Wind turbine blade circularity

Technologies and practices around the value chain

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Content

Disclaimer:
This study presents findings based on literature review and consultation of experts.

Wind energy in Europe

Brief overview

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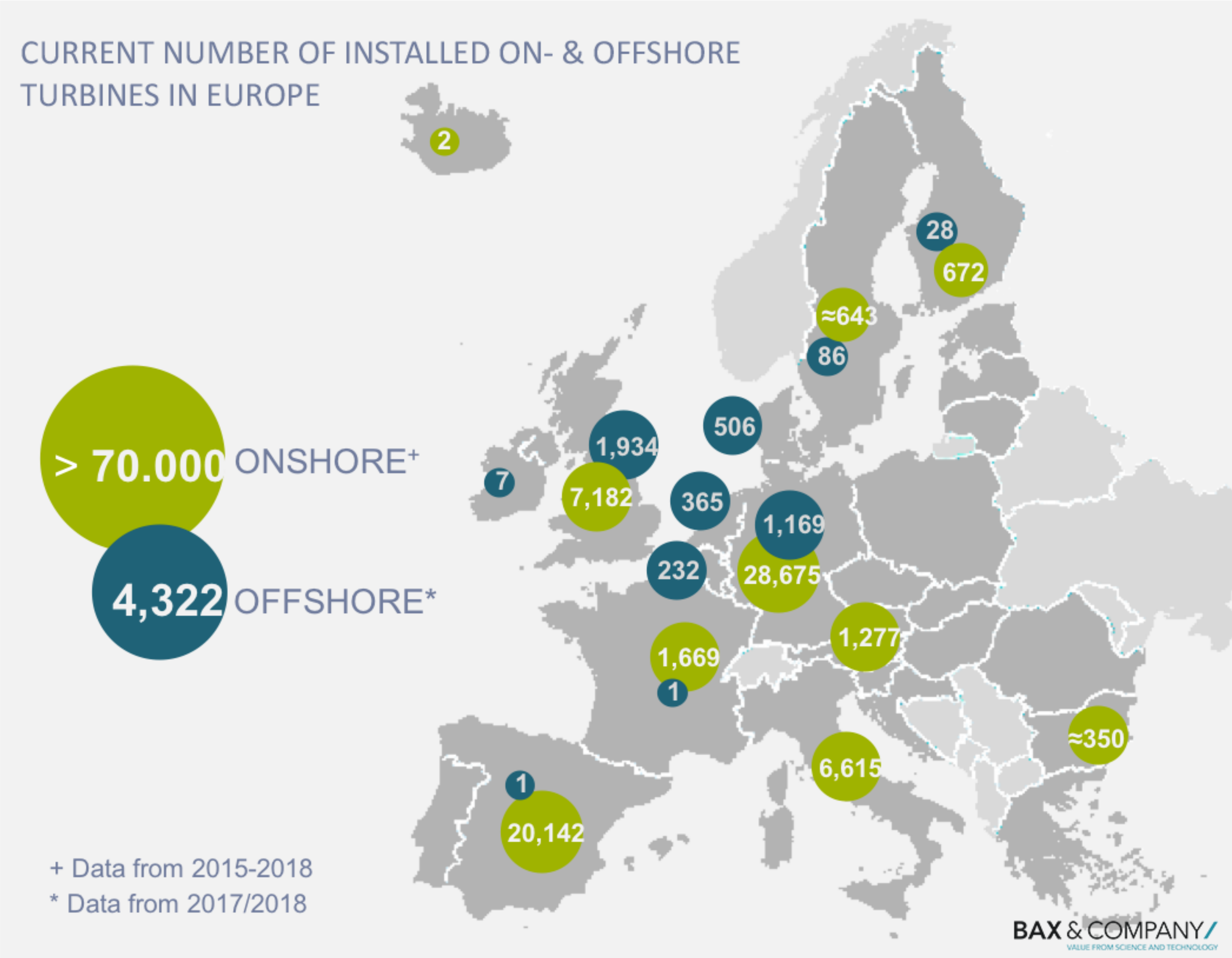
Wind energy in Europe

Status and material usage



1 MW = 12 to 15 tons of composites

More than **70,000 wind turbines** spinning in Europe with a combined **capacity of 189 GW** and an estimated **composite** material inventory of more than **2.5 million tons**.

42,000

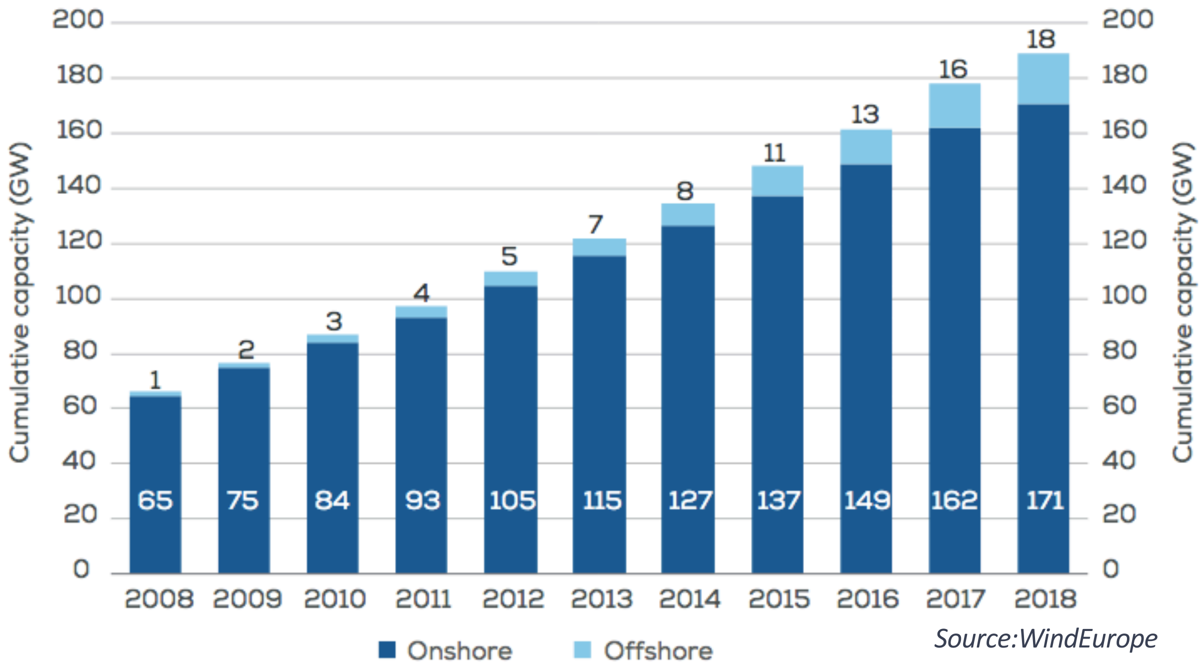
turbines decommissioned by 2020

Wind energy in Europe

Evolution of material usage

Evolution of amount of materials

The increasing attention given to wind energy throughout Europe will lead to a continuously growing demand for blade materials.

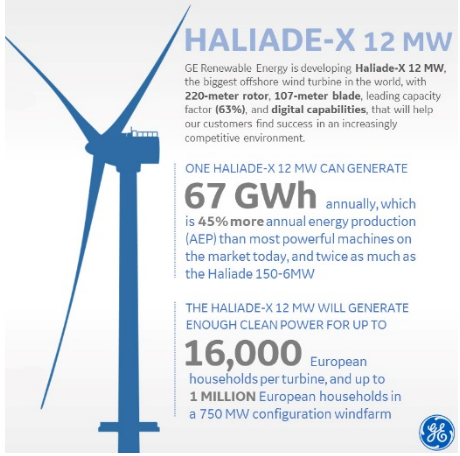


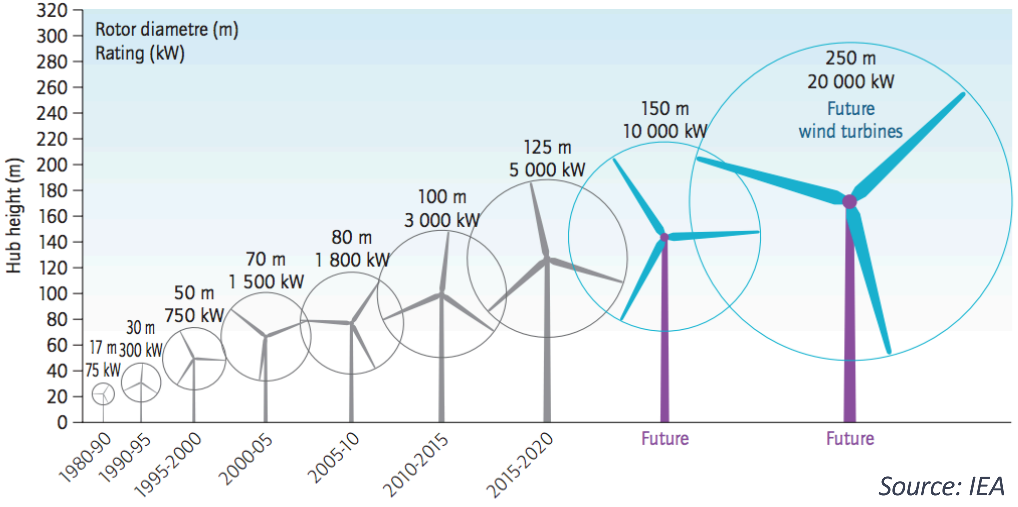
Source:WindEurope

Evolution of material types

Larger blades for the next generation of turbine blades to achieve higher energy yields lead to:

- Shift towards more carbon fibre use
- Shift towards more hybrid structures (glass and carbon fibre combinations)





Source: IEA

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A blade’s lifetime

Technologies and practices to increase circularity around the lifecycle

Disclaimer:
This study presents technologies that not all yet reached market maturity or have proven to improve circularity, but they have exhibited the potential to do so. The focus lays on the contribution of technologies to circularity and doesn’t necessarily include criteria like performance and costs.

