D2.1. Circularity performance and environmental-economic sustainability of EoLO-HUBs recycling technologies. Interim Report

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Executive summary

The implementation of wind energy generation systems is essential for the sustainable energy transition to achieve the carbon emission reduction and carbon neutrality goals for 2030 and 2050, respectively, set by the European Union (EU). However, the expansion of the wind energy sector is constrained by technical, socio-economical, policy and environmental factors. Focusing on the latter, the life cycle management of the wind turbine blades (WTBs) represents a relevant challenge to the sector as millions of tons of WTB wastes are expected to be generated in the EU and the globe over the next decade due to the decommissioning and/or repowering of old wind farms. Accordingly, the industry professionals, polycymakers and researchers are exploring alternative solutions for the sustainable end-of-life (EoL) management of WTBs.

The EoLO-HUBs project aims to provide effective innovative technological solutions for application in three main areas of the WTB recycling cycle: decommissioning and pretreatment (dismantling, inspectioning, cutting, decoating and material shredding and sorting), sustainable fiber reclamation processes (low carbon pyrolysis and green solvolysis) and material upgrading (production of recycled long fibre thermoplastics, nonwovens and composite sheets) for use in industrial applications (automobile and construction sector).

Accordingly, this report presents the preliminary findings from the qualitative and partial/simplified quantitative analysis of the circularity and sustainability performance of the EoLO-HUBs recycling processes (from WTB dismantling to material recovery for industrial use) to determine their potential resource, environmental and socio-economic improvements compared to the benchmark systems. This includes the identification of potential hotspots and the provision of recommendations for further improvement as the project develops, all based on the current state of development of the project and the data available.

This assessment was performed at four major levels (Section 4):

- EoLO-HUBs upstream recycling processes, involving decommissioning, inspectioning, cutting, decoating and material shredding and sorting (Section 4.1)
- EoLO-HUBs core recycling processes, including pyrolysis and solvolysis (Section 4.2)
- EoLO-HUBs downstream recycling processes, involving the upgrading of the recyclates for use as raw materials in industrial manufacturing sectors (automotive and construction) (Section 4.3), and
- The EoLO-HUBs system-level integrated hotspots assessment and recommendations for improvement (Section 5), including a discussion of key variables and aspects affecting the circularity and sustainability performance of WTB recycling systems.

However, as all the EoLO-HUBs solutions are currently under development, the information and data shared is preliminary and does not demonstrate yet the improved performance because some of the processes are not yet optimized as they are at the laboratory scale (e.g. WTB inspectioning, cutting, decoating and solvolysis). Likewise, there is no data yet available on the industrial tests related to the use of recycled glass and/or carbon fibres in the manufacture of automobile and construction products.

To address the limitation on the lack of information and data readily available, a practical action research methodology, involving exploratory, qualitative and quantitative analytical steps, was applied to determine the potential resource, environmental and socio-economic hotspots and improvements of EoLO-HUBs innovations compared to the benchmark and define recommendations for consideration as the project develops. Accordingly, the action research methodology involved i) the definition and characterization of WTB recycling systems (through an systematic literature review coupled with two cycles of stakeholder engagement) (Section 3.1), ii) a qualitative circularity and sustainability assessment (to identify the processes´ most relevant hotspots and potential areas for intervention) (Section 3.2) and iii) a simplified quantitative circularity and life cycle environmental assessment (through the preliminary calculation of life cycle impact assessment indicators to optimize resource efficiency and mitigate negative impacts) (Section 3.3).

Unsurprisingly, optimizing energy efficiency (in all processes), while minimizing the use of some environmentally sensitive materials, such as chemicals and additives (e.g. WTB decoating and solvolysis), abrasives (WTB decoating and waterjet cutting) and helium as well as optimizing the use of diamond wire (for cutting purposes) is considered critical to reduce the environmental burden and the cost of recovered carbon and glass fibres. Likewise, some relevant emissions for consideration and mitigation are CO2 emissions (by all processes) and particularly (considering safety and health issues) the emission of dust and particles (e.g. in WTB cutting and shredding processes), fumes (e.g. in laser cutting and thermal decoating) and organic volatile compounds (e.g. in chemical decoating and solvolysis). Focusing on technical and economic aspects, even if the recovered glass and carbon fibers could have a lower environmental footprint than virgin fibres, they end-use ultimately depends on meeting the technical specificities of industrial end-users (e.g. automobile and construction industries), in terms of physico-chemical properties, mechanical performance, safety and costs.

Consequently, evaluating the technical, economic, environmental and social opportunities and trade-offs of different recycling approaches at an early stage of development is critical to ensure that the solutions are optimized to increase the market uptake and the overall circularity and sustainability performance of the sector. This requires the development of detailed process and system models to track resource flows (including physical and monetary flows) for each recycling approach by relying on expert real business cases, expert consultations and academic and industrial literature.

Glossary of terms, abbreviations and acronyms

AGV	Autonomous Ground Vehicle
CSS	Circular Strategies Scanner
CF	Carbon Fibre
CFRP	Carbon Fibre Reinforced Polymer
ERPA	Environmentally Responsible Product Assessment
EoL	End-of-Life
EU	European Union
GF	Glass Fibre
GFRP	Glass Fibre Reinforced Polymer
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
METCO	Material, Energy, Toxicity, Circularity and Other
NA	Not applicable
NDT	Non-Destructive Testing
PEF	Product Environmental Footprint
PU	Polyurethane
rCF	recycled Carbon Fibre
rGF	recycled Glass Fibre
SLR	Systematic Literature Review
TRL	Technological Readiness Level
vCF	virgin Carbon Fibre
vGF	virgin Glass Fibre
WT	Wind Turbine
WTB	Wind Turbine Blade
WTB-EoL	Wind Turbine Blades´ End-of-Life

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1. INTRODUCTION

The present and future deployment of wind energy technologies is critical to support the sustainable energy transition to achieve the European Union (EU) climate goal to become carbon neutral by 2050 (European Commission 2019). Research forecasts indicate that the EU onshore wind capacity could reach 13.4 TW by 2050, generating approximately 34.3 PWh per year, with costs unlikely to exceed €0.06/kWh (Ryberg et al. 2019). Additionally, the EU onshore wind power production potential is estimated at 52.5 TW, which could significantly contribute to meeting low-carbon global energy demands through 2050 (Enevoldsen et al. 2019). Focusing on offshore wind energy production in Europe, it is projected to account for 8.6 TW by 2050, capable of generating 40 PWh per year at an average cost of €0.07/kWh (Caglayan et al. 2019). Accordingly, the EU installed capacity for wind power generation is expected to triple by 2030, compared to 2010 (EU and IRENA 2018), and wind energy technologies could be generating ca. 50 % of the total electricity in Europe (Lichtenegger et al. 2020).

However, the expansion of onshore and offshore wind energy technologies is constrained by technical (e.g. reliability and downtimes, insufficient transmission grids and/or grid connection issues), socio-economical (e.g. biodiversity issues, noise generation, land use, and manufacturing, operation, maintenance and decommissioning costs), policy (e.g. uncertain and unsupportive governmental policies and incentives) and environmental factors (e.g. increasing use of metals, critical raw materials and composites to produce wind turbine (WT) components) (Diógenes et al. 2020, Mendoza et al. 2022).

Focusing on resource efficiency and environmental sustainability, the circularity performance and life cycle environmental impacts of WTs are highly influenced by the type and amount of materials used in manufacturing (Kramer and Beauson 2023). Large on-shore and off-shore WTs contain over 25,000 components weighting several thousand tonnes (≈400 kt/GW) (Graulich et al. 2021). Among the most environmentally relevant materials, rare earth elements (e.g., neodymium (Nd), dysprosium (Dy) and praseodymium (Pr)) are used to manufacture the permanent magnets of the generators used in some WT models, which are subject to supply chain disruptions and environmental burdens due to their low recycling and material recoverability rates (Mendoza and Ibarra 2023). The Wind Turbine Blades (WTBs) represent also a WT component of concern as the assets installed over two-three decades ago are reaching the end of their design life (20-25 years) (Wind Europe 2020) and the generation of residual WTBs could account for up to 570 Mt between 2020 and 2030 (Sommer et al. 2020), although forecasts are variable (Delaney et al. 2023).

The WTB design is based on the use of glass and/or carbon reinforcement fibres, a thermoset-based polymer matrix (e.g. epoxies, polyesters, vinyl esters, polyurethane - PU or thermoplastics), a sandwich core (e.g. balsa wood or foams), coatings (e.g. polyethylene or PU), and metals (e.g. copper wiring and steel bolts) (Jensen and Skelton 2018). This mix of materials makes recycling technically complex because once thermoset composites are cured the polymers become cross-linked, undergoing an irreversible separation process (Jensen and Skelton 2018). Accordingly, the management of the End-of-Life (EoL) of WTB represents a critical global problem (Liu and Barlow 2017) that should be urgently handled.

Alternative EoL management solutions for WTBs, beyond sending them to landfills and/or incineration facilities, are being investigated (from repurposing solutions - understood as reusing a product or its parts for applications other than the original (e.g., Bank et al. 2018) - to recycling and material recovery strategies (e.g., Jani et al. 2022)), by incorporating circular economy criteria (Blomsma et al. 2019) to narrowing (use less), slowing (use for longer) and closing (use again) resource loops (Díez-Cañamero and Mendoza 2023).

A variety of recycling techniques (e.g., mechanical, thermal, chemical) have been developed to handle the residual WTBs and help to close material loops. However, they have different Technological Readiness Levels (TRL), and they have not been yet industrialized, beyond mechanical recycling that has been the most studied and implemented method so far (Lund and Madsen 2024). According to Sproul et al. (2023), the value of materials recovered through mechanical recycling is highly uncertain because the mixed feedstock produced may not perform as well as virgin materials, which could affect its market acceptance and economic viability. On the other hand, thermal (e.g. pyrolysis) and chemical (e.g. solvolysis) recycling systems have higher emissions due to their higher energy requirements. Also, mechanical WTB recycling offers a low-cost option but require the implementation of optimization methods and classification procedures to maximize the recovery of WTB materials, whereas thermal or chemical WTB recycling methods can recover Glass Fibres (GFs) and/or Carbon Fibres (CFs) from the thermoset matrix, but they often have lower mechanical properties for industrial use (Mamanpush et al. 2018). Likewise, the quality of fibres obtained after recycling, and subsequently future applicability of the recyclate in the industry, depends on adopted technology (Spini and Bettinni 2024). Accordingly, the technical performance, cost and environmental impacts can vary greatly between WTB recycling processes (Sorte 2023).

In any case, a Systematic Literature Review (SLR) performed by Lund and Madson (2024) demonstrates that there is a significant gap in empirical data from actual Wind Turbine Blades' End-of-Life (WTB-EoL) management projects. There is yet a lack of knowledge on the complete value chain, including requirements related to logistics, sectioning, pre-processing, and refining recovered materials for secondary applications, as well as the environmental, social, and cost impacts associated with all these processes. This has been previously highlighted by Delaney et al. (2023), who indicate that existing studies on WTB-EoL management often do not account for the entire decommissioning process, from WT dismantling to the final recycling and material recovery stage, leading to inaccurate forecasts and circularity and sustainability assessments. Besides, different studies have provided conflicting results on which recycling solutions are most sustainable, demonstrating a need to facilitate access to more information, data and real business cases or projects to develop comprehensive and reliable circularity and sustainability comparisons from multiple perspectives, as most current studies are t conceptual level or they are review-based (Lund and Madsen 2024, Fayyaz et al. 2023).

Consequently, developing and upscaling efficient and sustainable WTB recycling systems is of paramount importance to ensure WTB wastes generated in the short- to medium-term will be properly handled. But these systems should be properly designed, planned for their efficient and sustainable deployment and life cycle management. While some techniques represent temporary and partial solutions (e.g. repurposing, which in practice is a way to delay the problem at some point in the future where WTB-based repurposed products will have to be recycled), other already implemented techniques, such as cement co-processing (in substitution of clinker elements) is placed low in the hierarchy of CE solutions, meaning that their circularity and sustainability potential is reduced (Mendoza et al. 2022).

Within this context, the Horizon Europe´s EoLO-HUBs project (Agreement No 101096425 – EoLO-HUBs – HORIZON-CL5-2022-D3-01) aims at developing and demonstrating efficient WTB recycling systems for the circular and sustainable management of EoL-WTBs, validated through the development of comprehensive circularity and life cycle sustainability assessment studies by relying on the use of primary data and active stakeholder engagement.

2. EoLO-HUBs PROJECT

2.1. Project overview

The EoLO-HUBs project (https://www.eolo-hubs.eu/) aims to provide effective technological solutions for application in the three main areas of the WTB-EoL management processes:

i) Decommissioning and pre-treatment of WTBs, including handling, non- destructive inspection tools, cutting, shredding, and sorting.
ii) Sustainable fibre reclamation processes addressing two alternative technologies: Low carbon pyrolysis and green chemistry solvolysis.
iii) Upgrading processes for the recovered fibres, including both GF and CF.

Furthermore, a knowledge hub will be set up by means of a digital platform. This platform will provide a circular economy framework, an overview of circular solutions for WTBs and the organizations offering such solutions, and a toolset for sustainable business model development to enable the adoption of WTBs recycling in diverse regions across Europe. Development of secure material passports to provide accurate data on raw materials and design recommendations will further enhance turbine blade recycling in the future.

2.2. EoLO-HUBs WP2 and Task 2.1 on the comprehensive characterization of the life cycle of WTBs from cradle-to-cradle

The main goal of WP2 (Circular design principles for blade recycling processes) is to set the grounds for the adoption of circular design principles into the next-generation. In this process, the following specific goals were defined:

- Map, prioritize and characterize the technical, economic, environmental, and social aspects related to the life cycle management of WTBs recycling alternatives.
- Provide blade OEMs with design rules to design next-generation blades using circular design principles covering the full range of circular economy strategies.
- Develop a materials passport structure to track materials through multiple lifecycles in line with the expected EU regulation on material passports.
- Quantity impacts and benefits of EoLO-HUBs WTB designs and recycling technologies compared to business-as-usual approaches.

Accordingly, the main goal of Task 2.1 (running from Month 1 (January 2023) until Month 42 (June 2026)) is to characterize the most relevant technical, economic, environmental, and social aspects and hotspots related to the design, manufacturing, and EoL management of WTBs to improve circularity and sustainability performance through the project innovations. Task 2.1 is divided into three sub-tasks (ST):

- ST2.1.1. Mapping the technical, economic, environmental, and social aspects of the life cycle management of WTBs from cradle to cradle (M1-M12) (TNO, MGE, ULE)
- ST2.1.2. Analysis of the circularity performance of EoLO-HUBs recycling solutions (M6-M36) (MGE, TNO), and
- ST2.1.3 Environmental and economic sustainability assurance (M6-M42) (MGE, TNO)

The results from the development of these activities will be shared through the following project deliverables:

i) D2.1: Circularity performance and environmental-economic sustainability of EoLO-HUBs recycling technologies – Interim report (M18, MGEP) (*this report*)
ii) D2.2: Technical, economic, environmental, and social challenges and opportunities of WTB life cycle management from cradle to cradle (M24, TNO)
iii) D2.5: Final report on circularity performance and environmental-economic sustainability of EoLO-HUBs recycling technologies and management systems (M45, MGEP).

2.3. Deliverable D2.1 – circularity performance and environmental-economic sustainability of EoLO-HUBs recycling technologies

This report (D2.1) describes the main activities performed from M1 to M18 and presents the preliminary findings from the qualitative and partial/simplified quantitative analysis of the circularity and sustainability performance of the EoLO-HUBs recycling processes (from WTB dismantling to material recovery for industrial use) to determine their potential resource, environmental and socio-economic improvements compared to the benchmark. This includes the identification of potential hotspots and the provision of recommendations for further improvement as the project develops, all based on the current state of development of the project and the data available.

Detailed evaluations and discussions on the limitations and opportunities of WTB-EoL management processes, including the evaluation of alternative circular solutions (beyond recycling) to handle the residual WTBs will be provided in D2.2 (Technical, economic, environmental, and social challenges and opportunities of WTB life cycle management from cradle to cradle (M24)).

3. METHODOLOGY

As the EoLO-HUBs project is still in an early stage of development (M18 out of M48: 38%), a simplified and mostly qualitative/semi-quantitative, but practical and meaningful, approach has been applied to evaluate the potential circularity and sustainability performance of the project innovations.

A practical action research methodology, involving exploratory, qualitative and quantitative analytical steps, has been applied to ensure the achievement of the EoLO-HUBs project´s task 2.1 goals and the expected results. Action research is a flexible and well-suited approach to work with (and within) organizations (and business cases) to analyze socio-technological aspects through multiple iterations with stakeholders in order to effectively address problems that require practical solutions through collaboration (Prendeville et al. 2017a). This also helps to bring richness and uniqueness to projects and case studies (Prendeville et al. 2017b).

Figure 1 illustrates the action research methodology, involving three major analytical blocks comprising the following activities:

i. <u>Definition and characterization of WTB recycling systems</u>: SLR of academic and industrial literature coupled with two cycles of (internal and external) stakeholder engagement (questionnaires and individual online meetings), as well as several communications and exchanges via email, to examine the most relevant technical, economic, social and environmental aspects of benchmark and EoLO-HUBs WTB recycling systems (from decommissioning to end-users) as well as gathering process data (section 3.1).

ii. Qualitative circularity and sustainability assessment: definition and analysis of the processes´ most relevant resource inflows and outflows, and potentiatrade-offs, to get an overview of the most important circularity and sustainability aspects of concern by relying on the guidelines provided by Laurent et al. (2020) and Weidema et al. (2020). On the one side, an extended version of the Environmentally Responsible Product Assessment (ERPA) (Graedel 1996) and the Material, Energy, Toxicity, Circularity and Other (METCO) (Ihobe 2019) matrices coupled the Circular Strategies Scanner (CSS) (Blomsma et al. 2019) where used as support to define resource inflows and outflows, and potential circularity solutions (section 3.2).

iii. Simplified quantitative circularity and life cycle environmental assessment: partial quantitative assessment of the circularity performance and life cycle sustainability impacts of EoLO-HUBs recycling systems, compared benchmark WTB recycling processes, to identify hotspots and areas for intervention to optimize resource efficiency and mitigate negative impacts (section 3.3). The integrated assessment was based on Pihkola et al. (2022) and Luthin et al. (2023) approaches. The Life Cycle Assessment (LCA) was based on the Product Environmental Footprint – PEF (European Commission 2021), although a simplified LCA was performed at this stage of the project.

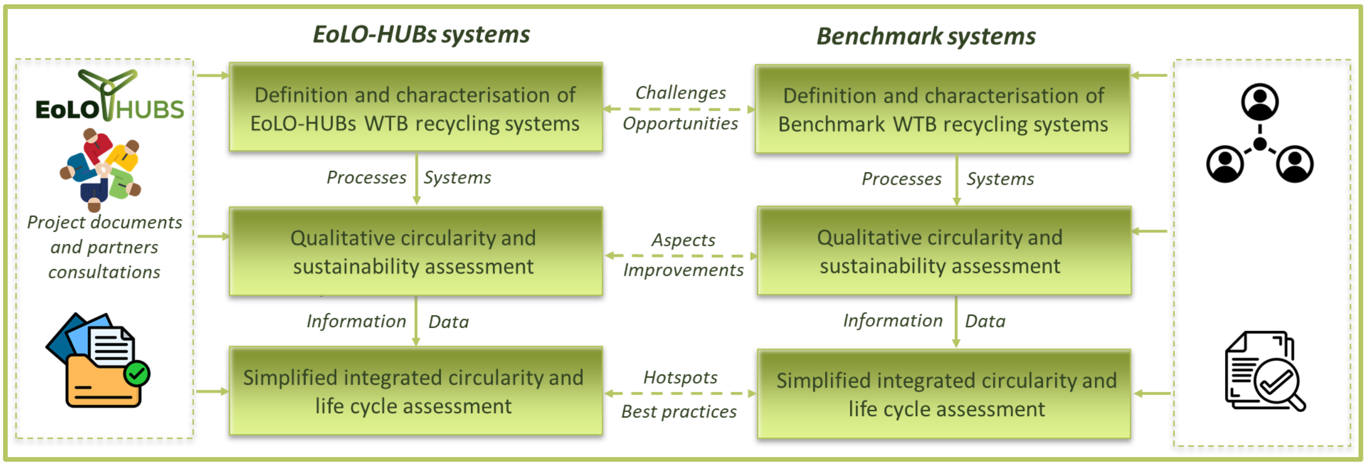

Figure 1. Preliminary EoLO-HUBs action research methodological approach.

Accordingly, the following sub-sections describe the most relevant methodological activities developed from M1 to M18 to meet the task 2.1 goals. Importantly, only the processes, technologies and materials under improvement (through innovation) within the EoLO-HUBs project were considered to estimate the potential resource and impact savings compared to the benchmark. This means that (in D2.1) the upstream and downstream WTB management processes prior to and after recycling, which are not subject to change due to the projects innovations (hence, out of scope within the project), have not been considered in the qualitative and (simplified) quantitative circularity and sustainability assessment. These processes are supposed to remain the same (in terms of operational performance) for both benchmark and EoLO-HUBs WTB recycling systems. Besides, at this still early stage in the project development it is hard to envision how the upstream and downstream WTB recycling processes that are going to actually change or be somewhat (as directly and/or indirectly, positively and/or negatively) influenced and/or affected by the project innovations, as they have not been yet fully developed and implemented in WP4 and WP5. In any case, more detailed technical, economic, environmental and social information and data on the entire WTB life cycle management processes from cradle to cradle, including the analysis of real-case scenarios, are provided in D2.2 (to be submitted in December 2024).

Accordingly, the preliminary circularity and sustainability assessment was addressed by considering the three major WTB goals and recycling stages of the project (as illustrated in Figure 2), where each of the EoLO-HUBs project partners is developing specific innovations and/or analytical studies (as described in Table 1).

