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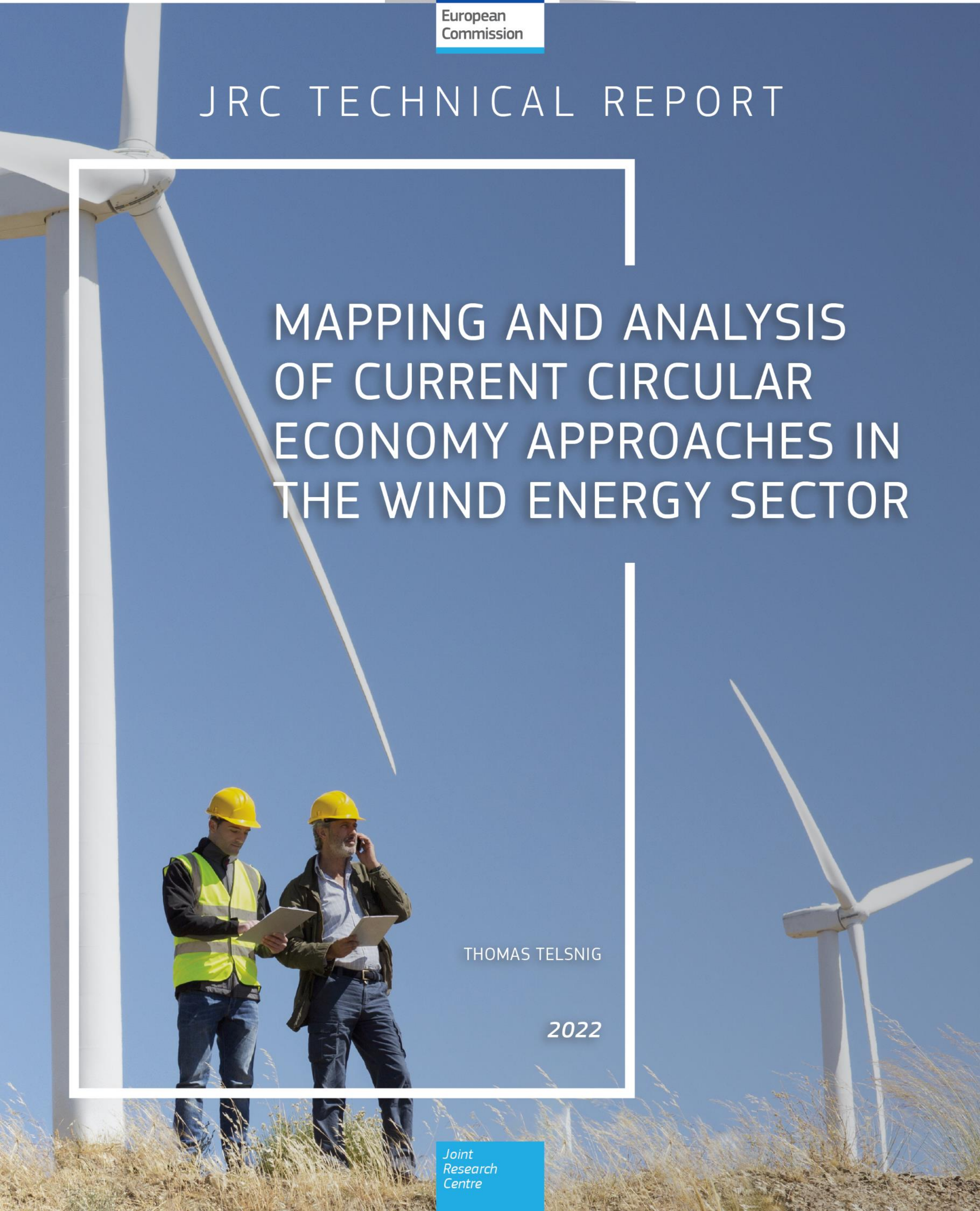

MAPPING AND ANALYSIS OF CURRENT CIRCULAR ECONOMY APPROACHES IN THE WIND ENERGY SECTOR

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Abstract

The aim of this report is to provide a review of current developments in the circularity of design in wind energy. The current state of play is described and challenges identified regarding the end-of-life treatment of wind energy components. The study maps industry initiatives, along with their respective industry players, and public research initiatives aiming for circularity in component design. A distinction is made, where possible, between EU and Rest of World (RoW) initiatives.

Although many initiatives in the wind energy sector focus on circularity approaches with respect to the blade component, we identify several innovative approaches that extend this approach to other parts of the wind energy supply chain (e.g. new tower concepts, moorings in floating offshore wind applications reducing the weight of conventional approaches, drivetrains, nacelle cover and novel grid integration methods). Yet the processes applied and technology readiness level (TRL) of these innovations vary. Based on the information provided, this report provides a first estimate of the TRL of the initiatives included (see **Table *1***).

The latest research on circular economy strategies for offshore wind stresses that current practice in the end-of-life treatment of offshore wind focuses mainly on recycling, energy recovery and landfill and less as a starting point for system regeneration. Researchers propose a 17-point framework of circular economy strategies for offshore wind which addresses the various circular economy approaches on material, product and infrastructure level. This study uses this framework/typology to categorise initiatives in the wind sector in order to identify the extent to which they follow a circularity approach.

In total the report identifies 35 initiatives with the majority (21) addressing the blade component of the wind turbine, followed by initiatives addressing the generator (5), tower, nacelle, mooring and grid integration. In addition to mapping and assessing the circular strategies used, the report identifies collaboration partners by type (industry or research) and origin, and records the funding sources accessed at national and EU level.

Table 1. Current collaborations and initiatives addressing circularity in design in the wind energy sector (see Annex 1 for full information on budget volume and R&D funding at national and EU level)

Component	Collaboration/Initiative	Type of process/innovation	Estimated TRL
Wind turbine blades	ZEBRA (Zero wastE Blade ReseArch)	New recycleable materials	n.a. (TRL 7 by 2024)
	CETEC project (Circular Economy for Thermosets Epoxy Composites)	Chemical (ChemCycling)	n.a.
	AIOLOS project (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	n.a.
	AKER – University of Strathclyde collaboration (Affordable and Innovative Manufacturing of Large Composites)	Thermal (fluidised bed)	3
	DecomBlades (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	n.a.
	SiemensGamesa RecycleBlades	Chemcial (Solvolysis)	6 to 8
	FibreEUse (Pyrolysis and Re-use)	Thermal (Pyrolysis)	8 to 9
	GE RE – Veolia (US) (Co-processing – Cement production)	Mechanical (Co-processing)	9
	GE RE – LaFargeHolcim and Neowa (EU) (Co-processing – Cement production)	Mechanical (Co-processing)	9
	BCIRCULAR (R3Fiber process)	Thermal (Pyrolysis & Gasification)	5 to 6
	HiPerDiF project (High Performance Discontinuous Fibre Composites)	Mechanical (Hydrodynamic alignment)	4 to 5
	Hohenstein Institute (Biotechnological recovery of fibers)	Biotechnological	1 to 2
	SusWIND initiative (Accelerating sustainable composite materials and technology for wind turbine blades)	Unknown	n.a.
	Colorado State University consortium (US) (Additive Manufacture of Fiber Reinforced Composites)	Additive manufacturing/ Recyclable materials	2 to 6
	GE Research – AMERICA project (US) (Additive and Modular Enabled Rotor Blades)	Additive manufacturing/ Recyclable materials	4 to 6
	NREL consortium (US)	Additive manufacturing/	4 to 6

	(Additive Manufactured Wind Blade Core Structure)	Recyclable materials	
	ORNL/UMaine/Orbital Composites (US) (On-Site, High-Throughput Additive Manufacturing)	Additive manufacturing/ Recyclable materials	2 to 6
	SANDIA consortium (US) (Additive manufacturing)	Additive manufacturing/ Recyclable materials	n.a.
	UMaine consortium – MEGAPRINT (US) (Additive Manufacturing for large modular blade moulds)	Additive manufacturing/ Recyclable materials	3 to 6
	UMichigan consortium (US) (Robot-Based Additive Manufacturing of modular moulds)	Additive manufacturing/ Recyclable materials	3 to 5
	Blade repurposing (multiple initiatives)	Reprocessing	7 to 9
Tower	GE RE – LaFargeHolcim (CH) and Cobod (DK) (3d-printing/co-processed cement)	Additive manufacturing	6
	Modvion (Modular wooden towers)	New recyclable materials	7
Mooring (Floating)	TFI (Load reducing polymer spring)	New component	5
Nacelle housing (Offshore wind turbine)	Greenboats – Sicomin (NFC offshore nacelle)	New recyclable materials	6 to 7
	GE/Fraunhofer/Voxeljet (Advance Casting Cell (ACC) 3D printer)	Additive manufacturing	4 to 6 (TRL 9 by 2025)
Drivetrain/Generator	ECOSwing (Superconducting Wind Generator)	New component	7 to 8
	GreenSpur (UK) (Rare Earth Free Permanent Magnet Generator)	New component	5
	GE (US) (High-efficiency ultra-light low temperature superconducting (LTS) generator)	New component	5
	VALOMAG (Upscale of Permanent Magnet Dismantling and Recycling)	Manufacturing (H2 Decrepitiation/HDDR or Hydrometallurgy)	2 to 4
	SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy)	Manufacturing (Sintering, HDDR, Sintering-debinding-shaping (SDS), recasting)	3 to 5
Grid integration - High voltage transmission	LIFEGRID (SF6-free High Voltage Circuit Breakers (HVCB))	New component	5
	SuperNode (MVDC transmission system based on superconducting cable technology)	New component	3
Grid integration - Hydrogen transport	SoluForce (Flexible Composite Pipes)	New component	8 to 9
Other / Collaborations addressing multiple components	MAREWIND (Material innovations for offshore wind life extension)	Multiple new components	n.a.

Source: JRC, 2021.

1 Introduction

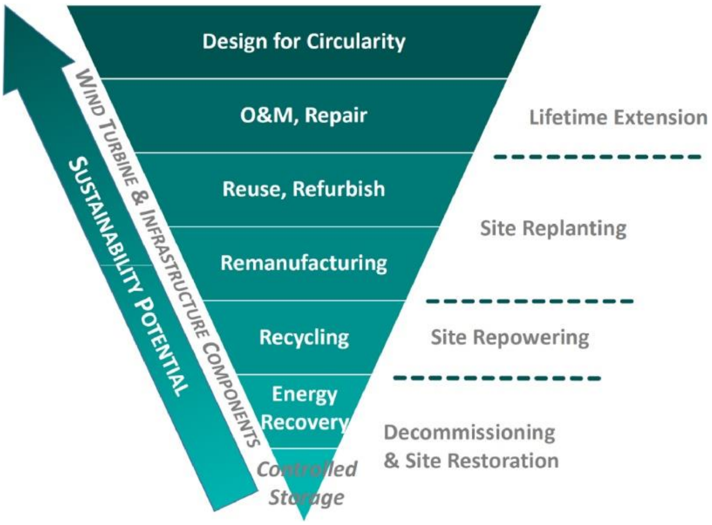
As part of the European Green Deal, the EU's Circular Economy Action Plan stresses the need to scale up the circular economy in order to achieve climate neutrality by 2050 and decouple economic growth from resource use. The plan proposes a transition towards a regenerative growth model that strives in the coming decade for a reduction in the EU's consumption footprint and a doubling of its circular material use rate[1].

Definitions of the concept of the circular economy vary in scientific literature. Kirchherr et al. (2017) analysed 114 definitions of the phrase and applied a coding framework based on 17 dimensions (involving e.g 4R framework, 9R framework, waste hierarchy, systems perspective, business models, consumers and sustainable development), finding only three studies which include all major dimensions in their definitions (see Liu et al. (2009)[2], Lieder and Rashid (2016)[3] and van Buren et al. (2016)[4]). Based on their analysis, the authors defined the circular economy as:

…an economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. *It operates at the micro level (products, companies, consumers), meso level (eco-industrial parks) and macro level (city, region, nation and beyond), with the aim to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers.*[5]

In the wind sector Jensen et al. (2020) provides a system overview of circular economy strategies for offshore wind (see **Figure 1**) stressing that current practice in offshore wind end-of-life treatment focuses mainly on the lower part of the triangle (recycle, energy recovery and landfill) and less as a starting point for system regeneration[6].

Figure 1. Whole system overview of circular economy strategies for offshore wind



Source: Jensen et al, 2020.

In accordance with this system overview an EPSRC-funded project put forward a 15-point framework of circular economy strategies for offshore wind (see **Figure 2**) which was developed into a 17-point framework after a dedicated workshop in 2021 (see **Table 2**)[7] [8].

1 COM(2020) 98 final, A new Circular Economy Action Plan - For a cleaner and more competitive Europe, https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

2 Liu, Q., et al., 2009. A survey and analysis on public awareness and performance for promoting circular economy in China: a case study from Tianjin. J. Clean. Prod. 17 (2), 265–270. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0959652608001479

3 Lieder, M., Rashid, A., 2016. Towards circular economy implementation: a comprehensive review in context of manufacturing industry. J. Clean. Prod. 115, 36–51.

4 van Buren, N., et al., 2016. Towards a circular economy: the role of dutch logistics industries and governments. Sustainability 647. Available at: http://www.mdpi.com/2071-1050/8/7/647

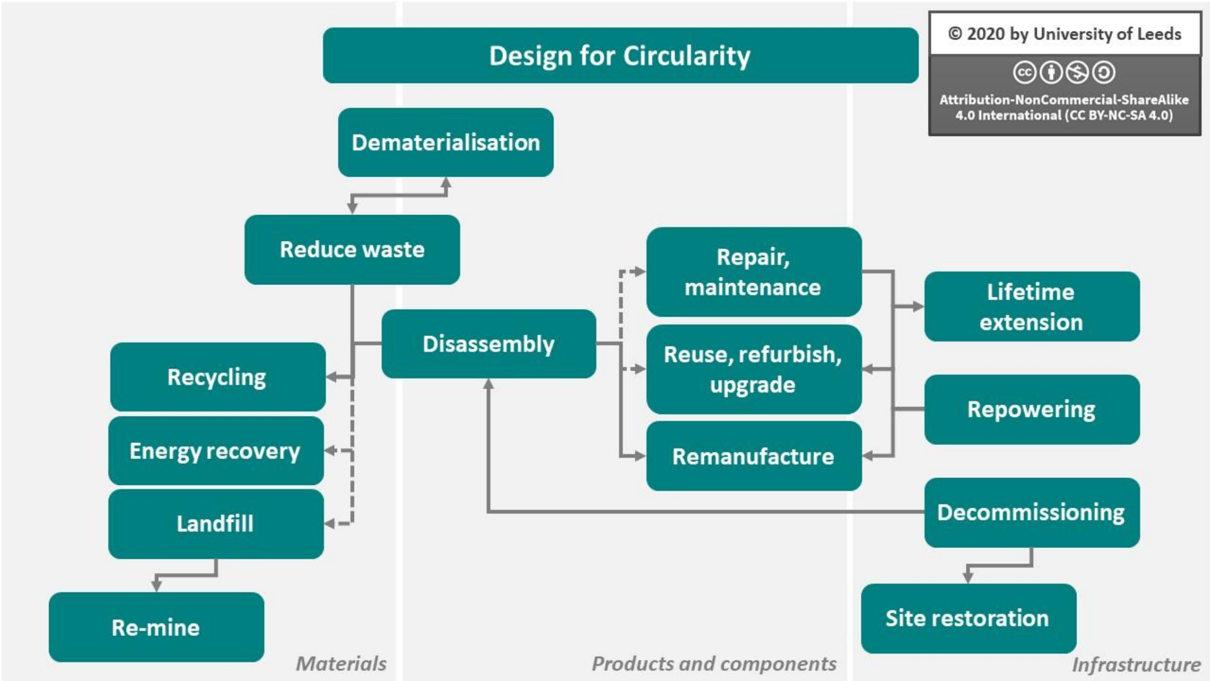
5 Julian Kirchherr, Denise Reike, Marko Hekkert, Conceptualizing the circular economy: An analysis of 114 definitions, Resources, Conservation and Recycling, Volume 127, 2017, Pages 221-232, ISSN 0921-3449, https://doi.org/10.1016/j.resconrec.2017.09.005.