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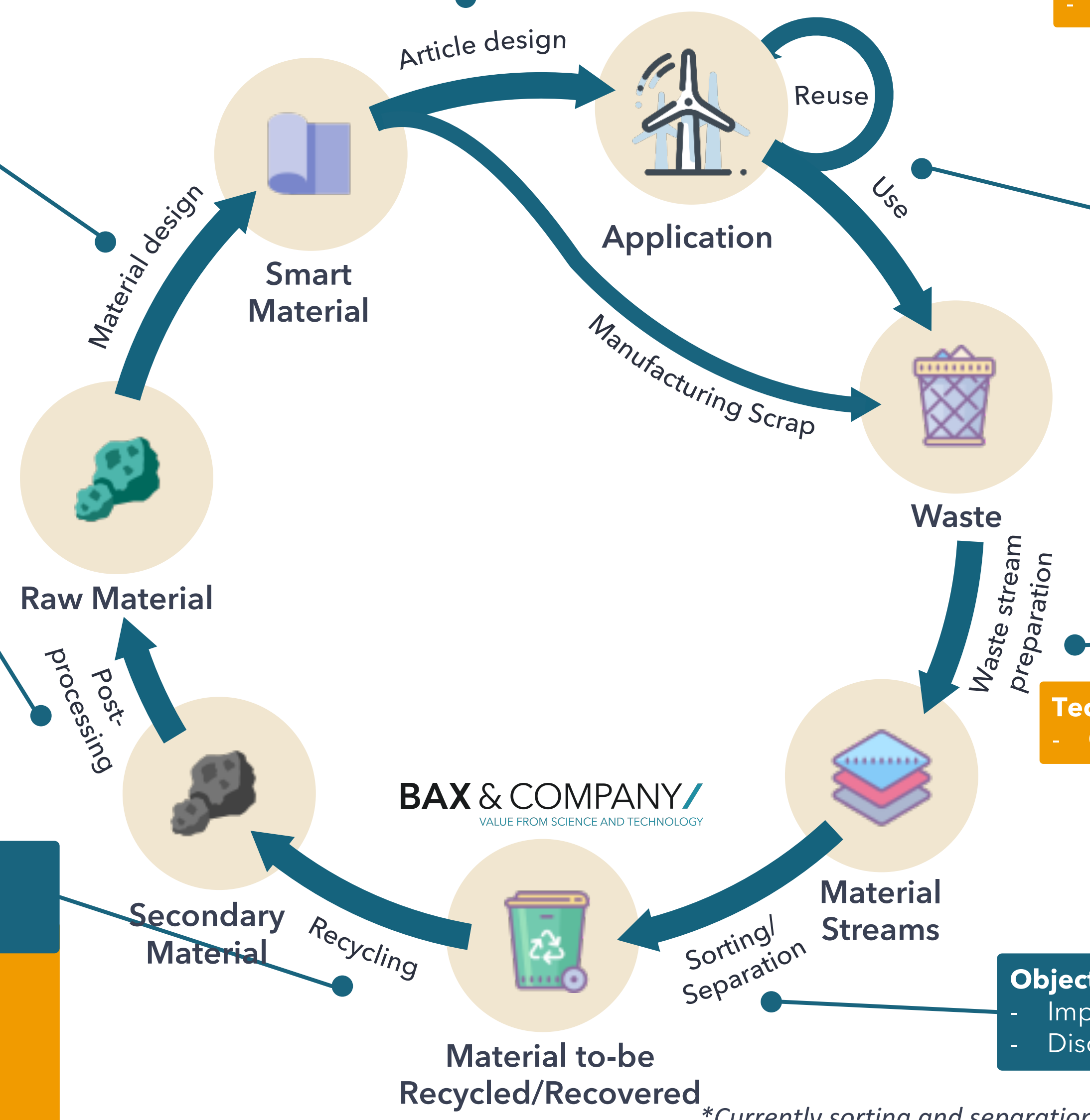
Technologies and practices around the lifecycle

That help increase the circularity of FRP wind turbine blades



Objectives
- Ease dismantling
- Decrease material use

Techs/Practices
- Eco-design/Multi-parameter design

Objectives
- Extend lifetime
- Improve aging-performance
- Improve sorting/separation
- Improve recyclability

Techs/Practices
- Self-healing polymers
- Bonding technologies
- Thermoplastic matrices
- Reversible thermoset resins

Objectives
- Extend lifetime

Techs/Practices
- On-site repair
- Refurbishment
- Health monitoring
- Health forecasting
- Reuse of components

Objectives
- Reinforce material properties

Techs/Practices
- Fibre surface treatment
- Fibre classification
- Fibre alignment
- Fibre sizing

Objectives
- Improve value of retrieved material
- Decrease recycling cost
- Decrease emissions

Techs/Practices
- On-site fragmentation

Objectives
- Enable (higher) material recovery
- Enable (higher) value recovery

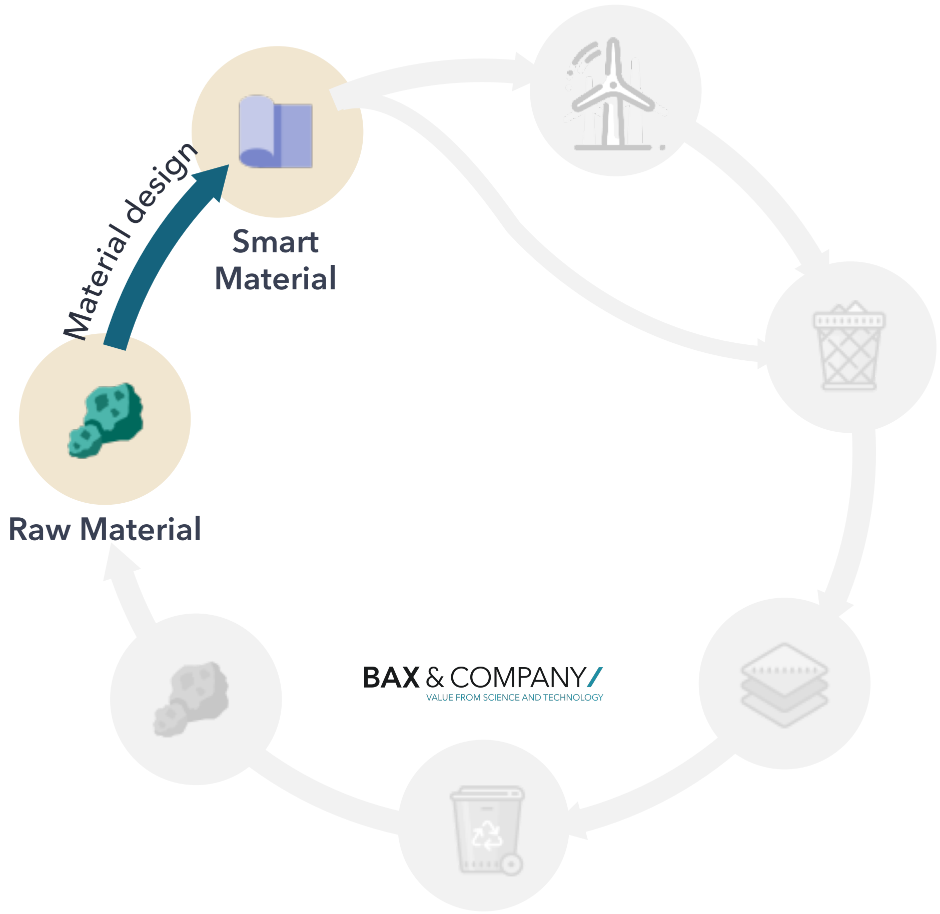
Techs/Practices
- Co-processing in cement kiln
- (Microwave) Pyrolysis
- Solvolysis
- Gasification (Fluidised bed)
- High voltage pulse fragmentation
- Mechanical grinding

Objectives*
- Improve value of retrieved material
- Discard non-useful material

**Currently sorting and separation of material components includes manual processes. There are currently no circularity enabling technologies known.*