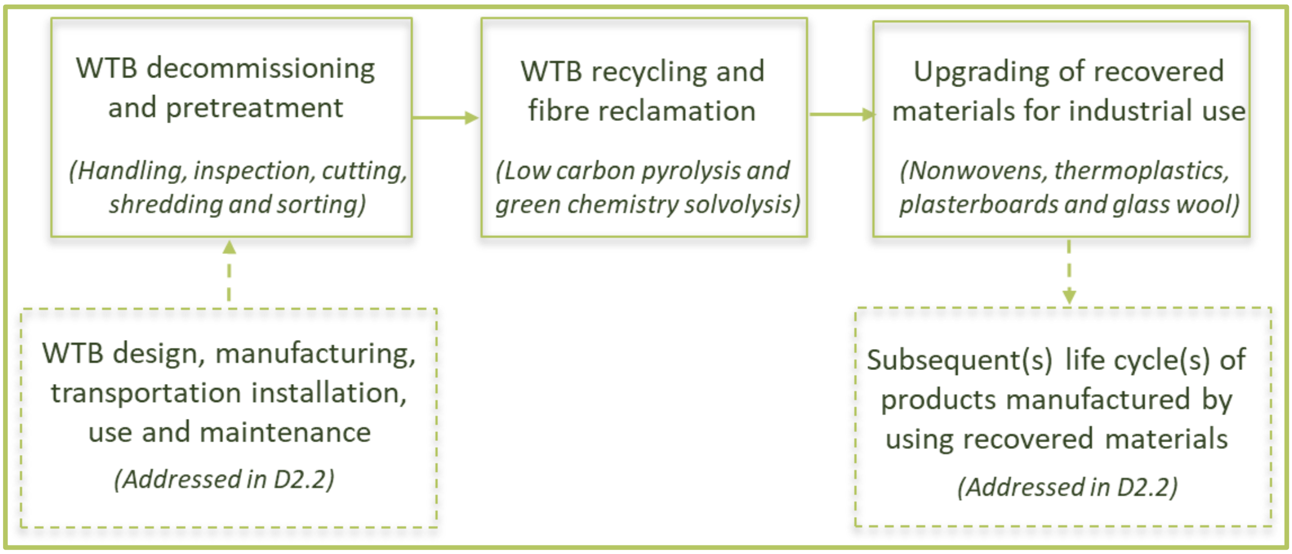

Figure 2. Major EoLO-HUBs recycling stages and innovations.

In the context of the report D2.1 it has been considered that WTB recycling does not only integrates the actual recycling process (from gate to gate; waste into recyclates) but also the required upstream processes (decommissioning and pre-treatment) and downstream processes (material upgrading for industrial use) (Figure 2). This is usually overlooked in the literature anaysing the performance of WTB recycling systems, which is a relevant gap and omission as large part of the cost and environmental burden of the WTB-based recycled Glass Fibre (rGF) and recycled Carbon Fibre (rCF) is determined by the upstream processes, as highlighted by Lund and Medsen (2024).

Table 1. WTB management stages and processes considered in the research, including the EoLO-HUBs partners´ contributions. Note: stages, processes and innovations on italic letters are excluded from the assessment as i) these studies are provided in other EoLO-HUBs project´s deliverables and/or ii) they are out-of-scope or not applicable for the D2.1 assessment.

WTB life cycle stages	**Partners**	**Processes**
WTB design, manufacturing, installation, use and maintenance (out-of-scope, analyzed in D2.2)	NORDEX	*WTB design and manufacturing*
WTB decommissioning and management	ADVANTIS	WTB diamond wire cutting
	AITIIP	WTB waterjet cutting and WTB decoating
	FHG	WTB shredding and sorting
	MTC	WTB inspectioning and laser-based cutting
	PLATA	WTB storage and logistics management
	JRG	WTB dismantling and management
	NCC	WTB material passport, WTB alternative designs
	TNO	WTB decommissioning tool
WTB Recycling	MCAM	WTB recycling through low carbon pyrolysis
	MOSES	WTB recycling through green solvolysis
Material upgrading and end-use	TNO	reLFT production
	NCC	Recycled long-fibre reinforced composite sheet production
	FHG	Recycled textile (nonwoven) production
	SGP	Production of recycled gypsum plasterboards and glass wool
	CRF	Production of injection molding car parts
Transversal processes and studies *(out-of-scope with the exception of MGEP activities, which belong to this deliverable D2.1; rest provided in the corresponding project deliverables)*	MGEP	Circularity and life cycle assessment
	TNO	*Material Flow Analysis and economic and social assessment*
	ULEEDS	*Circular economy framework, policy instruments and cement co-processing*
	ECHT	*Knowledge hub digital platform and business ecosystem*
	SDP	*Market assessment and business exploitation plan*
	POLYMERIS	*Dissemination, communication and replication*

Acronyms: AITIIP - Fundacion AITIIP, ECHT - ECHT Regie in Transitie B.V., NORDEX - NORDEX Energy GMBH, MOSES – MOSES Productos SL, MCAM - Mitsubishi Chemical Advanced Materials GMBH, PLATA - Consorcio Aerodromo Aeropuerto de Teruel, ADVANTIS - ADVANTIS APS, FHG – Fraunhofer Gesellschaft Zur Forderung der Angewandten Forschung EV, JRG - Jansen Recycling Group B.V., MGEP - Mondragon Goi Eskola Politeknikoa, SGP - Saint-Gobain PLACO IBERICA SA, SDP - Global Equity & Corporate Consulting SL, TNO – Nederlandse Organisatie Voor Toegepast Natuurwetenschappelijk Onderzoek, CRF - Centro Ricerche FIAT SCPA, re-LFT – recycled Long Fibre Thermoplastic, WTB – Wind Turbine Blades,

3.1. Definition and characterization of WTB recycling systems

On the one hand, benchmark WTB recycling systems were defined and characterized by performing a SLR of academic and industrial documents. On the other hand, the EoLO-HUBs´ WTB recycling systems were defined and characterized by relying on multiple projects´ documents and through the engagement of the project partners in online meetings and email consultations. The project partners also provided feedback on benchmark WTB recycling processes, which helped to complete the previous assessment.

3.1.1. Definition and characterization of benchmark WTB recycling systems

A SRL of academic (journal papers) and industrial (reports, projects, business associations, individual companies, regulations and guidelines) literature was performed to define WTB recycling systems and gather technical, economic, environmental and social information and data. A SLR is an independent academic method that aims to identify and evaluate all relevant literature on a topic in order to derive conclusions about the question under consideration (TUB 2024). Accordingly, the PRISMA protocol and flow diagram template to perform and communicate SLR (Page et al. 2021) was followed to make the literature review and selection process transparent and reproducible.

Figure 3 provides an overview of the SLR outcomes and the final sample of documents used in the research. by considering different databases, registers and sources.

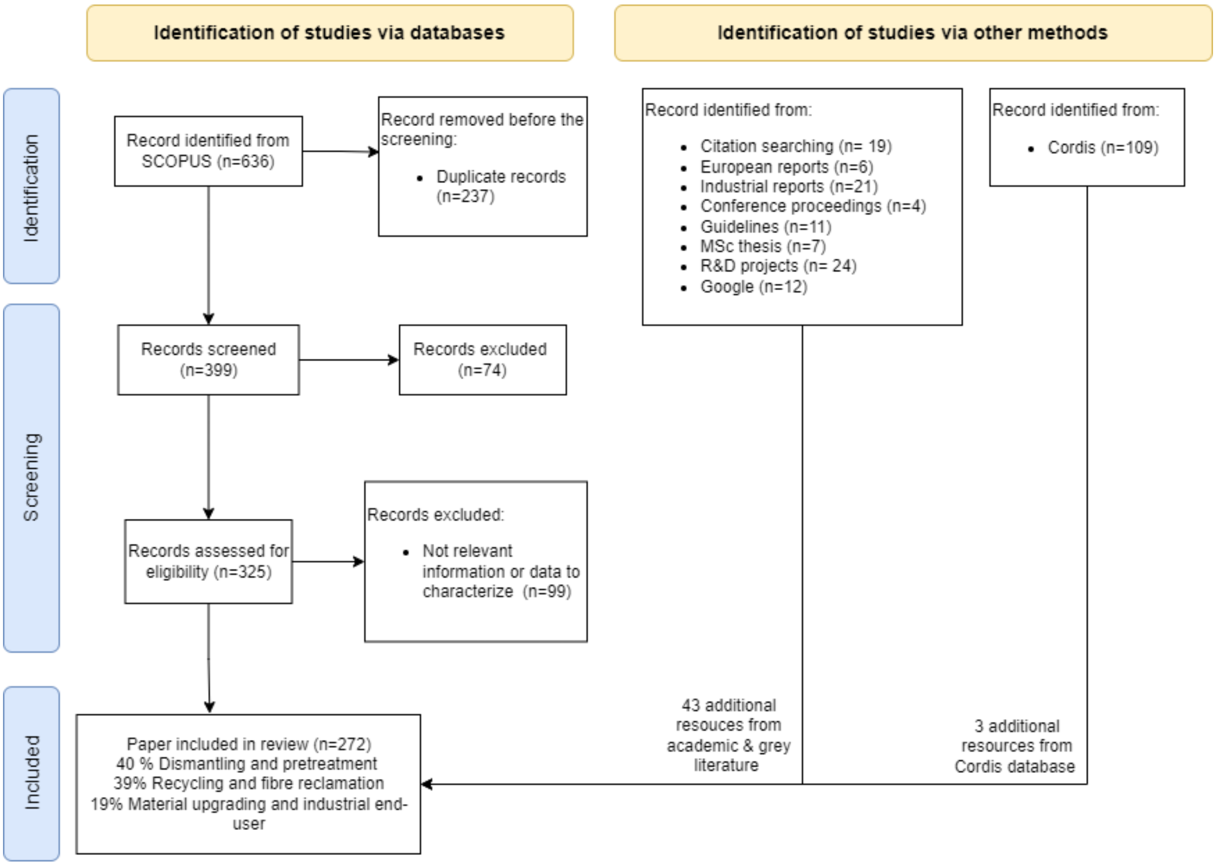

Figure 3. Systematic literature review procedure and outcomes. Based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyzes (PRISMA) flow diagram (Page et al. 2021).

As illustrated in Figure 3, a three-stage literature review was performed, including the analysis of academic and grey literature. A total of 272 resources (both academic and grey literature) were identified to define and characterize each stage of blade treatment, of which 40% were used to characterize the dismantling and pretreatment stage, 39% recycling (mechanical, thermal and chemical), and 19% for material upgrading and end-users. This shows the research gap in the characterization of the last phase which is crucial to ensure recyclates can be used in industrial applications.

Focusing on each individual SLR process, Table 2 presents the three specific literature searches performed to identify and analyze relevant literature on WTB decommissioning and pretreatment, WTB recycling and fibre reclamation, and material upgrading processes for industrial use.

Table 2. Literature searchers, keywords combinations and results obtained. Acronyms: WTB (Wind Turbine Blades), LCA (Life Cycle Assessment), LCI (Life Cycle Inventory).

Literature searchers	Streams		Keywords	Hits
WTB decommissioning and pretreatment	A	1	“Wind turbine blade*”	**24**
		2	decommissioning OR dismantling OR logistic* OR lifting OR transport* OR pre-processing OR handling OR cutting OR cut OR sawing OR saw OR "water jet" OR sectioning OR storage	
		3	"end of life" OR "end of life management" OR "end-of-life" OR "life cycle management" OR "life cycle thinking" OR "life cycle analysis" OR "life cycle assessment" OR "life cycle costing" OR "social life cycle assessment" OR "social life cycle analysis" OR "life cycle sustainability analysis" OR "life cycle sustainability assessment" OR "circularity" OR "circular economy" OR "material flow analysis" OR "material flow assessment" OR "business model" OR "value chain" OR "supply chain" OR "stakeholder network" OR "business ecosystem" OR "value network" OR "sustainability analysis" OR "sustainability assessment"	
	B	1	Same as above	**27**
		2	"circular economy" OR circularity	
	C	1	Same as above	**316**
		2	decommissioning OR dismantling OR logistic* OR lifting OR transport* OR pre-processing OR handling OR cutting OR cut OR sawing OR saw OR "water jet" OR sectioning OR storage	
WTB recycling and fibre reclamation	A	1	“Wind turbine blade*”	**37**
		2	recycl*	
		3	mechanic* OR grinding OR shedding OR thermal OR chemical OR pyrolysis OR solvolysis OR thermolysis	
		4	"end of life management" OR "end-of-life" OR "end of life" OR "life cycle management" OR "life cycle thinking" OR "life cycle analysis" OR "life cycle assessment" OR "life cycle costing" OR "social life cycle assessment" OR "social life cycle analysis" OR "life cycle sustainability analysis" OR "life cycle sustainability assessment" OR "circularity" OR "circular economy" OR "material flow analysis" OR "material flow assessment" OR "business model" OR "value chain" OR "supply chain" OR "stakeholder network" OR "business ecosystem" OR "value network" OR "sustainability analysis" OR "sustainability assessment"	
	B	1	“Wind turbine blade*”	**81**
		2	recycl*	
		3	mechanic* OR grinding OR shedding OR thermal OR chemical OR pyrolysis OR solvolysis OR thermolysis	
	C	1	"wind turbine blade*"	
		2	"fibre upgrad*" OR "fibre sizing" OR "fibre sizing" OR "fibre upgrad*" OR non-woven OR woven OR gypsum OR "gypsum plasterboard*" OR "gypsum composite molding"	**18**

			OR "recycled thermoplastic*" OR "glass wool" OR cement OR concrete OR asphalt OR "filler production" OR "automobile industry" OR "construction industry" OR "automobile product*" OR "constrction product" OR "cement clinker" OR "car product*" OR "car part*" OR "car mat*" OR "wind turbine material*" OR "wind turbine product*" OR "solvent recovery" OR "organic fraction recovery" OR "long fibre reinforced thermoplastic*" OR "long fibre reinforced thermoplastic*" OR "thermal insulation" OR "recycled glass fibre*" OR "recycled glass fibre*" OR "recycled carbon fibre*" OR "recycled carbon fibre*"	
		3	"end of life" OR "end of life management" OR "end-of-life" OR "life cycle management" OR "life cycle thinking" OR "life cycle analysis" OR "life cycle assessment" OR "life cycle costing" OR "social life cycle assessment" OR "social life cycle analysis" OR "life cycle sustainability analysis" OR "life cycle sustainability assessment" OR "circularity" OR "circular economy" OR "material flow analysis" OR "material flow assessment" OR "business model" OR "value chain" OR "supply chain" OR "stakeholder network" OR "business ecosystem" OR "value network" OR "sustainability analysis" OR "sustainability assessment"	
	D	1	"wind turbine blade*"	**69**
		2	"fibre upgrad*" OR "fibre sizing" OR "fibre sizing" OR "fibre upgrad*" OR non-woven OR woven OR gypsum OR "gypsum plasterboard*" OR "gypsum composite molding" OR "recycled thermoplastic*" OR "glass wool" OR cement OR concrete OR asphalt OR "filler production" OR "automobile industry" OR "construction industry" OR "automobile product*" OR "constrction product" OR "cement clinker" OR "car product*" OR "car part*" OR "car mat*" OR "wind turbine material*" OR "wind turbine product*" OR "solvent recovery" OR "organic fraction recovery" OR "long fibre reinforced thermoplastic*" OR "long fibre reinforced thermoplastic*" OR "thermal insulation" OR "recycled glass fibre*" OR "recycled glass fibre*" OR "recycled carbon fibre*" OR "recycled carbon fibre*"	
Material upgrading and industrial end-user	A	1	"LCA" OR "life cycle assessment" OR "LCI OR "life cycle inventory"	**40**
		2	"glass wool"	
	B	1	"LCA" OR "life cycle assessment" OR "LCI OR "life cycle inventory"	**13**
		2	"gypsum plasterboard"	
	C	1	"LCA" OR "life cycle assessment" OR "LCI" OR "life cycle inventory"	**2**
		2	"Pedals bracket " OR "Radiator fan" OR "Front cooling module" OR "Air intake manifold"	
	D	1	"LCA" OR "life cycle assessment" OR "LCI" OR "life cycle inventory"	**9**
		2	"Pedals bracket " OR "Radiator fan" OR "Front cooling module" OR "Air intake manifold" OR "Automotive	
		3	" Injection molding " OR " Injection "	

The searches for the literature review were performed using SCOPUS as a search engine. In all cases, the WTB keyword is used to focus the search on the main topic of the study. This second stream has been changed with different types of keywords related to dismantling, EoL phase, management, circular economy and logistics to cover as much as possible. For all the searches, only journal papers in English that were published between 2010 to the present were selected. The searches were mainly performed in December 2023, complemented by searches in April 2024.

In the WTB dismantling and pretreatment search, a total of 367 articles were found, in this case mostly cutting and to a lesser extent Y. Regarding the WTB recycling and fibres reclamation, 205 articles where found, most of them on mechanical recycling, as it has been the most widely used method so far, followed by pyrolysis, which has started to gain momentum in recent years, and very few articles on solvolysis, due to its fairly recent development. Finally for the material upgradding and industrial end-users few works have been found on LCA of the products to be manufactured in the EoLO-HUBs project, a total of 64 articles.

Therefore, the bibliographic searches performed yielded 636 results on the dismantling and pretreatment, recycling and upgrading phase of WTBs; the searches were performed using SCOPUS as the search engine. Of all the hits, 237 paper were discarded as they were duplicates; then, after reading the abstract of the remaining papers, 74 additional documents were discarded due to lack of focuse on the topic or not relevant to the assessment. Once these papers were analyzed (complete reading), a further 99 papers were removed due to the same reasons. Thus, the final sample of papers obtained through an academic literature review was 226 papers.

These SRL searches for academic documents were later on complemented and completed with a search for industrial literature, including reports, projects, business associations, individual companies, regulations and guidelines. The same approach for the literature search (divided into three major analytical blocks) was applied here to identify relevant industrial documents for consideration in the project (Table 3). In this process, Google was used as the primary search engine, which was combined with a search for relevant documents on the website of official bodies working on WTB life cycle management (e.g. Wind Europe, IEA Wind TCP Task 45, Spanish Wind Energy Association, NREL, etc) and consultation to the CORDIS database of EU projects (European Commission 2024).

Table 3. Overview of the number of industrial documents (grey literature) revised per type of source consulted.

Grey literature	Document type	Number
WTB decommissioning and pretreatment	Industry reports	10
	R&D projects	15
	Conferences proceedings	4
	MSc thesis	4
	Guidelines	9
WTB recycling and fibrereclamation	Industry reports	5
	R&D projects	9
	Citation searching	19
	European reports	6
	Google	12
	Cordis database	109
	MSc thesis	3
	Guidelines	2
Material upgrading and industrial end-user	Industry reports	6
TOTAL	**Grey literature**	**213**

In the literature on dismantling and pretreatment, industrial reports, R&D projects, theses, and guidelines have been considered to identify and define the different phases of dismantling and pretreatment more completely. The industrial reports and the R&D projects have been used to identify the machinery and the operating parameters of the benchmarks defined in each case. In the case of the theses, guidelines and industrial reports, they have served to define the guidelines and sub-processes within each of the processes described (dismantling, inspection, cutting, decoating, shredding and sorting).

On the other hand, for WTB and fibre reclamation recycling, industrial reports, R&D projects, thesis and guidelines have also been taken into account to identify and define in a more complete way the different phases of blade recycling. Industry reports and R&D projects have been used to identify real cases of blade recycling. In the case of thesis and guidelines, they have been used to define patterns and sub-processes within the type of recycling. Additionally, a search was conducted in the European Commission's CORDIS platform database with the aim of identifying mechanical recycling projects for WTB that have not been addressed in the academic and grey literature. This search was carried out in April 2024 and the term "mechanical recycling blades" was used as the search criterion. A total of 109 projects were identified. After excluding projects previously identified in the grey and academic literature, and those not focused on mechanical recycling of WTBs, a total of 3 relevant projects were identified (3% of total projects identified): EcoBlade, REFRESH and Green-Tech Fibre insulation.

Finally, for the material upgrading and industrial end-users, only industry reports, such as Environmental Product Declarations (EPDs) (https://www.environdec.com/home) have been used to identify final products, their composition and manufacturing process.

To structure and facilitate the process of information and data gathering from the selected academic and industrial literature an Excel-based template was developed, comprising the elements described in Table 4.

Table 4. Excel-based template used to gather information and data from the revised literature. Acronyms: GFRP (Glass Fibre Reinforced Polymers), CFRP (Carbon Fibre Reinforced Polymers), WTB (Wind Turbine Blade), EoL (End-of-Life).

Assessment	Aspects	Description
Literature	Type	General information about the revised documents
	Author	
	Title	
	Link	
WTB recycling stages and processes	Problem/solution	Problem or need addressed and solution proposed
	WTB type	GFRP, CFRP or mix
	Scenario	Based on Figure 2 (e.g. decommissioning and pre-treatment, recycling, material upgrading)
	Sub-scenario	Based on Figure 2 (e.g. type of recycling system: mechanical, thermal, chemical)
	Functional unit	Reference basis considered in the document
	Processes	WTB upstream, core and downstream recycling processes
	Technologies	Machinery and equipment used
	Technical aspects	Operational conditions and requirements
	Resource inflows	Energy, material, water as well as socio-economic requirements
	Resource outflows	Wastes, emissions, byproducts, products
Value chain considerations	Collaborators/Partners	Partners required to perform the different activities/processes
	Clients/Customers	Targeted customers and economic sectors/segments

Assessment	Aspects	Description
Sustainability considerations	Technical aspects	Technical challenges and opportunities
	Economic aspects	Economic challenges and opportunities
	Social aspects	Social challenges and opportunities
	Environmental aspects	Environmental challenges and opportunities

3.1.2. Definition and characterization of EoLO-HUBs WTB recycling systems

This activity involved the analysis of multiple internal project documents and the development of two cycles of stakeholder engagement to characterize the most relevant technical, economic, environmental and social aspects of the EoLO-HUBs WTB recycling systems, as described below.

The Grant Agreement 101096425 and all the project deliverables and partners´ presentations from M1 up to the submission of this report were revised to gather information and data on all the WTB recycling processes and innovations from WTB decommissioning up to material recovery and uptake in the industry. This allowed us to apply a "modular approach" to compile and categorize information and data per partner and major WTB recycling process from a life cycle thinking perspective.

In order to complete the information and data gathered from the revised project documents, the EoLO-HUBs technical project partners (WP4 and WP5) were contacted to further define and characterize their technology and process innovations as well as discussing the potential challenges and improvement opportunities compared to benchmark systems by responding to a number of questions and data requirements.

In this process, the WP4 and WP5 EoLO-HUBs partners participated in two cycles of stakeholder engagement:

i) The first stakeholder engagement cycle (which took place between October and November 2023) involved sharing an Excel-based template comprising a number of general questions and data requirements to be filled up by the project partners. The completed Excel files (who were received by MGEP between December 2023 and January 2024) were then revised to identify gaps and, therefore, define further information and data requirements to complete the assessment.
ii) The second stakeholder engagement cycle (which took place between February and March 2024) comprised the development of individual online meetings where a company technical sheet (an extended version of the Excel-file described in (i)) and link to a MIRO platform (https://miro.com/es/) was shared with the EoLO-HUBs partners to check, validate and/or provide further information and data for the circularity and sustainability assessment of the project innovations (section 3.2. and 3.3.). The partners also provided information on business model aspects required for the development of the activities described in WP3 (e.g. T3.4.1, deliverable D3.5 by M24).