6 Paul D. Jensen, Phil Purnell, Anne P.M. Velenturf, Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind, Sustainable Production and Consumption, Volume 24, 2020, Pages 266-280, ISSN 2352-5509, https://doi.org/10.1016/j.spc.2020.07.012.

7 Anne P.M. Velenturf, Towards A Circular Economy Framework for Offshore Wind, Circular Online - Chartered Institution of Wastes Management (CIWM), 27/10/2020, https://www.circularonline.co.uk/research-reports/towards-a-circular-economy-framework-for-offshore-wind/ (accessed 13/08/2021).

8 Velenturf, Anne P.M. (2021) Circular Economy Business Opportunities in Offshore Wind: Workshop proceedings. University of Leeds.

Figure 2. 15-point framework of circular economy strategies for offshore wind



Source: Velenturf, 2020.

Table 2. Description of 17-point framework of circular economy strategies for offshore wind

#	Circular economy framework strategies (in order of priority)
1	**Design for circularity:** proactive design to maximise the sustainability potential of a circular economy with a balanced mix of all the strategies listed.
2	**Dematerialisation:** reduced resource use through, for example, shape optimisation and using alternative materials.
3	**Prevent waste:** eliminating waste from production through design or by putting "wastes" and by-products to use through industrial symbiosis.
4	**Modularise:** design to avoid irreversible joints and promote using common and easily reusable/repairable modules
5	**Repair and maintain:** preventative, planned or ad hoc inspection/ servicing tasks, which may involve repairs to restore a component to a good working condition.
6	**Component reuse and repurposing:** components are used again for the same (reuse) or different (repurpose) function
7	**Refurbish and remanufacture components:** components are sorted, selected, disassembled, cleaned, inspected and repaired/replaced before being re-assembled and tested to function as good as new or better
8	**Disassemble:** a key step to take components apart to enable repair, reuse, upgrading, remanufacturing and recycling, to be considered at the design stage.
9	**Extend lifetime:** wind farms kept in use beyond the designed service life of 20-25 years
10	**Repower:** extend wind farms' service life by replacing some or all wind turbine components
11	**Recertify:** quality assurances about the processes followed and the quality of reused, repurposed, refurbished and/or remanufactured components and recovered materials.

12	**Decommission:** de-energising, dismantling and removal of some or all parts of a wind farm, followed by site restoration and monitoring
13	**Restore site:** returning a site to a similar state as before the wind farm development.
14	**Recycle materials:** the collection and preparation of wastes into materials that can re-enter production, and the reprocessing of recyclates into new components.
15	**Landfill and controlled storage:** storage and compaction of components and materials into defined cells that prevent pollutants from entering the surrounding environment, often combined with resource and energy recovery
16	**Re-mine:** recovery of materials from "Anthropogenic Ores" such as the industrial, municipal, metallurgical, and mining wastes that people have entrusted into geological storage
17	**Energy recovery:** recovery of the energetic input invested into the preparation of materials and components.

Source: Velenturf, 2021.

Building on the circular economy framework above, this report provides a review of current developments in the circularity of design in wind energy, and matches the various initiatives to the relevant framework strategies. We apply this framework to measures for circular design in both the offshore and onshore wind sectors, given the overlapping value chains of these technologies.

According to EC decarbonisation scenarios, wind energy will become a core component of the European energy sector with up to 1300 GW of wind capacity installed by 2050 (we have 178.7 GW today)[9]. Although 80-95% of the total mass of a wind turbine can be recycled some components, such as blades, pose a challenge. Given the ageing wind fleet and the substantial share of wind turbines reaching their end of life, recycling and the transition to a circular economy will become key (see **Table *3***). WindEurope (2020) estimates that by 2023 about 14 000 blades (or up to 60 000 tonnes) will be decommissioned and that composite waste from wind turbine blades will amount to about 400 000 by 2040[10]. Moreover, the wind industry called for a Europe-wide landfill ban on decommissioned wind turbine blades by 2025. Within the wind energy industry several companies and original equipment manufacturers have announced ambitious targets with respect to recycling and circularity approaches. In 2020, Vestas announced its intention to become carbon neutral by 2030 and to eliminate non-recyclable waste from the manufacturing, operation and decommissioning of its wind turbines by 2040. This was followed in October 2021 by the announcement of a roadmap that further increases the company's ambitions by adding commitments to increase material efficiency by 90%, achieve 100% rotor recyclability and reduce supply chain waste by 50%, all by 2030. Moreover, Vestas commits to the 55% utilisation of refurbished components by 2030, reaching 75% by 2040, in large part by creating new repair loops for minor components. The company's waste stream leading to landfill will be reduced to below 1%, ensuring a recycling rate of all manufacturing materials of more than 94%.[11] [12] [13].

Beyond the current approaches to keep composite waste from wind turbine blades out of landfill, this report aims to identify innovations and measures for circular design in other wind turbine components.

Table 3. Onshore wind fleet age structure and the EU

	EU	**Selected EU Member States**				
		Germany	Spain	France	Italy	Denmark
Share of cumulative capacity (%)						
older than 10 years	41%	43%	73%	22%	45%	55%
older than 15 years	18%	26%	27%	2%	9%	53%
older than 20 years	3%	4%	3%	0%	1%	23%

Source: JRC, 2020.

9 COM(2020) 562 final

10 WindEurope (2020), Accelerating Wind Turbine Blade Circularity, May 2020, Brussels.

11 WPM (2020), Vestas plans 'zero-waste turbines' by 2040, https://www.windpowermonthly.com/article/1671285/vestas-plans-zero-waste-turbines-2040, (accessed 30/09/2021)

12 WindEurope (2021), Wind industry calls for Europe-wide ban on landfilling turbine blades, https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/, (accessed 30/09/2021)

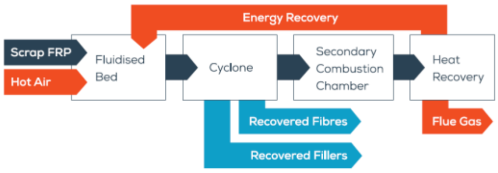
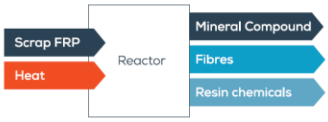
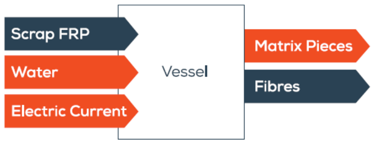
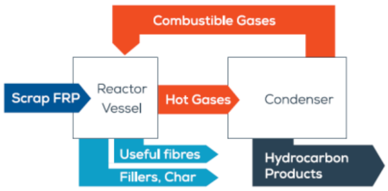
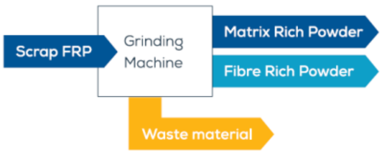
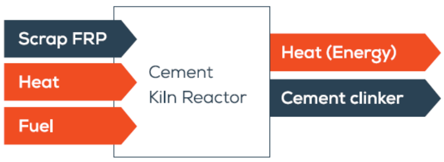
13 Vestas (2021), Vestas underlines sustainability leadership by outlining pathway to circularity, https://mb.cision.com/Public/18886/3431492/8b692e493471a985.pdf, (accessed 13/10/2021)

2 R&D&I on wind energy related circular economy strategies

2.1 Wind turbine blades

Wind turbine blades pose a challenge in terms of implementing a circular economy approach as current blades are using composite materials of fibres and resins which are hard to recycle at the end of life stage of a blade. Besides current co-processing practices (particularly for GFRP) several composite recycling technologies exist but are on different stages of development and economic viability. ETIPWind (2019) presents the main technologies and their technology readiness level (TRL) and proposes that research and innovation funding should target the a) composite recycling technologies of existing blades and b) the development of new materials for blades[14].

Figure 3. Status of the main composite recycling technologies. (Note: GFRP = glass fibre reinforced plastic, CFRP = carbon fibre reinforced plastic)

Technology	Process	TRL
Gasification (Fluidised Bed)		5/6
Solvolysis		5/6
High Voltage Pulse Fragmentation		6
Pyrolysis		9 (Microwave pyrolysis: 4/5)
Mechanical Grinding		GFRP: 9 CFRP: 6/7
Co-Processing		9

Source: ETIPWind, 2019.

[14] ETIPWind (2019), How wind is going circular – blade recycling, https://etipwind.eu/files/reports/ETIPWind-How-wind-is-going-circular-blade-recycling.pdf, (accessed 05/10/2021)

In 2021 a more refined review on the status of current composite recycling technologies is provided by ORE Catapult, differentiating between mechanical, thermal, chemical or reprocessing processes (see **Figure 4**). Moreover, a distinction is made between the technologies' suitability to process glass fibre reinforced plastic (GFRP) and carbon fibre reinforced plastic (CFRP). This becomes particularly relevant for the co-processing route which limited to GFRP as using CFRP would pose health and safety issues as consequence of unburned carbon fibres in the clinker. Pyrolysis represents the most developed recycling route for CFRP whereas other thermal and chemical process routes are at a lower TRL[15]. CFRP recycling companies can be found in Europe, Japan and the United States. Companies applying pyrolysis technology are Carbon Conversions (US), CFK Valley Stade Recycling GmbH & Co. KG (DE), ELG Carbon Fibre (UK), IACMI (US), KARBOREK RCF (Italy), SGL Automotive Carbon Fibres (DE/US), Takayasu (JP), Toray Industries (JP), BCIRCULAR S.L. (previously Thermal Recycling of Composites S.L. (TRC)) (ES) and provide processing capacities between 60 – 2000 ton/year. Fluidised bed technology is applied in a pilot plant at the University of Nottigham (UK) with an estimated capacity of 100 ton/year. The lower TRL solvolysis is followed by Hitachi Chemical (JP) and V-Carbon (US) at processing capacities of 12 ton/year and 1.7 ton/year, respectively[16].

[15] ORE Catapult (2021) SUSTAINABLE DECOMMISSIONING: WIND TURBINE BLADE RECYCLING REPORT FROM PHASE 1 OF THE ENERGY TRANSITION ALLIANCE BLADE RECYCLING PROJECT, https://ore.catapult.org.uk/wp-content/uploads/2021/03/CORE_Full_Blade_Report_web.pdf, (accessed 05/10/2021)

[16] Zhang J., Chevali V.S., Wang H., Wang C.H., Current status of carbon fibre and carbon fibre composites recycling, Composites Part B: Engineering, Volume 193, 2020, 108053, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2020.108053.

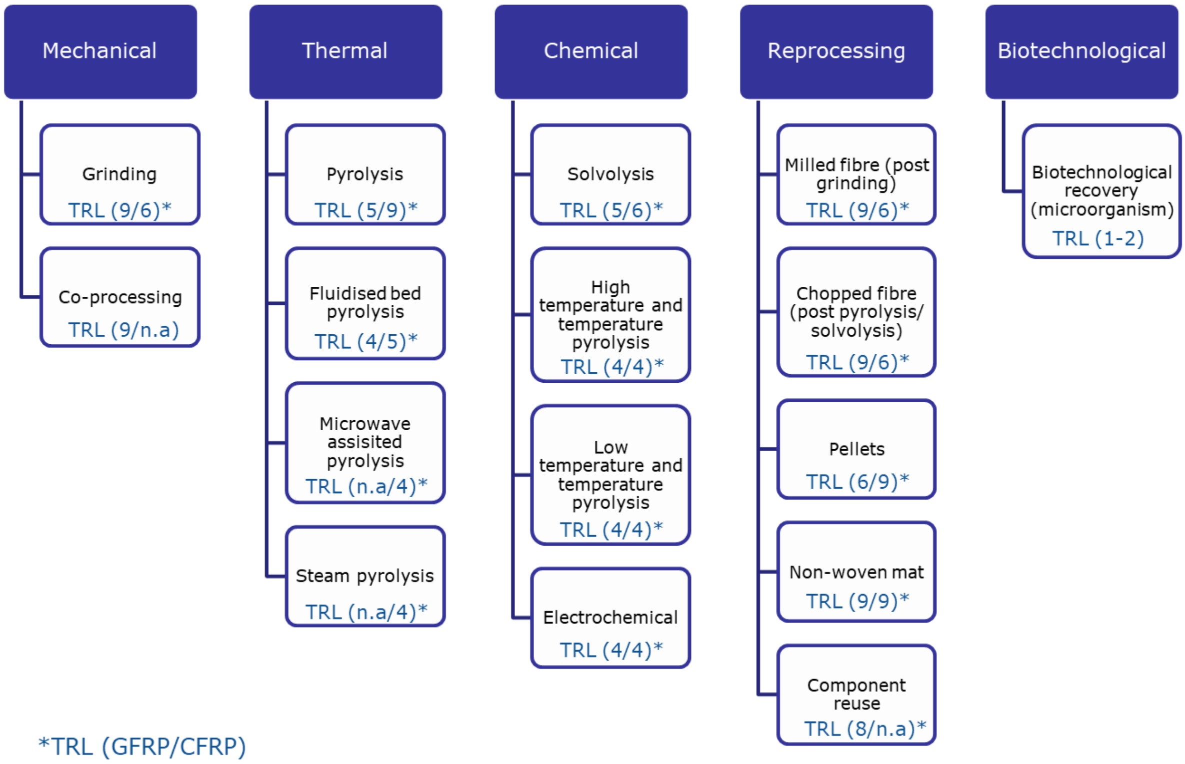
Figure 4. Categorisation of composite recycling technologies of the ORE Catapult Energy Transition Alliance technology review. (Note: GFRP = glass fibre reinforced plastic, CFRP = carbon fibre reinforced plastic, GF = glass fibre, CF = carbon fibre)