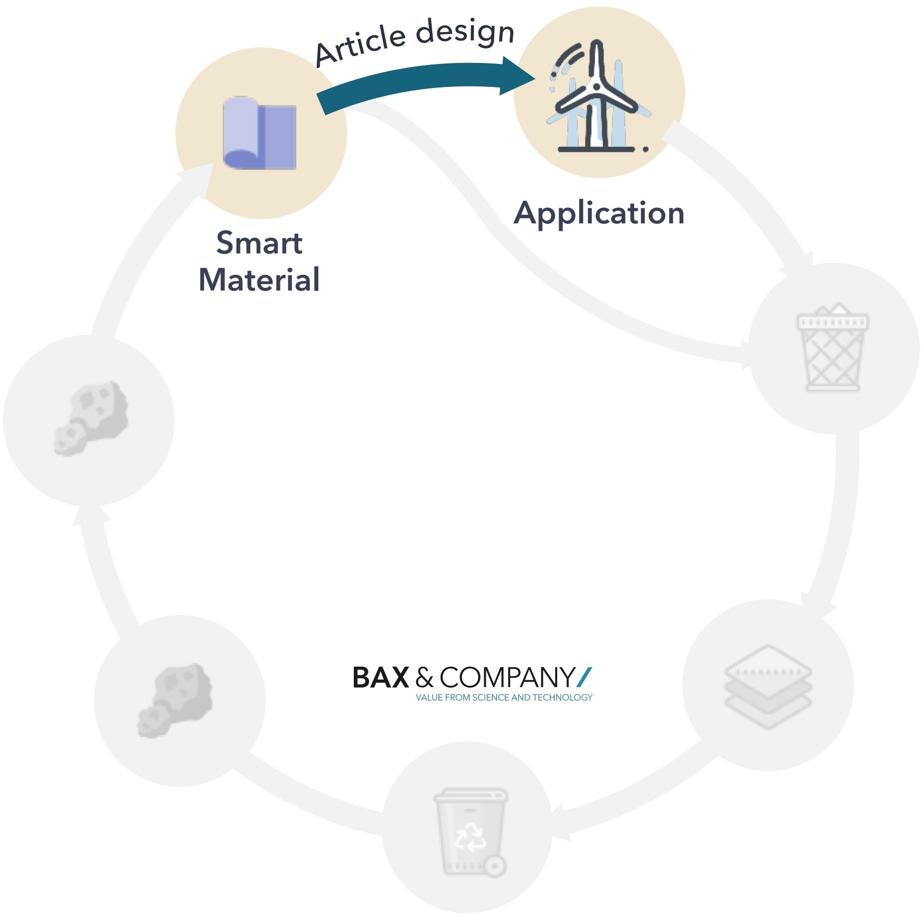
Material design

- **Extend lifetime of the blade**
  - **Self-healing** polymers (TRL 3)
  - Improving resin **ductility, fiber-resin adhesion and fatigue resistance**
  - Application of **gelcoats and surface coatings** (TRL 9)
- **Improve aging performance**
  - **Humectant** and **dispersant additives** as resin nano-reinforcement (TRL 7)
- **Improve separation** of components and materials at end-of-use
  - **Novel bonding** technologies (e.g. thermoplastic adhesives) (TRL 3)
  - **Reversible crosslinking** of thermoset resins (TRL 4)
- **Design for recyclability** at end-of-use
  - Blades made of **thermoplastic matrices** (TRL 6)



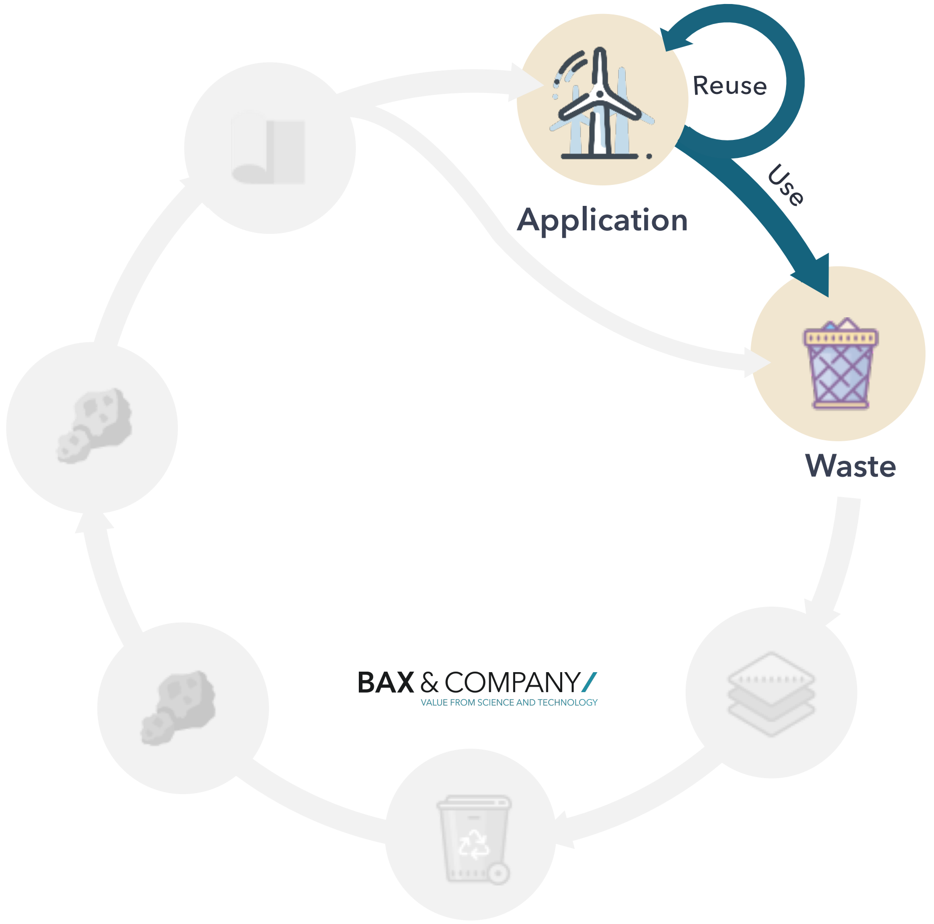
Article design

- **Decrease material usage and overall environmental footprint**
  - **Eco-design** tools (TRL 4)
    - Integrate circular criteria (e.g. ease of dismantling, recyclability, refurbishment) in blade design
  - **Multi-parameter design optimization** algorithms (TRL 3)
    - Use the right material at the right place and optimize its form to limit weight, maximize resistance etc.



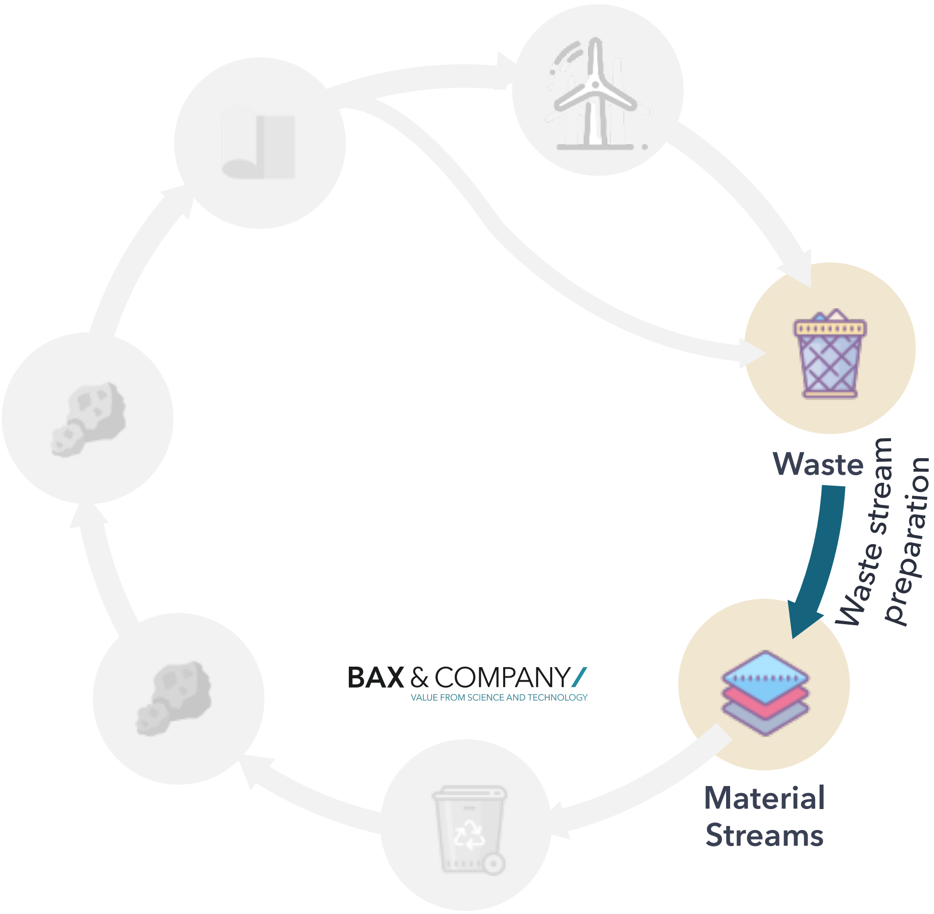
Use/ Reuse

- **Extend lifetime of the blade**
  - **Repair** (TRL9)
    - Small surface repairs to medium structural repairs
      - Laminate repairs through wet lay-up
      - Infusion and pre-preg repairs
      - Restitution of gel-coats and surface finishes
  - **Refurbishment** (reconditioning)
  - **Reuse** of blades in new installations (TRL 9)



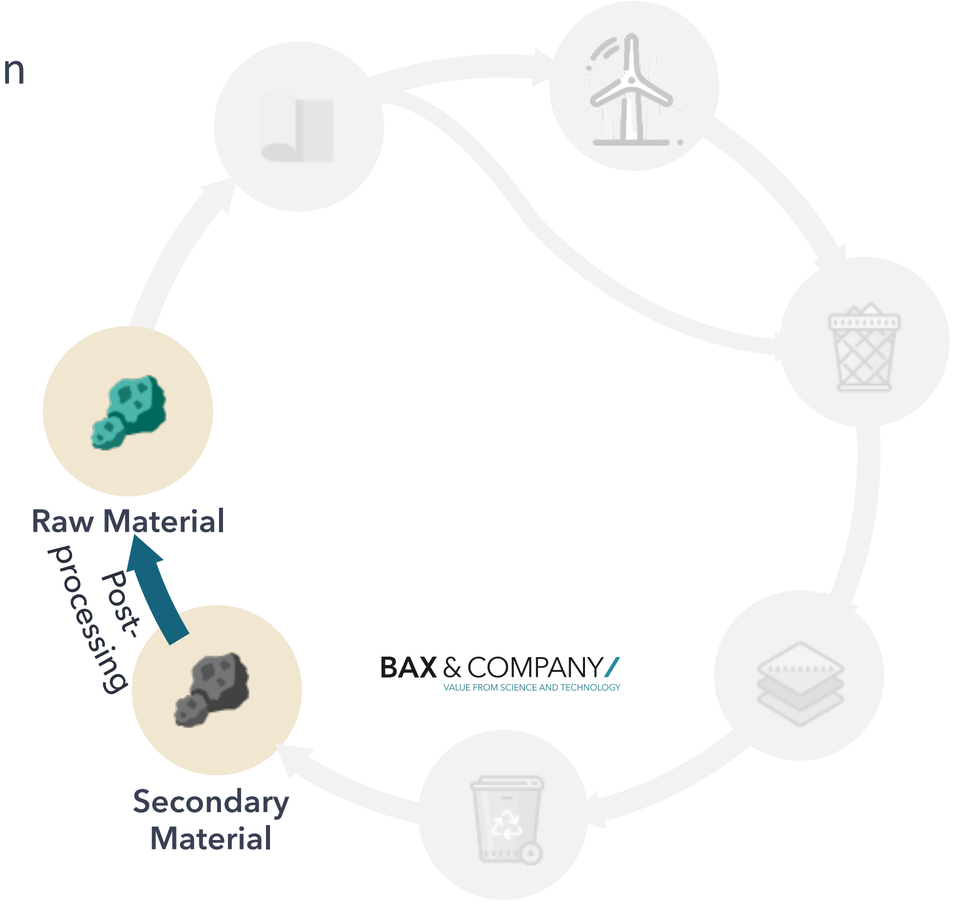
Waste stream preparation

- **Improve efficiency in transport logistics**
  - **On-site fragmentation**: Breaking up larger composite structures into smaller ones
    - Reduced GHG emissions