Accordingly, during the first stakeholder engagement cycle an Excel-based information and data collection sheet was developed and shared with the EoLO-HUBs project stakeholders, comprising the following structure (Figure 4):

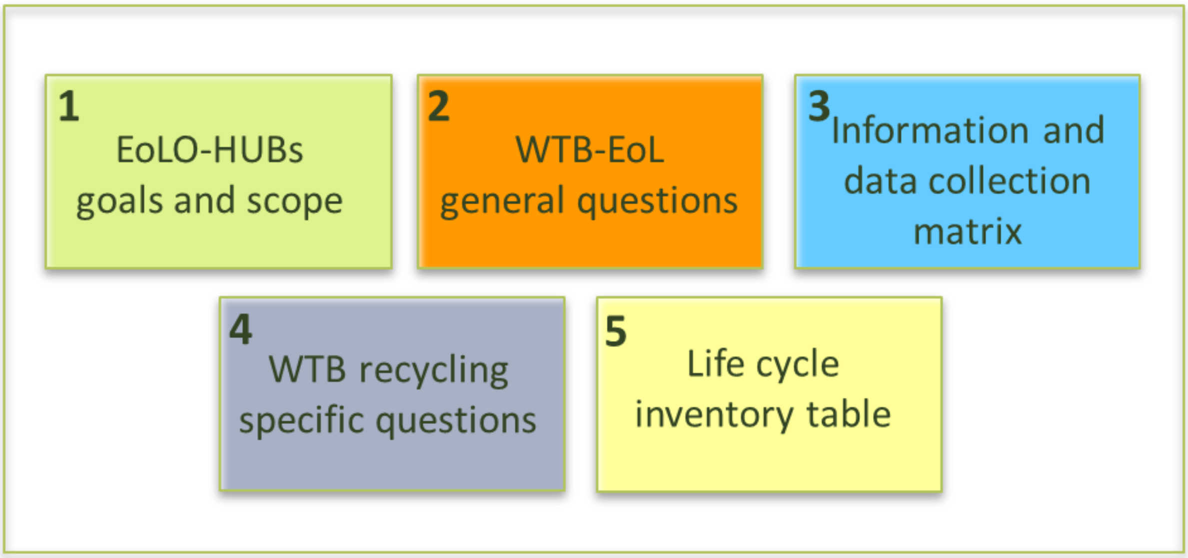

Figure 4. Illustration of the structure and content of the Excel-based data collection sheet shared with the project partners in the first engagement.

Accordingly, the shared Excel-file comprised the following tabs:

- Tab#1: An overview of the EoLO-HUBs goals, scope and project participant activities
- Tab#2: Ten general questions on WTB EoL management to get further information on the different technology and process innovations developed within the project, and their perception about the most relevant challenges and opportunities of EoLO-HUB recycling processes compared to benchmark systems.
- Tab#3: A qualitative assessment matrix (based on Graedel 1999 and Ihobe 2019) to identify/define the most relevant process hotspots with regard to energy, water, materials, products, byproducts, emissions and other (e.g. biodiversity, land use) inputs and outputs flows, toxicity and social risks (due to potential emissions and waste generation), economic costs, and circularity opportunities. To support the identification of circularity opportunities and/or solutions already implemented or under implementation and the selection of circularity opportunities with an interest for exploration, the CSS developed by Blomsma et al. (2019) was integrated into the Excel-sheet.
- Tab#4: specific questions about WTB recycling processes and the required industrial manufacturing processes to use the recyclates
- Tab#5: an inventory data collection table to provide the available data on the EoLO-HUBs innovations

All the EoLO-HUBs project partners completed the Excel file by themselves. However, a few online meetings were required to be performed (e.g. between MGEP and AITIIP, MOSES, FHG and MCAM) to clarify some aspects or doubts raised by the project partners about how to interpret and/or respond to some questions or queries.

Once the Excel files were completed and received, they were individually analyzed by the MGEP team to verify it and/or ask for further information during the second stakeholder engagement cycle. Accordingly, all the information and data received were centralized in a single Excel-file to get an overview of all the information and data available on the EoLO-HUBs project innovations and identify gaps or issues (at the individual level = process/partner and the whole project = system) required to be addressed through further consultations to the EoLO-HUBs partners.

Consequently, a second EoLO-HUBs stakeholder engagement cycle was performed to verify and/or ask for further information and data. It involved the development of 14 individual online meetings (lasting 1.5h to 2h) with all the technical partners from WP4 and WP5 (AITIIP, MOSES, MCAM, PLATA, ADVANTIS, FHG, JRG, SGP, TNO, CRF, NCC, MTC and NORDEX) as process and technology developers). Table 5 provides an overview on the dates were these meetings took place.

Table 5. List of online meetings developed with the technical (WP4 and WP5) project partners. Acronyms: WTB (Wind Turbine Blade), LCA (Life Cycle Assessment).

WTB life cycle stages	Partners	Processes	Online meetings
WTB manufacturing	NOR	WTB LCA	March 13, 14-6h CET
WTB decommissioning and management	ADV	Diamond wire cutting	February 27, 11:30-13h CET
	AITIIP	Waterjet cutting and decoating	March 7, 11-13h CET
	FHG	Shredding and sorting	March 4, 14-15:30h CET
	MTC	Inspectioning and laser-based cutting	February 26, 14-15:30h CET
	PLATA	Storage and logistics management	March 5, 15-16:30h CET
	JRG	Dismantling and management	March 11, 10:30-12h CET
	TNO	Decommissioning tool	February 22, 9:30-12h CET
WTB Recycling	MCAM	Low carbon pyrolysis	March 6, 11-12:30h CET
	MOSES	Green solvolysis	February 23, 10-12h CET
Material upgrading and end-use	TNO	reLFT production	February 20, 12-13:30h CET
	NCC	Recycled long-fibre reinforced composite sheet production	March 1, 14-15:30h CET
	FHG	Recycled textile (nonwoven) production	Same as above
	SGP	Production of recycled gypsum plasterboards and glass wool	February 29, 15-16:30h CET
	CRF	Production of injection molding car parts	February 22, 9-11:30h CET

To facilitate the online consultation meeting, an individual Power Point presentation and technical Excel sheet (representing an extension from the original) per company and innovation process was developed and shared during the meetings, including a MIRP platform that was populated directly during the interaction with the partners (Figure 5).

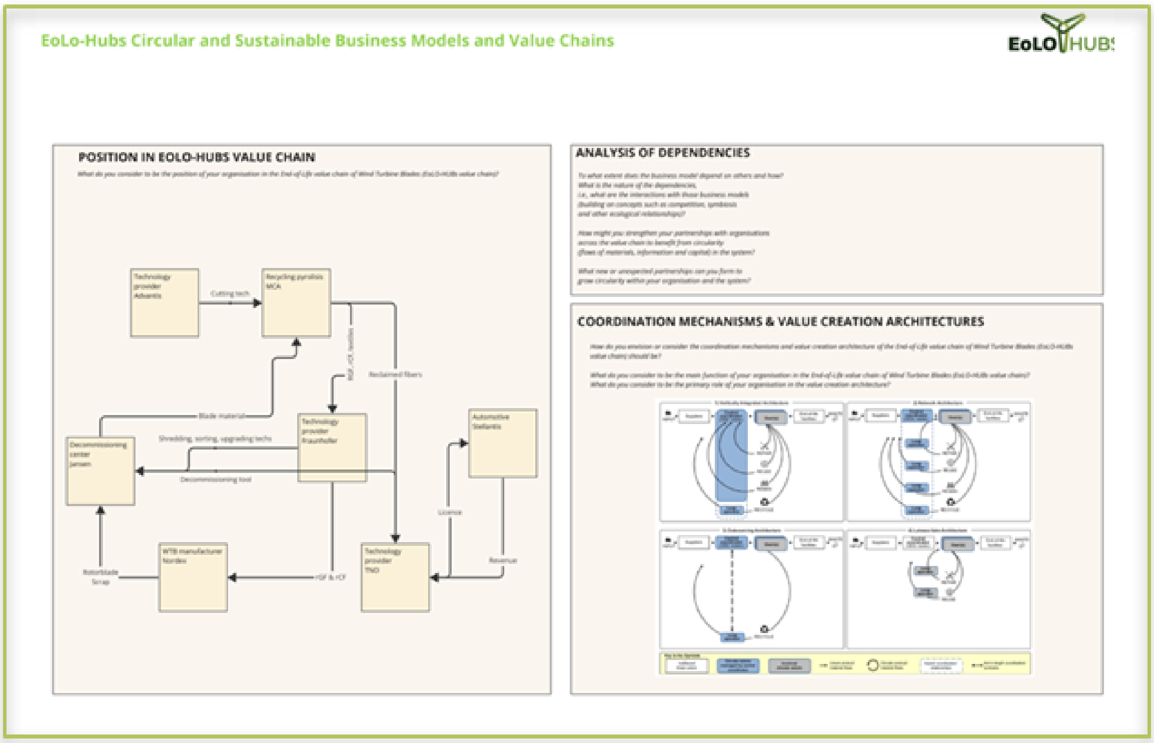

Figure 5. Illustration of part of the structure and content of the Excel-based and MIRO platform information and data collection sheet shared with the project partners during the second engagement cycle. Figure on the bottom-right corner gathered from Hansen and Revellio (2020).

As a result of the development of the activities described above, all the information and data available at this stage of the project development (M1-M18) was gathered and analyzed in an integrated manner to determine the most relevant technical, economic, environmental and social (positive and/or negative) aspects of the EoLO-HUBs innovations compared to the benchmark systems (section 3.1.1). To support this, an information gathering table was developed to allocate the corresponding aspects based on the outcomes from the different assessments (e.g. tabs in the Excel files). This analysis also helped to orient the subsequent more focused qualitative and preliminary (semi) quantitative circularity and sustainability LCA of the EoLO-HUBs recycling innovations compared to benchmark systems; studies that are described in the next subsections.

3.2. Qualitative circularity and sustainability assessment

Qualitative assessments are useful to determine if product and process innovations may potentially lead to negative and/or positive environmental, economic and/or social impacts. As Weidema et al. (2020, p.10) highlights, "*it is important to stress the word potentially: since this is a screening method, there are inherent limitations to robustness and detail*". Thus, results (in any case) must be validated through the development of subsequent quantitative assessments (section 3.3).

Qualitative assessments supported by the use of life cycle-based diagrams and matrices is therefore useful to identify and map all activities and processes that may be affected by the project innovations and estimate the potential significance of these effects (DDC 2024). This also helps to ensure that the system boundaries of the assessment can be iteratively adjusted not to be too broad (e.g. by including activities not – directly or indirectly – impacted by the project innovations, and/or that are negligibly impacted in practice) or too narrow (e.g. by omitting relevant processes and resource flows) (Laurent et al. 2020). Therefore, qualitative assessments serve to identify the potentially most relevant circularity and sustainability aspects for consideration in a simple, but practical and meaningful way, so that subsequent quantitative assessments are more focused. This, in turn, allows saving time and efforts, which are critical aspects for the development of LCA studies (Kiemel et al. 2022). Likewise, life cycle-based qualitative assessments are useful in early stages of project developments (such as the case of the EoLO-HUBs project) where there is limited information and data available on process, materials, products and technology innovations (Pacana et al. 2023).

Having this into consideration, the qualitative circularity and sustainability assessment of the EoLO-HUBs´ WTB recycling innovations (compared to benchmark processes) comprised the following two key activities (both based on the current knowledge and stage of development of the project):

i) Mapping the different EoLO-HUBs´ WTB upstream, core and downstream recycling processes and innovations to determine the major differences compared to benchmark systems (Laurent et al. 2020), and relying on evaluation matrices to get a global vision of the most relevant inputs and outputs related to each project innovation.
ii) Analysing the potential impacts and trade-offs of the EoLO-HUBs project´s innovations, and provide guidelines for potential improvement as the project develops. Trade-offs are understood as conflicts between the desired objectives where, if trade-offs are not acknowledged, there is a risk of accepting an initiative leading to sub-optimizations or higher impacts (Kravchenko et al. 2021).

Focusing on the former (i), this activity entailed the development of flow diagrams representing the EoLO-HUBs´ WTB recycling processes and innovations, and the main differences compared to benchmark systems (Section 4). This was done, on the one hand, by relying on the revision of the EoLO-HUBs project documents and benchmark literature, and, on the other hand, by relying on the feedback provided by the EoLO-HUBs partners and the external stakeholders (see section 3.1.2). In this process, a life cycle perspective was adopted to include in the assessment boundary all upstream and downstream processes that might be impacted (positively and/or negatively) by the project innovations.

According to Laurent et al. (2020), “effects” are changes in processes or activities that the innovation brings to the baseline situation, transforming it into a new system. These effects can be physical or non-physical. The former include effects: i) altering existing baseline processes, ii) introducing new processes to the baseline, iii) removing some processes from the baseline and/or iv) processes which are likely not to change but with uncertainty as to whether they might enter in one of the previous three categories (helping to ensure that all main processes are scrutinized to decide whether they should be discarded from the assessment). On the other hand, non-physical effects could include multiple structural and/or external changes, such as economic (e.g. changes in economic growth) or social (e.g. change in consumer behavior), among others.

Effects can also be direct or indirect. Direct effects refer to all those direct changes that an innovation generates in practice, whereas indirect effects are a secondary (and very often unintended) consequence of the implemented innovation. Finally, effects can be also positive (e.g. leading to a beneficial improvement or positive impact) and/or negative (e.g. leading to a detrimental action or negative impact).

Accordingly, once all the flow diagrams (or maps) of the EoLO-HUBs and benchmark WTB recycling processes were defined, tables containing operational information on the processes were developed to get an overview of the characteristics of the EoLO-HUBs process innovations compared to benchmark processes. This analysis was supported with the use of evaluation matrices to understand the links between the project innovations and the corresponding resource inflows and outflows changes (step ii above). An extension of the METCO matrix (IHOBE 2019), which in turn represents an adaptation of the original ERPA matrix (Graedel 1996), was used to facilitate the assessment of key environmental, economic and social aspects.

To facilitate the identification and pre-selection of useful circularity considerations and/or solutions for implementation in the different EoLO-HUBs WTB recycling processes, the CSS (Figure 6) was used as support. The CSS (Blomsma et al. 2019) represents a taxonomy, with a comprehensive set of definitions and examples, of 30 circular strategies organised into four CE-innovation goals ((i) reinvent, (ii) rethink and reconfigure, (iii) restore, reduce and avoid, and (iv) recirculate) for implementation by manufacturing companies. Thus, it was considered suitable to get an overview of the potential CE strategies for implementation in the WTB recycling industry. Accordingly, stakeholders were asked to select those circularity strategies that have already been implemented or that are interesting for exploration and implementation in the near future (within and/or beyond the EoLO-HUBs project).

Finally, a simplified Life Cycle Inventory (LCI) table (Saavedra-Rubio et al. 2022) was also integrated within the evaluation matrix to facilitate data collection (when available).

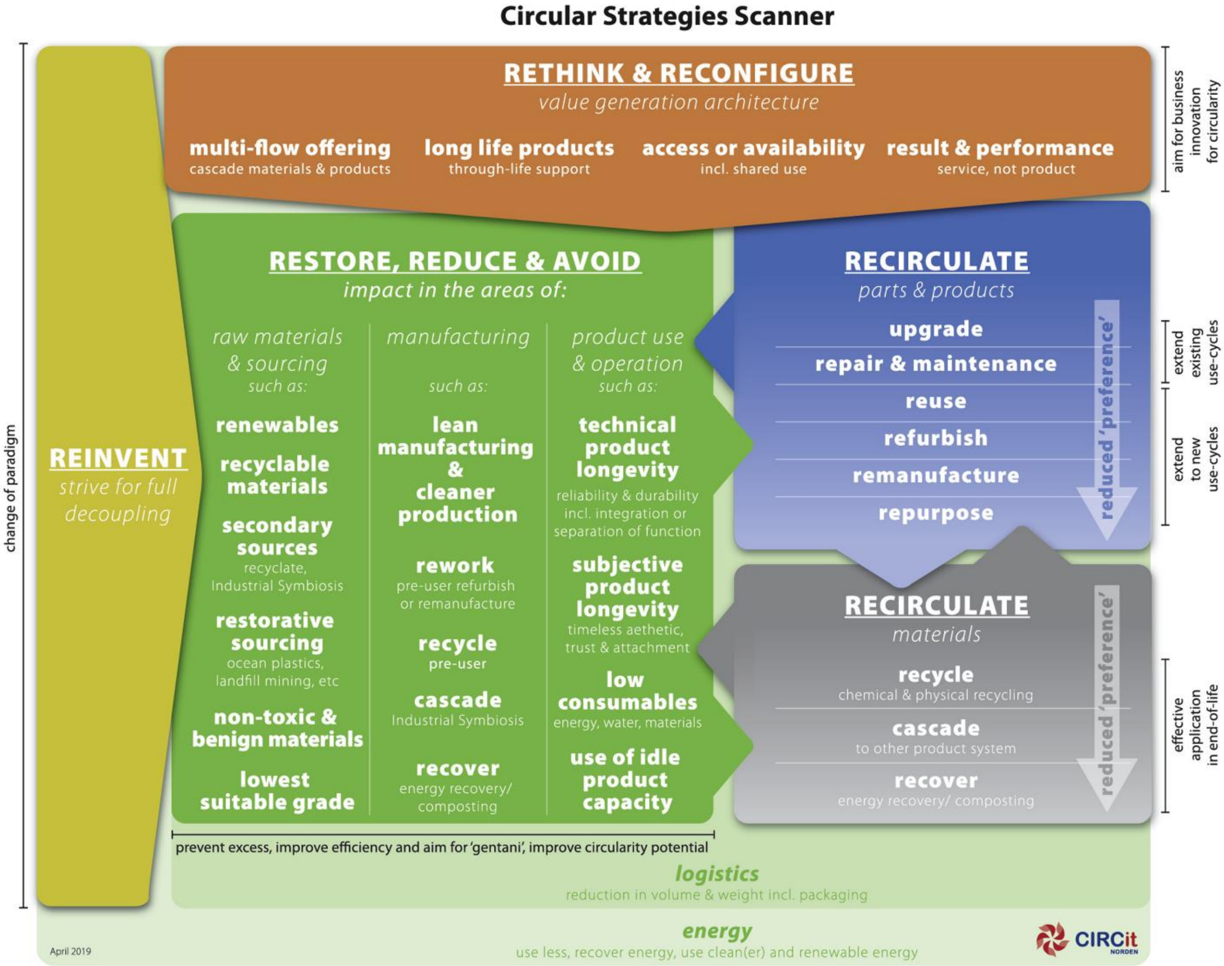

Figure 6. Circular Strategies Scanner (source: Blomsma et al. 2019).

This allowed to get an overview of the most relevant resource inflows and outflows per each EoLO-HUBs´ recycling process and therefore identify the potential resource benefits as well as major hotpots for consideration and improvement, compared to benchmark systems.

3.3. Simplified quantitative circularity and life cycle sustainability

Pihkola et al. (2022) and Luthin et al. (2023) recommend the combined calculation of both circularity and life cycle sustainability indicators, not only to identify the best solution in comparative studies (e.g. EoLO-HUBs vs benchmark WTB recycling) but also to identify and analyze the project innovations´ hotspots, and the trade-offs between improved circularity and the resulting environmental, economic, and social impacts, as basis for robust decision-support.

Based on the inventory data available, the energy, water and material efficiency for each WTB upstream, core and downstream process was calculated (when possible) (Section 4). However, as much data was not yet available qualitative considerations to measure and improve the circularity of the EoLO-HUBs systems were discussed in Section 5.

With regard to the life cycle sustainability assessment of the EoLO-HUBs´ project innovations compared to the benchmark, Pihkola et al. (2022) guidelines, built upon the EU PEF guide (European Comission 2021), were considered (only for the environmental dimension due to the lack of information and data to perform LCC and S-LCA studies).

In any case, due to the lack and/or limited data available on the EoLO-HUBs recycling innovations at this stage of the project development (as technical tests are still running in WP4), a simplified (semi-) quantitative circularity and LCA was performed. This means that in cases where there was inventory data available on benchmark and EoLO-HUBs recycling systems, it was used to perform a simplified calculation of the corresponding circularity and LCA indicators; simplified because as the EoLO-HUBs project is still ongoing, a comprehensive quantitative circularity and LCA cannot be addressed yet. On the other hand, when data was not available, or it was limited or not robust enough, the processes´ circularity and life cycle sustainability performance was analyzed from a qualitative perspective by considering the different variables of the indicators´ formulas. This helped to get an overview of were the potential circularity and sustainability hotspots can be and how to mitigate and/or correct them.

The LCA impacts were calculated by using the software GaBi (Sphera 2024) and the Ecoinvent database (Ecoinvent 2024). Different functional units (FUs) have been defined based on the WTB upstream, core and downstream recycling process considered, as the scope of the assessment was process-based and modular (gate-to-gate), meaning that a single simplified LCA per WTB recycling process was performed but not added up to calculate the total impact for the recycling and recovery of rGF and rCF due to the lack of data or the data quality (e.g. partial data and/or estimations) available at this stage of the project to do so. Also, the environmental impact related to the management of wastes and/or byproducts has been excluded due to the lack of information and/or data available on the respective processes. Finally, not all the resource flows indicated in the corresponding inventory tables were considered in the LCA calculations due to the lack of specifications and/or information available in the Ecoinvent dataset used.

3.4. Definition of guidelines and recommendations for the circularity and sustainability improvement of the EoLO-HUBs innovations

The development of all the activities described in sections 3.1 to 3.3 helped to identify major hotspots and high-level improvement opportunities to optimize resource efficiency, while mitigating negative impacts through the development of the EoLO-HUBs innovations. First, the assessment was performed at the process level (Section 4) providing guidelines for the potential improvement of each particular process. Subsequently, all the results were analyzed from an integrated perspective (Section 5) to determine the potential performance of the demo 1 and demo 2 cases within the EoLO-HUBs project and provide the corresponding guidance at the system-level.

4. RESULTS AND DISCUSSION

The preliminary results presented in this section respond to two major goals within WP2 (see section 2):

- Map and characterize the technical, economic, environmental, and social aspects related to EoLO-HUBs recycling technologies compared to existing (benchmark) techniques, and
- Quantify the potential life cycle impacts and benefits of EoLO-HUBs recycling technologies compared to business-as-usual approaches.