	PROCESS	TRL GFRP	TRL CFRP	COST	SCALE	END PRODUCT/ USES	INNOVATION CHALLENGES
Mechanical	Grinding	9	6	Low	Large	GFRP powder for filler or reprocessing	Microplastics and dust
	Cement kiln co-processing	9	N/A	Low	Large	Energy recovery and cement clinker	Potential pollutants and particulate matter
Thermal	Pyrolysis	5	9	High	Small	Low quality GF High quality CF (90%) Oils from resins	Energy Intensive
	Fluidised bed pyrolysis	4	5	High	Small	Good quality, clean CF (70-80%)	Energy Intensive
	Microwave assisted pyrolysis	N/A	4	High	Very Small	Good quality CF (75%)	Less energy intense
	Steam pyrolysis	N/A	4	High	Very Small	High quality CF (>90%)	Energy Intensive
Chemical	Solvolysis	5	6	High	Small	Good quality GF (70%) High quality CF (90%) Matrix material	Additional cleaning process required Energy Intensive
	High temperature and pressure solvolysis	4	4	High	Very Small	Good quality, clean CF	High energy intensive Corrosive, high pressure
	Low temperature and pressure solvolysis	4	4	High	Very Small	Good quality, clean CF Epoxy monomers	Less energy intensive Acids required that are difficult to dispose of
	Electrochemical	4	4	Very High	Very Small	Reasonable GF	High energy intensive Inefficient
Reprocessing	Milled fibre (post grinding)	9	6	Low	Large	Powder additive/filler for tailored electrical & thermal conductivity	Microplastics and dust
	Chopped fibre (post pyrolysis/ solvolysis)	9	6	Low	Medium	Thermoplastic compounding/SMC/ BMC, cement reinforcing, prepreg tape	Handling of dry fibres
	Pellets	6	9	Low	Medium	Injection moulding (thermoplastic)	Microplastics and dust
	Non-woven mat	9	9	Low	Medium	Press moulding, resin infusion, wet pressing, prepregs, semi-pregs and SMCs	Handling of dry fibres
	Component reuse	8	N/A	Medium	Very Small	Structural components: bridge support, bike shelter, roofing, etc	Low impact as no need for energy intensive methods to reclaim and process materials

Source: ORE Catapult, 2021.

The current collaborations and activities on circular economy approaches identified in this chapter are in line with both aforementioned categorisations with the exception of the biotechnological recovery of fibres (see section 2.1.11) which could be seen as an independent category. **Figure 5** summarises and amends the categorisations by .ETIPWind and ORECatapult.

Figure 5. Categorisation of composite recycling technologies and estimated TRL. (Note: GFRP = glass fibre reinforced plastic, CFRP = carbon fibre reinforced plastic)



Source: JRC adapted from ETIPWind and ORE Catapult, 2021.

2.1.1 ZEBRA (Zero wastE Blade ReseArch)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	IRT Jules Verne (FR), Arkema (FR), ENGIE (FR), LM Wind Power (US), Owens Corning (US), SUEZ (FR), CANOE (FR)	2020 - 2024	MEUR 18.5

Within the ZEBRA project LM Wind power will design and manufacture two prototype blades at its factory in Cherbourg (FR) using Arkema's Elium glass fiber reinforced resin. The aim of the project is to demonstrate a highly recyclable composite wind turbine blade based on a thermoplastic resin. A focus is set on developing and optimizing the manufacturing process, to reduce energy consumption and waste from production. Moreover, methods to recycle the materials used in the prototype blades into new products will be investigated. The project includes a life cycle analysis assessing the environmental and economic viability of the thermoplastic material in future wind turbine blades[17] [18].

[17] LM WindPower (2020), 'ZEBRA project' launched to develop first 100% recyclable wind turbine blades, September 2020, https://www.lmwindpower.com/en/stories-and-press/stories/news-from-lm-places/zebra-project-launched, (accessed 13/08/2021)

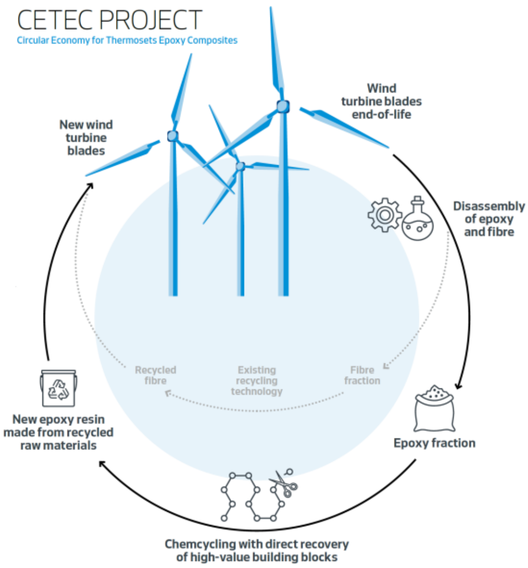
[18] CANOE (2020), RECYCLING Elium®GLASS FIBERSIN PMMA THERMOPLASTICS, http://www.plateforme-canoe.com/en/wp-content/uploads/sites/2/2020/01/News-recyclage-Elium-Fibres-verre-matrices-TP-24-01-2020-v2-ENG-REV-2.pdf, (accessed 13/08/2021).

2.1.2 CETEC project (Circular Economy for Thermosets Epoxy Composites)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	Danish Technological Institute (DK), Aarhus University (DK), Vestas Wind Systems A/S (DK), OLIN Epoxy / Blue Cube Germany Productions GmbH & Co. KG (DE)	2021 - 2024	Partly funded by Innovation Fund Denmark with: MDKK 10.5 (MEUR 1.41) Total: MDKK 15.8 (MEUR 2.12)

The CETEC project (building on the DreamWind project (2016-2020)) aims to present a solution to recycle thermoset composites in order to close the gap towards a fully recyclable wind value chain. The process encompasses a two main steps: a) the disassembly of the composites into fibre and epoxy and b) a novel chemical treatment (chemcycling) in which the epoxy fraction is further deconstructed from highly stable polymer chains into its base components (molecular building blocks), allowing the material to be re-used in the manufacturing process of blades (see **Figure 6**) [19].

Figure 6. Schematic description of the CETEC process



Source: DTI, 2021.

2.1.3 AIOLOS project (Affordable and Innovative Manufacturing of Large Composites)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste)	Siemens Gamesa Renewable Energy A/S (DE/ES), FORCE Technology (DK), Aalborg University (DK), Technical University of Denmark (DK), Pontis Engineering B.V. (NL), Finetune ApS (DK)	2021 - 2024	Partly funded by Innovation Fund Denmark with: MDKK 38.38 (MEUR 5.15) Total: MEUR 10.42

[19] DTI (2021) https://www.dti.dk/specialists/new-coalition-of-industry-and-academia-to-commercialise-solution-for-full-recyclability-of-wind-turbine-blades/43144 (accessed 13/08/2021)

The AIOLOS project aims to optimize blade factory output at low cost and prevent the need to construct new production facilities. Building on automatisation and digitalisation techniques the project will implement its innovations in the existing production facilities at Aalborg of SiemensGamesa. Besides the cost related improvement claimed, the project consortium aims for a reduction of production waste and a reduction of deviations within production of large composite structures[20].

2.1.4 AKER – University of Strathclyde collaboration (Affordable and Innovative Manufacturing of Large Composites)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	Aker Offshore Wind (NO), Aker Horizons (NO), University of Strathclyde (UK)	unknown	n.a.

In 2021, Aker Offshore Wind and Aker Horizons and the Advanced Composites Group (ACP) of University of Strathclyde agreed to develop and scale up a process for thermal recovery and post-treatment of glass fibres from Glass-reinforced polymer composites (GRP) scrap. The technology builds on ACP's ReCoVeR project which is focussed on enabling cost-effective regeneration of the performance and value of glass fibres obtained from thermal recycling of end-of-life GRP and GRP manufacturing waste. Within the ReCoVeR project ACP focuses on property changes of recycled glass fibres (RGF), cost effective treatments to regenerate RGF performance, the development of an in-house fluidised bed recycling technology and the production of products using RGF[21] [22].

2.1.5 DecomBlades (Affordable and Innovative Manufacturing of Large Composites)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	Ørsted (DK), LM Wind Power (US), Vestas Wind Systems A/S (DK, Siemens Gamesa Renewable Energy (DE/ES), FLSmidth (DK), MAKEEN Power (DK), HJHansen Recycling (DK), Energy Cluster Denmark (ECD) (DK), University of Southern Denmark (SDU) (DK) and Technical University of Denmark (DTU) (DK).	2021 - 2024	Partly funded by Innovation Fund Denmark with: MDKK 22 (MEUR 2.96) Total: MEUR 5.4

The DecomBlades project involves ten partners investigating and developing solutions to recycle the composite material in wind turbine blades. The project focuses on three processes: shredding of blades to allow the material to be used in different products and processes; use of shredded blade material in cement production; and pyrolysis, a method to separate the material under high temperatures. A pyrolysis plant will be developed by MAKEEN Power (DK) attempting to commercialise this technology for CRP recycling [23] [24].

[20] IFD (2021) https://innovationsfonden.dk/da/investeringer/investeringshistorier/konsortium-i-danmark-starter-forskningsprojekt-indenfor (accessed 16/09/2021)

[21] WPM (2021), Aker supports wind blade recycling development, https://www.windpowermonthly.com/article/1713822/aker-supports-wind-blade-recycling-development (accessed 16/09/2021)

[22] Thomason J.L., Yang L. (2021), Towards a new generation of glass fibre products based on regenerated fibres recycled from end-of-life grp and grp manufacturing waste, ETIPWind 2021, (accessed 16/09/2021)

[23] IFD (2021), DecomBlades consortium awarded funding for a large, cross-sector wind turbine blade recycling project, https://innovationsfonden.dk/da/nyheder-presse-og-job/decomblades-consortium-awarded-funding-large-cross-sector-wind-turbine-blade (accessed 16/09/2021)

[24] WPM (2021), Ørsted-led consortium researching blade decommissioning, https://www.windpowermonthly.com/article/1705573/orsted-led-consortium-researching-blade-decommissioning (accessed 16/09/2021)

2.1.6 SiemensGamesa RecycleBlades

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	Siemens Gamesa Renewable Energy (DE/ES)	2021 (launch)	n.a.

In September 2021, SiemensGamesa introduced a full recycleable wind turbine blade. Six 81 meter RecycleBlades were produced at its facility in Aalborg (DK) and first agreements are met with RWE, EDF Renewables and wpd to install the technology at upcoming offshore wind projects (e.g. Kaskasi wind farm in Germany). SiemensGamesa claims that existing manufacturing process can be used, the main innovation is the resin in use allowing to recover blade materials through a solvolysis process. The blade is immersed into a heated mild acidic solution, which separates the resin from fiber glass, plastic, wood and metals. After reclaiming the separated components SiemensGamesa claims that materials can be reused in new products matching the technical properties of the materials (e.g. consumer goods)[25] [26].

2.1.7 FibreEUse – Pyrolysis and Re-use

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	Politecnico di Milano (IT); Siemens Gamesa Renewable Energy (DE/ES); Tecnalia (ES); another 18 partners both research and industry from IT, FR, ES, FI, UK, DE, AT, BE	2017 - 2021	2017: H2020 funding MEUR 9.8 Total: MEUR 11.9

The FiberEUse project (Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites) aims at integrating in a holistic approach different innovation actions aimed at enhancing the profitability of composite recycling and reuse in value-added products. One of the three use cases of the project is the thermal recycling of long fibers (glass and carbon) and re-use in high-tech, high-resistance applications. The input product will be EoL wind turbine and aerospace components. The re-use of composites in automotive (aesthetical and structural components) and building will be demonstrated by applying controlled pyrolysis and custom remanufacturing.

The recovery of glass fibres and carbon fibres from End-of-Life (EoL) parts originating from the wind energy and aerospace sectors is performed by a low temperature oxygen-free pyrolysis process (<400 ºC, developed by partner Tecnalia (ES)) which is able to partially retain the strength and flexibility of the glass and carbon fibers. This allows to reuse the material in rGFRP (recycled Glass Fiber Reinforced Plastics) and rCFRP (recycled Carbon Fiber Reinforced Plastics) applications. A replacement of at least 20% of the virgin glass fibre or carbon fibre is applied to different demonstration products for the automotive sector (e.g. Clutch Pedal, Front End Carrier and Cowl Top Support) or the products for the building sector (rGFRP for building components like rooflight panels and valley gutters for tiled and flat roofs) [27] [28] [29].