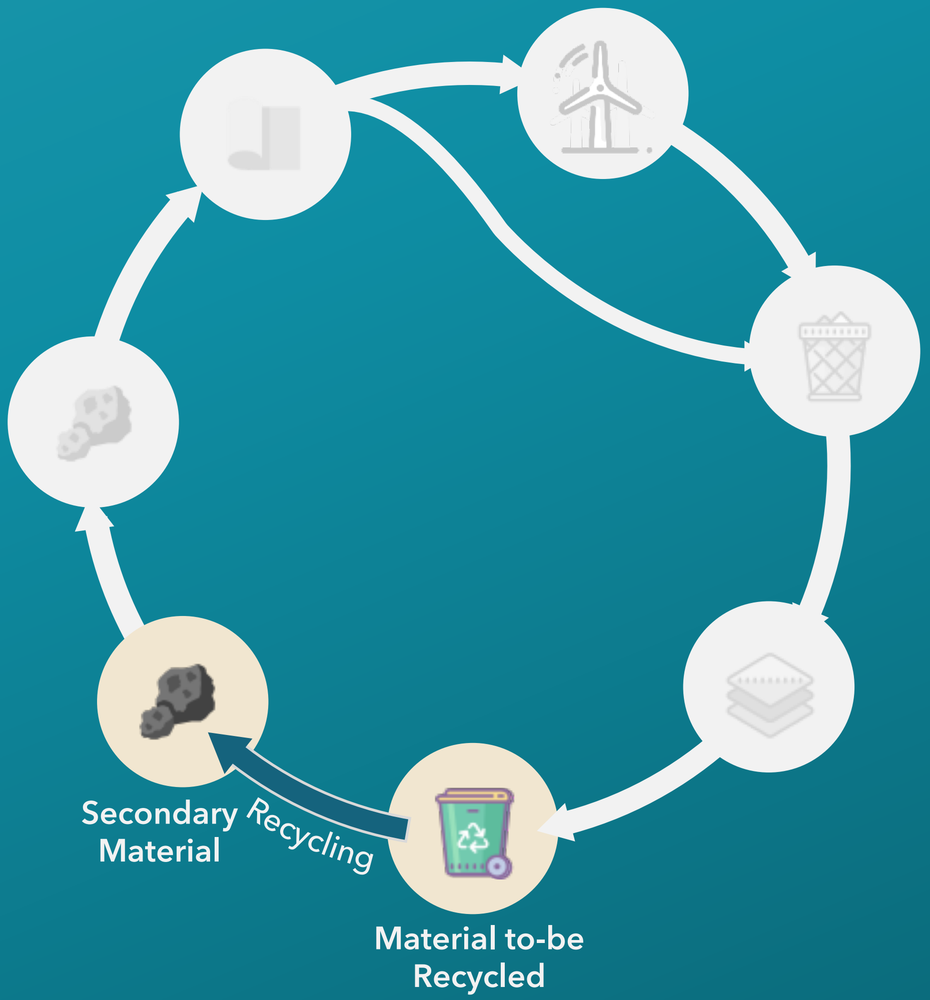
Post-Processing

- **Improve bonding** between recyclate and matrix in secondary application
  - Recycled fiber **surface treatment** (e.g. oxygen plasma)
  - Fiber **sizing**
- **Reinforce recycled material properties**
  - Fiber **alignment** along a single axis (e.g. hydrodynamic alignment method)
  - Fiber **classification**
  - Fiber **sizing**



Recycling technologies

Overview



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Referral to other publications

The following slides present recycling technologies currently in practice or under investigation for composite recycling and applicable for wind turbine blades.

The recycling technologies, their strengths and limitations as well as points of attention (related to health and safety) are listed for each process. The latter are expected to already be addressed accordingly by the industry and therefore don't require further statements.

We refrain from describing and explaining each technology in detail and refer for further information to previous SusChem studies and White Papers.

Mechanical Grinding

Strengths:

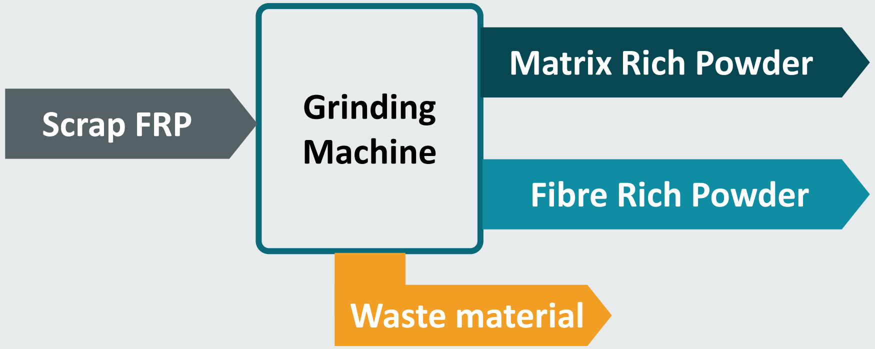
- Efficient waste management process (high throughput rates)

Limitations:

- High decrease of (mechanical) properties
- Material undergoes downcycling
  - Small, unstructured, coarse and non-consistent fibres
  - Recyclate with a high content of other material (incl. polymers, contaminants, paint, coatings)
- Cost efficiency
  - High operational costs and capital investment (running costs, installations)
  - Up to 40% material waste

Points of attention:

- Fine dust released into the surrounding atmosphere
  - Potential of fibers to stick into human skin or mucous membranes causing irritation



GFRP **TRL 9**

CFRP **TRL 6/7**

Pyrolysis

Strengths:

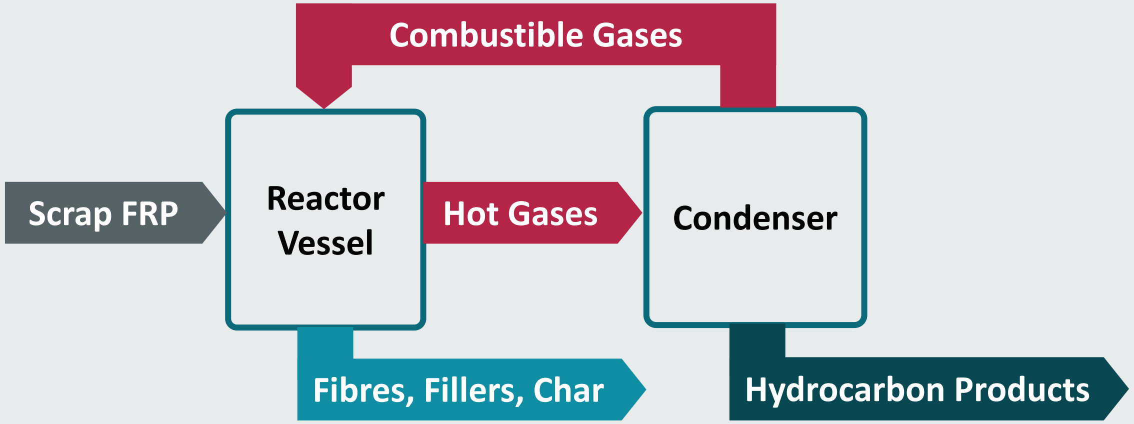
- Pyrolysis gas and oil can be used as energy source -> self-sustained process
- Wax recyclate as well as gases can also be used as fuels or intermediates for chemicals production
- Easily scaled-up to multi-tonne capacity
- **Microwave Pyrolysis:** Material is heated with microwave radiation at its core -> easier control of the heating process leading to decreased induced damage to the fibre material

Limitations:

- Fibre product may retain oxidation residue or char
- Sizing degradation of glass fibres -> changes in the composition (chemical structure)
  - For glass fibres it is currently not economically viable

Points of attention:

- Potential combustible gases leakage from waste treatment chambers



Pyrolysis **TRL 9**

Microwave Pyrolysis **TRL 4/5**

Co-Processing (Cement Kiln)

Strengths:

