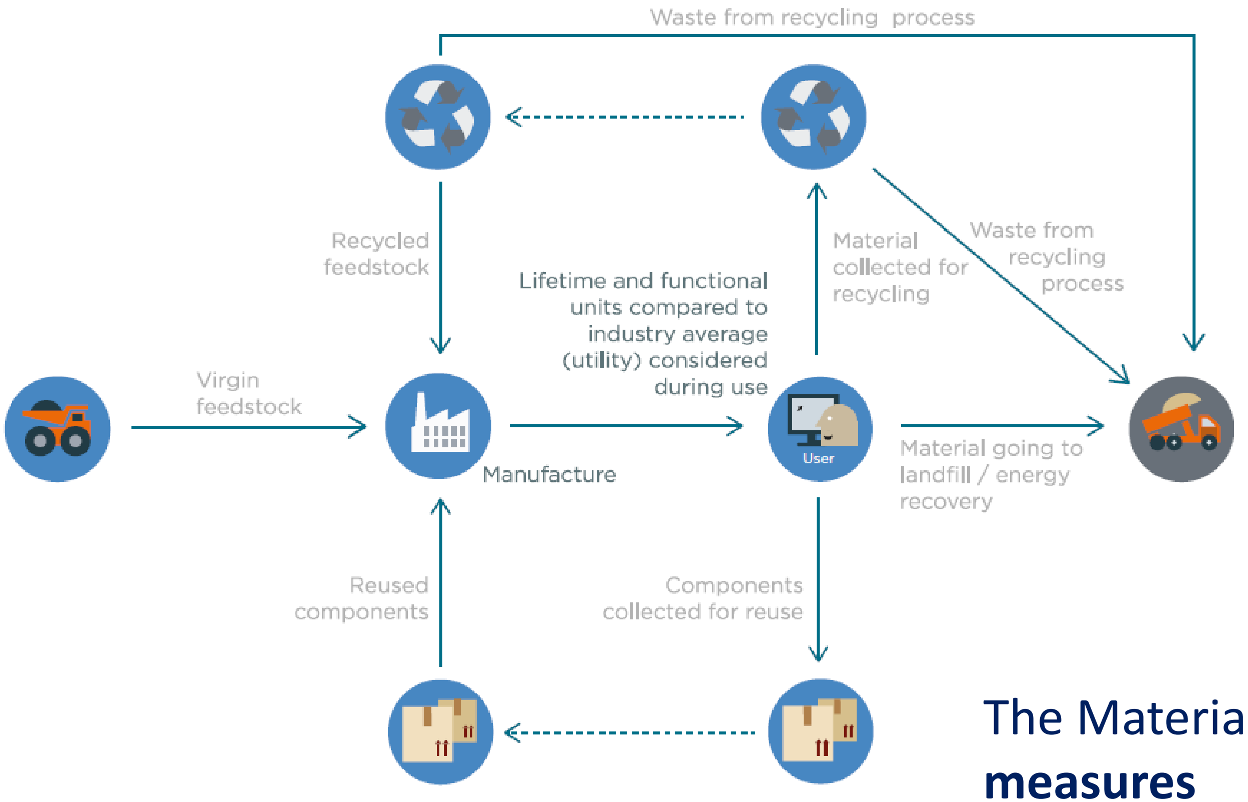
- Fibre recovery process ➔ milling vs. pyrolysis
- Fibre lengths (aspect ratio) ➔ short vs. long fibres
- Volume fraction of composite ➔ injection molded vs. compression
- Orientation of the fibres ➔ random vs. aligned





https://ellenmacarthurfoundation.org/material-circularity-indicator

Circularity indicator



The Material Circularity Indicator (MCI) for a product **measures**

- **the extent to which linear flow has been minimised**
- **restorative flow maximised for its component materials,**
- **<u>and</u> how long or intensively it is used** compared to a similar industry-average product.