[25] SiemensGamesa (2021), Siemens Gamesa pioneers wind circularity: launch of world's first recyclable wind turbine blade for commercial use offshore, https://www.siemensgamesa.com/newsroom/2021/09/launch-world-first-recyclable-wind-turbine-blade (accessed 17/09/2021)

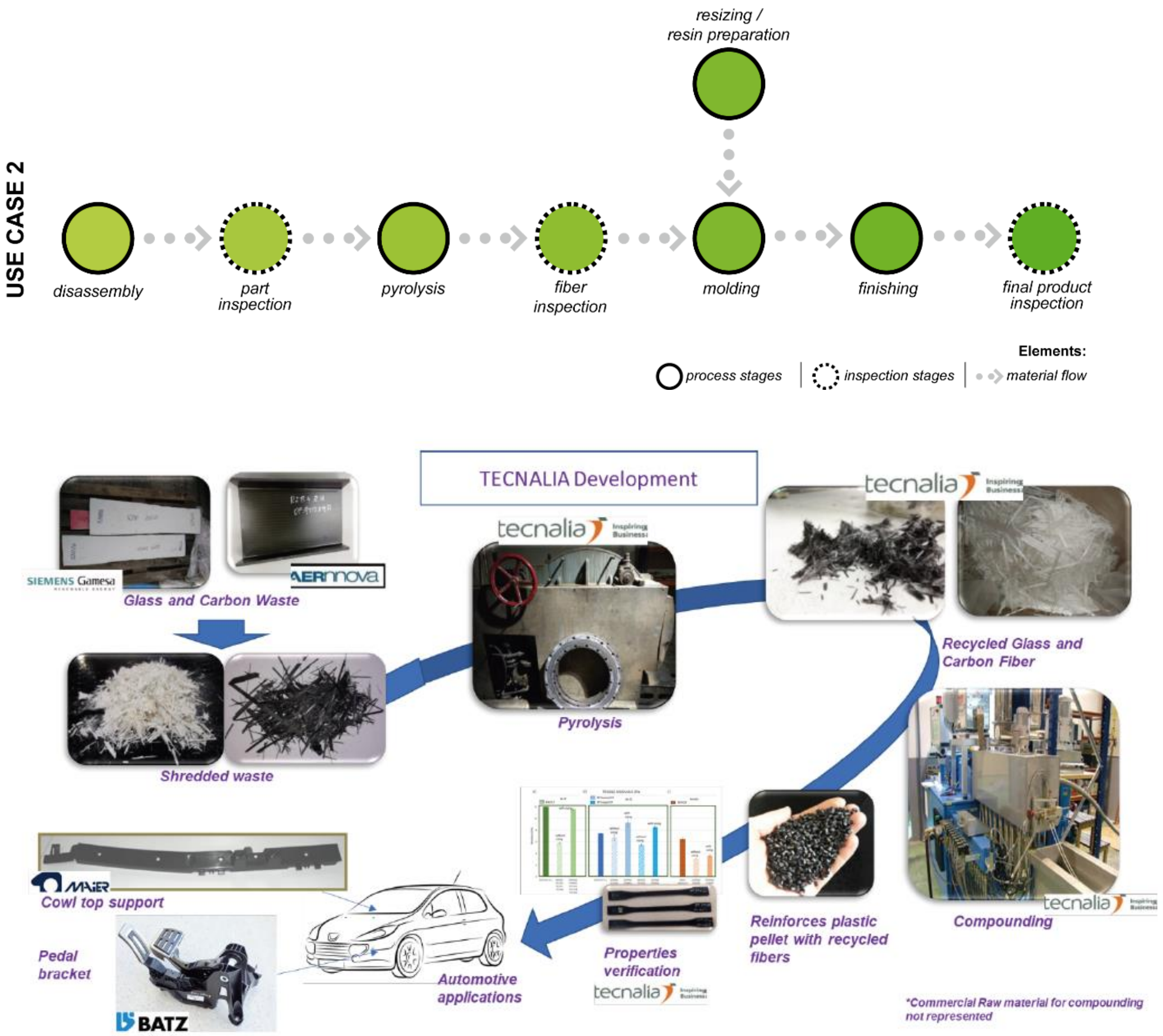
[26] CompositesWorld (2021), Siemens Gamesa launches recyclable wind turbine blade, https://www.compositesworld.com/news/siemens-gamesa-launches-recyclable-wind-turbine-blade, (accessed 17/09/2021)

[27] EC 2021, CORDIS Large scale demonstration of new circular economy value-chains based on the reuse of end-of-life fiber reinforced composites, https://cordis.europa.eu/project/id/730323, (accessed 01/10/2021)

[28] FiberEUse (2021), Thermal recycling (Use-case 2) of long fibers (glass and carbon) and re-use in high-tech, high-resistance applicationshttp://fibereuse.eu/index.php/detail/for-thermal-recycling, (accessed 01/10/2021)

[29] FiberEUselibrary (2021), https://fibereuselibrary.com/2021/07/09/fibra-vetro-3-tecnalia/, (accessed 01/10/2021)

Figure 7. Thermal recycling (Use-case 2) of long fibers (glass and carbon) and re-use in high-tech, high-resistance applications



Source: FiberEUse.eu, 2021; FiberEUselibrary.com, 2021.

2.1.8 GE RE – Veolia (US)/ LaFargeHolcim and Neowa (EU) (Co-processing – Cement production)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle) 17 (Energy recovery)	a) General Electric RE (US), Veolia North America (US) b) General Electric RE (US), LaFargeHolcim (Geocycle) (CH) c) General Electric RE (US), Neowa (DE)	2020 - ?	n.a.

General Electric RE announced three agreements with partners in order to develop a more circular approach at the end of life of their wind turbine blades. In the US a cooperation with waste treatment company Veolia North America will first shred the blade material before utilising it as an input material in cement production. It is expected that this process reduces CO2 emissions in the cement production by about 27% as compared to the conventional cement production route[30].

30 WPM (2021), GE signs deal to use old turbine blades in cement production, https://www.windpowermonthly.com/article/1702248/ge-signs-deal-use-old-turbine-blades-cement-production, (accessed 17/09/2021)

A similar agreement was met between General Electric RE (US) and LaFargeHolcim's (CH) Geocycle branch which also focuses on co-processing of the wind turbine blades. Currently Geocycle is co-processing blades only in Germany but evaluates the possibilities for this solution in other parts of Europe[31].

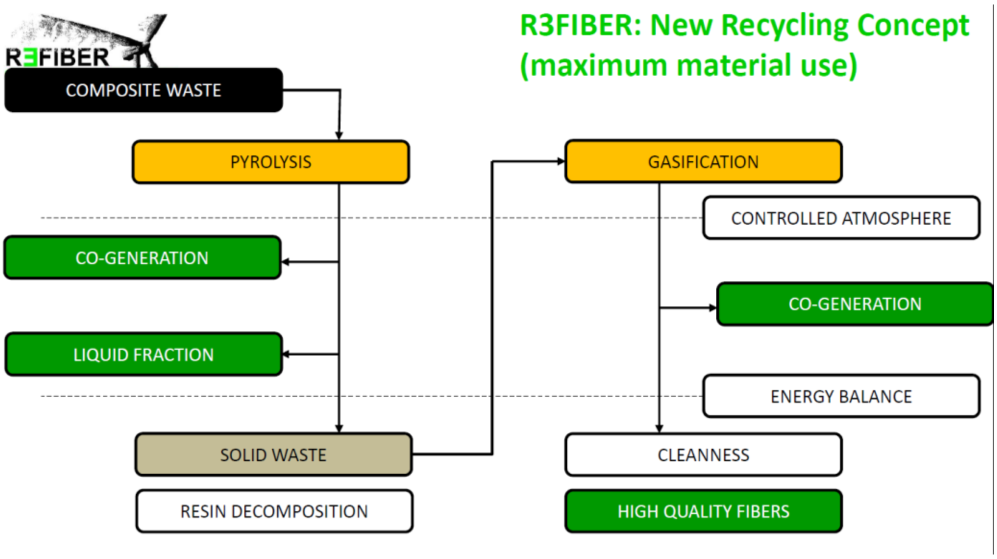
A separate collaboration was announced between General Electric RE (US) and Neowa (DE). Neowa will provide deinstallation services and recycle up to 90% of the wind turbine. With respect to the wind turbine blades Neowa will use a shredding process to produce pellets that can be further used in the cement production. GE claims that this cement can be used to build foundations and towers of new wind turbines, offering a CO2 reduction of about 20% as compared to conventional processes[32].

2.1.9 BCIRCULAR – R3Fiber process

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing) 14 (Recycle) 17 (Energy recovery)	BCIRCULAR S.L. (ES)	2016 -	2018: H2020 funding kEUR 50

A spin-off of the Spanish Higher Council for Scientific Research (CSIC), BCIRCULAR S.L. (previously Thermal Recycling of Composites S.L. (TRC)) aims to industrially develop, exploit and commercialise a technology for the recycling of composite materials, allowing for complete valorisation of mass, energy and materials in a zero-residue process. The R3FIBER process, validated at pilot plant scale, recycles wind turbine blades and other composites into reusable glass and carbon fibres, heat and energy. BCIRCULAR reports that the concept uses a combined pyrolysis and gasification step which leads to comparable values as for original fibres in terms of material properties (same nominal diameter of fibres, 88-93% of original tensile strength, young modulus at 85%). Moreover, the company reports a substantial decrease in CO2 footprint when using the process to build new wind blades [33] [34].

Figure 8. R3Fiber composite recycling concept



Source: TRC/BCIRCULAR, 2019.

[31] Geocycle (2021), Partnering towards a circular wind energy industry, https://www.geocycle.com/partnering-towards-a-circular-wind-energy-industry, (accessed 20/09/2021)

[32] GE (2021), GE Renewable Energy announces onshore wind turbine decommissioning and recycling agreement with neowa, https://www.ge.com/news/press-releases/ge-renewable-energy-announces-onshore-wind-turbine-decommissioning-and-recycling-agreement-with-neowa, (accessed 20/09/2021)

[33] TRC/BCIRCULAR (2019), Presentation R3Fiber, http://www.suschem-es.org/docum/pb/Jornadas/innovaplasticos_240919/8_TRC_OLGA_RODRIGUEZ.pdf, (accessed 01/10/2021)

[34] EC (2021), CORDIS - Eco-innovation in Composites Recycling for a Resource-Efficient Circular Economy, https://cordis.europa.eu/project/id/809308, (accessed 01/10/2021)

2.1.10 HiPerDiF project – High Performance Discontinuous Fibre Composites

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 6 (Component reuse and repurposing) 8 (Disassemble) 14 (Recycle)	University of Bristol (UK), Airbus Group (FR), BAE Systems (UK), Coriolis Composites (UK), ELG Carbon Fibre (UK), Hexcel Composites (US), Hitachi (JP), National Composites Centre (UK), Oxford Advanced Surfaces (UK), Solvay Group (BE), Toyota (JP)	2017 - 2021	EPSRC funding: 1.22 MEUR (1.04 MGBP)

The HiPerDiF (High Performance Discontinuous Fibre) project proposes an alternative way to produce carbon fibres moving form currently used continuous fibres to a manufacturing process of highly Aligned Discontinuous Fibre Reinforced Composites (ADFRCs). The concept proposes that if discontinuous fibres are accurately aligned and their length is significantly longer than the critical fibre length, the tensile modulus, strength and failure strain of the obtained composites are comparable to those of continuous fibre composites. The HiPerDiF method was developed at the University of Bristol. It is a continuous hydrodynamic alignment process. It uses the sudden momentum change of a fibrewater suspension directed, through a nozzle, into a narrow gap between two parallel plates to mechanically align discontinuous fibres into highly aligned dry preforms. The HiPerDiF concept allows to remanufacture reclaimed fibers into an economically valuable high-performance composite with high mechanical properties[35] [36] [37]. In 2020 the project consortium reported that the construction of the third generation of the HiPerDiF machine, capable of high throughput (kg/hour quantities of prepreg) with full instrumentation, is close to completion in the National Composites Centre (NCC) in Bristol [38].

2.1.11 Hohenstein Institute – Biotechnological recovery of fibers

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 14 (Recycle)	Hohenstein Institut fuer Textilinnovation gGmbH (DE)	2018 - 2020	BMWi funding: 247 kEUR

Biotechnological recovery of fibres from carbon fibre composite materials are still at the lower TRL scale (TRL1-3). A first experiment uses the metabolic performance of certain microorganisms (the fungus aspergillus niger) given their ability to break down plastics such as epoxy resins. A project funded by the German BMWi (Federal Ministry for Economic Affairs and Energy) was performed by the Hohenstein Institut fuer Textilinnovation gGmbH. First laboratory scale experiments showed that the cultivation of the fungus in a 1-liter bioreactor capable to degradate the CFRP's epoxy matrix is possible. However, there is a need for further research to optimize processes and implement them on an industrial scale. At this stage especially the very slow speed of the degradation process represents a major challenge for the development of industrial applications. Based on this, the project consortium suggests that further research in this area might benefit from combining an upstream pyrolysis process with the biotechnical recovery process. This would allow microorganisms an easier access into the carbon fibre matrix thus speeding up the degradation process [39] [40] [41].

[35] CW (2019), Going discontinuous, for continuous improvement, https://www.compositesworld.com/articles/going-discontinuous-for-continuous-improvement

[36] EPSRC (2021), Details of Grant - EP/P027393/1, https://gow.epsrc.ukri.org/NGBOViewGrant.aspx?GrantRef=EP/P027393/1, (accessed 05/10/2021)

[37] Tapper R.J., Longana M.L., Yu H., Hamerton I., Potter K.D., Development of a closed-loop recycling process for discontinuous carbon fibre polypropylene composites, Composites Part B: Engineering, Volume 146, 2018, Pages 222-231, ISSN 1359-8368, https://doi.org/10.1016/j.compositesb.2018.03.048.

[38] Aravindan P. et al 2020, Remanufacturing of Woven Carbon Fibre Fabric Production Waste into High Performance Aligned Discontinuous Fibre Composites, J. Compos. Sci. 2020, 4, 68; doi:10.3390/jcs4020068

[39] IGF (2021), Biotechnische Rückgewinnung von Carbonfasern aus schwer recyclebaren Faserverbundwerkstoffen, https://igf.aif.de/innovationsfoerderung/industrielle-gemeinschaftsforschung/igf-steckbrief.php?id=20937&suchtext=19586, (accessed 05/10/2021)

[40] Hohenstein (2020), Biotechnologische Rückgewinnung von Carbonfasern aus schwer recyclebaren Faserverbundwerkstoffen, https://www.hohenstein.de/de/wissen/forschung/forschungsprojekte/detail/cfk-recycling, (accessed 05/10/2021)

[41] Hohenstein (2020), Schlussbericht zum IGF-Vorhaben – Arbeitsgemeinschaft industrieller Forschungsvereinigungen - Biotechnologische Rückgewinnung von Carbonfasern aus schwer recyclebaren Faserverbundwerkstoffen, IGF-Vorhaben Nr. 19586 N, September 2020

2.1.12 SusWIND initiative – Accelerating sustainable composite materials and technology for wind turbine blades

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
No information on CE approach	National Composites Centre (UK), Offshore Renewable Energy (ORE) Catapult (UK), The Crown Estate (UK), Vestas (DK), SSE Renewables (UK), Renewable UK (UK), Shell (NL), BVG Associates (UK), EDF Renewables (FR), Net Zero Technology Centre (UK)	2021 - ongoing	n.a.

The SusWIND initiative aims to develop technologies, processes and materials that address the recyclability and future development of composite wind turbine blades. The consortium claims to demonstrate viable technologies for recycling of existing wind turbine blades in secondary applications (re-use) such as composite parts in bridges, electric vehicles or thermal insulation. Moreover, the use of more sustainable materials in blade design is envisaged such as bio-derived feedstock or thermoplastics. Another aspect of the initiative concerns the development of innovative design approaches having in mind the disassembly and end of life[42].

2.1.13 Colorado State University – Additive Manufacture of Fiber Reinforced Composites for Novel Internal Wind Blade Structure with Radically Reduced Tooling Requirements

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 14 (Recycle)	Colorado State University (US) Owens Corning (US), National Renewable Energy Laboratory (US), Arkema Inc. (US), Vestas Blades America (DK)	2021 - 2022	DOE funding: MUSD 2.0 (MEUR 1.7) TOTAL: MUSD 2.5 (MEUR 2.2)

Colorado State University (CSU) aims to develop a novel additive manufacturing process focussing on fabrication processes for the internal blade structure based on polymer materials. Material samples and sub-scale representative blade components will be fabricated and tested. The project foresees a production of components at laboratory scale (several cm scale) using commercially available polymers as well as at pilot scale (blade component length of up to 20m) incorporating all internal structures of a wind blade. Moreover the integration of the internals into a blade section should demonstrate compatibility of the technology. Within the project consortium Vestas will perform pilot-scale fabrication of representative components while Arkema will perform material characterization [43] [44] [45].