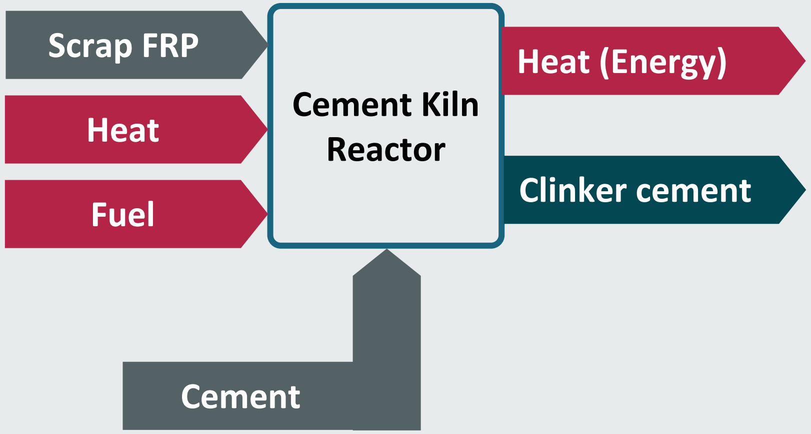
- Highly efficient and fast process: residence time of 4-5 sec in cement kilns. (Cement kiln processing capacity significantly higher than composite waste generated)
- Large quantities can be processed
    - Up to 75% substitution of cement raw materials -> significantly reduces CO_2 that is emitted by the cement industry
- No ash left over, minerals are trapped in the matrix of the clinker

Limitations:

- Loss of original material form (fiber form)
- Additional energy sources to reach high processing temperatures"

Points of attention:

- Pollutants and particulate matter emissions



TRL 9

Solvolysis

Strengths:

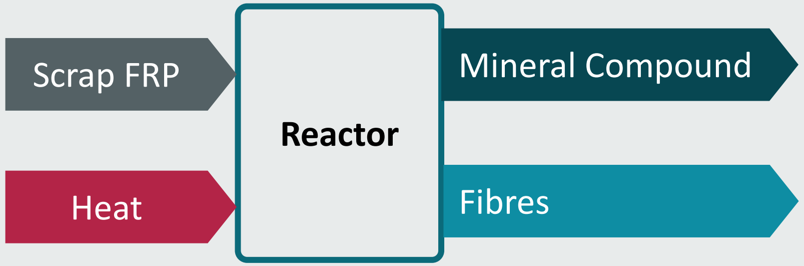
- Recovery of clean fibres in their full length
- Recovery of resin (oligomers or polymers) which can be re-used

Limitations:

- Insufficient efficiency (throughput) of the technology
- High energy consumption due to the high-temperature and high-pressure
- Use of large amounts of solvents (although reuse options could be explored)

Points of attention:

- Gas emissions (depending on catalysts potentially toxic, e.g. from alkali catalysts)
  - Human health impact and ecotoxicity



TRL 5/6

High Voltage Pulse Fragmentation

Strengths:

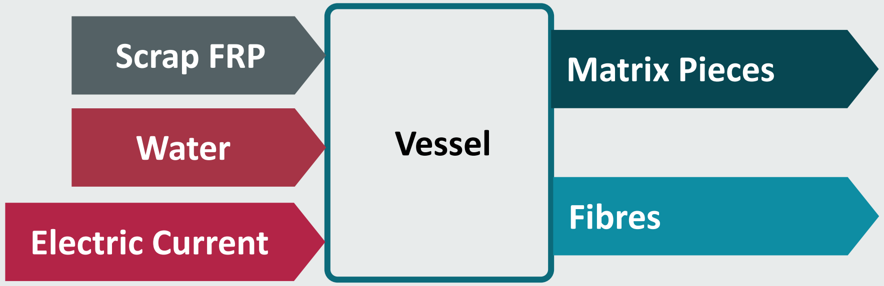
- Able to treat industrial quantities -> sufficient scalability of the process to treat larger capacities
- Low investments required to reach the next TRL

Limitations:

- Only laboratory- and pilot-scale machines are available
- Heavily decreased modulus of glass fibres

Points of attention:

- Working near high voltage



TRL 6

Gasification (Fluidised Bed)

Strengths:

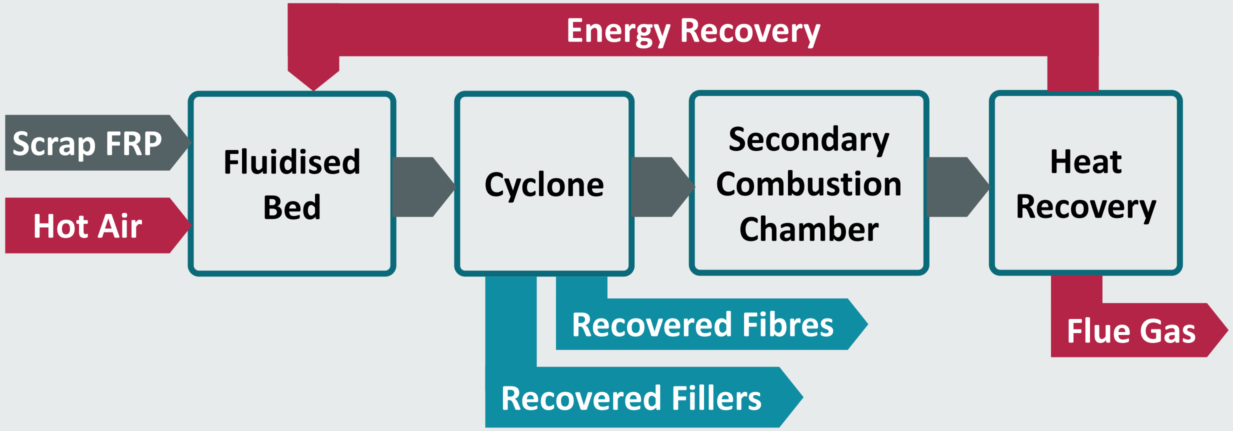
- Highly flexible (in terms of different process capabilities) and simple process
- Gases are recovered:
    - Energy recovery for the reduction of the energy demand
    - Opportunity to recover precursor chemicals
- High efficiency of heat transfer

Limitations:

- Low fibre qualities for glass fibres (significantly reduced fibre tensile strength)
- Will only be economically viable if it reaches capacities of more than 10,000 tonnes per year (Yang et al.)
- De-fluidisation is problematic: fluidised bed can locally collapse

Points of attention:

- Emissions (e.g. CO_2) related to the process



TRL 5/6

Comparison

Between the different recycling options

Disclaimer:
This study includes comparative analyses based on literature review as well as comments and validation through industry experts and doesn't present absolute values.

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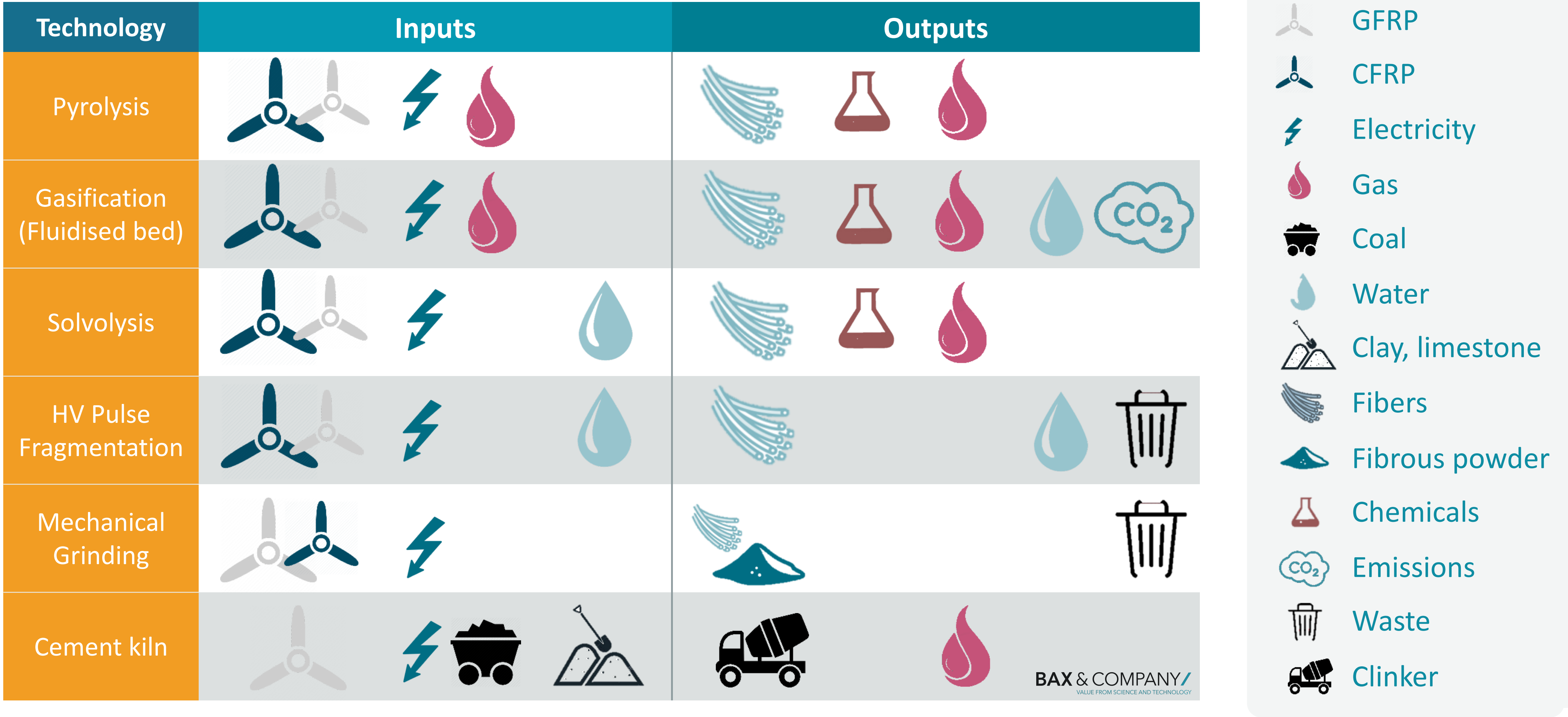
Inputs and outputs