Circular economy pillars

The classic representation of the five pillars of the circular economy includes:

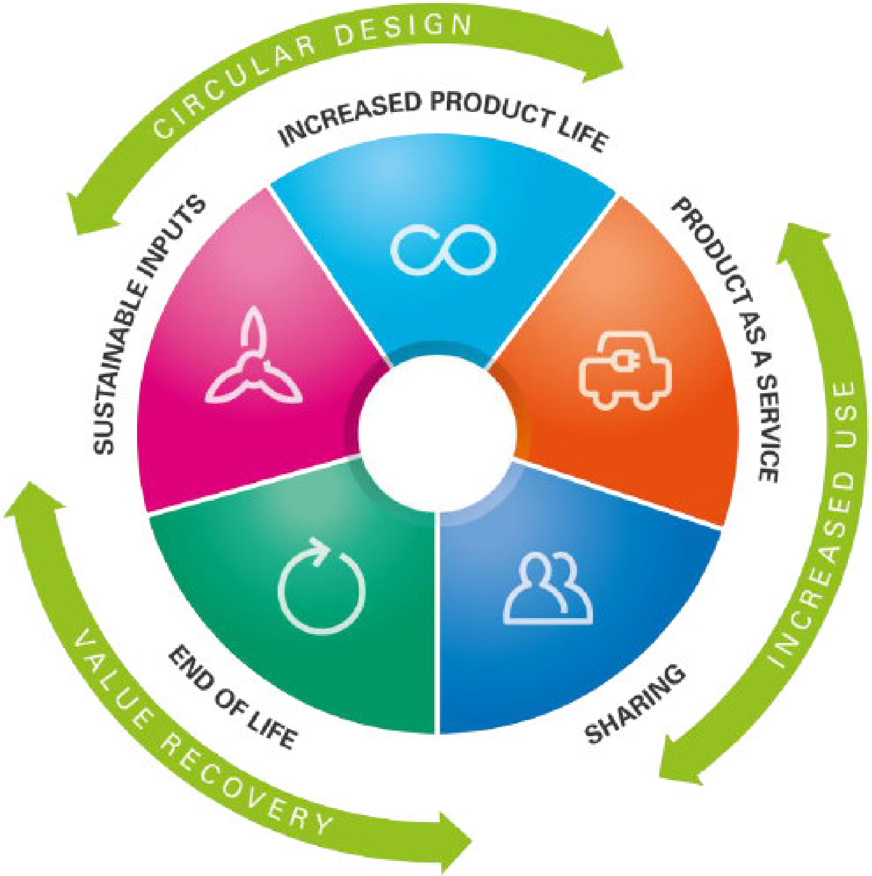
Circular inputs
Production and use model based on renewable inputs or previous life cycles (reuse and recycling).

Useful life extension
Approach to the design and management of an asset or product aimed at extending its useful life, e.g. by means of modular design, facilitated repairability, predictive maintenance.

Product as a service
Business model in which the customer purchases a service for a limited time, while the company maintains the properties of the product, maximizing the utilization factor and useful life.

Shared platforms
Management systems in common among multiple users of products, assets, or skills.

New life cycles
All solutions aimed at preserving the value of an asset at the end of its life cycle thanks to reuse, regeneration, upcycling or recycling, in synergy with the other pillars

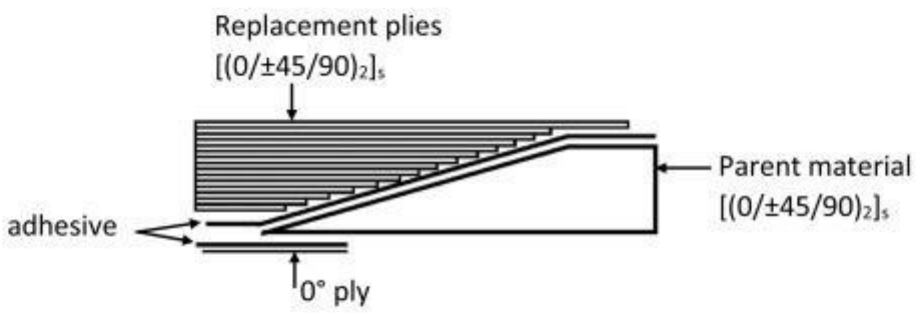


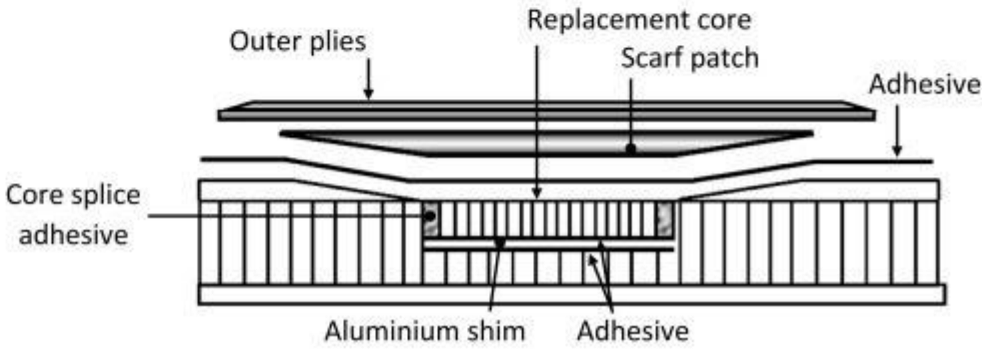
Design for Durability - Increasing lifetime