2.1.14 GE Research (US) – Additive and Modular Enabled Rotor Blades and Integrated Composites Assembly (AMERICA)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise) 14 (Recycle)	GE Research (US), Oak Ridge National Laboratory (US), National Renewable Energy Laboratory (US), LM Wind Power (US), GE Renewable Energy (US)	2021 - 2023	DOE funding: MUSD 4.0 (MEUR 3.4) TOTAL: MUSD 6.7 (MEUR 5.8)

42 NCC (2021), SusWIND - Accelerating sustainable composite materials and technology for wind turbine blades, https://www.nccuk.com/sustainable-composites/activities/suswind/, (accessed 05/10/2021)

43 USASpending.gov (2021), https://www.usaspending.gov/award/ASST_NON_DEEE0009404_8900 (accessed 14/10/2021)

44 EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

45 DOE (2021), Application Additive Manufacture of Fiber Reinforced Composites for Novel Internal Wind Blade Structure with Radically Reduced Tooling Requirements, https://www.energy.gov/sites/default/files/2021-08/CX-024183.pdf, (accessed 14/10/2021)

A GE Research led consortium aims to develop and demonstrate an integrated additive manufacturing process for novel high- performance blade designs for the future of large rotors. More specifically the consortium claims to develop a full-size blade tip ready to be structurally tested, as well as three blade tips that will be installed on a wind turbine. A key innovation involves the use of advanced thermoplastic resins allowing better recycling than their thermoset counterparts. Moreover the structural cores of a 13m demonstrator will be 3D printed at ORNL. The innovation should enable to produce lighter blades using a low cost, recyclable thermoplastic skin coupled with printed reinforcement[46],[47] [48].

2.1.15 NREL (US) – Additive Manufactured Wind Blade Core Structure Enabling Thermal Welding of Advanced Large Blades

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise) 6 (Component reuse and repurposing) 14 (Recycle)	National Renewable Energy Laboratory (US), Vanderbilt University (US), The Institute for Advanced Composites Manufacturing Innovation (US), Ingersoll Machine Tools (US), Additive Engineering (US), TPI Composites (US)	2021 - ?	DOE funding: MUSD 2.0 (MEUR 1.7) TOTAL: MUSD 2.5 (MEUR 2.2)

In the last years NREL developed substantial experience in the development and deployment of innovative materials in blade design and its capabilities in advanced manufacturing of composite materials. In a next step a NREL led consortium aims to develop, demonstrate, and provide a path to commercialization for an novel design and manufacturing approach to produce next-gen wind turbine blades. The project will deliver a core structure of a blade using 3D printed thermoplastic material that allows to apply thermal welding techniques. NREL claims that thermal welding holds the potential to eliminate bonding adhesives which would allow to reduce costs and weight of the blade. Moreover, the project aims to investigate the use of recycled composite material to manufacture new composite wind blade structures[49] [50].

2.1.16 ORNL/Orbital Composites (US) – On-Site, High-Throughput Manufacturing of Wind Blade Tips with Large Scale Continuous Fiber Additive Manufacturing

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise) 5 (Repair and maintain) 6 (Component reuse and repurposing) 14 (Recycle)	Oak Ridge National Laboratory (US), University of Maine (US), Orbital Composites Inc. (US)	2021 - ?	DOE funding: MUSD 4.0 (MEUR 3.4) TOTAL: MUSD 5.0 (MEUR 4.3)

ORNL, UMaine and Orbital Composites aims for developing containerized 3D printing robots that can be used to manufacture wind turbine blades at the wind farm site, thus reducing costs and transportation needs. Moreover, the project builds on the partners' knowledge in additive manufacturing such as ORNL's experience in 3D printing of blade moulds or UMaine's 120 ft long 3D printer. This is complemented by Orbital Composites work on a modular platform which uses a twelve-axis robot arm to enable additive manufacturing of non-planar surfaces and a software that allows multi-robot collaboration. The company already demonstrated thermoplastic and thermoset additive manufacturing reinforced with continuous carbon and glass fibres. The DOE-funded project proposes to demonstrate the use of additive manufacturing for cost-effective scaling of large blade sizes (greater than 100-meter-length), novel additive

[46] GE (2021), GE Awarded DOE Grant to Research 3-D Printing of Wind Turbine Blades https://www.ge.com/news/press-releases/ge-awarded-doe-grant-to-research-3-d-printing-of-wind-turbine-blades, (accessed 14/10/2021)

[47] EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

[48] DOE (2021), Additive and Modular Enabled Rotor blades and Integrated Composites Assembly, https://www.energy.gov/sites/default/files/2021-07/CX-023970.pdf, (accessed 14/10/2021)

[49] NREL (2021), DOE Advanced Manufacturing Office Funds Next-Gen Turbine Blades and Morehttps://www.nrel.gov/news/program/2021/doe-advanced-manufacturing-office-funds-next-gen-turbine-blades-and-more.html, (accessed 14/10/2021)

[50] EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

manufacturing-enabled blade designs and lower tooling costs. Moreover Orbital Composites claims to create a new, repairable wind turbine blade[51] [52].

2.1.17 SANDIA (US) – Additive Manufactured, System Integrated Tip for Wind Turbine Blades

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
No information on CE approach	Sandia National Laboratories (US), Stratasys Direct Manufacturing (US), Wetzel Wind Energy Services (US)	?	DOE funding: MUSD 2.0 (MEUR 1.7) TOTAL: MUSD 2.5 (MEUR 2.2)

No detailed information available aside title, project partners and funding[53].

2.1.18 UMaine (US) – MEGAPRINT – Using the World's Largest 3D Printer for Precision Manufacturing of Large Modular Wind Blade Tooling

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise) 14 (Recycle)	University of Maine (US), TPI Composites (US), Siemens Gamesa Renewable Energy Inc. (DE/ES), Ingersoll Machine Tools Inc. (US), Techmer PM LLC (US), Oak Ridge National Laboratory (US)	?	DOE funding: MUSD 2.8 (MEUR 2.4) TOTAL: MUSD 3.5 (MEUR 3.0)

The MEGAPRINT project proposes an innovative additive manufacturing technique for fabrication of large segmented wind blade moulds in order to replace monolithic tooling structures. The innovation is expected to offer a faster blade production process configurations and reduce transportation requirements and costs. Moreover, project objectives address circularity through the development of recyclable cellulose-filled thermoplastics for the tooling segments. This bio-based materials derived from wood should allow to reduce feedstock cost to USD 4.4/kg as compared to currently used thermoplastic feedstocks (CFR acrylonitrile butadiene styrene) which costs about USD 11/kg. It is planned to demonstrate the fabrication of two full scale mould segments as well as to manufacture a 34.4m mid-span portion of an SGRE blade[54] [55] [56].

[51] CompositesWorld (2021), Orbital Composites to demonstrate containerized 3D printing robots for AM wind blade manufacture, https://www.compositesworld.com/news/orbital-composites-to-demonstrate-containerized-3d-printing-robots-for-am-wind-blade-manufacture, (accessed 14/10/2021)

[52] EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

[53] EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

[54] DOE (2021), MEGAPRINT: Using the World's Largest 3D Printer for Precision Manufacturing of Large Modular Wind Blade Tooling, https://www.energy.gov/sites/default/files/2021-08/CX-024186.pdf, (accessed 14/10/2021)

[55] EERE (2021), Advanced Manufacturing Office FY20 Multitopic FOA Selections Table, https://www.energy.gov/eere/amo/advanced-manufacturing-office-fy20-multitopic-foa-selections-table, (accessed 14/10/2021)

[56] GlobalSpec (2021), World's largest 3D printer to halve wind turbine blade costs, https://insights.globalspec.com/article/15935/worlds-largest-3d-printer-to-halve-wind-turbine-blade-costs, (accessed 15/10/2021)

2.1.19 UMichigan (US) – Robot-Based Additive Manufacturing of Lego-Type Modular Molds for Wind Blades

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise)	University of Michigan (US), Raytheon Technologies (US), TPI Composites (US), Penn State University Park (US)	?	DOE funding: MUSD 2.7 (MEUR 2.3) TOTAL: MUSD 3.4 (MEUR 2.9)

A UMichigan led consortium aims to produce modularised moulds at demonstration scale (at 1:100 and 1:20 scale) using additive manufacturing (3D printed aluminium moulds). The project aims to reduce the cost and lead time of the moulds as well as facilitate blade transportation without sacrificing blade quality. The demonstration moulds are expected to meet the requirements for blade lengths between 120m and 150m[57].

2.1.20 Blade repurposing (multiple initiatives)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
3 (Prevent waste) 6 (Component reuse and repurposing)	Multiple initiatives	n.a.	n.a.

Examples for repurposing of wind blades are mainly demonstration projects. WindEurope (2020) reports various examples for structural elements in street or building infrastructure (e.g. parts of pedestrian bridges, bike shelters, street furniture)[58]. Jensen and Skelton (2018) reviewed in the framework of the Danish GENVIND innovation consortium the possibilities of repurposing and secondary use of blades. The authors report repurposing of blades in bridges but also highlighting the challenges which are mainly connected to standardisation issues of this approach such as economics, testing of old blades, cutting to meet design requirements, transport at installation site or foundation requirements. With respect to the usage as playground or urban furniture the Jensen and Skelton (2018) give several examples in the Netherlands using this approach (e.g. REwind Willemsplein, Wikado, Kringloop Zuid, REwind Almere) and estimate that using wind blades for 5% of the yearly production of urban furniture could remove the annual wind blade waste stream of the country [59].

As part of the EC H2020 ECOBULK project a repurposing of wind turbine blades is performed through a set of thermos-mechanical processing steps (shredding and metal separation, material formulation by hot-mixing) to extrude or injection mould the GFRP waste into thermoplastics. The extrusion technology is provided by ECOBULK project partner and technology developer Conenor (FI) aiming for licensing the material manufacturing technology worldwide. Main applications of the technology for re-purposing are the automotive sector or outdoor infrastructure [60].

2.2 Tower

2.2.1 GE RE – LaFargeHolcim (CH) and Cobod (DK) (3d-printing/co-processed cement)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
6 (Component reuse and repurposing) 14 (Recycle) 17 (Energy recovery)	General Electric RE (US), LaFargeHolcim (Geocycle) (CH), Cobod (DK)	2020 - ?	n.a.

Besides the cooperation mentioned earlier between General Electric RE and LaFargeHolcim (see section 2.1.8), another cooperation together with the 3D printing start-up Cobod (DK) aims for the tower component of a wind turbine. The partnership will co-develop optimised 3D printed concrete tower pedestals allowing to construct towers with increased

[57] DOE (2021), Robot-based Additive Manufacturing of Lego-type Modular Molds for Wind Blades, https://www.energy.gov/sites/default/files/2021-06/CX-023765.pdf, (accessed 15/10/2021)
[58] WindEurope (2020), Accelerating Wind Turbine Blade Circularity, https://windeurope.org/wp-content/uploads/files/about-wind/reports/WindEurope-Accelerating-wind-turbine-blade-circularity.pdf
[59] Jensen J.P., Skelton K., Wind turbine blade recycling: Experiences, challenges and possibilities in a circular economy, Renewable and Sustainable Energy Reviews, Volume 97, 2018, Pages 165-176, ISSN 1364-0321, https://doi.org/10.1016/j.rser.2018.08.041.
[60] ECOBULK (2018), Closing the loop for wind turbine blades, https://www.ecobulk.eu/news/wind-turbine-blade-circular-options-the-ecobulk-way/, (accessed 05/10/2021)

height in order to increase electricity generation at lower cost and prevention of transportation issues. A first 10m prototype was successfully printed in Copenhagen in 2019[61]. Moreover LaFargeHolcim claims that the developed prototypes using 3D printing/additive manufacturing technology are stronger, more efficient, and can be built ten times faster than conventional towers [62].

With respect to additive manufacturing GE builds on earlier cooperation in the US with Oak Ridge National Laboratory (ORNL). In the period 2018 -2019 a technical cooperation project developed additive manufacturing capabilities that enabled the partners to manufacture of large cement structures at a potential wind farm. The project included testing and definition of the materials and deposition functions of an on-site additive manufacturing system. This resulted in printing an early tower pedestal prototype (2.6 m in diameter and 1.2m in height) at a test site and in developing a basic concrete mix [63].

2.2.2 Modvion – Modular wooden tower

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise) 6 (Component reuse and repurposing) 14 (Recycle)	Modvion (SE)	n.a	2019: H2020 funding kEUR 50 2020; EIC Accelerator funding MEUR 6.5 (MSEK 69)

The engineering company Modvion developed a commercial pilot of a modular, segmented wooden tower. The structural materials used are glue-laminated timber (GLT) and laminated veneer lumber (LVL). A first step was the installation of a 1:5-scale prototype tower with a 30-meter hub height near Gothenburg in April 2020. In end-2019 Swedish wind power company Rabbalshede Kraft AB signed a letter of intent to order ten modular wooden towers from Modvion for its Fagremo wind project. Cooperation agreements with Vattenfall and Vestas followed in 2020 and 2021, respectively. Modvion claims a 90% CO2 reduction during the production process as compared to conventional steel towers, moreover the use of wood further allows to mitigate CO2 [64] [65]. The company claims that with minor adjustments the technology will also be applicable in offshore wind projects[66].

2.3 Mooring

2.3.1 TFI – Load reducing polymer spring

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste)	TfI Marine (IE)	n.a	2019: H2020 funding MEUR 0.35 2020: NOWRDC funding: undisclosed

The engineering company TfI Marine develops soft mooring designs for floating offshore wind turbines by incorporating innovative load reducing polymer spring in the mooring lines. The spring technology developed by TfI, has the potential to reduce peak loads by more than 50%, enabling reduction in both size and required holding capacity of anchors. As such, these polymer springs could reduce installation vessel requirements, enabling reductions in cost for FOWT station-keeping

[61] Cobod (2021), Cobod GE Tower, https://cobod.com/ge-tower/, (accessed 20/09/2021)

[62] Holcim (2021) GE Renewable Energy and Holcim Team Up For a More Circular Wind Industry, https://www.holcim.com/ge-renewable-energy-and-lafargeholcim-team-a-more-circular-wind-industry (accessed 20/09/2021)

[63] ORNL (2019), On-Site Manufacture of Large Cement Structures, CRADA FINAL REPORTNFE-18-07309, https://www.ornl.gov/sites/default/files/2019-10/GE%20Phase%201%20Final%20Report.pdf, (accessed 15/10/2021)

[64] Modvion (2020), Modvion Awarded Multimillion-Euro EU Grant for Wooden Wind Turbine Towers, https://www.modvion.com/wp-content/uploads/2020/06/200615_Modvion-Awarded-Multimillion-Euro-EU-Grant-for-Wooden-Wind-Turbine-Towers_EN.pdf (accessed 20/09/2021)

[65] Lundman, O., Modular Wooden Towers for Tall Wind Turbines, Presentation at ETIPWind workshop on "Delivering circularity through innovative materials and recycling technology, May 2021.