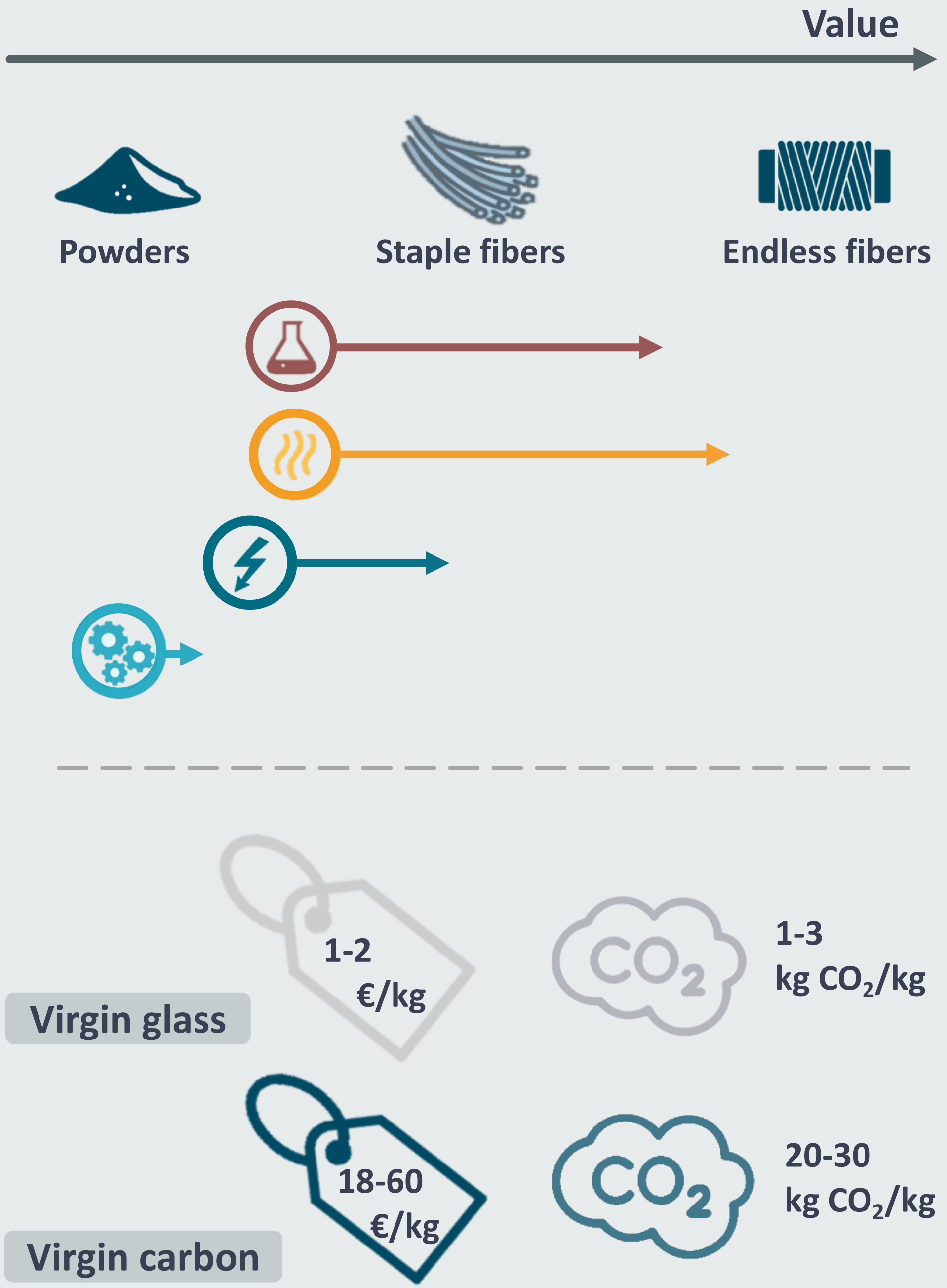
Additional baselines for comparison

Comparing processes in regards with:

1. Material properties/**quality** (e.g. form, mechanical strength, modulus)
2. Energy demand and **GHG emissions**
3. **Costs/value**

… requires additional considerations in terms of:

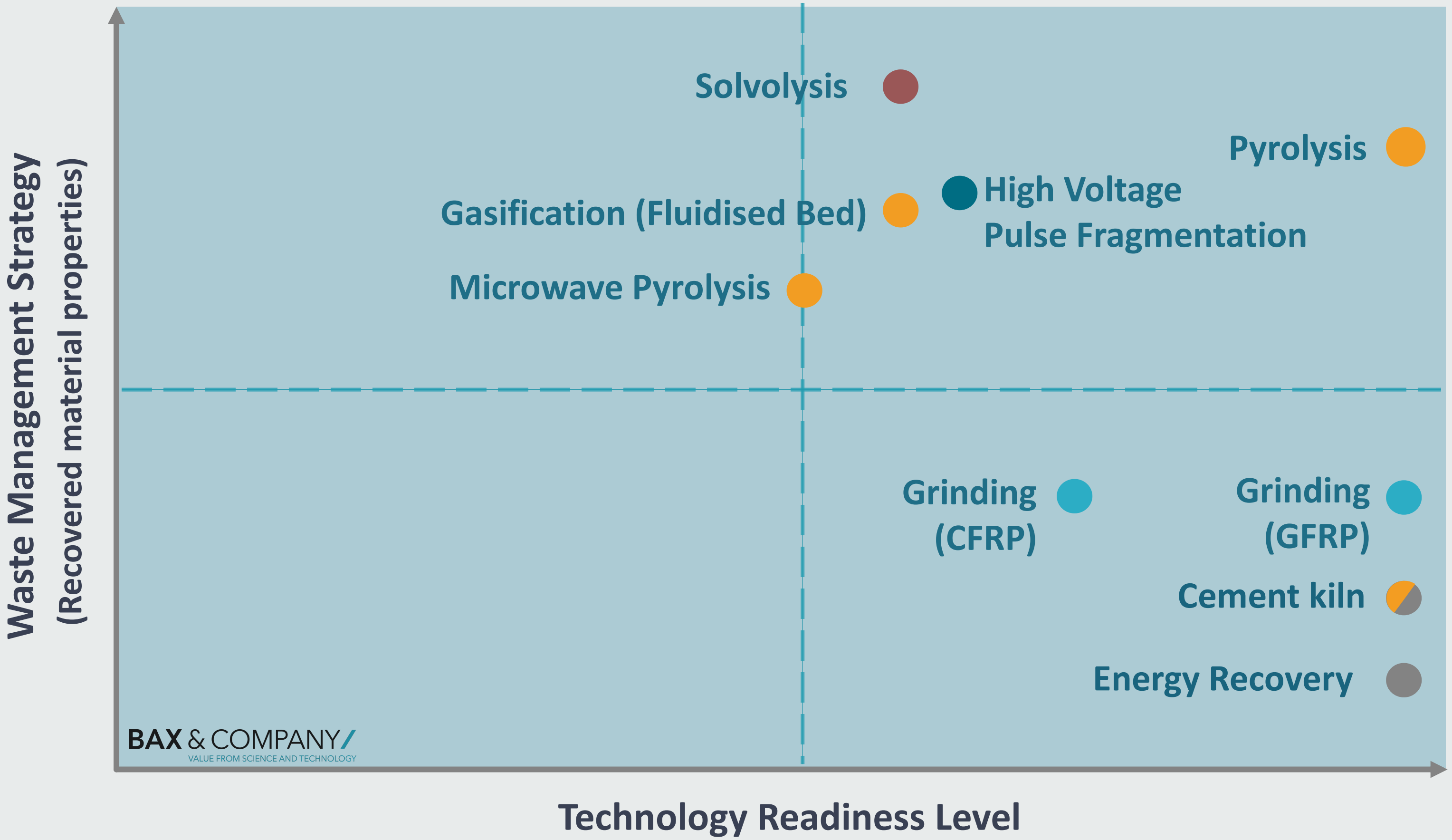
1. The **type of material** that is processed: glass and/or carbon
2. The **material form** that is recovered: fibrous powders, fibers (varying length distribution), clinker
3. How it is **further used/processed**:
   - Yarns, non-wovens, fibers, powders
   - Type of application and substitution of other processes
4. The **varying process parameters**, specifications and material qualities among recyclers
5. The **process capacity** at industrial scale



Output material quality

Comparative analysis

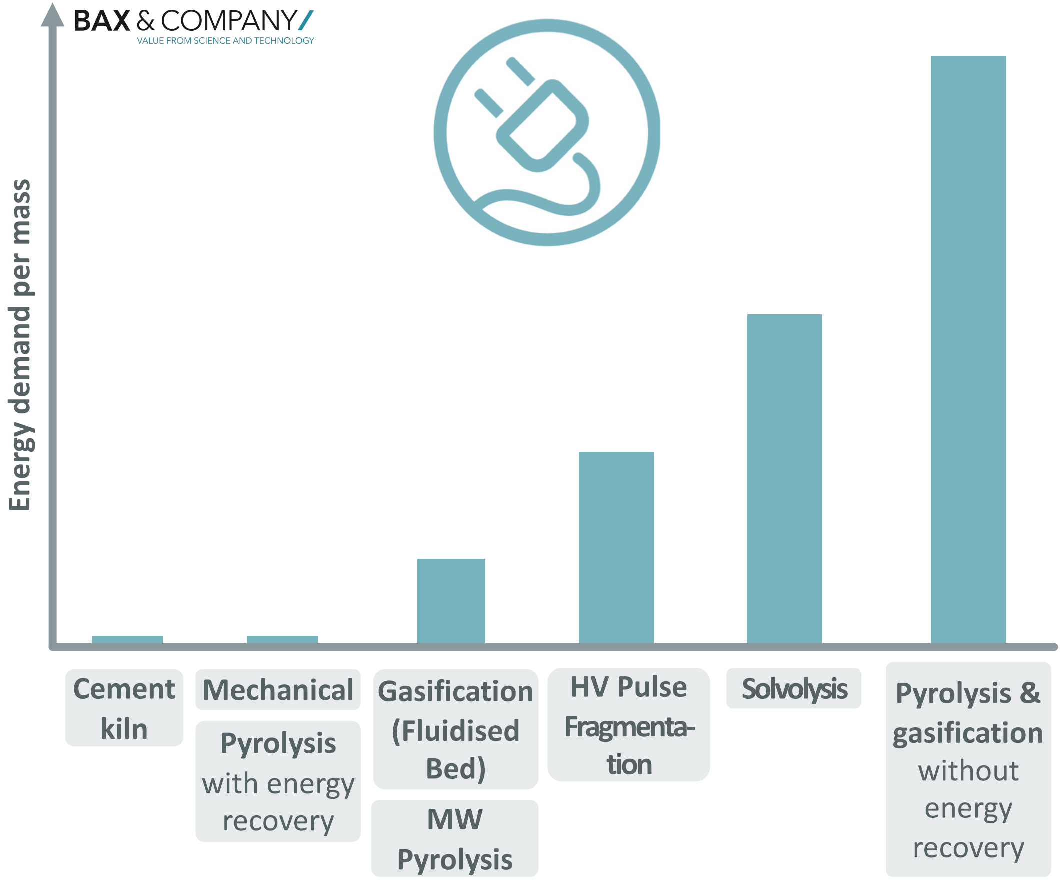
The analysis and evaluation of the recovered material properties is related to the baselines defined in the previous slide and linked to the current technology readiness level of each process.