However, as it was indicated in section 3, as the EoLO-HUBs project is still in an early stage of development, not all the (upstream, core and/or downstream) WTB recycling process and technology innovations have been developed, tested and implemented yet. Therefore, the results provided in this section are preliminary and mostly qualitative and/or semi-quantitative. In any case, it is worth mentioning that qualitative assessments are useful in early stages of the project development to identify major potential hotspots and evaluate what could be relevant for consideration in the subsequent quantitative circularity and sustainability assessment of products and processes (Pikhola et al. 2022). Figure 7 provides an overview of the main WTB life cycle management stages addressed within the EoLO-HUBs project, including upstream and downstream recycling processes.

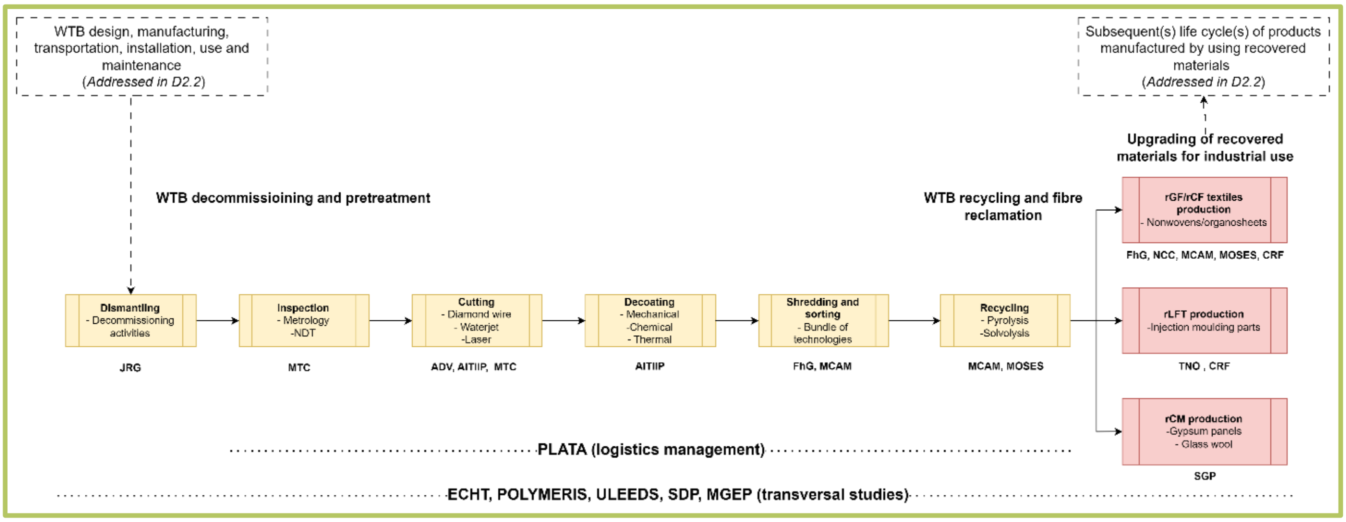

Figure 7. Major WTB life cycle management stages and processes addressed within the EoLO-HUBs project. Acronyms: WTB (Wind Turbine Blade), rGF (recycled Glass Fibre), rCF (recycled Carbon Fibre), rLFT (recycled Long Fibre Thermoplastics), rCM (recycled Construction Materials), partners´ names (described in Table 1).

Importantly, efficient WTB recycling is not only about having optimized thermal (e.g. low-carbon pyrolysis) and/or chemical (e.g. green solvolysis) recycling systems in place (Figure 7) but also optimizing upstream WTB decommissioning and pre-treatment processes as well as downstream material upgrading processes to reduce costs and negative impacts, while improving the quality of the outcomes for industrial use (Sorte et al. 2023). For instance, optimal WTB recycling requires, on the one hand, separating material streams (e.g. balsa wood, foams, metals and fabrics) in the best possible way prior to the actual recycling process. This entails the implementation of solutions for efficient dismantling, inspection, cutting (large to medium and/or small pieces), transportation, and (depending on the recycling operational requirements) decoating, and shredding and sorting (Figure 7). On the other hand, fibres and other outcomes (e.g. gases, oils, resins) obtained in the recycling process, must be refined or upgraded (e.g. fibre length extension and gases, oils and resins purification) to ensure their actual industrial use (e.g. in automobile and construction industries).

In this regard, Lund and Madsen (2024, p.8) provide the following example: *"a 60-m-long blade can be sectioned on site for transportation, allowing it to be transported by a standard truck, while transporting the blade in its full size requires a special crane, a larger truck, a dedicated trailer, escort cars supporting the transportation process, and approval from local authorities. These choices will have a significant impact on the fuel consumption, physical operation procedures, legal considerations, and costs".* Consequently, the technical, economical, environmental and social performance of WTB recycling systems must be analyzed as a whole by applying system thinking, as it is not practical to analyze WTB recycling (e.g. pyrolysis and solvolysis) in isolation without considering the performance of upstream and downstream processes, which will determine in practice the circularity, environmental burden and economic value of the system outcomes (Yang et al. 2023).

The next subsections provide a qualitative and semi-quantitative assessment of the circularity and sustainability performance of the EoLO-HUBs recycling innovations at the process level (in consonance with section 3 and the processes chain illustrated in Figure 7). First, the qualitative circularity and sustainability performance of the benchmark and EoLO-HUBs WTB recycling processes is analyzed and compared. Second, the most relevant technical, economic, social and environmental aspects of benchmark and EoLO-HUBs WTB recycling systems are described. Third, a simplified (and preliminary) semi-quantitative circularity and life cycle sustainability assessment of benchmark and EoLO-HUBs WTB recycling processes is presented. Four, based on the results, guidelines for the possible improvement of EoLO-HUBs recycling processes (as the project develops) are provided.

Finally, all the outcomes from these studies at the processes level are analyzed in an integrated manner (section 5) to discuss the major potential hotspots, challenges and improvement opportunities for the circular and sustainable deployment and management of the demo 1 (mobile intelligent scanning, slicing and decoating dismantling platform with zero waste flexible chemical recycling) and demo 2 (mobile cutting and zero waste flexible pyrolysis recycling) technology systems.

4.1. WTB decommissioning and pre-treatment

The dismantling and pretreatment phase comprise different sub-processes in which the WTBs are disassembled from the WTs and their size is subsequently reduced as well as the resulting pieces pre-processed to facilitate recycling processes and material recovery (Figure 8).

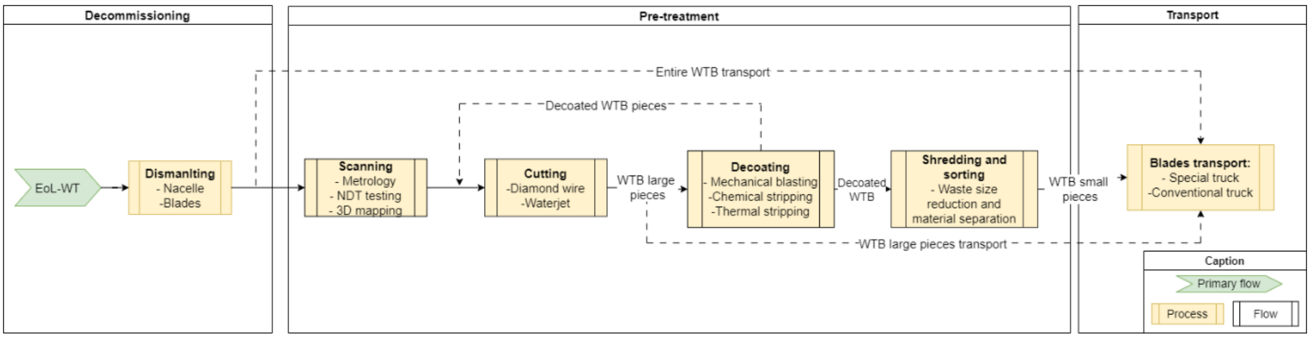

Figure 8. EoLO-HUBs´ WTB decommissioning and pretreatment flow diagram. Acronyms: EoL-WT (End-of-Life Wind turbine), WTB (Wind turbine blade), NDT (Non-destructive testing).

Once the WTBs are dismantled, the EoLO-HUBs project looks to implement a scanning process to determine both the composition and material thicknesses of the WTBs to optimize subsequent cutting processes to recover high value-added material. Within EoLO-HUBs, three WTB cutting systems are being explored (diamond wire saw, waterjet and laser) to reduce time requirements, dust emissions and costs. Another novelty of the EoLO-HUBs project is the decoating of the WTBs coating to recover coating to give them a second life, while facilitating subsequent recycling processes (e.g. solvolysis). Before and/or after decoating, shredding and sorting operations (Hechler, 2019b) can take place, seeking to shred the WTB pre-cut pieces and separate the materials according to their composition for subsequent material processing steps. Within EoLO-HUBs, shredding processes aim to be optimized, while new sorting techniques will be developed to maximize material separation into different streams. The last WTB pretreatment step before recycling is the transportation of the WTB pieces to the recycling facilities (which can be performed at different steps of the WTB dismantling and pre-treatment stage). For instance, the WTBs can be transported to processing facilities right after dismantling without implementing any onsite pre-treatment, whereas WTBs can be cut on site and the pieces transported to processing facilities (e.g. shredding companies and/or recycling centres) (Jakobsen, 2021). The EoLO-HUBs project will contribute to optimize (reduce) transport operations by facilitating better WTB cutting processes (e.g. through the implementation of the ADV diamond wire cutting technology) (section 4.1.3).

The EoLO-HUBs project aims to reduce the WTB decommissioning and pre-treatment times and costs by 50% (e.g. from 10 to 5 days) and 10%, respectively, thanks to the process automation and improvement. Focusing on WTB cutting, EoLO-HUBs aims to achieve a 40% reduction in process time, leading also to 87% reduction in Greenhouse Gas (GHG) emissions due to more optimal transport operations facilitated by the cutting processes themselves. Each process is described below, with a qualitative and quantitative analysis comparing the innovations of the EoLO-HUBs with the benchmarks identified for each process (if applicable) and concluding with best practice recommendations.

4.1.1. WTB dismantling

Among the various stages for the dismantling of WTs, the removal of the WTBs is a particularly complex task. Specialized heavy equipment is required to handle and transport large and heavy-weight WTBs, which is very time consuming and expensive (Lahuerta et al., 2023). Likewise, the lack of internationally-recognized standards to perform decommissioning and management projects for WTs, and WTBs, adds additional challenges as the solutions and practices that could be implemented are quite diverse (Lund and Madsen 2024).

The dismantling process can be executed in various ways. One approach involves dismantling the WT by removing each WTB individually, a task estimated to take between 2-3 hours per WTB. Another option is to lower the hub along with the WTBs, a process estimated to take between 2-6 hours (Pers. Com. External stakeholders), and then dismantle the WTBs once they are on the ground. A middle-ground alternative between these two options is to disassemble one blade and lower the hub with the remaining two blades intact (Hechler, 2019).

This process is not directly addressed within the EoLO-HUBs project innovations. However, drawing on the experience of several collaborators, relevant data have been gathered to define and characterize the benchmark WTB dismantling process. In this process, two cranes of type CC380-1 can be used to disassembly each individual WTB from the decommissioned WT. Other types of cranes can be used, such as the Mobile crane Liebherr LH40 and LH60 (used by JRG).

4.1.1.1. Qualitative analysis of WTB dismantling

Figure 9 shows the main input and output flows of the process, while Table 6 presents operating parameter for WTB dismantling through the use of a CC380-1 crane as a benchmark.

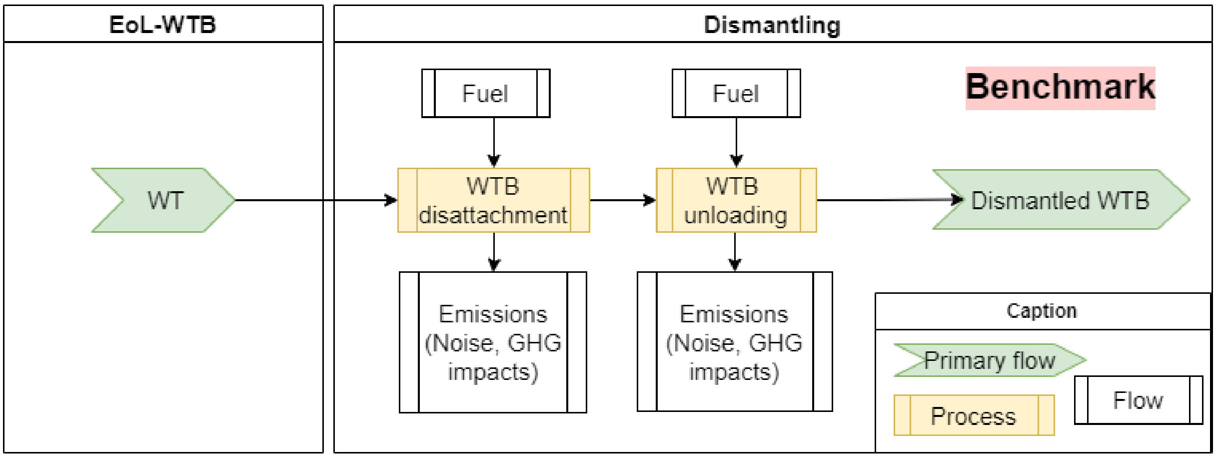

Figure 9. Dismantling WTB process flow diagram. Acronyms: WT (Wind Turbine), WTB (Wind Turbine Blade), EoL (End-of-Life), GHG (Greenhouse Gases).

Table 6. Operation parameters for the dismantling of 1 WTB (FU) by using a CC380-1 crane. References: (Demag-Tadano Group, 2022; Pers.Com. SURUS, 2024).

Operative parameters		**Benchmark (CC380-1 crane)**
Machinery characteristics	Crane lifting capacity, t	650
	Crane power, kW	390
	Crane weight, t	430
Use parameter	Emissions	EU Stage IV/ EPA Tier 4f
Operational parameter	Operating time, hours/blade	3
	Workers	6

As shown in Figure 9, the WTB dismantling process involves two sub-processes: the separation of the blade from the rest of the WT and then its unloading to the ground. Two cranes are used; each crane attached at one end of the WTB and positioned parallel to the ground to facilitate the dismantling operation. To execute this operation, operators must coordinate closely to prevent the blade from falling (Wind Systems, 2024). The use of the cranes determines the associated resource flows and emissions related to fuel consumption by on the operational conditions (Table 6). In addition, the logistical operations required to transport this machinery to the wind farm must be considered.

4.1.1.2. Technical, economic, environmental and social characterization of WTB dismantling

The most relevant technical, economic, environmental and social aspects of the WTB decommissioning process are shown in Table 7.

Table 7. Most relevant technical, economic, environmental and social aspects of the WTB dismantling process, including suggestions for improvement by the EoLO-HUBs partners. Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark dismantling process	EoLO-HUBs challenges and opportunities	Source
Technical	• Special machinery requirement (-) • Complicated logistics (-) • Non-standardized process (-)	• Implement on-site recycling to reduce costs (+) • Develop more efficient methods to unload WTBs (+)	(Ortegon et al., 2013; Topham and McMillan, 2017) (Pers.Com. LEZAMA and Renercycle 2024)
Economic	• High-cost operation (-)	• Well logistics planning to minimize costs (+)	(Gilsmi, 2017; Lahuerta et al., 2023), (Pers.Com.SURUS, 2024)
Environmental	• Emissions and noise generation (-)	• Difficult to handle, dependent on machinery used	(Wind Europe, 2018)
Social	• Specialized operators are required (-) • Risk of accidents (-)	• Labor intensive (-)	(Hechler, 2019a) (Pers.Com. LEZAMA,2024)

Focusing on the technical aspects, the use of special machinery, and the complicated logistics are among the biggest challenges of this process. Another important technical aspect is their non-standardization, which means that the companies carrying out the decommissioning have to create a different roadmap depending on the characteristics of each wind farm and the clients requirements. For example, in the case of offshore installations, TNO believes that other process variants than reverse installation should be evaluated, as they could reduce costs, duration and emissions footprint, mainly when decommissioning is carried out with vessels other than those used to install the wind farm (Pers.Com, TNO, 2024). Other challenges identified by some EoLO-HUBs partners have been the need to develop efficient methods in the blade-lowering process and to carry out on-site recycling to reduce costs.

From an economic perspective, wind farm decommissioning is very costly due to the use of specialized equipment. To mitigate this, meticulous planning of logistics and processes requirements is crucial. This can be achieved by maintaining a precise and updated inventory of the state of the WT components, identifying key parts for reuse, and implementing exploitation plans (Pers.Com. JRG, 2024).

When it comes to the environment, emissions (due to fuel consumption by machinery) and noise generation (due to machinery use) represent the most significant environmental aspects. However, a more efficient disassembly process could potentially improve this, reducing the environmental impact of the decommissioning process.

Finally, regarding social aspects, specialized operators and the required human resources are needed to use this type of machinery. Technicians should be well-trained to perform disassembly operations.

4.1.1.3. Quantitative analysis of WTB dismantling

Once both the main sub-processes and the operational aspects of the benchmark have been defined, the system's LCI has been determined in Table 8. The inputs and outputs of each sub-process into which dismantling is divided have been differentiated; both operations can be carried out with the same machinery.

Table 8. Resource inputs and outputs for the dismantling of 1 WTB (FU). Acronyms: n.a (not applicable)

FU: 1 blade (N100)	Benchmark		Ecoinvent processes
Inputs	Separation of 1 WTB, kg	13,000	n.a
	Energy consumption (Diesel), kWh (calculated based on Table 7)	1,170	GLO: diesel, burned in building machine ecoinvent 3.10
Outputs	Unloaded WTB, kg	13,000	n.a

With the crane capacity and the operating time, it has been possible to determine the energy consumed in the dismantling process of a WTB (e.g. considering N100 model), which has a mass of 13 tons. It is estimated that approximately 90 kWh/t of diesel are needed per WTB.

An analysis of the impacts of the process was carried out via GaBi v10.0 software (Thinkstep, 2016) using the Ecoinvent 3.10 database (Ecoinvent Centre, 2016). The EF3.1 characterization method (JRC, 2023) was used to determine the impacts, through which a total of 16 environmental indicators were calculated. Table 9 shows the values obtained for each of the impact categories.

Table 9. Environmental impacts for the dismantling of 1 WTB (FU).

Impact category	Unit	Benchmark for WTB dismantling
Acidification	[Mole of H+ eq.]	3.46E-01
Climate Change - total	[kg CO2 eq.]	3.83E+01
Ecotoxicity, freshwater - total	[CTUe]	7.03E+01
Eutrophication, freshwater	[kg P eq.]	1.12E-03
Eutrophication, marine	[kg N eq.]	1.61E-01
Eutrophication, terrestrial	[Mole of N eq.]	1.76E+00
Human toxicity, cancer - total	[CTUh]	1.50E-07
Human toxicity, non-cancer – total	[CTUh]	8.24E-08
Ionising radiation, human health	[kBq U235 eq.]	2.25E-01
Land Use	[Pt]	3.49E+01
Ozone depletion	[kg CFC-11 eq.]	5.86E-07
Particulate matter	[Disease incidences]	9.71E-06
Photochemical ozone formation, human health	[kg NMVOC eq.]	5.24E-01
Resource use, fossils	[MJ]	4.97E+02
Resource use, mineral and metals	[kg Sb eq.]	1.37E-05
Water use	[m^3 world equiv.]	1.54E+00

In order to evaluate the relevance of these impact categories, it is necessary to have another system for comparison of the results, which is not the case in EoLO-HUBs as no innovations are targeted for WTB dismantling in particular. For example, the most decisive parameters for determining these impacts have been the type of vehicle, together with its fuels, as well as the operating time. Thus, the different impacts analyzed could be reduced by improving the operating time or replacing the vehicle with others that are more environmentally friendly.

4.1.1.4. Guidelines and opportunities for WTB dismantling

The dismantling of WTBs is a logistical challenge for the wind industry. The type of machinery used, and the costs and emissions associated with the process make it a complicated operation, which is difficult to manage as it is greatly dependent on the type and location of the wind farm under decommissioning. Some industries, such as PLATA, identify the need to improve the dismantling and management processes of WTBs, always considering the efficiency and eco-friendly aspects of the process. In addition, the lack of an official standardized process for the decommissioning of wind farms (beyond recommendations provided by Wind Europe and other national EU bodies) makes it difficult to make decisions when elaborating a decommissioning project.

4.1.2. WTB inspection

WTB inspection comprises scanning the entire surface of the blade to determine its structure and material composition. Within EoLO-HUBs, metrology and Non-Destructive Testing (NDT) solutions are being developed to facilitate this process.

NDT for blades is the main scanning technology used today to determine the internal and external structure of the blade to improve quality, safety, and risk prevention. This scanning technique is mainly used to detect possible blade failures during operation or manufacturing (García Márquez and Peco Chacón, 2020).

Different methods, such as thermography, ultrasonic, or radiographic, are used in NDT technologies. Thermography determines the temperature differences on the surface, providing qualitative information about the dimensions of the boundary layers of the structure. Ultrasonic Testing (UT) allows for determining the thickness of the internal and external structure of the WTB using frequencies of 5 and 10 MHz (Amenabar et al., 2011). Radiographic testing is one of the most efficient NDT tests to determine the internal flaws of composite sandwich panels. For this purpose, X-ray Computed Tomography is often used, which allows the process to be carried out in situ and in real-time (Amenabar et al., 2011; Garcea et al., 2018).

Since this type of process has not been used so far as an intermediate stage between decommissioning and blade cutting, defining a market benchmark was not possible. However, within the EoLO-HUBs project, MTC is developing a WTB inspection technology solution by combining metrology, NDT and 3D mapping (Figure 10) to obtain the most accurate and detailed information about the blade's structure and composition. In metrology, two technologies based on laser tracking are being investigated to determine the surface structure of the blade.

4.1.2.1. Qualitative analysis of WTB inspection

Figure 10 shows the flow diagram corresponding to the scanning in which the processes studied by incorporating MTC have been added.