- Natural fibres are highly hydrophilic in nature and therefore absorb water well, which can negatively affect mechanical performance.
- Hybridisation
- Coatings

Reuse and repair

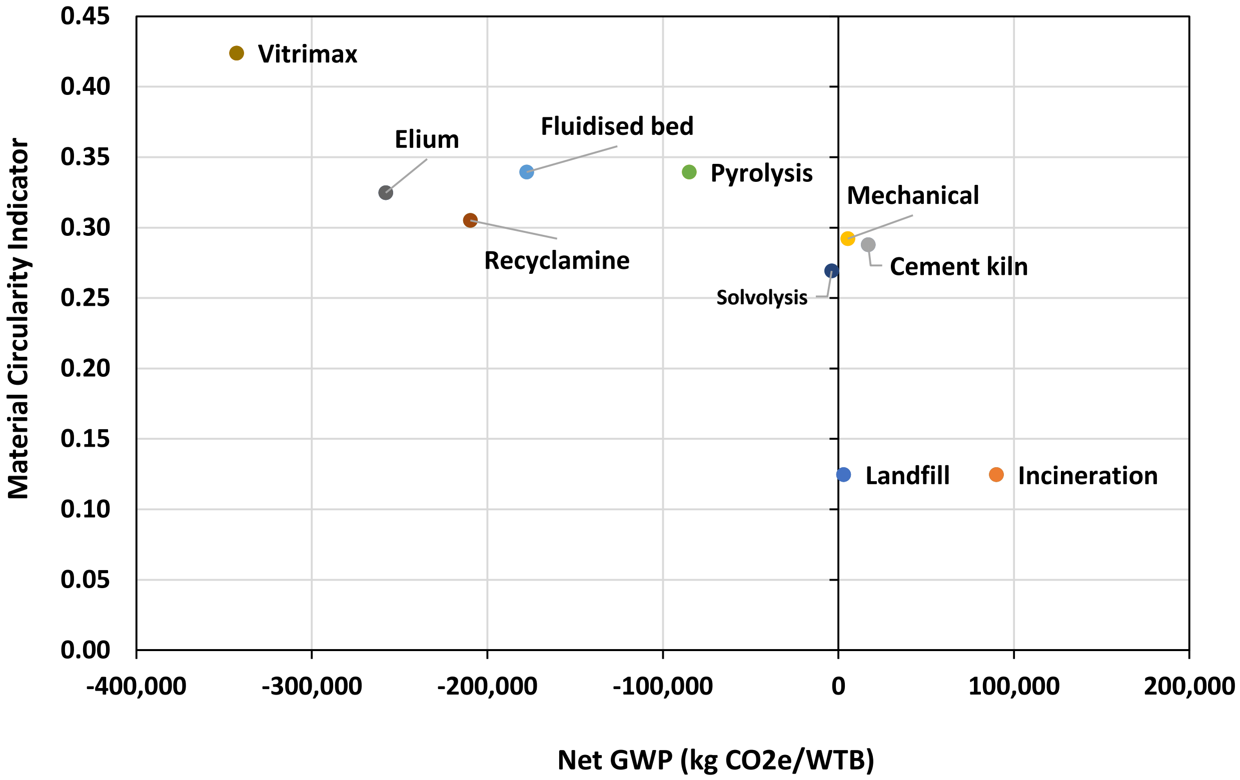
- Patches
- Liquid resin injecting
- Self healing





Design for Recycling

- Triggered degradation thermosets
- Vitrimers



MCI tells us that emerging tech is considerably better

Questions to answer

What is the demand for Composite Materials?

- Wind turbines
- Hydrogen
- Transportation

What does UK composite waste look like – now and future?

- Decommissioning wind over next 30 years

What is the environmental impact of proposed solutions?

- Mix of materials, currently landfilled

What sustainable solutions SHOULD be pursued?