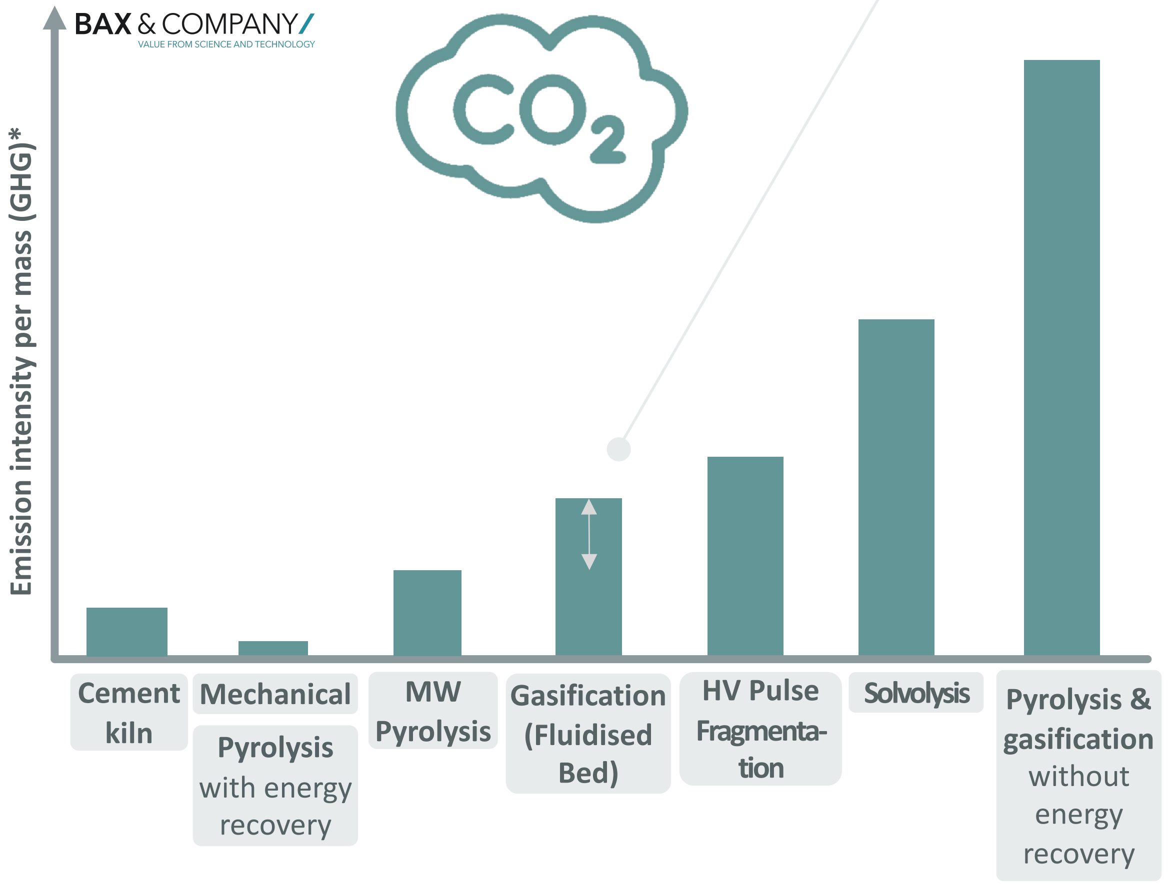


Energy demand and GHG emissions

Comparative analysis

GHGs are mainly related to the energy demand (electricity and depending on the process also gas or coal) and in some cases to by-products (e.g. gasification: CO_2 is emitted during the process).

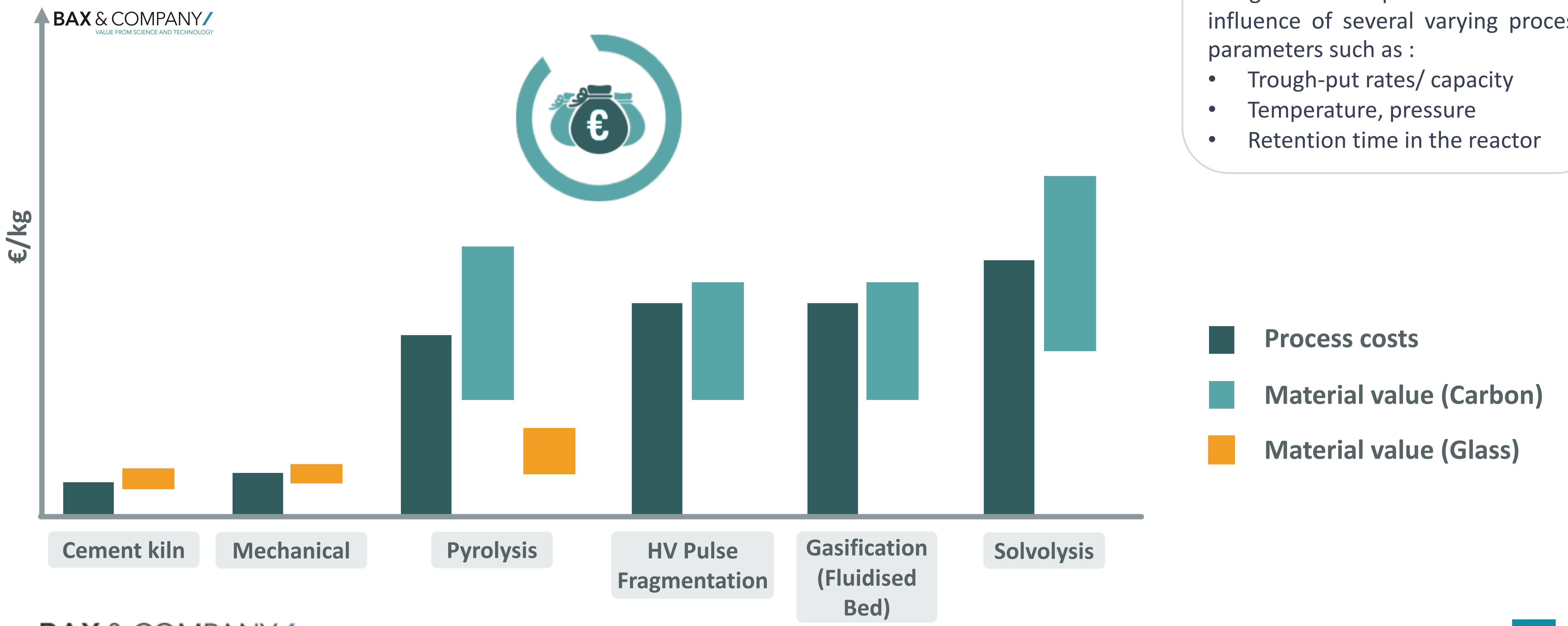




** The intensity of emissions depends on the energy source. Most processes use (at least partly) electricity, for which we consider the same mix.*

Process related costs and material value

Comparative analysis



Process costs and material value vary significantly even among EU recyclers using the same process due to the influence of several varying process parameters such as :

- Trough-put rates/ capacity
- Temperature, pressure
- Retention time in the reactor