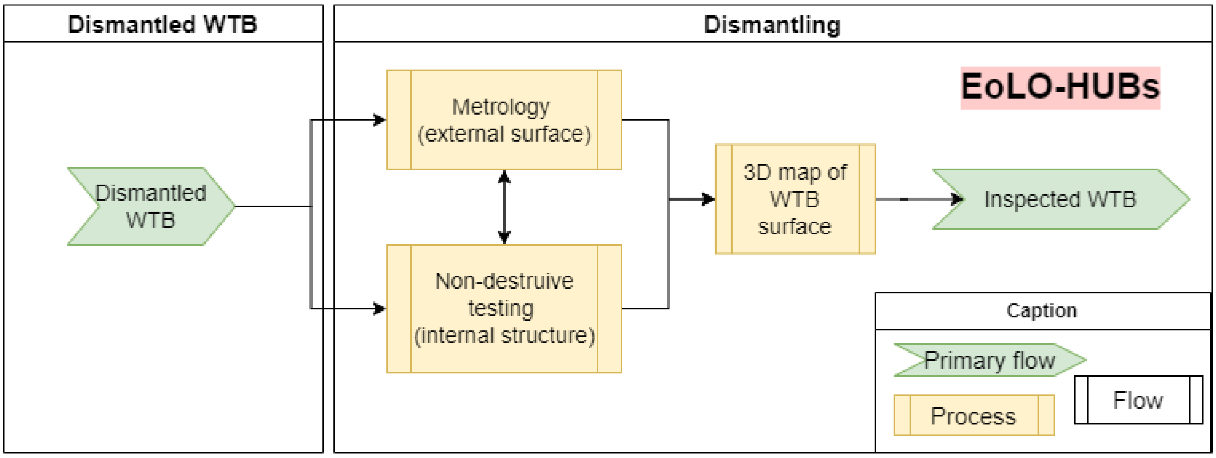

Figure 10. WTB scanning process flow diagram based on the EoLO-HUBs innovations. Acronyms: WTB (Wind turbine Blade)

Metrology is one of the techniques studied within the EoLO-HUBs project for external surface definition. The use of different scanning equipment is being studied (e.g. Leica ATS600, Leica AT960 and T-Scan 5) to determine which is the most optimal solution. To carry out the NDT the use of three different technologies is contemplated (e.g. Proceq GP8000 to carry out the GPR, Zetec TOPAZ 64 and Pundit Ultrasonic PD8050 for the UT and the Viken Nighthawk-HBI for the X-ray Backscatter (XBS). Finally, for the 3D mapping of the WTB structure, different softwar are being studied. Once both the surface and internal features are captured, they will be combined/integrated into a 3D map of the WTB's structure. This can determine an optimized path for the cutting tool/technology. The cutting path will focus on limiting material waste of high-value recyclable material.

The technology being developed within EoLO-HUBs will allow to obtain more precise measurements on the structure of the blade, even being able to determine the composition of the fibre. This improves current processes as it will facilitate subsequent operations, making it possible to recover material with high added value.

The integration of these new technologies in the WTB inspectioning process does not have a significant influence on the economic and environmental aspects as it is not a high cost and/or energy consuming process compared to other WTB-EoL management requirements. However, from a technical and social point of view, there are some challenges and opportunities for consideration, as indicated in the subsection below.

In any case, WTB inspectioning can substantially improve WTB-EoL management processes, as one of the critical aspects to perform optimal WTB cutting and recycling activities is to know the structure and composition of the WTBs.

4.1.2.2. Technical, economic, environmental and social characterization of WTB inspection

Table 10 shows the technical, economic, environmental and social characterization of the EoLO-HUBs WTB inspectioning innovation.

Table 10. Most relevant technical, economic, environmental and social aspects of the WTB inspection process. Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	EoLO-HUBs WTB inspectioning	Source
Technical	• The WTB surface scanning improve the cutting process (+) • The use of multiple inspection technologies would lead to more complex solutions but minimize the loss of recyclable materials (+) • Most critical process is the determination of internal WTB structure and identification of materials (-)	(Pers.Com. MTC, 2024)
Economic	• Expensive (-)	
Environmental	• Recovery of high-value-added materials (+)	
Social	• Depending on the identification technology, appropriate security considerations will have to be taken into account (-)	

Technically, determining the blade's internal structure will facilitate more optimal cutting processes. By knowing the internal structure and the thickness of the materials, it is possible to separate them during WTB cutting. However, using multiple inspection technologies would lead to more complex solutions that could be challenging to handle.

From an economic standpoint, this process will incur additional costs to the entire WTB-EoL management process, not contemplated today. However, the ability to separate materials during cutting would significantly offset these additional costs. In fact, MTC does not identify any major economic challenge for WTB inspection.

Focusing on the environmental aspects, WTB inspectioning will allow to recover materials with higher added value, thereby benefiting the environment through efficient management of resources as higher amount and quality of residual materials will account for higher environmental credits when they substitute the use of virgin materials in the end-industries.

Finally, regarding the social aspects, depending on the type of NDT solution carried out, appropriate safety measures for the workers will need to be considered. For instance, if an (XBS) or similar system is selected as the most appropriate system, considerations are required to ensure personnel safety. Space for a safe zone will need to be allocated during the inspection process, or an enclosure will need to be made.

4.1.2.3 Quantitative analysis of WTB inspection

Since there are not benchmark systems to be used for comparison purposes, as WTB inspectioning is one of the major novelties of the EoLO-HUBs project, and there was no quantitative data yet available for the processes due to the current stage of development of the project, simplified quantitative circularity and LCA study was not possible to be addressed. In any case, the environmental burden associated with WTB inspectioning are not expected to be relevant compared to other WTB-EoL management processes.

4.1.2.4. Guidelines and opportunities for WTB inspection

The implementation of WTB inspectioning technologies will have a positive influence on subsequent WTB cutting and recycling operations. However, some aspects still need improvement, such as determining the internal structure of the blade, measuring thicknesses, and time constraints. All the challenges in applying this technology are due to the blade's geometry, which is why one of the main hotspots is scaling the process for this type of geometry. Therefore, combining these technologies will improve material management, although it still presents a technical challenge in its application to blades, which will be tested during the project.

4.1.3. WTB cutting

A highly efficient method for WTB sectioning and further cutting, not only facilitates subsequent WTB recycling processes (if purer material streams are available) but also optimizes transport operations, reducing costs.

Among the WTB cutting technologies, circular saw, diamond wire saw or waterjet cutting represent some technologies that could be used (EPRI,2018). Circular saw represents a conventional alternative (as well as shear cutters, for example) applied to cut WTBs. It comprises the use of manual or hydraulic machines having cutting blades up to 2 m of diameter. They can be used to cut WTB of all sizes, although multiple cuts will be necessary depending on the WTB length and structure. One of their main advantages is that the cuts can be carried out independently in all directions (Jensen and Skelton, 2018a). However, they can generate large amounts of dust that must be properly collected and treated. Also, the cut performed by shear cutters (instead of circular saws) is much more irregular and inefficient than in the previous technology (Pers.Com. SURUS and JRG, 2024). Due to the high emissions of dust and chips, and considering the risks for workers, the use of this technology is being displaced by alternative solutions (Johst et al., 2023).

Diamond wire saws represent an interesting alternative to support WTB cutting processes. It comprises the use of steel wire with diamond teeth that is placed around the surface to be cut. In addition to cutting all types of materials, the cut is not limited to the dimensions of the WTBs. The process is relatively environmentally friendly regarding dust and noise emissions and allows the recycling of cooling water. As a result, smooth and well-defined cuts can be obtained, although the process is time-consuming (Jensen and Skelton, 2018a; Hechler and Operations, 2019b; Johst et al., 2023).

Another alternative is WTB cutting by relying on a high-pressure water jet, including also dust collection through the water filtration system. In this case, unlike the previous technologies, there is no risk of tool degradation and the safety risks for the operators are supposed to be lower, while the quality of the finished surface is increased (Johst et al., 2023; Joustra et al., 2021; Sebbe et al., 2022).

Finally, WTB cutting can be performed by relying on laser-based solutions. This technology stands out for its high speed, cutting quality and efficiency. However, it is a thermal process, which can constraint the quality of the recovered composite materials compared to other cutting techniques (Wu et al. 2021).

Within the EoLO-HUBs project, three WTB cutting technologies are being developed: i) ADV is developing a diamond wire cutting technology, integrating an appropriate dust collection system, ii) AIT is developing waterjet cutting technology embedded in a robotized system, and iii) MTC is developing a laser cutting system. For performance comparison, a circular saw cutting technology

(TYROLIT WSE 1621, TYROLIT Hydrostress, 2018) has been selected as benchmark, while the three EoLO-HUBs WTB cutting technologies are compared one to the other.

4.1.3.1. WTB Diamond wire cutting

ADV is developing a versatile WTB cutting system to be transported in containers mounted on a trailer truck for deployment at wind farms. The technology will integrate an optimal dust collection method (either wet - water-based or dry – vacuum-based). Below, a qualitative and semi-quantitative assessment of this technology is provided, compared to the use of circular saws.

4.1.3.1.1 Qualitative analysis of diamond wire cutting

In order to make a qualitative comparison, a flow diagram has been defined for these processes (Figure 11), together with a table showing the operational aspects of each (Table 11).

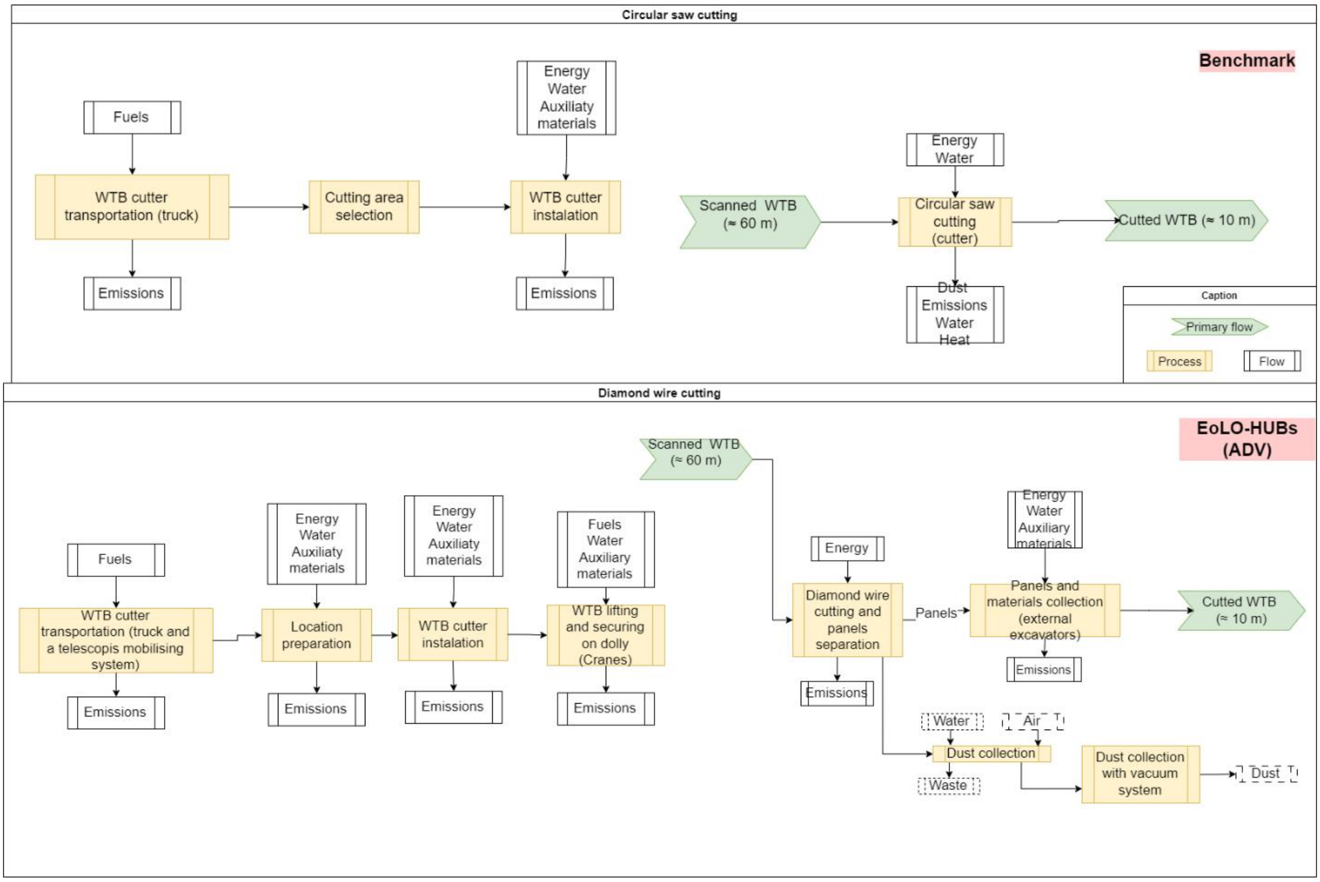

Figure 11. Flow chart for the circular saw and diamond wire cutting systems. Acronyms: WTB (Wind Turbine Blade)

Table 11. Operating parameters for the benchmark (circular saw) and EoLO-HUBs (diamond wire) alternatives (considering the cutting of 1 WTB of 60 m long as FU). References: (TYROLIT Hydrostress, 2018; Hilti, 2023 ; Pers.Com. Advantis, 2024). Acronyms: n.a (not applicable)

<table>
<tr><th colspan="2">Operative parameters</th><th>Circular saw cutting (Benchmark)</th><th>Diamond wire cutting (EoLO-HUBs)</th></tr>
<tr><td rowspan="8">Machinery parameters</td><td>Sound emission, dB</td><td>124</td><td>Not possible to be determined</td></tr>
<tr><td>Electric motor, kW</td><td>20</td><td>25</td></tr>
<tr><td>Weight, kg</td><td>51.3</td><td>Not possible to be determined</td></tr>
<tr><td>Energy source</td><td>Electric</td><td>Electric (low voltage)</td></tr>
<tr><td>Expected lifetime</td><td>Not possible to be determined</td><td>10-20 cuts</td></tr>
<tr><td>Machine setup, h</td><td>Not possible to be determined</td><td>2</td></tr>
<tr><td>Blade setup process, h</td><td>Not possible to be determined</td><td>1</td></tr>
<tr><td>Diamond wire length, m</td><td>n.a</td><td>100 (6500-10000€)</td></tr>
<tr><td rowspan="3">Operational parameters</td><td>Cutting time, h</td><td>2</td><td>1.2</td></tr>
<tr><td>Operating time reduction, %</td><td>Not possible to be determined</td><td>40</td></tr>
<tr><td>Water (tap water), l/min</td><td>1.5</td><td>2</td></tr>
</table>

The logistics requirements to perform WTB cutting is different for both technologies. When circular saws are used, it is necessary to transport the machinery, adapt the cutting area (avoiding that it is an area with obstacles as well as flatten it, which can involve removing 10 cm of soil), and finally, prepare and tune the machine before the process. The setup is more straightforward than the installation of diamond wire technologies due to the machine's simplicity. On the contrary, to carry out the diamond wire cutting, it is necessary to transport the cutting machinery, for which, in this case, a truck and a telescopic mobilizing system will be necessary. Next, preparing the land before cutting it and installing electrical and water connection equipment on the wind farm is necessary. Then, the blade cutter is installed, and the cutter is mobilized. Finally, the lifting and securing of the dolly are carried out, for which 1-2 mobile cranes are needed to handle the positioning blades on the dolly and blade cutter (Pers. Com, ADV, 2024).

Cutting by circular saw requires cooling water and energy (which determine the costs) and dust and chips are produced (which can harm human health) (Jensen and Skelton, 2018). Likewise, this technology involves a higher risk for workers in terms of potential accidents. Regarding the diamond wire technology developed by ADV, vertical and horizontal cuts are performed on the WTB surface to separate the materials during the cutting process. The WTB is cut using four wires simultaneously, reducing the cutting time. A wet (water-based) cutting system versus a dry (air-based) cutting system is being studied to identify the best alternative to perform the cutting process, while collecting the dust generated in the process. In any case, the dust generated during the use of the diamond wire saw can degrade the cutting performance (Pers.Com. ADV, 2024).

ADV's technology is meticulously designed to not only enhance material separation efficiency and increase cutting speed but also to significantly reduce dust exposure for workers. While initial studies suggest a potential increase in energy cost compared to conventional processes, this could be offset by improved cutting efficiency. This promising innovation should be carefully considered in decision-making, offering a hopeful outlook for the future of cutting technologies.

Regarding the operating parameters in Table 11, one of the goals established in the project is to reduce the cutting time by 40% concerning current technologies. Therefore, knowing the cutting time for the circular saw cutting (2h), the cutting time for the innovation developed in EoLO-HUBs could be reduced to 1.2 h per WTB.

4.1.3.1.2. Technical, economic, environmental and social characterization of diamond wire cutting

Table 12 summarizes the technical, economic, environmental and social aspects of the circular saw and diamond wire cutting processes.

Table 12. Most relevant technical, economic, environmental and social aspects of different WTB cutting technologies. Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Circular saw cutting	Diamond wire saw cutting (EoLO-HUBs-ADV)	Sources
Technical	• Independent cuts in all directions (+) • Low logistics requirements (+) • Manual technology (-) • Irregular cuts (-) • Material separation is highly time inefficient (-)	• More efficient material separation (+) • Not limited to the dimensions of the WTBs (+) • The cuts are relatively smooth, sharp and well-defined (+) • More logistics requirements (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. ADV, 2024)
Economic	• Cheap technology (+) • Frequent maintenance and replacement of saw blades (-)	• Potential reduced WTB cutting costs thanks to increased efficiency and material separation (+) • Diamond wires are costly (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. ADV, 2024)
Environmental	• Noise and dust emissions (-)	• More efficient dust collection (+) • Energy requirements could be higher (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. ADV, 2024)
Social	• Potential safety hazards for the operators (-)	• Less dust and accidents exposure for the workers (+)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. ADV, 2024)

In terms of technical aspects, circular saw cutting can be carried out in all directions, and the simplicity of the equipment makes logistical operations simpler than the use of diamond wire solutions. Another critical aspect of saw cutting is that the cuts that are carried out are more irregular, unlike what happens with wire cutting. In addition, ADV's development of this technology is expected to improve the separation of materials during the process itself.

Economically, the use of circular saws is cheaper than diamond wire cutting, for which the high cost is mainly due to the diamond wire themselves and the potential higher use in the energy requirements. Although, it can lead to higher profits thanks to a more efficient material separation process.

Regarding possible environmental risks, diamond wire cutting could have a higher energy footprint with the corresponding additional impacts (data on energy use indicated in Table 13 is an estimation based on the EoLO-HUBs goal of reducing cutting times by 40% considering the baseline data). Finally, dust collection (which is being developed for diamond wire cutting in EoLO-HUBs) is expected to reduce the risks to which the worker will be exposed in contrast to conventional methods, where the worker is exposed to dust inhalation.

4.1.3.1.3. Quantitative analysis of diamond wire cutting

Energy and water requirements have been calculated from the operating data of both systems (Table 12). Accordingly, Table 13 provides the inventory data for the cutting of a 60 m blade (Functional Unit, FU), to which five cuts are required, obtaining blade pieces of 5-10m. It was estimated that in the case of diamond wire technology, the water is recirculated except for 10%, which is lost by evaporation, as opposed to circular saw cutting, where the water is not recirculated.

Table 13. Preliminary inventory data with resource inputs and outputs for the 1 WTB (FU) cutting for circular saw (benchmark) and diamond wire (EoLO-HUBs) cutting processes. References: (Pers.Com, ADV, 2024; TYROLIT Hydrostress, 2018; Hilti, 2023; Finn, 2022; Kazuhisa, 2003) Acronyms: n.a (not applicable), WTB (Wind turbine blade)

FU: 1 blade (N100)		**Circular saw (benchmark)**	**Diamond wire saw (EoLO-HUBs)**	**Ecoinvent process**
Inputs	1 WTB (60m), kg	13,000	13,000	n.a
	Electricity, low voltage, kWh	40	30 (-25%)	Market group for electricity, low voltage, origin European Network of Transmission Systems Operators for Electricity (ENTSO-E)
	Tap water, kg	180	14.4 (10% water loss from 144 kg required) (-92%)	Europe, tap water production, conventional treatment
Outputs	Dust, kg	100	70 (-30%)	n.a
	Blade pieces, m	5-10	5-10	n.a

Concerning the balances of both processes, it is observed that the EoLO-HUBs process is more energy and water efficient. However, EoLO-HUBs diamond wire cutting can have a greater material impact, due to the consumption of diamond wires, which could not be measured at this stage of the project.

This study has been extended by developing a simplified LCA focused on the processes that will change between the reference and EoLO-HUBs processes. GaBi v10.0 software (Thinkstep, 2016) with the Ecoinvent 3.9.10 database (Ecoinvent Centre, 2016) has been used to perform the LCA, for the results E.F 3.1 characterization method (JRC, 2023) has been chosen. The different impact categories analyzed for the benchmark and EoLO-HUBs process are summarized in Table 14. Figure 12 also shows graphical comparisons of the most relevant impact categories.

Table 14. Environmental impacts for circular and diamond wire cutting of 1 WTB (FU), based on preliminary results.

Impact category	Unit	Circular saw (Benchmark)	Diamond wire (EoLO-HUBs)	Difference
Acidification	[Mole of H+ eq.]	2.00E-02	1.48E-02	-26%
Climate Change - total	[kg CO2 eq.]	3.53E+00	2.62E+00	-26%
Ecotoxicity, freshwater - total	[CTUe]	1.53E+01	1.13E+01	-26%
Eutrophication, freshwater	[kg P eq.]	3.47E-03	2.58E-03	-26%
Eutrophication, marine	[kg N eq.]	3.16E-03	2.34E-03	-26%
Eutrophication, terrestrial	[Mole of N eq.]	2.73E-02	2.03E-02	-26%
Human toxicity, cancer - total	[CTUh]	8.97E-09	6.61E-09	-26%
Human toxicity, non-cancer – total	[CTUh]	6.40E-08	4.77E-08	-26%
Ionising radiation, human health	[kBq U235 eq.]	2.28E+00	1.69E+00	-26%
Land Use	[Pt]	2.02E+01	1.50E+01	-26%
Ozone depletion	[kg CFC-11 eq.]	6.67E-08	4.95E-08	-26%
Particulate matter	[Disease incidences]	7.04E-08	5.18E-08	-26%
Photochemical ozone formation, human health	[kg NMVOC eq.]	9.08E-03	6.73E-03	-26%
Resource use, fossils	[MJ]	8.79E+01	6.53E+01	-26%
Resource use, mineral and metals	[kg Sb eq.]	4.91E-05	3.67E-05	-25%
Water use	[m³ world equiv.]	1.10E+01	2.42E+00	-78%

Circular saw cutting has higher impacts in all categories compared to diamond cutting. This is mainly due to the higher water and electricity usage compared to the innovation. Thus, the EoLO-HUBs system could lead to 25-78% environmental savings, depending on the impact category considered. However, these results are preliminary since the development of diamond wire cutting is still under study and there the inventory data is just an estimation, while some relevant aspects, such as material use in both systems, are not yet included.

Figure 12 shows the impact contribution to climate change, human toxicity (cancer and non-cancer), resource use (fossil, minerals, and metals), and water use by each process based on the corresponding resource flows.