[66] Modvion (2021), Modvion FAQ, https://www.modvion.com/wp-content/uploads/2020/12/Modvion-FAQ_Eng.pdf, (accessed 20/09/2021)

systems in shallow waters[67]. Moreover, from a circular economy perspective the technology represents an alternative to conventional steel mooring systems.

Tfl is part of the H2020 project FLOTANT which aims to develop an innovative and integrated Floating Offshore Wind solution, optimized for deep waters (100-600m) and to sustain a 10+MW wind turbine generator, composed by: a mooring and anchoring system using high performance polymers and based on Active Heave Compensation to minimise excursions, a hybrid concrete-plastic floater and a power export system with long self-life and low-weight dynamic cables. The project includes enhanced O&M strategies, sensoring, monitoring and the evaluation of the techno-economic, environmental, social and socio-economic impacts. The entire FLOTANT project is funded with MEUR 4.9 of which MEUR 0.35 are awarded to TfL Marine [68].

As part of an international consortium led by Principle Power (US), TfI Marine (IE) together with National Renewable Energy Laboratory (US), Aker Solutions (NO), the American Bureau of Shipping (ABS, US) has been awarded a contract in 2020 by the U.S. government's National Offshore Wind Research and Development Consortium (NOWRDC) for a project entitled Demonstration of Shallow-Water Mooring Components for Floating Offshore Wind Turbines (ShallowFloat). The project aims to design a bankable, low-cost, shallow-water mooring solution that has an approval-in-principle (AIP) from ABS and to provide developers with reliable technical and economic data about the ability of floating foundations to potentially offer a more competitive, lower-risk solution compared to bottom-fixed jacket structures in certain shallow water sites [69]. Until early 2022, TfI Marine envisages to demonstrate its innovative mooring design in the Scotland, France and the United States[70]. In 2021 mooring components were validated in the Dynamic Marine Component (DMaC) of the University of Exeter.

2.4 Nacelle (Offshore wind turbine)

2.4.1 Greenboats/Sicomin – NFC offshore nacelle housing

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation)	Greenboats (DE)	n.a	n.a.
3 (Prevent waste)	Sicomin (FR)		
14 (Recycle materials)	Bcomp (CH)		

The engineering company Greenboats and bio-epoxy resin company Sicomin developed a natural fibre composite (NFC) nacelle in order to offer a more sustainable alternative to conventional nacelles building on steel, aluminium, polyester-based/epoxy-based glass-fibre reinforced composites. The demonstrator nacelle has a length of 7.3m and a surface area of 100m^2 and is reported to satisfy all DNV GL nacelle load cases applicable for nacelle structures. Greenboats provided the structural engineering, manufacturing and assembly of the nacelle using Bcomp's ampliTex flax reinforcements, FSC certified balsa wood cores and Sicomin's GreenPoxy bio-based resins.[71] [72] [73].

[67] TFI 2021, TFI Marine https://www.tfimarine.com/#SECTION-8 (accessed 20/09/2021)

[68] EC (2021) https://cordis.europa.eu/project/id/815289 (accessed 24/09/2021)

[69] Principle Power (2020), Principle Power partners with an innovative Irish company Technology From Ideas (TfI) to develop novel mooring solutions for transitional waters, https://www.principlepower.com/news/principle-power-partners-with-an-innovative-irish-company-technology-from-ideas-tfi-to-develop-novel-mooring-solutions-for-transitional-waters, (accessed 24/09/2021)

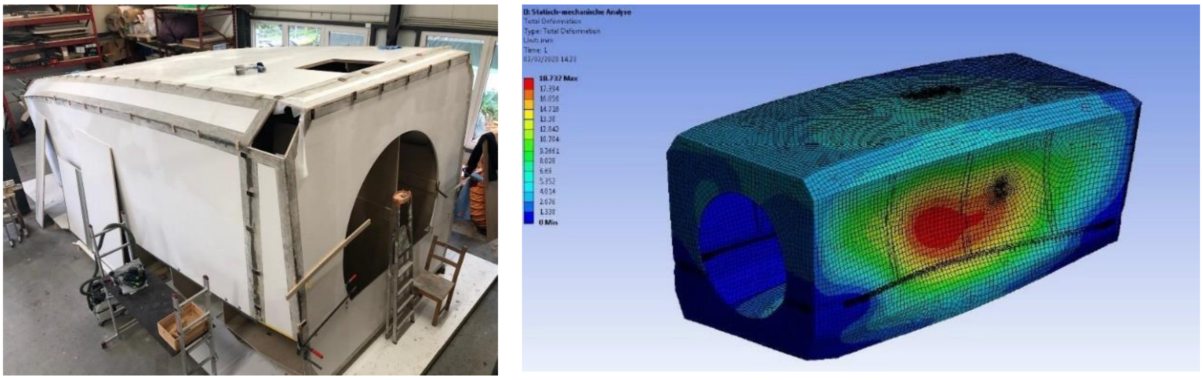
[70] 4COffshore (2020), Consortium to develop shallow-water mooring solutions for floating wind, https://www.4coffshore.com/news/consortium-to-develop-shallow-water-mooring-solutions-for-floating-wind-nid19242.html, (accessed 24/09/2021)

[71] BCOMP (2021) Green Nacelle – Selected as JEC Innovation Awards 2021 Finalist, https://www.bcomp.ch/news/jec-innovation-awards-2021-finalist/, (accessed 24/09/2021)

[72] SICOMIN (2021) SICOMIN GREENPOXY® RESINS CHOSEN BY GREENBOATS® FOR FIRST NATURAL FIBRE COMPOSITE NACELLE, http://sicomin.com/news/sicomin-greenpoxy-resins-chosen-by-greenboats, (accessed 24/09/2021)

[73] Greenboats (2021), NFC Off-Shore Nacelle, https://green-boats.de/nacelle, (accessed 24/09/2021)

Figure 9. Manufacturing of the NFC nacelle demonstrator (left) and testing of deformation under wind loads according to satisfy DNV GL load cases (right)



Source: Greenboats, 2021.

2.4.2 GE/Fraunhofer/Voxeljet – Advance Casting Cell (ACC) 3D printer

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 4 (Modularise)	GE (US) Fraunhofer IGCV (DE) Voxeljet AG (DE)	2021 - 2023	BMWi: MEUR 2.6

GE together with Fraunhofer IGCV and 3D printer firm Voxeljet AG are forming a research partnership to develop the world largest Advance Casting Cell (ACC) 3D printer producing sand moulds for the highly complex metal parts of offshore wind turbine nacelles. The innovation uses Voxeljet's 'Binder-Jetting' technology capable to produce moulds for casting of extended size and weight (up to 9.5m in diameter and more than 60 tons in weight). The collaboration is funded by the German Federal Ministry for Economic Affairs and Energy (BMWi) and will print moulds for cast components that will be installed inside the GE Haliade-X nacelle. The consortium claims a time reduction in the manufacturing of moulds from 10 weeks to only 2 weeks. A central aspect of this innovation lies in eliminating the need to transport large parts from a central location as the printer can be operated in close vicinity to the site of final deployment (e.g. ports). Moreover, the consortium claims process related improvements in terms of avoidance of misprints, miscasts as well as resource reduction and waste prevention (savings on binder and activator material). The project is expected to be launched in 3rd quarter of 2021 with first printer trials starting in early 2022 (TRL 4 – 6)[74]. The project consortium aims for a follow-up project bringing the technology to serial-production readiness by 2025[75].

2.5 Drivetrain/Generator

2.5.1 ECOSwing – Superconducting Wind Generator

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 14 (Recycle materials)	Envision (DK); Eco 5 GmbH (DE); Jeumont Electric SAS (FR); Delta Energy Systems GmbH (DE); Theva Dunnschichttechnik GmbH (DE); Sumitomo Cryogenics of Europe Limited (UK); Germanischer Lloyd Industrial Services GmbH (DE); Universiteit Twente (NL); Fraunhofer IWES (DE)	2015 - 2019	2020: H2020 MEUR 10.59 Total Budget: MEUR 13.85

[74] Fraunhofer IGVC (2021), Research partnership to develop the world's largest sand 3D printer for offshore wind turbines, https://www.igcv.fraunhofer.de/en/press_downloads/press_releases/sand_bitter_jetting_3d_printer_offshore_wind_turbines.html, (accessed 14/10/2021)

[75] Personal communication with IGCV on 25/10/2021

EcoSwing, a project investigating a superconducting low-cost and lightweight drivetrain, demonstrated their concept on a 3.6 MW modern wind turbine. The concept reduces generator weight by 40% compared to commercial permanent magnet direct-drive generators (PMDD). For the nacelle this means a weight reduction of 25% while at the same time the reliance on rare earth metals is down by at least two orders of magnitude. The concept operated more than 650 hours and generated about 660 MWh. Although an even higher TRL (7-8) was achieved, the present system is currently considered as not fully suitable for industrialization as for example the quench protection was reported to be rethought in terms of necessity and design. So far, no indication of patenting out of the project could be observed[76] [77].

2.5.2 GreenSpur – Rare Earth Free Permanent Magnet Generator

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 14 (Recycle materials)	GreenSpur (UK) ORE Catapult (UK) Warwick Manufacturing Group (UK)	2019 - ongoing	2019: Innovate UK: MEUR 1.4 (MGBP 1.25)

Greenspur designs ferrite-based direct-drive permanent magnet generators which use an axial flux architecture as compared to conventional radial designs. The rotor and stator are arranged as discs along the axis of the machine, and the magnetic flux flows parallel to this axis which opens up a greater area of interaction between magnets and coils. The use of ferrite replaces the need for rare earth materials. A 250kW prototype stage that could be combined to a 1MW project was tested in 2019 at ORE Catapult's 1MW powertrain rig. The company envisages a market-ready design by 2022 and design of a 12MW+ concept by stacking three 4MW modules in parallel[78] [79].

2.5.3 GE – High-efficiency ultra-light low temperature superconducting (LTS) generator

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 14 (Recycle materials)	General Electric (GE) Research (US)	2019 - ongoing	2019&2021 DOE funding: MEUR 18.0 (USD 20.8)

The U.S. Department of Energy (DOE) has selected General Electric (GE) Research to receive up to USD 20.3 million to build and test a scaled prototype of their generator on a wind turbine, following a first call of each USD 0.5 million to identify the most promising technology out of three concepts by WEG Energy Corporation (direct drive lightweight generator), American Superconductor Corporation (high-temperature superconductor (HTS) generator) and General Electric (GE) Research (ultra-light low temperature superconducting (LTS) generator)[80]. General Electric (GE) Research claims that relative to a 10MW direct-drive (DD) permanent magnet generator (PMG), a 15MW superconducting generator (SCG) can lower mass by 40%, increase torque density by 218%, increase efficiency by 2%, decrease LCOE by 27%, and reduce rare earth content by 100%[81].

[76] EC (2021), CORDIS - EcoSwing - Energy Cost Optimization using Superconducting Wind Generators - World's First Demonstration of a 3.6 MW Low-Cost Lightweight DD Superconducting Generator on a Wind Turbine, https://cordis.europa.eu/project/id/656024/de, (accessed 06/10/2021)

[77] JRC (2020), Wind Energy Technology Development Report 2020, EUR 30503 EN, Publications Office of the European Union, Luxembourg 2020, ISBN 978-92-76-27273-1, doi:10.2760/742137, JRC123138.

[78] Greenspur (2021), Our generator, https://www.greenspur.co.uk/new-page-2, (accessed 30/09/2021)

[79] ORECatapult (2021), GreenSpur Renewables, https://ore.catapult.org.uk/stories/greenspur-renewables/, (accessed 30/09/2021)

[80] DOE (2021), Department of Energy Selects Projects to Develop High-Efficiency, Lightweight Wind Turbine Generators for Tall Wind and Offshore Applications, https://www.energy.gov/eere/articles/department-energy-selects-projects-develop-high-efficiency-lightweight-wind-turbine, (accessed 30/09/2021)

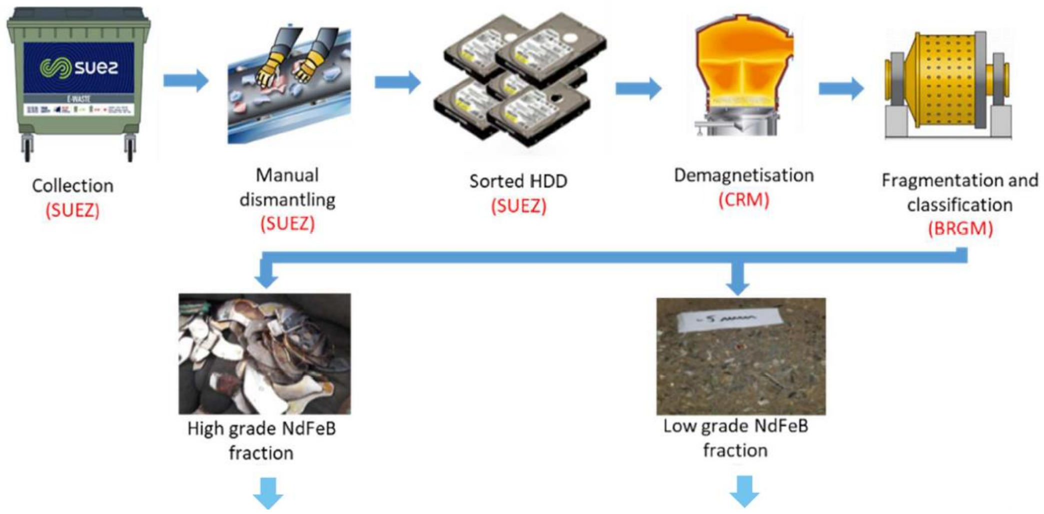
[81] GE (2021), High Efficiency Ultra-Light Superconducting Generator, https://www.ge.com/research/project/high-efficiency-ultra-light-superconducting-generator, (accessed 30/09/2021)

2.5.4 VALOMAG – Upscale of Permanent Magnet Dismantling and Recycling

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 7 (Refurbish) 14 (Recycle materials)	SUEZ Groupe SAS (FR), The French Geological Survey (FR), Centre de Recherches Métallurgiques asbl (CRM Group) (BE), French Alternative Energies and Atomic Energy Commission (FR), Kolektor Group Vodenje in upravljanje druzb d.o.o. (SI), Leiden University (NL), Delft University of Technology (NL)	2020 - 2022	2020 EC EIT funding: undisclosed Total budget: MEUR 2.5