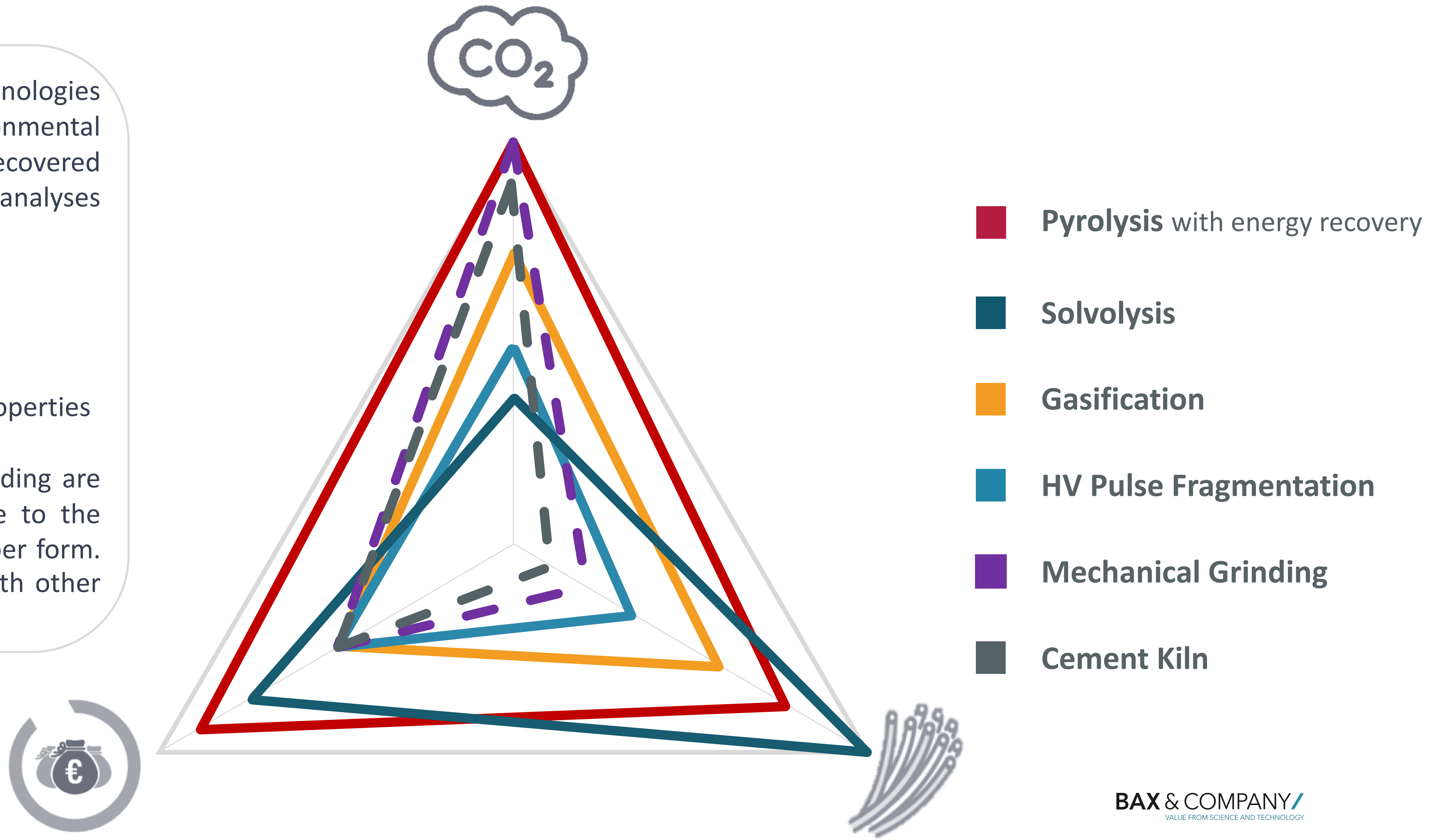
Comparative overview

The overall evaluation of the technologies in the context of their environmental impact, economic viability and recovered material quality is based on the analyses from previous slides.

High ratings relate to:

- Low environmental impacts
- High economic viability
- Low degradation of material properties

Cement kiln and mechanical grinding are highlighted in this overview due to the fact that the recylate is not in fiber form. This limits their comparability with other processes.



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** Visual represents average performance for the family of technologies. In practice, different variations of each technology can positively or negatively influence their performance*

Initiatives in the area

Past and current innovation projects and initiatives

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Past und current projects and initiatives

Focus	Project name	Duration	Programme	Lead Partner(s)	Focus/ Scope
General	FiberEUse	2017 - 2021	H2020	Politecnico de Milano	Identification of **recycling and reuse** options for wind turbine blades. **Large scale demonstration** of new circular economy value-chains based on the reuse of end-of-use fiber reinforced composites.
General	RECYCLED FIBER	2013 - 2016	Eco-innovation	Ucomposites AsP	Developing **demonstrators and business cases for new applications of secondary raw materials** stemming from composite waste streams. The project's goal was to transform successful results into a viable European business that can handle the majority of the waste.
Material design	NANOLEAP	2015 - 2018	H2020	Universidad de Castilla	Extending life time of wind turbines through **anti-weathering and anticorrosion nanocomposite** coatings
Material design	SAMBA		FP7	TU Delft	Extending life time through **self-healing coatings**
Use-Phase	HIPRWIND	2010 - 2015	FP7	Fraunhofer IWES	**Structural health monitoring** for offshore wind energy systems.

Past und current projects and initiatives

Focus	Project name	Duration	Programme	Lead Partner(s)	Focus/ Scope
Recycling	BRIO	2014 - 2017	EC LIFE+	Iberdrola, Gaiker-IK4 & Tecnalia	Development of a **mechanical recycling** process.
	R3FIBER	2018	H2020	TRC	**Thermal recycling** process: Technical and economic feasibility of R3FIBER process, obtaining high quality glass and carbon fibres in a self-sustained process.
	SELFRAG CFRP	2012 - 2014	FP7	SELFRAG AG	Development of a **high voltage pulse fragmentation** process for the recycling of thermoset composite materials.
	EURECOMP	2009 - 2012	FP7	Plastic Omnium Auto Exterieur Services	Development and demonstration of a **solvolysis**. Definition of the best process conditions to recover materials with the highest possible value.
	GenVind	2012 - 2016		Teknologisk Institut	Consideration of **several scenarios** and process steps, from dismantling to reuse of complete blades and development of technologies and future applications.
	SUSRAC	2011 - 2013	FP7	Consiglio Nazionale delle Ricerche	**Mechanical recycling** of aircraft composites using grinding and identification of novel applications.
	EXHUME	2013 - 2016	EPSRC	Universities of Exeter Cranfield, Manchester & Birmingham	Development of new and resource efficient composite **recycling and re-manufacturing processes** in collaboration with industry.

Conclusions

Findings and suggested next steps

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Objectives and strategies along the value chain

Overview

Strategies	Turbine blade value chain					
	Material design	Article design	Use/ Reuse	Waste stream preparation	Recycling	Post-Processing
Objectives: Extend lifetime	• Self-healing polymers		• On-site repair • Refurbishment • Health monitoring • Health forecasting • Component reuse			
Decrease material use		• Eco-Design/ Multi-parameter design				
Ease Dismantling	• Reversible bonding technologies	• Eco-Design/ Multi-parameter design				
Improve recyclability	• Thermoplastic matrices • Reversible thermoset resins					
Enable material recovery					• All recycling technologies	
Enable (higher) value recovery					• All recycling technologies	• Surface treatment, Sizing, • Classification, Alignment
Decrease recycling costs				• On-site fragmentation		
Decrease emissions			• On-site repair	• On-site fragmentation		

Findings

- The comparison is based on hardly comparable processes:
  - Same main input material but different output materials are compared
  - (Environmental) impact can not only be assessed through absolute values of the process itself but through comparison with the “opportunity cost”
- Currently few recycling technologies operate at commercial scale (Pyrolysis & Cement kiln)
  - More mature technologies (Pyrolysis) already up-scaled to large capacities absorb the current CFRP waste supply. As a result, new technologies that are now entering market maturity don´t have enough waste supply to upscale to market viable scales. This is considered to be a temporary saturation since the volume is expected to increase.
  - GFRP waste streams are not sufficiently tackled due to the low economic value of recyclate (e.g. mechanical grinding).
- LCAs for wind turbine that consider other waste management options than landfill and incineration are hardly available.
  - Incineration and in some member states also landfill gate fees are still too low, making it hard for recycling to make the business case

Findings

- The low price of virgin glass fibres is a significant barrier for technology commercialization as glass fibre recyclates have to compete with the low market price while showing reduced properties.
- At the moment recycling has the greatest attention (reflected in the low TRL of other technologies) even though it is not the most desirable waste management strategy
  - Direct reuse of blade parts is possible (e.g. blade FRP panels as building facades) although at the moment its more an exhibition solution. More work is needed to make this a viable solution (e.g. design considerations).
  - Definition of End-of-Use scenario(s) at the manufacturing stage of blades needs to be implemented industry-wide.
- Currently recyclate quantities and qualities are insufficient for a wider use
  - Due to the quality of waste input: contaminated waste streams or damaged blades have a high impact on the recovered output quality.
  - Due to uneven process parameters in most processes: recyclers across Europe use all their own specific processes although in principle these are based the processes explained in this study.

Findings

- Shift towards more carbon fiber use in the next generation of turbine blades to achieve higher energy yields
    - Push for already established carbon fiber recycling technologies (e.g. Pyrolysis)
    - Scale-up opportunities for lower TRL technologies (e.g. Solvolysis, Combustion)
- Shift towards more hybrid structures (glass and carbon fiber combinations) for improved performance and costs.
    - Creates new challenges due to the inherent difficulty of recycling.
    - Creates the need for robust solutions for proper separation of CF and GF based composite waste streams
- Each circularity practice might lead to other challenges that will reduce circularity in another stage to a certain extent (e.g. additives to increase lifetime)

Recommendations for next steps

1. Generate a more **in-depth analysis** and comparison between the technologies, with specific End-of-Use scenarios (including life cycle assessments to back study with real data)
2. Ensure a reliable and consistent quality of secondary raw materials by:
   - Developing **standards** for virgin and recycled FRP materials
   - Introducing **material/blade passports**
3. Set-up of **pilot lines** to assess the viability of technologies in the context of the entire value chain to create a true lifecycle solution involving stakeholders from multiple parts of the value chain, not only of the first useful life, but subsequent ones as well
4. Market barriers need to be addressed in order for recycling technologies to be commercialized:
   - **Harmonization of waste legislation** between countries
   - Creation of a "gap" between price of virgin and recycled fibers
   - Education of relevant end-users regarding the performance of recycled fibers
5. Explore the **combination of several circularity practices** to achieve better results (should be addressed in the in-depth analysis, point 1)
6. Explore options beyond the discussed strategies to reduce the overall impact and costs
   - Switch to lower GHG intensive energy sources
   - Options to reduce transport costs and impact at End-of-Use (e.g. fragmentation/ intermodal transport)

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