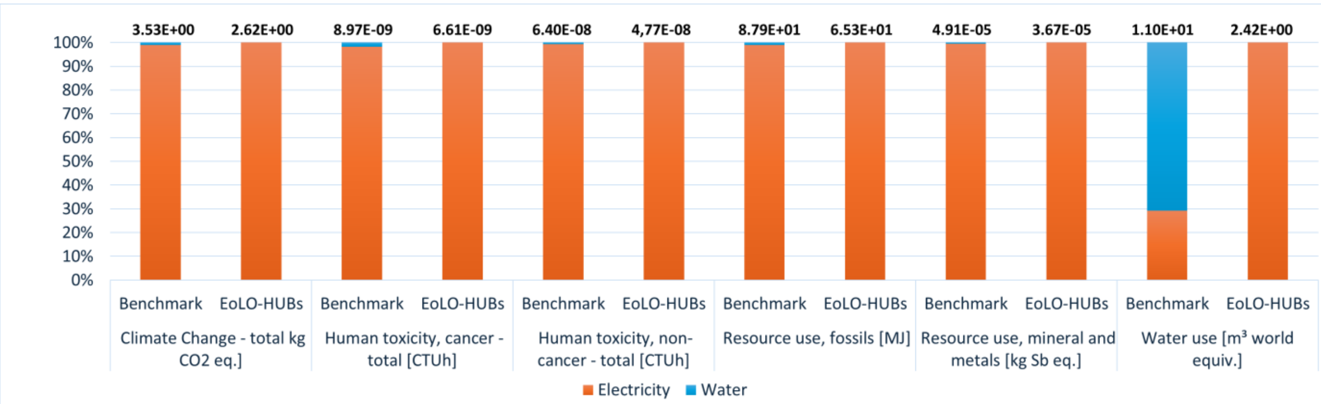

Figure 12. Comparison of the climate change, ecotoxicity, ozone depletion and water use for circular and diamond wire saw cutting techniques (considering 1 WTB as FU).

Electricity is the most influential flow in all impact categories for both the benchmark and the EoLO-HUBs system. Additionally, the recirculation of water in diamond wire cutting versus circular saw cutting is one of the main reasons for the different contribution to impact in water use.

4.1.3.1.4. Guidelines and opportunities for diamond wire cutting

Circular saw cutting has been one of the most widely used blade cutting alternatives. However, dust emissions, cutting quality and associated occupational hazards have created the need for research and development of more sophisticated techniques to carry out this process.

The technology developed by ADV will reduce the cutting operation time and energy and water consumption compared to the benchmark cutting system. However, it is still necessary to implement a system to collect the dust generated during the cutting process to reduce its environmental impact and give it a second application. Concerning the quantitative analysis carried out with the preliminary data, diamond wire cutting shows improvements in terms of emission reduction for the impact categories analyzed. However, the need to reduce water losses has been identified to make the process more efficient and reduce its impacts.

Therefore, this preliminary analysis and comparison of the EoLO-HUBs system concerning the benchmark show the improvements being developed in EoLO-HUBs in terms of cutting technology, which in turn will improve the following processes of pre-treatment of blade waste.

4.1.3.2. Waterjet cutting

AIT is developing this cutting technology, however, as all the studies carried out so far have been developed at laboratory scale.

4.1.3.2.1. Qualitative analysis of waterjet cutting

AIT is developing a robotic-guided autonomous system to handle the WTBs through waterjet cutting. Figure 13 shows the flow diagrams corresponding to the alternative. It is also necessary to consider that the operating parameters (in this case, being the FU the cutting of a blade surface of 0.03 m^2 as shown in Table 15.

As well as applies for the diamond wire cutting system, the AIT waterjet system would entail the transportation and set up of the machinery in the wind farm, which can require higher logistics than the use of conventional circular saws. While the specific steps for conducting the cutting process are still under consideration, the proposal is to conduct the cutting on-site to streamline the transportation of the WTB pieces. This approach involves moving the cutting platform to the desired area using the Autonomous Ground Vehicle (AGV) and cutting using the WJC machine. Improvements have been made to both software and hardware to achieve these developments. A new software system for robot programming has been created utilizing intelligent tools. This system includes several high-performance cameras that record the robot's movements. After automatically analyzing these recordings, the robot can execute the movements (Pers.Com. AIT, 2024).

As the waterjet cutting system is being developed at the lab scale, they cannot be directly compared with the operating parameters for the circular saw cutting the calculation of the corresponding impacts, beyond doing it on a qualitative level (Table 16) and analyzing the potential hotspots of the process itself (Table 17).

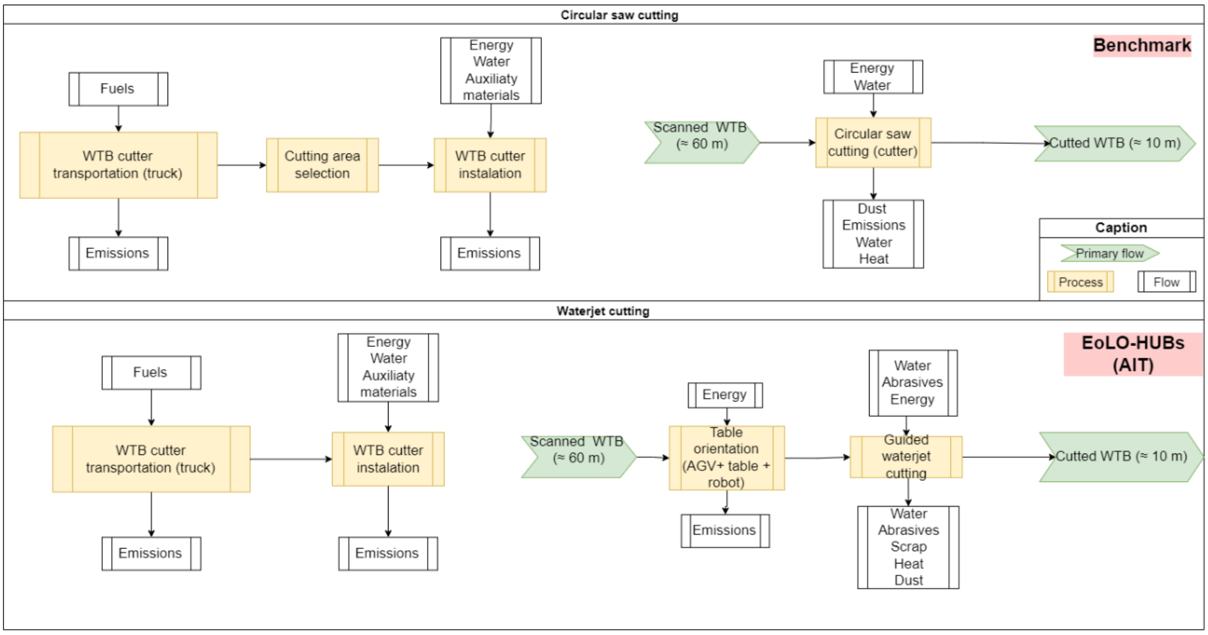

Figure 13. Flow diagram for circular and waterjet cutting (EoLO-HUBs) technology. Acronyms: WTB (Wind turbine Blade), AGV (Autonomous Ground Vehicle).

Table 15. Operational parameters for waterjet cutting for AIT innovation of blade surface of 0.03 m^2 (FU) at laboratory scale. References: (Hilti, 2023; Pers. Com. AIT, 2024; Sproul et al., 2023).

Operative parameters		Waterjet cutting (EoLO-HUBs)
Machinery parameters	Sound emission, dB	Not possible to be determined
	Electric motor, kW	Not possible to be determined
	Weight, kg	Not possible to be determined
	Energy source	Not possible to be determined
	WJC machine, kWh	0.68
	Robot, kWh	0.1
	Water pump, kWh	0.0072
	Compressor, kWh	0.45
	Inverters, kWh	0.0031
	Total energy (electricity)	1.24
Operational parameters	Cutting time, h	0.019
	Robot total time, h	0.025
	Compressor time, h	0.03
	Water tap water, l/min	3.8
	Abrasives, kg/min	0.3
Economic parameters	Abrasive, €/kg	0.30
	Water, €/l	0.0044
	Wear, €/h	0.58
	Worker, €/h	0.38
	Energy, €/kWh	0.14

4.1.3.2.2. Technical, economic, environmental and social characterization of waterjet cutting

Table 16 shows the technical, economic, environmental and social comparisons between the circular saw cutting and the EoLO-HUBs innovation for the waterjet cutting.

Table 16. Most relevant technical, economic, environmental and social aspects of circular and EoLO-HUBs innovation for waterjet cutting including suggestions for improvement by the EoLO-HUBs partners. Note: (-) refer to negative aspects, (+) refers to positive aspects.

Sustainability aspects	Circular saw cutting	Waterjet (EoLO-HUBs-AIT)	Sources
Technical	• Independent cuts in all directions (+) • Less logistics requirements (+) • Manual technology (-) • Irregular cuts (-)	• Optimize the process for a minimum consumption of energy and time (+) • Automatized guided system (+) • Not limited to the dimensions of the WTBs (+)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers. Com. AIT, 2024)
Economic	• Cheap technology (+) • More frequent maintenance and replacement of saw blades (-)	• Higher cost of conventional techniques (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers. Com. AIT, 2024)
Environmental	• Noise and dust emissions (-)	• Possibility of reusing water and abrasive (+) • Energy savings (+) • Dust emissions (-) • Waste management (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers. Com. AIT, 2024)
Social	• Potential safety hazards for the operators (-)	• Find workers with proper expertise in the dismantling processes (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers. Com. AIT, 2024)

Technically, the waterjet cutting process can be optimized by reducing energy consumption and time requirements. One of the great advantages over conventional cutting is that it is an automatic process which facilitates the entire process. Regarding economic aspects, it's important to note that saw cutting, despite its logistical requirements, remains a cost-effective technology. In contrast, waterjet cutting is expected to be a more expensive technology due to the sophisticated machinery and cutting technology compared to conventional cutting.

One of the environmental aspects of waterjet cutting is waste management and the generation of dust emitted during cutting. However, the recirculation of both water and abrasives will allow the consumption of fewer materials and energy savings. Finally, another critical aspect of both processes is the need for experienced workers in this type of process and technology.

4.1.3.2.3. Quantitative analysis of waterjet cutting

Table 17 shows the inventory data for AIT innovation on waterjet cutting (functional unit: 0.03 m^2 of blade surface). As it is a lab-scale process, the quantitative analysis has been performed only for innovation and not compared to circular saw cutting (which is at industrial level).

Table 17. Resource inputs and outputs for the waterjet cutting of 0.03 m^2 blade surface (FU). References: (Pers.Com. AIT, 2024). Acronyms: n.a (not applicable)

FU: 1 blade surface of 0.03 m^2	Waterjet cutting (AIT)		Ecoinvent process
Inputs	WTB piece length, mm^3	0.00129	n.a
	Energy consumption, kWh	0.68	ENTSO-E: market group for electricity, low voltage
	Water consumption, kg	4.46 (not yet recirculated)	Europe without Switzerland: tap water production, conventional treatment
	Abrasives consumption (garnet), kg	0.35	n.a
Outputs	Waste material (scrap), m^3	4.52E-05	n.a

Data on water, energy and abrasive consumption have been provided directly by AIT. A simplified LCA has been applied by using the GaBi v10.0 software (Thinkstep, 2016) with the Ecoinvent 3.9.10 database (Ecoinvent Centre, 2016) to calculate the EF 3.1 impact categories (Table 18). In this case, the impacts associated with abrasive have not been considered since there is no flow available in Gabi that refers specifically to the garnet used in this case.

Of the 16 categories analyzed, the one with the greatest impact is resource use fossils, due to the use of water, electricity and abrasives involved in the process. It should be noted that since this is a process developed on a laboratory scale, the values are not significantly high. Therefore, it would be convenient that once the process is scaled up, to carry out the same study to compare with the conventional process and to analyze the differences of the process at industrial and laboratory scale.

Table 18. Environmental impacts for the waterjet cutting of 0.03 m^2 blade surface (FU).

Impact category	Unit	EoLO-HUBs Waterjet cutting
Acidification	[Mole of H+ eq.]	3.43E-04
Climate Change - total	[kg CO2 eq.]	6.03E-02
Ecotoxicity, freshwater - total	[CTUe]	2.61E-01
Eutrophication, freshwater	[kg P eq.]	5.93E-05
Eutrophication, marine	[kg N eq.]	5.40E-05
Eutrophication, terrestrial	[Mole of N eq.]	4.67E-04
Human toxicity, cancer - total	[CTUh]	1.54E-10
Human toxicity, non-cancer – total	[CTUh]	1.09E-09
Ionising radiation, human health	[kBq U235 eq.]	3.88E-02
Land Use	[Pt]	3.45E-01
Ozone depletion	[kg CFC-11 eq.]	1.14E-09
Particulate matter	[Disease incidences]	1.21E-09
Photochemical ozone formation, human health	[kg NMVOC eq.]	1.55E-04
Resource use, fossils	[MJ]	1.50E+00
Resource use, mineral and metals	[kg Sb eq.]	8.37E-07
Water use	[m^3 world equiv.]	2.47E-01

Figure 14 shows the contributions of water and electricity for different impact categories.

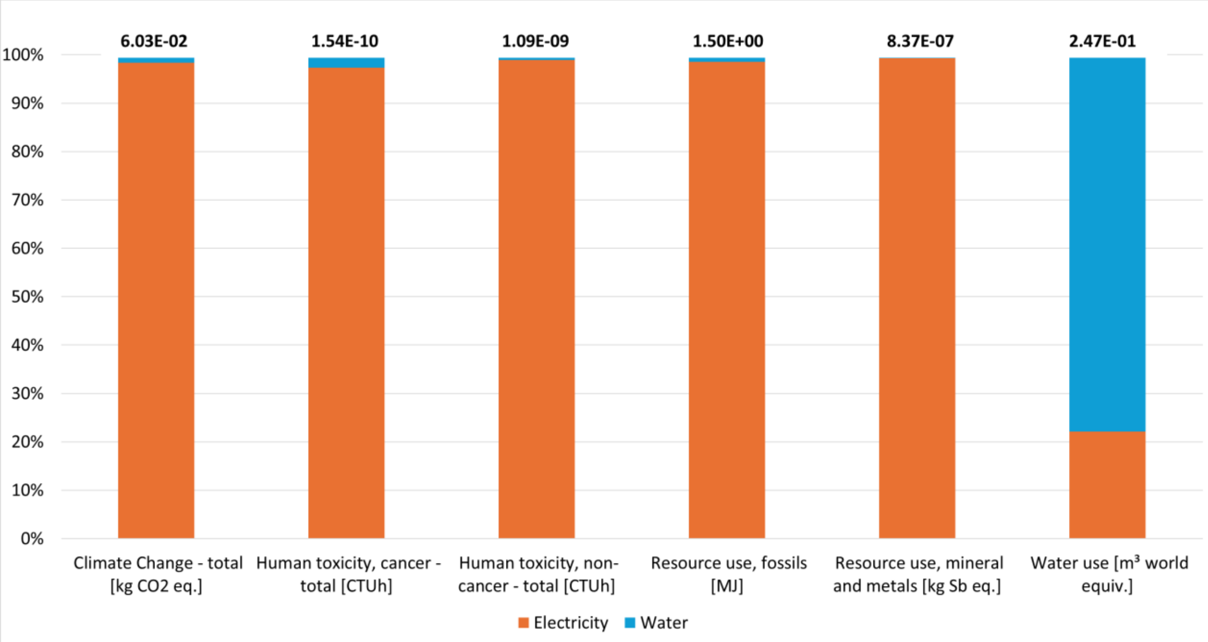

Figure 14. Comparison of the climate change, ecotoxicity, ozone depletion and water use for waterjet cutting techniques (considering 0.03 m^2 of blade surface cutting as FU).

In this case, electricity negatively influences the impacts of the different categories. It would be necessary to have a benchmark system at the same work scale to make a quantitative comparison in this case. Nevertheless, it would be good to take into account how both electricity and water consumption are affected when scaling up the process to avoid possible future impacts.

4.1.3.2.4. Guidelines and opportunities for waterjet cutting

Although waterjet cutting is more sophisticated and can lead to higher material and logistics requirements compared to conventional cutting systems, it can optimize cutting efficiencies. However, energy efficiency (as well as the reuse of abrasives and water) should be improved to minimize the impact of this WTB cutting system.

4.1.3.3. WTB laser cutting

The last technology under development within EoLO-HUBs is laser cutting, run by MTC.

4.1.3.3.1. Qualitative analysis of laser cutting

MTC is developing a laser cutting method using the Synova LCS305 laser system. Figure 15 shows the flow chart for waterjet cutting (compared to circular saw cutting), while Table 19 presents its operational parameters (considering the use of Synova LCS305).

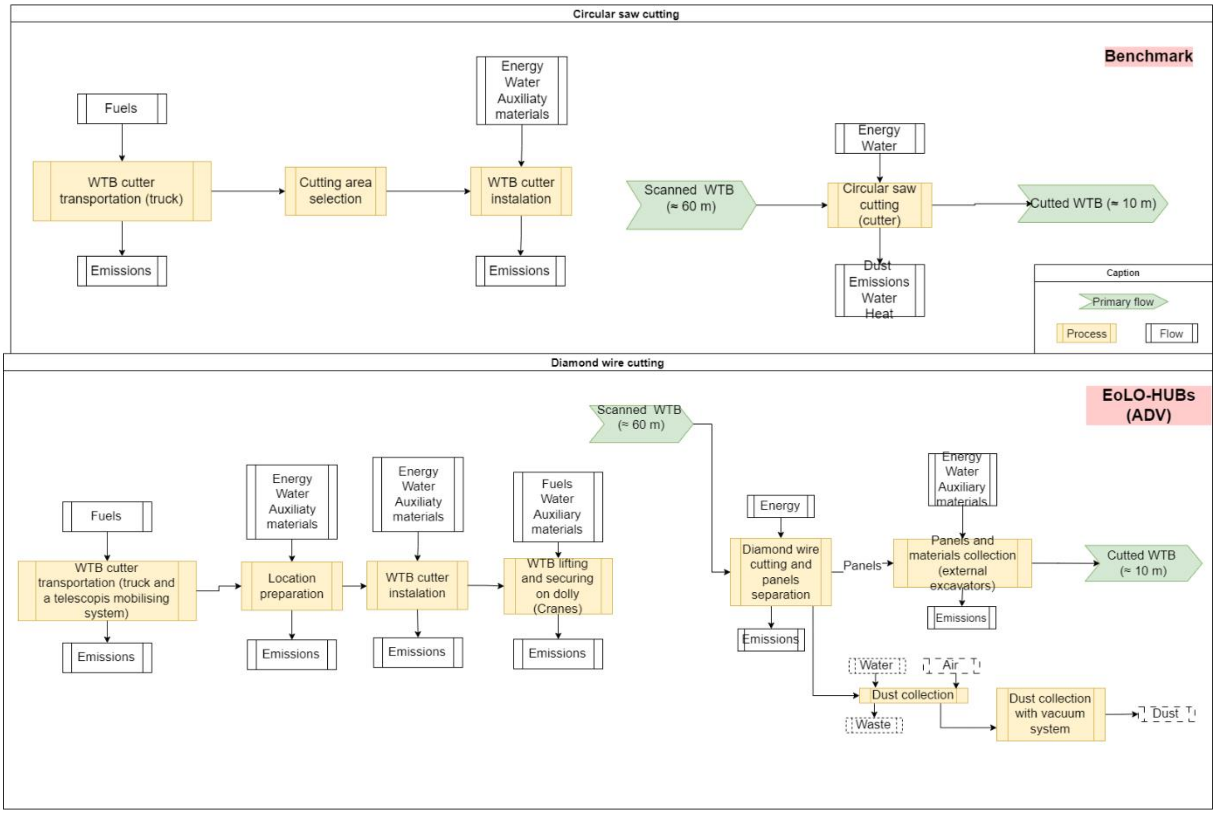

Figure 15. Flow diagram for circular (benchmark) and laser (Eolo-HUBs) WTB cutting technologies. Acronyms: WTB (Wind turbine Blade), AGV (Autonomous Ground Vehicle).

Table 19. Operation parameters for the laser-based WTB cutting process considering 8 mm thick piece as FU.

Operative parameters		**Laser WTB cutting (EoLO-HUBs)**
Machinery parameters	**Energy source**	Electric
	Lasers	Diode-pumped solid-state pulsed Nd:YAG lasers
	Lasers operating range, nm	1064 - 532
	Maximum Average Power, W	400
	Waterjet pressure, bar	50-800
	Nozzles composition	Sapphire or diamond
	Nozzles diameter, µm	20-100
Operational parameters	**Cutting time, h**	Not possible to share
Economic parameters	**Synova LCS305 CapEx, €**	1,276,000
	Laser + operator, €/p*h	~290

The laser cutting process of WTB requires an integral system consisting of a chiller, helium gas bottle, laser unit, laser chiller, extraction unit and water pump unit. In addition, an extraction system and adequate ventilation are needed due to the fumes generated during cutting. The Synova LCS305 uses a pressurized water jet protected by helium gas, which guides the laser beam by total internal reflection at the air/water interface to the irradiation zone on the workpiece. The continuous application of water during cutting provides cooling, significantly reducing the adverse effects of laser heating and preventing thermal damage to the material (Laser microjet technology, 2020).

4.1.3.3.2. Technical, economic, environmental and social characterization of laser cutting

Table 20 shows the technical, economic, environmental and social comparation between circular and laser cutting techniques, although laser cutting is not yet at the same TRL.

Technically, laser cutting allows cutting the thickness of blades, although it is a process that is difficult to scale due to the technology and logistics requirements. From an economic perspective, laser cutting technology presents two significant drawbacks. First, the machinery required for laser cutting is expensive, which can pose a financial barrier to its adoption. Secondly, the use of helium, a finite resource, adds to the cost and generates sustainability concerns, potentially impacting its development.

Regarding the environment, laser cutting emits fumes and vapour, which represent a source of environmental and human hazards if they are not properly handled with security measures. In fact, these emissions can be more harmful than the noise and dust generated by conventional cutting methods, underscoring the need for careful consideration of its environmental impact. Finally, during laser cutting, it will be necessary to take the necessary protective measures for workers, using appropriate protective equipment or implementing safe areas. Therefore, the risks to which workers are exposed in this case could be more harmful than conventional cutting.

Table 20. Most relevant technical, economic, environmental and social aspects for circular (benchmark) and laser (EoLO-HUBs) WTB cutting. Note: (-) refers to negative aspects, (+) refers to positive aspects.