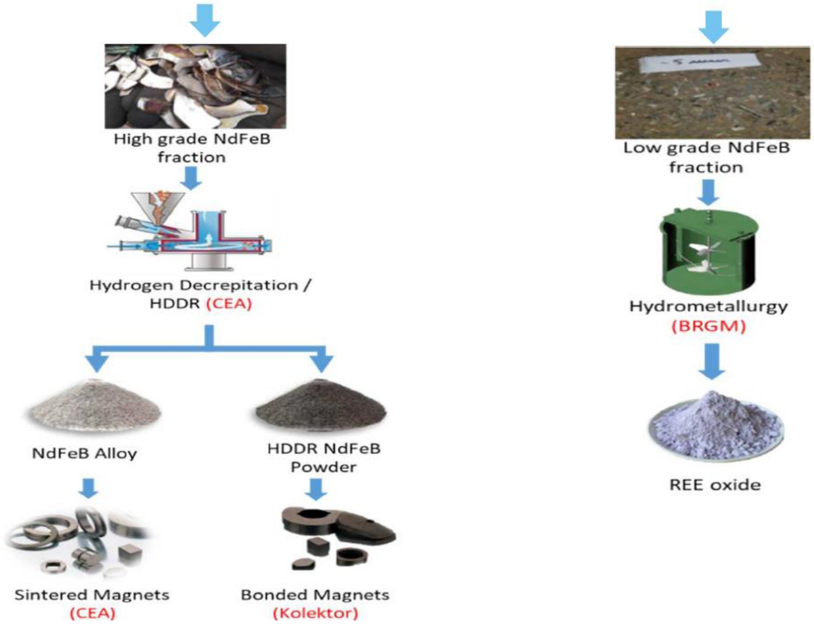
The VALOMAG project proposes to supply a technical solution for permanent magnet disassembly of EOL applications like hard disc, electric vehicles and wind turbine and to assess two short loop recycling technologies (HD/HDDR and stripcasting) for high and medium quality magnets with a third alternative route using hydrometallurgical processes for low quality magnets (see **Figure 10**). The project combines different key players who bring together their expertise to develop a new value proposal which answers the need of the permanent magnets market. The project focuses on a) the sourcing of End of Life products containing permanent magnets and characterization of the magnets, b) the dismantling and the pre-processing of the extracted materials focusing on the magnets, c) the recycling processes of magnets (Decrepitation, Melting and Hydrometallurgy) and d) the technical and economical evaluation of the whole value chain and all processes through LCA and flowsheet simulation. The consortium claims that the recycling process has significantly less environmental impact than production from raw materials with about 31% to 55% compared to the virgin magnet production. The project consortium aims for a TRL level of 6 to 7 in extracting and recycling of magnets [82] [83].

Figure 10. Process chart of recycling routes followed in the VALOMAG project



[82] EIT (2021), Innovation projects – Valomag, https://eitrawmaterials.eu/innovation-projects/page/11/?tax_input%5Beit_innovation_theme%5D%5B0%5D=134, (accessed 30/09/2021)

[83] VALOMAG (2021), Upscaling of permanent magnet dismantling and recycling through VALOMAG project, https://valomag.tudelft.nl/wp-content/uploads/2021/09/RawMat_Coelho-Read-Only.pdf, (accessed 30/09/2021)



Source: VALOMAG, 2021.

2.5.5 SUSMAGPRO – Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 7 (Refurbish) 14 (Recycle materials)	Hochschule Pforzheim (DE), The University of Birmingham (UK), Stena Recycling Interantional AB (SE), Rise Research Institutes of Sweden AB (SE), Inserma Anoia SL. (ES), Less Common Metals Limited (UK), Mimplus Technologies GmbH & Co KG (DE), Netherlands (NL), Magenti Ljubljana Podjetje Za Proizvodnjo Magnetnih Materialov DD (SI), Kolektor Magnet Technology GmbH (DE), ZF Friedrichshafen AG (DE), B&C Speakers (IT), Grundfos Holding AS (DK), Bunting Magnetics Europe Limited (UK), Universiteit Leiden (NL), Fotec Forschungs- und Technologietransfer GmbH (AT), Sennheiser Electronic GmbH & Co KG (DE), Montanuniversitaet Leoben (AT), Institut Jozef Stefan (SI), Steinbeis Innovation GGmbH (DE)	2019 - 2023	2020 EC EIT funding: MEUR 13.0 Total budget: MEUR 14.7

The SUSMAGPRO project aims to develop a pilot supply chain (new sensing and robotic sorting lines for the identified EoL products) from recycled neodymium magnets in Europe and builds on knowledge build under the FP7 Remanence project. New hydrogen based technologies will be demonstrated at scale for separating and purifying NdFeB powders from the robotically sorted. The separated powders will be re-manufactured into sintered magnets, injection moulded magnets, metal injection moulded magnets and cast alloys[84]. The project involves the demonstration of four Pilot reprocessing routes in Germany, Slovenia and the United Kingdom for the remanufacturing of magnets using different technology pathways such as sintering with and without blending, hydrogen decrepitation deabsorbation recombination (HDDR), sintering-debinding-shaping (SDS)(see also EU H2020 REProMag project) and re-casting with new pyrometallurgical

[84] EC (2021), CORDIS - Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy (SUSMAGPRO), https://cordis.europa.eu/project/id/821114, (accessed 30/09/2021)

processes and purification. The end-user-ready permanent magnets are benchmarked against primary materials and demonstrated in a variety of products, with respect to wind energy SUSMAGPRO magnets are tested to Siemens Gamesa specifications for wind turbines[85].

2.6 Grid integration - High voltage transmission

2.6.1 LIFEGRID – SF6-free High Voltage Circuit Breakers (HVCB)

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation)	General Electric - Grid Solutions SAS (US) Leibniz Institute for Plasma Science and technology (DE) Université de Technologie de Brno (CZ)	2019 – 2022	2020: LIFE Programme funding MEUR 2.2 Total Budget: MEUR 4.1

Gas insulated switchgears have been the standard solution at high voltage offshore transmission substations due to the limited space availability offshore. The objective of the LIFEGRID project is to replace the highly potent greenhouse gas sulphur hexaflouride SF6 used in High Voltage Circuit Breakers (HVCB) with an environmental-friendly alternative called g3. g3 is a mixture of gases for dielectric insulation and as arc quenching medium inside the switchgear. Using g3 reduces the climate impact of the gas in the switchgear by more than 99%. The technical feasibility has already been demonstrated for 145 kV gas-insulated substations (GIS), however, the aim is here to tackle the translation towards the highest voltage level for Europe, namely 420 kV, for which there is no solution currently available. To achieve this goal, the project partners within the LIFE GRID project will develop successive pilots in order to prepare an integrated 420 kV SF6-free GIS solution for European transmission networks, with the support of Transmission System Operators (TSOs) [86] [87] [88].

Elimination of SF6 from current use in the industry is also reflected in the EU F-Gas Regulation (517/2014).

2.6.2 SuperNode – MVDC transmission system based on superconducting cable technology

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste)	SuperNode (IE)	n.a.	n.a.

The company SuperNode develops a superconducting cable technology in order to deliver an MVDC transmission system capable in excess of 2GW of bulk power transfer. A potential use case promoted by SuperNode is its DC Connection Concept to allow for offshore transmission with significantly longer distances than existing SC projects. The power generation from offshore wind energy will be collated using the SuperNode Collector Station followd by a connection with superconducting cable technology to the electricity grid. The concept includes also the use of a cryogenic fluid system that cools the superconductor consisting of a high performance cryostat which minimizes thermal ingress to the system and pipe losses, and through intermediary cooling and pumping stations (the subsea pressure vessel 'SuperNode Cooling and Pumping Pod Station Concept'). The company claims that an implementation of the technology would lead to a substantial reduction in infrastructure. Offshore collectors stations would see a weight reduction by factor 30 when compared to conventional systems in use [89] [90].

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85 SUSMAGPRO (2021), About SUSMAGPRO – Solutions, https://www.susmagpro.eu/about/about-susmagpro-solutions, (accessed 30/09/2021)

86 EC (2021), LIFE Public Database - Greenhouse gas Reduction process via an Innovative high voltage circuit breaker Development, https://webgate.ec.europa.eu/life/publicWebsite/project/details/5056 (accessed 30/09/2021)

87 LIFEGRID (2021), https://www.lifegrid.eu/ (accessed 30/09/2021)

88 GE (2021), EU supports GE's development of a 245 kV g3 circuit-breaker to accelerate decarbonization of Europe's electrical grid, https://www.ge.com/news/press-releases/eu-supports-ges-development-of-245-kv-g3-circuit-breaker-accelerate-decarbonization-europe-electrical-grid (accessed 30/09/2021)

89 SuperNode (2021), SuperNode – technology, https://supernode.energy/technology/, (accessed 30/09/2021)

90 Byrne M. (2021), Superconductors for renewables integration, ETIPWind workshop on circularity, May 2021, https://etipwind.eu/files/events/210504-Sustainability%20workshop/Presentations/Session%202/210405-ETIPWind-workshop-circularity-Marcos%20Byrne-Supernode.pdf, (accessed 30/09/2021)

2.7 Grid integration - Hydrogen transport

2.7.1 SoluForce – Flexible Composite Pipes

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste)	SoluForce (NL)	n.a.	n.a.

Engineering company SoluForce developed a flexible pipeline systems for hydrogen transportation and distribution. The Reinforced Thermoplastic industrial Piping system (RTP, also known as Flexible Composite Pipes (FCP)) is certified for hydrogen applications up to 42 bar of operating pressure. As compared to conventional steel piping, the company claims a 75% lower CO2eq footprint, no hydrogen embrittlement or corrosion as well as an easy installation procedure. First application of the SoluForce Hydrogen solution is planned at Groningen Seaports in 2021, where four kilometres (2.5 miles) of SoluForce infrastructure will be installed. This infrastructure will ultimately distribute green hydrogen produced by wind mills in the North Sea to companies in the chemical and industrial sectors in the Eemshaven[91] [92].

Figure 11. Reinforced Thermoplastic industrial Piping system (SoluForce Hydrogen Tight (H2T)) for hydrogen applications

Source: SoluForce, 2021.

2.8 Other / Collaborations addressing multiple components

2.8.1 MAREWIND consortium – Material innovations for offshore wind life extension

Applicable Circular Economy strategies	Partners (Country)	Period	Volume
2 (Dematerialisation) 3 (Prevent waste) 14 (Recycle materials)	L'Urederra (ES); TWI Limited (UK); Cetma (IT); Inegi (PT), Idener (ES); INL (PT); Tecnan (ES); Eirecomposites Teoranta (IE); Navarra de Tecnicas de Soldadura Y Fijacion S.L. (ES); Acciona Construccion SA (ES); Naval Energies (FR); EDF (FR); Koshkil Systems SL (ES); RINA Consulting SPA (IT); PNO Innovation (BE); European Federation for Welding Joining and Cutting (BE)	2020 - 2024	2020: H2020 MEUR 6.71 Total Budget: MEUR 7.95

[91] RVO (2021), Excelling in Hydrogen Dutch technology for a climate-neutral world, https://www.rvo.nl/sites/default/files/2021/03/Dutch%20solutions%20for%20a%20hydrogen%20economy.pdf (accessed 30/09/2021)

[92] SoluForce (2021), SoluForce Hydrogen Tight (H2T), https://www.soluforce.com/product-overview/pipe-types/hydrogen-tight.html, (accessed 30/09/2021)

MAREWIND targets the main aspects related to materials durability and maintenance in offshore wind energy structures. The consortium aims to increase durability and anticorrosion protection of metallic materials exposed to harsh environments, to increase the durability of concrete for structural components and to enhance the long-term durability of antifouling coatings without biocides. Moreover the project addresses the blade component by improving the leading-edge protection system in increased erosion resistance and the development of a structural health monitoring system for offshore wind. The project aims for developing recyclable by design materials for wind turbine blades. The consortium claims that it plans to demonstrate also scalable manufacturing technologies for these innovations. MAREWIND stresses that these innovations will lead to improved durability in the different components such as an improved durability of corrosion protective coatings (>25years), reinforced structural concrete, (> 50% durability increase), antifouling coatings (> 5 years), anti-erosion blade paints (>10 years). Besides cost reductions the consortium estimates a 35% reduction in the environmental impact as compared to reference systems[93] [94].

[93] EC (2020), CORDIS - MAterials solutions for cost Reduction and Extended service life on WIND off-shore facilities, MAterials solutions for cost Reduction and Extended service life on WIND off-shore facilities | MAREWIND Project | Fact Sheet | H2020 | CORDIS | European Commission (europa.eu) (accessed 6/10/2021)

[94] MAREWIND (2021), https://www.marewind.eu/documents/, (accessed 6/10/2021)

3 Conclusions

This report presents current initiatives, R&D collaborations and product innovations along the wind energy supply chain which aim for circularity in design. The identified measures are analysed with respect to their consortium structure, period of research and utilised source of funding. Moreover, the analysis draws on a recently developed 17-point framework of circular economy strategies[95,96] to categorise the different initiatives and the extent to which they contribute towards a circular economy approach (see **Table *4***).

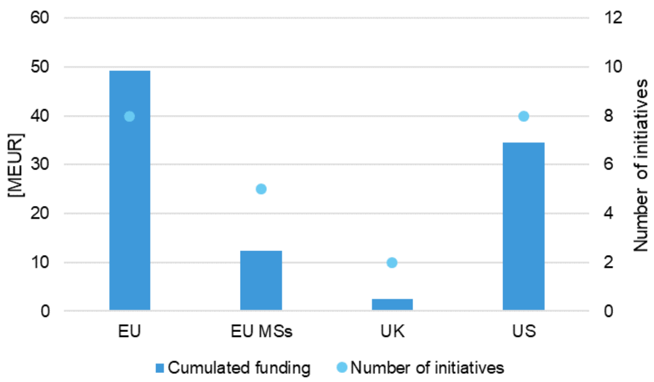
In total, the report identifies 35 initiatives with the majority (21) addressing the blade component of the wind turbine, given the difficulty of recycling the composite waste materials used. The methods used to process the blade component include mechanical, thermal, chemical, reprocessing or biotechnological processes and differ in terms of technology readiness level. Moreover, the circular economy strategies pursued by the initiatives are mostly at the level of materials and products/components.

Besides circular economy strategies addressing the blade component, some initiatives also address other parts of the wind energy supply chain (e.g. components such as the tower, mooring, nacelle housing and grid integration technologies). Notably, almost all of them address circular economy strategies at the material level by using alternative materials (Circular Economy strategy ‘Dematerialisation’) or by eliminating waste from production through design (Circular Economy strategy ‘Prevent waste’).

When categorising the various initiatives identified according to the 17-point framework, we could not find evidence of any addressing infrastructure-related circular economy strategies (e.g. the strategies ‘Extend lifetime’, ‘Repower’, ‘Recertify’, ‘Decommission’ or ‘Restore site’). This might be because most circular economy initiatives address a single component/material rather than operating at wind park level.