Revision questions

- How does planned obsolescence contribute to material consumption?
- What is LCA and what are the steps involved in conducting LCA?
- What is the hierarchy of end-of-life options?
- What are some potential obstacles for widespread recycling of plastics?
- What is the difference between embodied energy and processing energy?
- Compare and contrast linear and circular materials economy?
- What is triple bottom line and how can industries use this framework to achieve sustainable goals?
- Which phase is the most critical for built structure such as a multi-storey car park?

Previous Exam question

The bill of materials used in the construction of wind turbines is given in the table. The mass per kW and the embodied energy per kg of these materials are also provided.

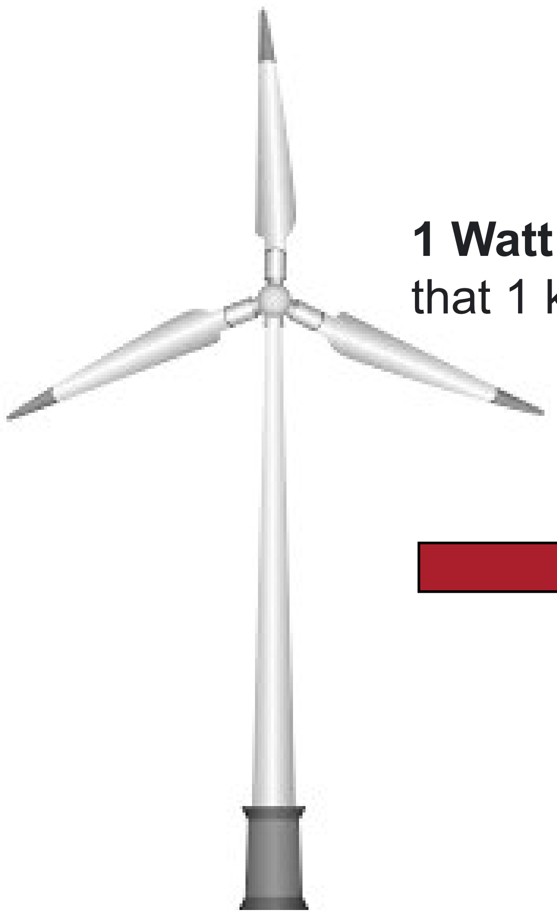
Bill of materials	Mass per installed unit of power capacity (kg/ kW)	Embodied energy (MJ/kg)
Concrete	400	1.8
Steel	100	25
CFRP	8	480
GFRP	10	160
Plastics	5	80
Aluminium	2	200
Copper	1.5	65
Neodymium magnets	0.012	85

1. Calculate the total embodied energy for a 1 MW wind turbine?
2. What is the duration of operation of the turbine to break even of the embodied energy used in the construction?
3. If the turbine can be operated at 25% of its rated capacity, then how does it affect the break-even duration?

Bill of materials	Mass per installed unit of power capacity (kg/kW)	Mass for 1MW turbine (kg)
Concrete	400	400000
Steel	100	100000
CFRP	8	8000
GFRP	10	10000
Plastics	5	5000
Aluminium	2	2000
Copper	1.5	1500
Neodymium magnets	0.012	12
Total		**526512**

Bill of materials	Mass per installed unit of power capacity (kg/kW)	Mass for 1MW turbine (kg)	Embodied energy (MJ/kg)	Embodied energy (MJ)
Concrete	400	400000	1.8	720000
Steel	100	100000	25	2500000
CFRP	8	8000	480	3840000
GFRP	10	10000	160	1600000
Plastics	5	5000	80	400000
Aluminium	2	2000	200	400000
Copper	1.5	1500	65	97500
Neodymium magnets	0.012	12	85	1020
Total		**526512**		**9558520**

Energy Produced (kWh)= 1,000kW × 24hours/day × 365days/year



1 Watt = 1 Joule per second (1W = 1 J/s) which means that 1 kW = 1000 J/s

Input energy (J)

9.56E+12

Output energy J per sec	1.00E+06
Output energy J per year	3.15E+13

Duration (years) 3.03E-01

Duration at 25% 1.21

Summary

- Historical background of manufacturing paradigms
- Sustainability indicators
- Direct digital manufacturing
- Environmental, economic and social impacts
- Future challenges

Source: Chen D, Heyer S, Ibbotson S, Salonitis K, Steingrímsson JG, Thiede S. Direct digital manufacturing: definition, evolution, and sustainability implications. Journal of Cleaner Production. 2015 Nov 16;107:615-25.

Aircraft size and fuel efficiency