Sustainability aspects	Circular saw cutting	Laser cutting EoLO-HUBs (MTC)	Sources
Technical	• Independent cuts in all directions (+) • Less logistics requirements (+) • Manual technology (-) • Irregular cuts (-)	• Capable of cutting through the thick materials in WTBs (+) • Difficult process upscaling (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. MTC, 2024)
Economic	• Cheap technology (+) • More frequent maintenance and replacement of saw blades (-)	• High cost of laser (-) • Finite supply of helium (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. MTC, 2024)
Environmental	• Noise and dust emissions (-)	• Fumes emitted from melting/vaporising the WTB material with laser (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. MTC, 2024)
Social	• Potential safety hazards for the operators (-)	• Laser must be enclosed to avoid skin & eye exposure (-)	(Jensen and Skelton, 2018a; Johst et al., 2023; Pers.Com. MTC, 2024)

4.1.3.3.3. Quantitative analysis of laser cutting

From the operating parameters, the water and helium flows, the cutting time and the motor power are known. Although these parameters are not shown in this table as they are confidential data of the project. For this reason, Table 21, where the LCI of the laser cuting process has been collected, shows the values corresponding to the water, electricity and helium consumptions corresponding to the preliminary values obtained from the laboratory scale tests for cutting an 8 mm piece of blade.

Table 21. Resource inputs and outputs for laser cutting technology (based on preliminary laboratory results) considering the cutting of an 8 mm thick piece as FU. References: Pers.Com.MTC (2024). Acronyms: n.a (not applicable)

FU: WTB piece of 8 mm thick		Laser cutting (EoLO-HUBs- MTC)	Ecoinvent process
Inputs	Energy consumption, electricity, kWh	0.0093	ENTSO-E: market group for electricity, low voltage
	Water consumption, kg	0.23	Europe without Switzerland: tap water production, conventional treatment
	Helium consumption, l	1.4	GLO: market for helium
Outputs	Cut WTB piece	-	n.a

Subsequently, as for all previous studies, the impacts have been analyzed using EF3.1 (JRC, 2023) as the characterization method, which is the methodology recommended by the PEF (PEFCR, 2017). This was done using GaBi v10.0 software (Thinkstep, 2016) and the Ecoinvent 3.10 database (Ecoinvent Centre, 2016). Table 22 shows the comparison of the 16 impact categories calculated and the difference in each.

Table 22. Environmental impacts for the laser-based cutting system considering 8 mm thick piece as FU.

Impact category	Unit	Laser cutting (EoLO-HUBs)
Acidification	[Mole of H+ eq.]	1.37E-05
Climate Change - total	[kg CO2 eq.]	3.85E-03
Ecotoxicity, freshwater - total	[CTUe]	1.60E-02
Eutrophication, freshwater	[kg P eq.]	1.30E-06
Eutrophication, marine	[kg N eq.]	2.94E-06
Eutrophication, terrestrial	[Mole of N eq.]	2.85E-05
Human toxicity, cancer - total	[CTUh]	1.91E-11
Human toxicity, non-cancer – total	[CTUh]	3.42E-11
Ionising radiation, human health	[kBq U235 eq.]	6.78E-04
Land Use	[Pt]	9.59E-03
Ozone depletion	[kg CFC-11 eq.]	2.38E-10
Particulate matter	[Disease incidences]	8.25E-11
Photochemical ozone formation, human health	[kg NMVOC eq.]	2.27E-05
Resource use, fossils	[MJ]	1.92E-01
Resource use, mineral and metals	[kg Sb eq.]	1.72E-08
Water use	[m³ world equiv.]	1.11E-02

In this case, of the 16 impact categories analyzed, the categories with the most significant impact are resource use, fossils and ecotoxicity, and freshwater (total). The impact of these categories may be due to the use of helium and energy in the process. On the other hand, the category with the lowest environmental impact is human toxicity cancer, followed by particle matter, which leads to the conclusion that the process does not generate carcinogenic compounds or emit suspended particles.

To extend this study, the contribution of the different flows in different impact categories has been studied. Figure 16 shows the contribution of electricity, water, and helium to the laser cutting process developed by MTC at a laboratory scale.

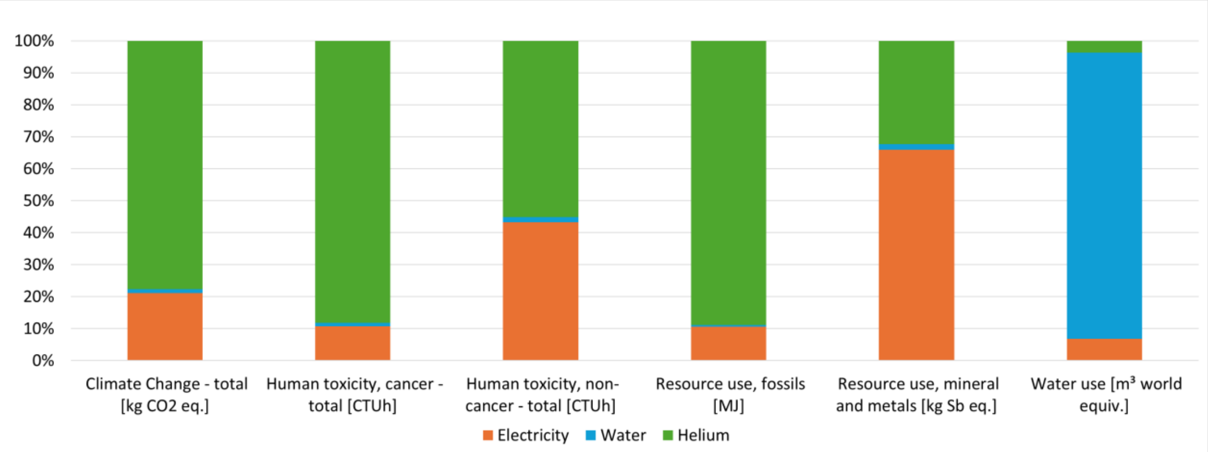

Figure 16. Comparison of the climate change, ecotoxicity, ozone depletion and water use for laser cutting (considering 8 mm thick piece as FU).

Helium stands out as the most influential resource flow, as it determines the highest impact share in four of the six impact categories presented in Figure 16. The reasons about the potential impact of helium, as well as the impact for other resource flows is provided in Section 5.1. Therefore, the use of helium would be one of the most critical hotspots to address to improve the sustainability performance of this WTB cutting alternative. In any case, results are preliminary and based on laboratory-level considerations.

Electricity represents the resource flow with the greatest weight in the category of resource, mineral, and metal use, due to the energy mix used at the EU level. While its impact is not as significant as helium, it influences multiple categories. Therefore, it's vital to reduce electricity consumption as much as possible.

4.1.3.3.4. Guidelines and opportunities for laser cutting

Laser cutting can reduce cutting times, improve efficiency, and develop WTB pieces with an improved surface finish. However, it is still a development process, and all the challenges of upscaling it to the industry level should be properly evaluated.

The results (although relying on laboratory data) revealed that helium is the most influential flow in most impact categories and can determine a large share of the technology cost as well. Water serves as a coolant for the laser, and exploring the potential for its recirculation or reuse in other industrial processes could significantly reduce its impact. Finally, electricity consumption should be optimized to mitigate impacts further.

4.1.3.4. Comparison of EoLO-HUBs cutting technologies

From a technical point of view, the three technologies' cutting efficiency are expected to be superior to conventional cutting. As for diamond wire cutting, this process is not limited by the dimensions of the WTBs and is the only process scaled up to the industrial level, as diamond wire cutting is taking place already in the sector. Waterjet cutting is an automated technology that can optimize energy consumption and time requirements; however, its influence has yet to be evaluated on an industrial scale. The same applies to laser cutting that is promising to cut WTBs of different thicknesses but they should be tested in real-life applications on site. In any case, the three technologies face logistical difficulties for the transportation and the deployment of the machinery on site. Therefore, logistics requirements between EoLO-HUBs and benchmark cutting systems should be well-analyzed on a case-by-case basis.

From an economic point of view, these three technologies could have a higher cost compared to conventional cutting techniques. All are expensive technologies due to the use of specific materials (e.g. diamond wires in diamond wire cutting, abrasives in waterjet cutting and helium in laser cutting). Therefore, the implementation of circular solutions for material efficiency is crucial to mitigate costs (and environmental impacts).

From an environmental point of view, diamond wire cutting can consume more electricity than conventional methods and, like conventional methods, emits dust (although the best way to collect it is being investigated). Waterjet cutting could save energy but relies on the use of a continuous flow of water, so it can be a high-water intensive process if it is not properly recirculated. Finally, laser cutting emits fumes from the blade material's vaporization. Therefore, from an environmental perspective, these processes must investigate the best methods to control dust emissions and optimize material and energy consumption.

Finally, social aspects are common to all three technologies, highlighting the need to find qualified personnel knowledgeable in specific techniques, in addition to the implementation of the use of protective equipment for workers. In the case of diamond wire cutting, the development of effective dust collection methods will reduce workers' exposure to particle inhalation. Laser cutting, however, requires much more specific protective measures due to the significant risks posed by its exposure to skin and eyes, which can be highly damaging.

4.1.4. WTB decoating

The aircraft industry uses coating removal processes during the aircraft repainting activities. So before repainting an aircraft, the paint layer is removed by adding an abrasive that lifts the paint from the surface. Afterwards, the surface is cleaned and repainted (Insider Tech, 2017). EoLO-HUBs tries to apply this process to the wind industry, based on how it works in the aeronautical industry.

Accordingly, the implementation of three WTB decoating techniques (mechanical blasting, chemical decoating and thermal stripping) is being studied by AIT to facilitate subsequent WTB recycling processes, while facilitating a second use for the recovered coats. Importantly, WTB decoating, could take place before (e.g. in the case of large pieces) or after (e.g. in the case of smaller pieces) cutting processes. Therefore, the process could be flexible to the case requirements.

4.1.4.1. Qualitative analysis of decoating

Figure 17 shows the flow diagrams of the three decoating alternatives and Table 23 summarizes the most relevant operational aspects of each process under study. All operational aspects presented in Table 23 are at laboratory scale.

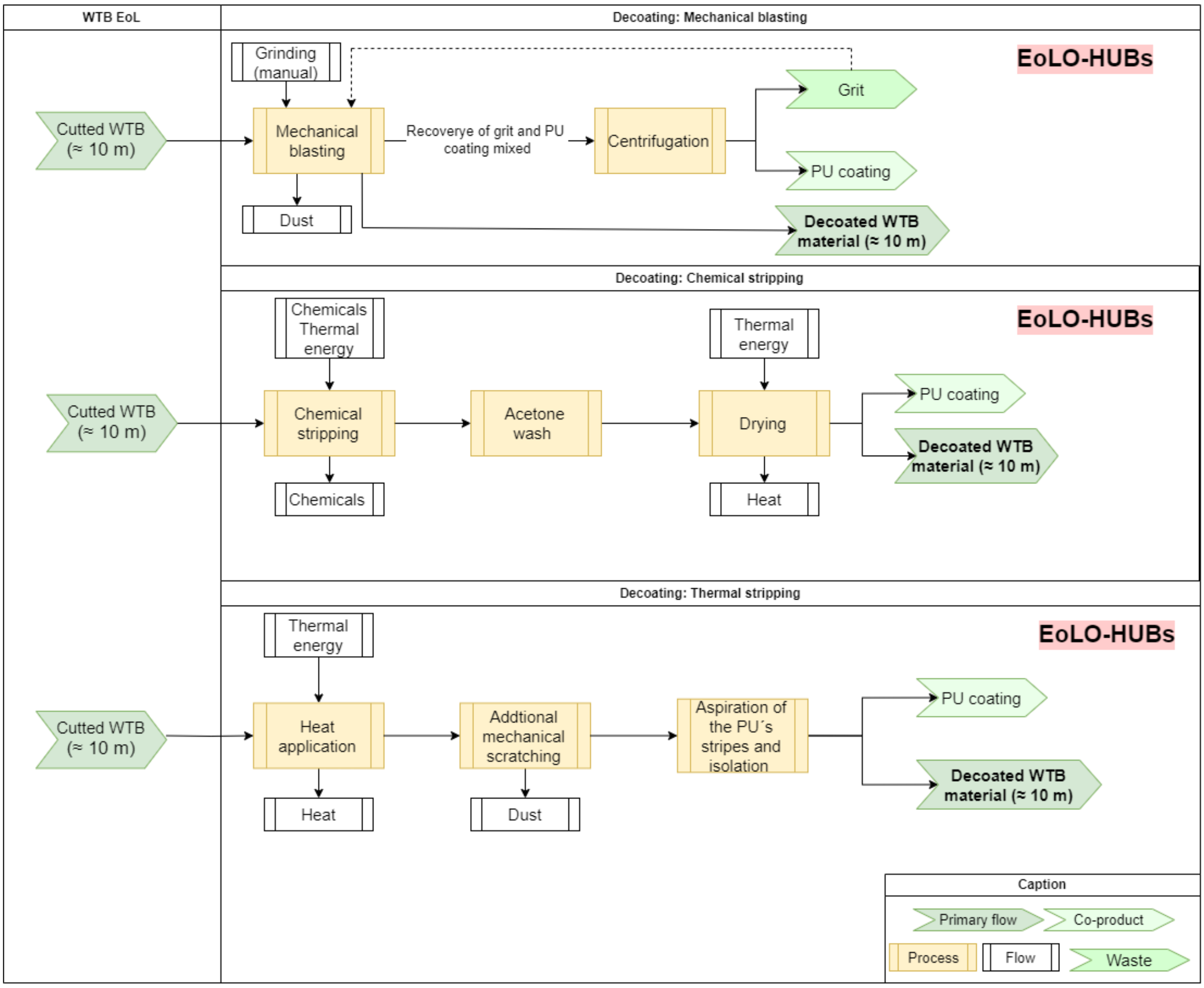

Figure 17. Flowchart of different decoating processes studied in EoLO-HUBs. Acronyms: WTB (Wind Turbine Blade), PU (Polyurethane)

Mechanical blasting consists of manually applying abrasives to the WTB surface expelled under pressure so that part of the surface and the PU coating is released (and mixed into a powder). The resulting powder is then centrifuged to separate the two components: abrasives for reuse in the same process, and PU coating for use as an input in a solvolysis process or in other industries. One of the main difficulties of mechanical blasting is to optimally separate this powder mixture, which can result in the recovered PU having impurities. The costs associated with the process are assummed to be determined by the energy costs and those associated with the use of mineral abrasives.

In chemical stripping, a chemical mixture (acetic acid + H_2N_2) is applied to the WTB surface with temperature (60°C) for 15 minutes. The surface is then washed with acetone and dried, and part of the PU coating (by-product) is recovered. Additional heat treatment is usually necessary to optimally separate the coating from the surface. This means that, in addition to the costs associated with the chemicals, energy costs can be relevant.

Finally, thermal stripping involves applying heat to the surface (140-150 °C) to lift the surface coating, which seems to be the most efficient alternative so far. After heat is applied, mechanical scraping allows to remove additional coating, while a PU suction process is performed to recover the coating. This is the simplest alternative from a technical point of view, and it can be highly scalable at the industrial level, even though energy costs should be controlled.

Table 23. Operational parameters for decoating processes studied in the EoLO-HUBs project of 1 m^2 surface area of a 1 blade (FU). References: (Pers. Com. AIT, 2024). Acronyms: n.a (not applicable)

Operative parameters		**Mechanical blasting**	**Chemical stripping**	**Thermal stripping**
Machinery parameters	**Machinery model**	PEENMATIC - MICRO 620s	Not possible to be determined	Steinel HG 2320 E
Operative parameters	**Power density, kW/m²**	1.48	4.28	17.41
	Chemical application on surface	n.a	60°C during 15 minutes	n.a
	Drying conditions	n.a	80°C for 6-8 hours	n.a
	Drying energy, W/cm²	n.a	22.4	n.a
Use parameters	**Workers**	2	2	2
	Heat application	n.a	n.a	Maximum 2 minutes at 2 cm (140-150°C)
	Process time	2 minutes for manual application	15 minutes for chemical application + 420 minutes for drying	2 minutes for heat application
Economic parameters	**Grit cost, €/m²**	0.07	n.a	n.a
	Energy cost, €/m²	85.7	0.22 (Chemical application) 1.12 (Drying)	0.87
	Acetic acid cost, €/m²	n.a	1064	n.a
	Acetone cost, €/m²	n.a	136.2	n.a

4.1.4.2. Technical, economic, environmental and social characterization of decoating

Table 24 shows the most relevant aspects of each process (EoLO-HUBs innovations) in terms of technical, economic, environmental and social aspects.

From a technical point of view, thermal stripping could be the most straightforward and scalable industrial process. Regarding mechanical blasting, the separation between the grit and the recovered PU could be challenging, while in the case of chemical stripping the use of chemicals can lead to relevant cost, environmental and social impacts.

Focusing on economic aspects, the costs associated with each process is highly dependent on the energy (especially for thermal decoating) and material costs (e.g. abrasives for mechanical blasting and chemicals for chemical stripping).

Table 24. Most relevant technical, economic, environmental and social aspects of the WTB decoating. Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Mechanical blasting	Chemical stripping	Thermal stripping	Sources
Technical	• Difficult to separate shot blasting powder and PU (-) • Not scalable process (-)	• Need for additional heat treatment (-)	• Simple and scalable technique for industry (+)	(Pers.Com, AIT,2024)
Economic	• Energy and mineral grit costs (-)	• Chemical and energy costs (-)	• Energy costs (-)	
Environmental	• Dust generation (-)	• Chemical waste management (-)	• Mechanical scraping may generate dust (-)	
Social	• Worked dust inhalation (-)	• Chemical products handling risks (-)	• Toxic fumes inhalation (-)	

The emissions generated by the processes related mostly with dust emissions (especially for mechanical blasting) and organic volatile compounds (for the case of chemical decoating). The waste generated by these products will have to be managed in the most sustainable way possible, which is more critical in the case of chemical stripping. Finally, it will be necessary to consider the risks to which workers will be exposed in each case, such as smoke inhalation (e.g. in thermal decoating) or exposure to chemical products (in chemical stripping).

4.1.4.3. Quantitative analysis of decoating

Data from the first laboratory-scale tests (Table 25) have been used to perform a preliminary quantitative analysis for each alternative decoating process.

Table 25. Resource inputs and outputs for different EoLO-HUBs decoating techniques, considering the treatment of for 1 m^2 of blade surface (FU). Acronyms: n.a (not applicable)

Resource flows	Processes		Mechanical blasting	Chemical stripping	Thermal stripping	Ecoinvent process
Inputs	Blasting application	Mineral grit, kg/min	0.1	n.a	n.a	n.a
		Electricity consumption, kWh	0.05	n.a	n.a	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
	Chemical application	Energy consumption, kWh	n.a	1.07	n.a	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
		Acetic acid + H_2N_{2}, l/m^2	n.a	20	n.a	n.a
	Acetone wash	Acetone rinsing, l/m^2	n.a	60	n.a	RER: market for acetone, liquid ecoinvent 3.10
	Drying	Energy consumption, kWh	n.a	156.8	n.a	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
	Heat application	Energy consumption, kWh	n.a	n.	0.58	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
Outputs	PU material recovered %		95	Not possible to be determined	85 (51 kg/m^2)	n.a
	PU scrap %		5		0.15 (9kg/m^2)	n.a
	Grit, gr/cm^2		0.71	n.a	n.a	n.a

It is observed that the overall energy consumption is higher for the chemical stripping process (157.08 kWh), being much higher than mechanical blasting (0.05 kWh) and thermal stripping (0.58 kWh). This is because adding chemicals and applying heat requires more time (and thus energy). In this case, as in the case of water jet cutting, abrasives have not been considered when calculating the impacts. Although garnet ore is known to be used as an abrasive, no such flow is available in GaBi. Table 26 shows the resulting environmental impacts for each of the decoating processes.

Table 26. Environmental impacts for decoating blade surface of 1 m^2 (Preliminary impact results considering laboratory scale data)

Impact category	Unit	Mechanical blasting	Chemical stripping	Thermal stripping	Difference (mechanical vs thermal)
Acidification	[Mole of H+ eq.]	2.47E-05	6.35E-01	2.87E-04	-91%
Climate Change - total	[kg CO2 eq.]	4.36E-03	1.23E+02	5.06E-02	-91%
Ecotoxicity, freshwater - total	[CTUe]	1.89E-02	2.14E+02	2.19E-01	-91%
Eutrophication, freshwater	[kg P eq.]	4.31E-06	2.49E-02	4.99E-05	-91%
Eutrophication, marine	[kg N eq.]	3.90E-06	9.50E-02	4.53E-05	-91%
Eutrophication, terrestrial	[Mole of N eq.]	3.38E-05	1.00E+00	3.92E-04	-91%
Human toxicity, cancer - total	[CTUh]	1.10E-11	7.26E-08	1.28E-10	-91%
Human toxicity, non-cancer – total	[CTUh]	7.94E-11	5.92E-07	9.22E-10	-91%
Ionising radiation, human health	[kBq U235 eq.]	2.82E-03	1.12E+01	3.27E-02	-91%
Land Use	[Pt]	2.50E-02	1.41E+02	2.90E-01	-91%
Ozone depletion	[kg CFC-11 eq.]	8.25E-11	1.95E-06	9.57E-10	-91%
Particulate matter	[Disease incidences]	8.63E-11	4.70E-06	1.00E-09	-91%
Photochemical ozone formation, human health	[kg NMVOC eq.]	1.12E-05	5.67E-01	1.30E-04	-91%
Resource use, fossils	[MJ]	1.09E-01	3.35E+03	1.26E+00	-91%
Resource use, mineral and metals	[kg Sb eq.]	6.11E-08	5.00E-04	7.09E-07	-91%
Water use	[m^3 world equiv.]	4.03E-03	7.26E+01	4.67E-02	-91%

Chemical stripping has more significant impacts in all cases than the other two processes. For this reason, a comparison has been made between mechanical blasting and thermal stripping (the latter being chosen as the reference system). This comparison is shown in the difference column and has been carried out to determine to what extent mechanical blasting decreases the environmental impacts of thermal stripping. It is observed that mechanical blasting reduces impacts by 91% compared to thermal recycling for all categories. Therefore, with the preliminary data analyzed, it can be deduced that mechanical blasting will be the process with the lowest environmental impacts.

The impact categories of climate change, human toxicity (cancer and non-cancer), resource use (fossils, mineral and metals) and water use are analyzed in depth in Figure 18. It shows the value obtained in each of the categories (upper part), and the influence of electricity, acetone and acetic acid in each of them.