We were able to identify R&D funding at national or EU level for 23 out of 34 initiatives. EU funding through various programmes (H2020, EIC accelerator, LIFE programme) accounts for EUR 49.3 million, followed by US initiatives (EUR 34.6 million), funded through the DOE on Advanced Manufacturing and the development of an ultra-light low temperature superconducting (LTS) generator as well as through the US National Offshore Wind Research and Development Consortium (NOWRDC) to develop innovative mooring for floating offshore wind. We observe that the national R&D funding for addressing circularity identified in EU member states (EUR 12.45 million) happens mainly in Denmark, through its Innovation Fund Denmark programme, and addresses the wind blade component in particular. Moreover we found two projects in the UK, funded by EPSRC and the Innovate UK programme aiming for hydrodynamic alignment of discontinuous fibres and Rare Earth Free Permanent Magnet Generators (EUR 2.6 million). The remainder of current initiatives are privately funded R&D collaborations for which there was no information on the overall budget.

Figure 12. R&D funding at national or EU level on the circularity initiatives identified



Source: JRC, 2021.

With respect to the types of organisation active in the various initiatives, we observe a strong participation of industry players. In total, the identified collaborations count 124 participations by industry players as compared to 50 by research institutions. Moreover, wind energy OEMs and energy utilities such as LM Wind (US), Vestas (US), SiemensGamesa (DE/ES), GE RE (US) and Ørsted (DK) are leading some of the most recent collaborations on circularity strategies in the blade component, confirming their commitment to their ambitious targets in pursuance of carbon neutrality and the elimination

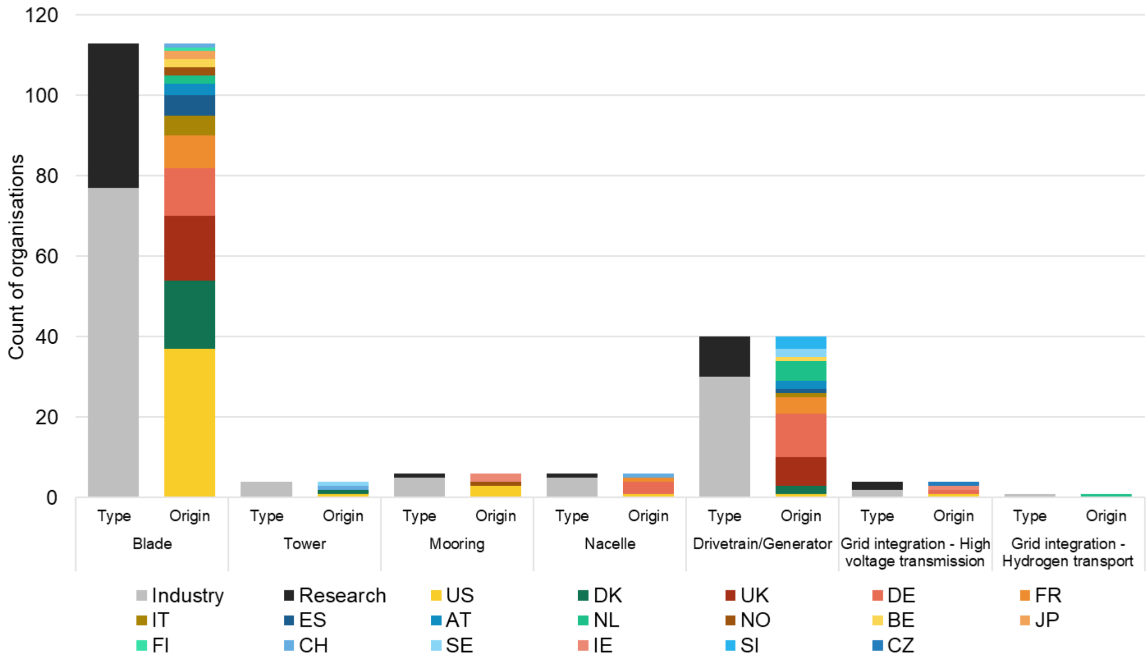
95 Paul D. Jensen, Phil Purnell, Anne P.M. Velenturf, Highlighting the need to embed circular economy in low carbon infrastructure decommissioning: The case of offshore wind, Sustainable Production and Consumption, Volume 24, 2020, Pages 266-280, ISSN 2352-5509, https://doi.org/10.1016/j.spc.2020.07.012.

96 Anne P.M. Velenturf, Towards A Circular Economy Framework for Offshore Wind, Circular Online - Chartered Institution of Wastes Management (CIWM), 27/10/2020, https://www.circularonline.co.uk/research-reports/towards-a-circular-economy-framework-for-offshore-wind/ (accessed 13/08/2021).

of non-recyclable waste. If participation in collaborations is analysed by country of origin, the US leads with 44 counts, mainly because of the projects recently launched and funded by DOE on additive manufacturing processes in advanced wind blade production (32 in total). Notably, the main EU wind OEMs (Vestas and SiemensGamesa RE) are among the collaboration partners in these projects which are otherwise dominated by US organisations. Among European countries, Germany shows the strongest participation across all components (27 counts) followed by the United Kingdom (23) and Denmark (20). In total, organisations from EU27 member states show strong participation in all components of the wind energy supply chain, accounting for 99 out of 174 participation counts in the identified dataset.

Figure 13. Number of organisations active in collaborations on circularity in design by wind energy component, type of organisation and origin of organisation.

Note: Organisations which are part of multiple initiatives are counted based on the number of participations.



Source: JRC, 2021.

Table 4. Categorisation of current circularity approaches in the wind energy sector

Component	Initiative	Lead organisation (Country)	Design for circularity (# of applicable Circular Economy strategies)		Dematerialisation	Prevent waste	Modularise	Repair and maintain	Component reuse and repurposing	Refurbish and remanufacture components	Disassemble	Extend lifetime	Repower	Recertify	Decommission	Restore site	Recycle materials	Landfill and controlled storage	Re-mine	Energy recovery	National R&D funding (Country)	EU R&D funding
Blades	ZEBRA	LM Wind (US)	5																			
	CETEC	Vestas (DK)	4																		DK	
	AIOLOS	SiemensGamesa RE (DE/ES)	2																		DK	
	AKER – University of Strathclyde	AKER (UK)	4																			
	DecomBlades	Ørsted (DK)	4																		DK	
	RecycleBlades	SiemensGamesa RE (DE/ES)	4																			
	FibreEUse	Politecnico di Milano (IT)	4																			EU
	GE RE – Veolia (Co-processing)	GE RE (US)	5																			
	GE RE – LaFargeHolcim and Neowa (Co-processing)	GE RE (US)	5																			
	BCIRCULAR – R3Fiber	BCIRCULAR (ES)	4																			EU
	HiPerDiF	University of Bristol (UK)	5																		UK	
	Biotechnological recovery	Hohenstein Institut (DE)	2																		DE	
	SusWIND	National Composites Centre (UK)	?																			
	Additive Manufacture of Fiber Reinforced Composites	Colorado State University (US)	3																		US	
	AMERICA	GE Research (US)	4																		US	

	Initiative	Lead organisation (Country)	Design for circularity (# of applicable Circular Economy strategies)		Dematerialisation	Prevent waste	Modularise	Repair and maintain	Component reuse and repurposing	Refurbish and remanufacture components	Disassemble	Extend lifetime	Repower	Recertify	Decommission	Restore site	Recycle materials	Landfill and controlled storage	Re-mine	Energy recovery	National R&D funding (Country)	EU R&D funding
	Additive Manufactured Wind Blade Core Structure	NREL (US)	5																		US	
	On-Site Manufacturing of Wind Blades	ORNL/Orbital Composites (US)	6																		US	
	AM System Integrated Tip for Wind Turbine Blades	SANDIA (US)	?																		US	
	MEGAPRINT	University of Maine (US)	4																		US	
	Robot-Based AM of Modular Molds for Blades	University of Michigan (US)	3																		US	
	Blade repurposing (multiple initiatives)		2																			
Tower	GE RE – LaFargeHolcim (CH) and Cobod (DK)	GE RE (US)	3																			
	Modvion - Modular wooden tower	Modvion (SE)	5																			EU
Mooring	TFI – Load reducing polymer spring	TFI (IE)	2																		US	EU
Nacelle housing	Greenboats/Sicomin – NFC offshore nacelle	Greenboats (DE)	3																			
	Advance Casting Cell (ACC) 3D printer	GE/Frauhofer/Voxeljet	3																		DE	
Drivetrain/Generator	ECOSwing	Envision (DK)	3																			EU
	GreenSpur - RE-free PM generator	GreenSpur (UK)	2																		UK	
	GE - LTS generator	GE Research (US)	3																		US	
	VALOMAG	SUEZ Groupe SAS (FR)	4																			EU
	SUSMAGPRO	Hochschule Pforzheim (DE)	4																			EU

	Initiative	Lead organisation (Country)	Design for circularity (# of applicable Circular Economy strategies)		Dematerialisation	Prevent waste	Modularise	Repair and maintain	Component reuse and repurposing	Refurbish and remanufacture components	Disassemble	Extend lifetime	Repower	Recertify	Decommission	Restore site	Recycle materials	Landfill and controlled storage	Re-mine	Energy recovery	National R&D funding (Country)	EU R&D funding
Grid integration - High voltage transmission	LIFEGRID	General Electric Grid Solutions SAS (US)	1																			EU
	SuperNode	SuperNode (IE)	2																			
Grid integration - Hydrogen transport	SoluForce – Flexible Composite Pipes	SoluForce (NL)	2																			
Other	MAREWIND	L'UREDERRA (ES)	3																			EU
Circular economy strategy relates to…																						
	Materials																					
	Products and components																					
	Infrastructure																					

Source: JRC based on CE strategies categorisation as proposed by Velenturf et al, 2021.

Annexes

Annex 1. Circular economy strategies in the wind energy sector (processes, national & EU funding, estimated TRL)

Component	Collaboration/Initiative	Type of process/innovation	Volume [MEUR]	R&D Funding? [MEUR]		Estimated TRL
				EU	National	
Wind turbine blades	ZEBRA (Zero wastE Blade ReseArch)	New recycleable materials	18.5			n.a.
	CETEC project (Circular Economy for Thermosets Epoxy Composites)	Chemical (ChemCycling)	2.1		1.4	n.a.
	AIOLOS project (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	10.4		5.2	n.a.
	AKER – University of Strathclyde collaboration (Affordable and Innovative Manufacturing of Large Composites)	Thermal (fluidised bed)	unknown			3
	DecomBlades (Affordable and Innovative Manufacturing of Large Composites)	Manufacturing (Automatisation/Digitalisation)	5.4		3	n.a.
	SiemensGamesa RecycleBlades	Chemcial (Solvolysis)	unknown			6 to 8
	FibreEUse (Pyrolysis and Re-use)	Thermal (Pyrolysis)	11.9	9.8		8 to 9
	GE RE – Veolia (US) (Co-processing – Cement production)	Mechanical (Co-processing)	unknown			9
	GE RE – LaFargeHolcim and Neowa (EU) (Co-processing – Cement production)	Mechanical (Co-processing)	unknown			9
	BCIRCULAR (R3Fiber process)	Thermal (Pyrolysis & Gasification)	unknown	0.05		5 to 6
	HiPerDiF project (High Performance Discontinuous Fibre Composites)	Mechanical (Hydrodynamic alignment)	unknown		1.2	4 to 5
	Hohenstein Institute (Biotechnological recovery of fibers)	Biotechnological	unknown		0.25	1 to 2
	SusWIND initiative (Accelerating sustainable composite materials and technology for wind turbine blades)	Unknown	unknown			n.a.
	Colorado State University consortium (US) (Accelerating sustainable composite materials)	Additive manufacturing/ Recyclable materials	2.2		1.7	2 to 6
	GE Research – AMERICA project (US) (Additive and Modular Enabled Rotor Blades)	Additive manufacturing/ Recyclable materials	5.8		3.7	4 to 6
	NREL consortium (US) (Additive Manufactured Wind Blade Core Structure)	Additive manufacturing/ Recyclable materials	2.2		1.7	4 to 6
	ORNL/UMaine/Orbital Composites (US) (On-Site, High-Throughput Additive Manufacturing)	Additive manufacturing/ Recyclable materials	4.3		3.4	2 to 6
	SANDIA consortium (US)	Additive manufacturing/ Recyclable	2.2		1.7	n.a.

	(Additive manufacturing)	materials				
	UMaine consortium – MEGAPRINT (US) (Additive Manufacturing for large modular blade moulds)	Additive manufacturing/ Recyclable materials	3.0		2.4	3 to 6
	UMichigan consortium (US) (Robot-Based Additive Manufacturing of modular moulds)	Additive manufacturing/ Recyclable materials	2.9		2.3	3 to 5
	Blade repurposing (multiple initiatives)	Reprocessing	n.a.			7 to 9
Tower	GE RE – LaFargeHolcim (CH) and Cobod (DK) (3d-printing/co-processed cement)	Additive manufacturing	n.a.			6
	Modvion (Modular wooden towers)	New recyclable materials	unknown	6.55		7
Mooring	TFI (Load reducing polymer spring)	New component	unknown	0.35	undisclosed	5
Nacelle housing (Offshore wind turbine)	Greenboats – Sicomin (NFC offshore nacelle)	New recyclable materials	unknown			6 to 7
	GE/Fraunhofer/Voxeljet (Advance Casting Cell (ACC) 3D printer)	Additive manufacturing	2.6		2.6	4 to 6
Drivetrain/Generator	ECOSwing (Superconducting Wind Generator)	New component	13.9	10.6		7 to 8
	GreenSpur (UK) (Rare Earth Free Permanent Magnet Generator)	New component	unknown		1.4	5
	GE (US) (High-efficiency ultra-light low temperature superconducting (LTS) generator)	New component	unknown		18	5
	VALOMAG (Upscale of Permanent Magnet Dismantling and Recycling)	Manufacturing (H2 Decrepitiation/HDDR or Hydrometallurgy)	2.5	pending		2 to 4
	SUSMAGPRO (Sustainable Recovery, Reprocessing and Reuse of Rare-Earth Magnets in a Circular Economy)	Manufacturing (Sintering, HDDR, Sintering-debinding-shaping (SDS), recasting)	14.7	13		3 to 5
Grid integration - High voltage transmission	LIFEGRID (SF6-free High Voltage Circuit Breakers (HVCB))	New component	4.1	2.2		5
	SuperNode (MVDC transmission system based on superconducting cable technology)	New component	unknown			3
Grid integration - Hydrogen transport	SoluForce (Flexible Composite Pipes)	New component	unknown			8 to 9
Other / Collaborations addressing multiple components	MAREWIND (Material innovations for offshore wind life extension)	Multiple new components	8	6.7		n.a.

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