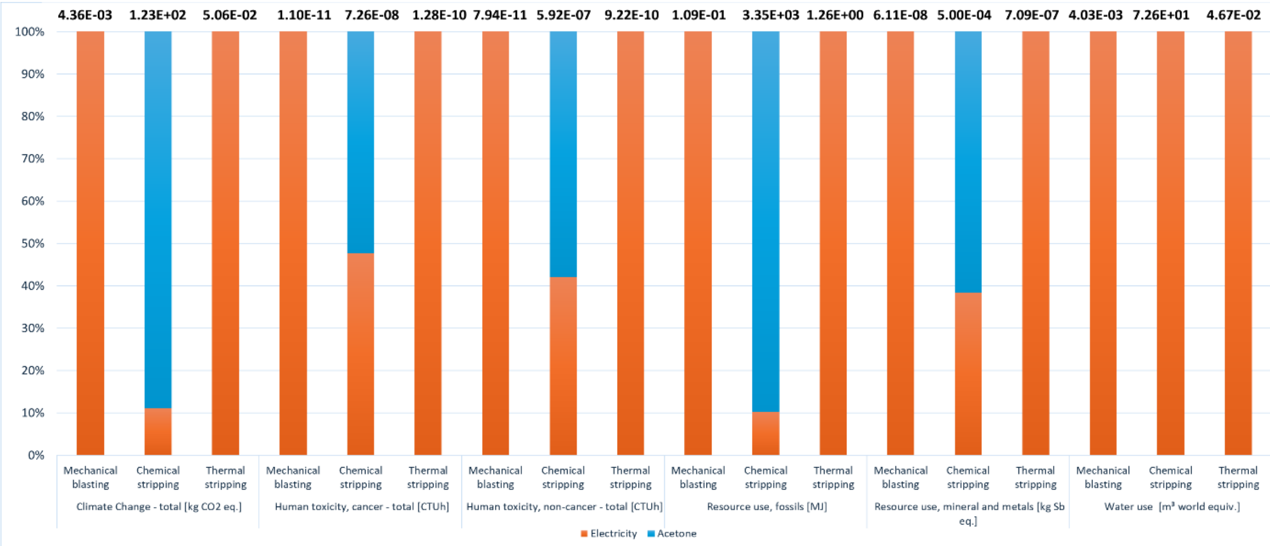

Figure 18. Comparison of the climate change, ecotoxicity, ozone depletion and water use decoating techniques (considering 1m^2 of blade surface as FU).

In this case, acetone significantly influences the impact categories of chemical stripping. The use of the compound, the pollution and its management make this process have more significant impacts than the other two methods. Thermal stripping has the second highest impact due to its high energy use compared to mechanical blasting, which has lower impacts and less energy use.

4.1.4.4. Guidelines and opportunities for decoating

Implementing WTB decoating processes is expected to facilitate the recovery of their coatings to give them a second life, and/or using it as an input for solvolysis. It is estimated that the most promising alternative is thermal stripping (Pers.Com. AITIIP, 2024) due to its simplicity and industrial scalability potential. However, one of the significant challenges faced by AIT is the need to know the nature of the coating on the old WTBs, which could vary significantly the process parameters of the different alternatives under study. Therefore, a preliminary analysis of the coating material is crucial to be performed prior starting the decoating process, if information and data (e.g. in material passports) of the WTBs is not readily available (Pers. Com. AITIIP, 2024). The same applies to solvolysis, as discussed in section 4.2.

4.1.5. WTB shredding and sorting

Shredding comprises reducing the size of the WTB pieces (obtained through cutting) further so that it is more manageable for transportation and/or to comply with the WTB recycling process requirements (e.g. size of inputs materials to oven - in pyrolysis - or reactor - in solvolysis - see section 4.2). Sorting involves separating materials based on their nature and composition (Jensen and Skelton, 2018a). Within the EoLO-HUBs project, MCAM and FHG are exploring on the one hand how shredding processes can be optimized, and, on the other hand, how smarter sorting processes can be implemented.

As in practice shredding and sorting can be considered techniques supporting mechanical recycling, the effects of optimizing these processes in EoLO-HUBs and the expected benefits and savings compared to the benchmark are analyzed and discussed in Section 4.2.1.

4.2. WTB recycling and fibre reclamation

The growing momentum towards a sustainable future, exemplified by landfill bans in Europe and stricter EoL directives, is creating a crucial challenge: the lack of robust and widely adopted methods for sustainable recycling WTB materials (Oudheusden, 2019). Thus, the first generation of wind farms reaches the end of their 25-year lifespans, a circular and sustainable solution for WTB recycling is becoming imperative (OGTC and ORE Catapult, 2021). The ultimate goal of any WTB recycling process, regardless of the specific technology employed, is to transform the WTB material into a new product or material with a different functional use (WindEurope, 2020a). However, all recycling processes require some level of resource consumption, such as energy, raw materials, or water (WindEurope, 2020b), which can lead to environmental impacts that could (sometimes) offset the potential savings of material recovery and reuse in the industry. Understanding these issues is crucial to facilitate the deployment of resource-efficient and sustainable WTB recycling systems.

WTB waste can be recycled through mechanical (shredding, grinding), thermal (pyrolysis, fludised bed, microwave-assisted pyrolysis), thermo-chemical (solvolysis) or electro-mechanical (high voltage pulse fragmentation) processes or combination of these; e.ch one has a different technological development (WindEurope, 2020a). In the following sections, the mechanical (crushing and grinding), thermal (pyrolysis) and chemical (solvolysis) recycling methods are analyzed, comparing the benchmark situation with the systems designed in the EoLO-HUBs project.

4.2.1. WTB mechanical recycling

Mechanical recycling involves the decomposition of WTBs through grinding, shredding, crushing, and milling processes using mechanically driven technology (Fonte and Xydis, 2021, Jani et al., 2022). This process yields small particle material (resin-rich fraction) and coarse components (fibre-rich fraction) for various applications, such as filler and reinforcement, respectively. Additionally, mechanical recycling of WTB serves (which integrates shredding and sorting processes, section 4.1.5) as a preliminary stage for other recycling processes (thermal and chemical) and recovery processes (e.g., co-processing in cement kilns) (Sorte et al., 2023, Lund and Madsen, 2024). Essentially, all EoL options require the WTB to be reduced in size during or before the recycling process (Liu et al., 2022). The goal of the mechanical recycling process for multi-material composites is to find the optimal balance between the needed disintegration of each material (Glass Fibre Reinforced Polymer – GFRP, Carbon Fibre Reinforced Polymer – CFRP, metal, wood, plastics) and obtaining a specific fibre length the various materials, and therefore receive single-origin material streams (Per. Com. FHG, 2024).

Most authors agree that the mechanical recycling process consists of three main stages: two steps of WTB waste size reduction (shredding and grinding), followed by a classification step of the recycled material obtained in the previous stages (Life ReFibre, 2024, Life+Brio, 2024, Cordis, 2024c, OGTC and ORE Catapult, 2021, Burner, 2022, Pender and Yang, 2024, Liu et al., 2022, Oudheusden, 2019, Khalid et al., 2023, Spini and Bettini, 2024). However, some authors do not consider the classification stage as part of mechanical recycling (WindEurope, 2022a, Sorte et al., 2023, Appropedia, 2024, Sommer and Walther, 2021, Lund and Madsen, 2024). Additionally, certain authors suggest that the mechanical recycling process begins with cutting the dismantled WTB into pieces, followed by shredding and grinding the waste into powder and fibre particles of tens of millimeters or micrometers in size (Liu et al., 2019, Sorte et al., 2023).

The benchmark mechanical recycling process (to compare the performance of the EoLO-HUBs pyrolysis and solvolysis recycling systems) has been formulated based on publicly available information provided by leading European projects dedicated to WTB mechanical recycling, as well as academic and grey literature (Section 3.1). However, each project has developed its own mechanical recycling process and technology, meaning that there is a wide variety of mechanical recycling processes and technologies across different projects (e.g. Life ReFibre 2024).

Based on the revised projects, there are two types of mechanical recycling processes for WTB management (depending on whether the final classification stage is included in the process): i) mechanical recycling with two phases of size reduction of the residual material (shredding + grinding); and ii) mechanical recycling with two phases of size reduction of the residual material (shredding + grinding) and a classification phase of the recycled material. The benchmark recycling process, along with typologies, is elaborated in the next section.

4.2.1.1. Qualitative analysis of mechanical recycling

Figure 19 presents the stages comprising the benchmark mechanical recycling process, with the typologies of mechanical recycling (type 1 comprises a shredding stage, a crushing stage and a classification stage; type 2 comprise a shredding stage and a sorting stage in two phases), and the mechanical recycling process devised under the EoLO-HUBs project (related to shredding and sorting, Section 4.1.5). Processes presented in Figure 19 are based on Bunner (2022), Khalid et al. (2023); Life ReFibre (2024), Life+Brio (2024), Cordis (2024c), Liu et al. (2022), OGTC and ORE Catapult (2021); Oudheusden (2019); Pender and Yang (2024), Spini and Bettini (2024), WindEurope (2022a), Dorte et al. (2023), Sommer and Walther (2021); Lund and Madson (2024), Per. Com., FHG (2024).

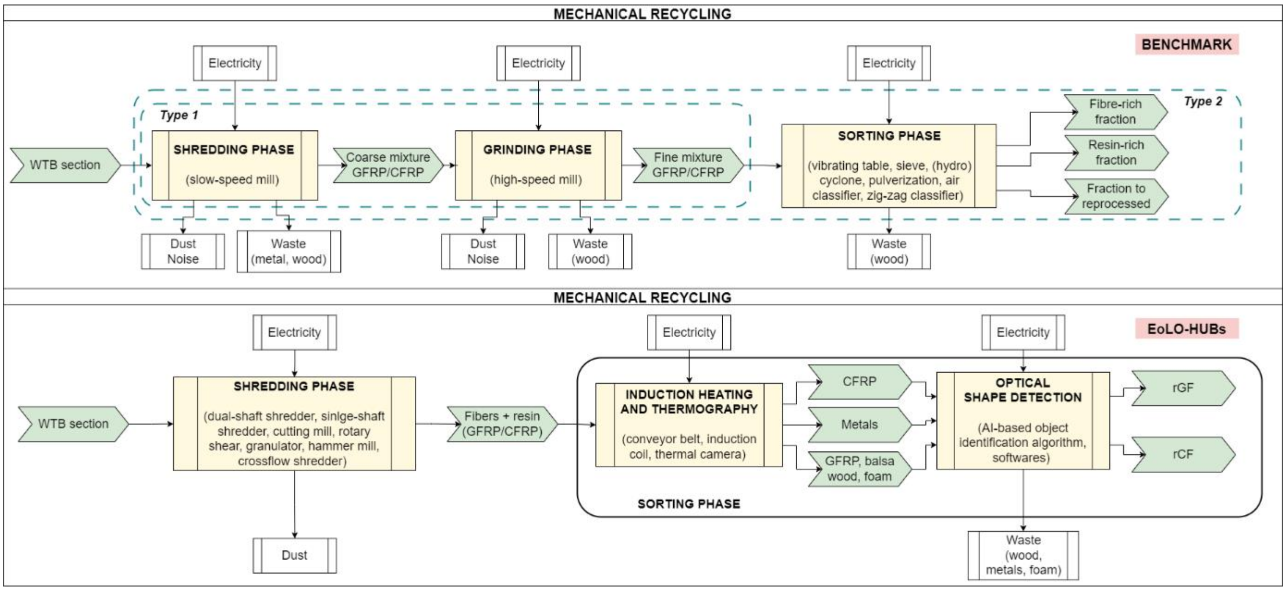

Figure 19. Flow chart for the benchmark mechanical recycling process and EoLO-HUBs system. Acronyms: WTB – Wind Turbine Blade; GFRP – Glass Fibre Reinforced Polymer; CFRP – Carbon Fibre Reinforced Polymer; AI – Artificial Intelligence; rGF – recycled Glass Fibre; rCF – recycled Carbon Fibre.

Shredding has the objective of reducing the WTBs into more manageable-sizes using electrical slow-speed cutting mills, such as crushing mill (OGTC and CORE Catapult, 2021, Khalid et al., 2023, Oudheusden, 2019). In this way, the WTB sections can be reduced into particles approximately 50 - 100 mm in size, forming a coarse mixture (OGTC and ORE Catapult, 2021). During this phase, metallic inserts/components can be removed (OGTC and ORE Catapult, 2021, Spini and Bettini, 2024), and dust waste is generated (Life ReFibre, 2024).

Then, a grinding phase is carried out, during which the composite particles are crushed into a fine material (OGTC and ORE Catapult, 2021). The particle size ranges from 50 µm to 100 mm (Spini and Bettini, 2024). Other sources report that the particle size varies between 2 mm and 25 mm (Liu et al., 2024). The technology used includes electrical high speed-cutting mill, such as hammer mill (Spini and Bettini et al., 2024, life ReFibre, 2024, Liu et al., 2022). In addition to recycled material, dust and waste (e.g., balsa wood) are generated (Life ReFibre, 2024).

The second type of mechanical recycling requires a final classification phase, where the recycled material obtained in the previous phase is categorized based on its resulting size (OGTC and ORE Catapult, 2021). Unlike the preceding size reduction phases (shredding and grinding), which typically employ more homogeneous technologies, the classification of the recycled material encompasses a wider array of tools and configurations. According to Liu et al (2022) multi-stage classification systems can be configured for this purpose.

In this stage, various electrical tools are utilized, including vibrating tables (Life ReFibre, 2024), sieves (Spini and Bettini, 2024, Khalid et al., 2023, Oudheusden, 2019, Burner, 2022, OGTC and ORE Catapult, 2021, Life+Brio, 2024), hydrocyclones (Burner, 2022), cyclones (Spini and Bettini, 2024, OGTC and ORE Catapult, 2021), pulverization (Burner, 2022), air classifier (Spini and Bettini, 2024) or zig-zag classifier (Pender and Yang, 2024). However, sieves are the most commonly used technology.

The products obtained can vary among projects and authors, but it can generally be affirmed that two main products are consistently obtained: i) a fibre-rich coarse fraction suitable for use as reinforcement (up to 10 mm particle size), and ii) a resin-rich finer powder fraction suitable for use as filler (less than 50 µm). In some cases, a third material may also be obtained, which is a material intended for reprocessing (coarse recyclate) (Liu et al., 2022, Fonte and Xydis, 2021, Jani et al., 2022, Diez-Cañamero and Mendoza, 2023). The proportion of quantities obtained in recycling typically ranges from 21-42% for the fibre-rich fraction, 30-51% for the resin-rich fraction, and 28% for the material intended for reprocessing (Liu et al., 2022, Fonte and Xydis, 2021).

Nevertheless, according to OGTC and ORE Catapult (2021), there is no separation of the resin from fibres in this process, resulting in a mixture of the two materials. For instance, Oudheusden (2019) suggests that the resin-rich fraction may contain 13% glass content and 87% resin and organic content (14 µm particle size). On the other hand, Pender and Yang (2024) confirm the classification of four different material fractions: two distinct fibre-rich fraction, one powder fraction, and one coarse resin-rich fraction (for landfill).

After the mechanical recycling process, the resulting product is sent to end-users, where it may undergo further processing. This can include the addition of a binder (Cordis, 2024c), specialized vacuum infusion techniques (Spini and Bettini, 2024), reheating (Bunner, 2022), or remoulded (Bunner, 2022). Finally, both the fibre-rich fraction and the resin-rich fraction can be utilized across various sectors.

The most frequently mentioned applications in the literature include:

- The polymer composite sector for the production of Bulk Molding Compound (BMC), Sheet Molding Compound (SMC), Dough Molding Compound (DMC), wood plastic composites, thermoset composites, and PLA filament for 3D printing;
- The outdoor construction sector, where they are used in the manufacture of (polymer) mortar and concrete, as well as products like thermal insulation, fences, mounting keys, and acoustic barriers; and

- The indoor construction sector, where they are employed in the production of products such as particleboard and sandwich structures, wood coatings, and thermal insulation.
- Other potential destinations for these recycled materials include the automotive sector, where they can be used to manufacture products such as lighting frames and shelves for motorhomes (Deremco, 2024, REFRESH, 2024, SusWIND, 2024), as well as the sports sector, where they can be utilized to produce items like rails for ski bindings (Deremco, 2024).

The process outlined within the framework of the EoLO-HUBs project (e.g. optimized shredding and selective and digitalized sorting, Per. Com., FHG 2024), maintains the same number of phases as the benchmark process but the configuration of these phases is different (Figure 19). Within EoLO-HUBs, the shredding phase involves reducing the blade sections (measuring 1x1 m) into fibre particles ranging from 6 to 30 mm in length. Subsequently, the recycled material undergoes two classification steps aimed at obtaining single-origin fractions with edge lengths of up to 50 mm, ensuring high-quality recycling.

Initially, induction thermography technology is employed. The material is conveyed on a belt and passed underneath an induction coil, generating an electromagnetic impulse that induces eddy currents into electroconductive materials. Consequently, these materials heat up distinctly compared to poorly conductive materials. Subsequently, the material passes under a thermal camera, enabling differentiation based in distinct heating patterns. This process categorizes materials into three groups: good conductors (CFRP), medium conductors (metals), and poor conductors (GFRP, balsa wood and foams). A scale up of this sorting technology in terms of speed (up to 50 cm/s) is planned as well as the testing of different sizes of shredded parts (up to 50 mm edge length).

Finally, Artificial Intelligence-based object identification technology can be also utilized. By analyzing a large number of images of shredded material (approximately 1,000 per material), and using various machine learning algorithms, the software learns to differentiate between materials. This approach enables the classification of different materials into single-origin fractions, subsequently assigning them to appropriate end-user categories. The WTB waste size reduction system is similar to that used in the benchmark process. Nevertheless, the classification system represents a significant innovation compared to the benchmark process, as it facilitates the categorization of recycled material without depending on traditional mechanical techniques. Instead, it leverages digitization techniques such as AI, machine learning, and other digital methods.

The operational data for the benchmark mechanical recycling process and the EoLO-HUBs system are shown in Table 27.

Based on the information analyzed in the literature, the yield of mechanical recycling, from a global perspective, varies between 58% (prototype scale) and 75% (industrial scale) (Life ReFibre, 2024, Liu et al., 2019, Sommer and Walther, 2021). However, the shredding and sorting system designed in the EoLO-HUBs project aims to achieve an overall separation yield of 90-96% (Per. Com., FHG, 2024).

The quality of the recycled material obtained, as determined by the retained tensile strength of the recycled fibre compared to the virgin fibre, ranges between 70%-78% for fibre-rich powder of rGF, and 50% for fibre-rich powder of rCF (Fonte and Xydis, 2021, Sommer and WaltHer, 2021). More specifically, Liu et al. (2022) determined the percentage of virgin performance conserved in recyclate for the following products: i)78% for fibre of GF, ii) 0% for fibre of CF, iii) 100% for filler of GF and CF, and iv) 0% for resin of GF and CF. Quality data for the recycled material produced through mechanical recycling, as part of the EoLo-HUBs project, is still unavailable.

Literature suggests that the cost of mechanical recycling varies within a range of 150-300 euro/t in Europe (WindEurope, 2020a). Specifically, the cost of the grinding phase varies between 85.6 euro/t of composite material and 89.4 euro/t of rGF (Gennitsaris et al., 2023, Fonte and Xydis, 2021).

Table 27. Operations parameters for the benchmark mechanical recycling and EoLO-HUBs system. Acronyms: N/A – Not Applicable; GF – Glas Fibre; CF – Carbon Fibre; rGF – recycled Glass Fibre; rCF – recycled Carbon Fibre; GFRP – Glass Fibre Reinforced Polymer; WTB – Wind Turbine Blade; CapEx – upfront capital expenditure.

Aspect	Benchmark	EoLO-HUBs
Yield	• Process (GF and CF): 58%-75% (prototype scale and industrial scale, respectively) • Performance by material type: ○ Fibre yield: 42%-58.3% (GF); 0% (CF). ○ Filler yield: 41.7%-58% (GF); 100% (CF) ○ Resin yield: 0% (GF and CF)	• Process: 90-96%
Quality	• Retained tensile strength (recycled compared to virgin fibre): ○ Fibre-rich fraction: 70%-80% (rGF); 50% (rCF) • % virgin performance conserved in recyclate: ○ Fibre: 78% (GF); 0% (CF) ○ Filler (GF and CF): 100% ○ Resin (GF and CF): 0%	*Undetermined*
Economic	• Mechanical recycling cost: 150-300 euro/t (Europe) ○ Grinding cost: 85.6 euro/t of composite material 89.39 euro/t of rGF (Europe) [a] • Economic variables of recycling process (Europe) [a]: ○ CapEx: 390,000 euro ○ Labour (24 h): 37 euro/t of material recycled ○ Electricity: 7 euro/t of material recycled ○ Maintenance: 4 euro/t of material recycled ○ Overheads: 12 euro/t of material recycled ○ Depreciation: 7 euro/t of material recycled ○ Administration, research & sales: 23 euro/t of material recycled	*Undetermined*
Energy	• Energy consumption of mechanical recycling process (GF and CF): 0.1-4.8 MJ/kg (electricity) [b] • Energy consumption of specific machines: ○ Shredding machine: 0.04 MJ/kg (electricity) ○ Hammer mill (grinding phase): 0.22 MJ/kg (electricity) ○ Zig-zag classification machine: 5 kJ/Kg GFRP (three repetitions) (electricity)	*Undetermined*
Output	• Recycled material obtained [c]: ○ Fibre-rich fraction (reinforcement): 21%-42% ○ Resin-rich powder (filler): 30%-51%. ○ Coarse recyclate (fraction to reprocess): 28% [d] • Average size of WTB waste in different stages of the recycling phase: ○ Cutting: 30 x 50 cm sections [e] ○ Shredding: 25 mm - 100 mm particles ○ Grinding: 50 µm - 25 mm particles ○ Classification: fibre-rich fraction: up to 10 mm [f]; resin-rich powder: less than 50 µm [g] • Potential material substitution rates in new products: ○ Fibre-rich fraction and resin-rich fraction: 1%–10%	• Average size of WTB waste: ○ Shredding: fibre length of 6 mm - 30 mm particles ○ Sorting: up to 50 mm edge length particles
Source	Bunner, 2022; Fonte and Xydis, 2021; Gennitsaris et al., 2023; Jani et al., 2022; Life+Brio, 2024; Life ReFibre, 2024; Liu et al., 2019; Liu et al., 2022; OGTC and ORE Catapult, 2021; Oudheusden, 2019; Pender and Yang, 2024; Rathore and Panwar, 2023; Sommer and Walther, 2021; Spini and Bettini, 2024; Sproul et al., 2023; WindEurope, 2020a	Per. Com., FHG, 2024

Notes: [a] This value is assumed for a recycling plant with a capacity of 6000 t/year in Europe (useful output of 961 kg/h) (Fonte and Xydis, 2021); [b] Depending on the used machinery and process scale (e.g., the energy consumption is 2.03 MJ/kg for a feed rate of 10 kg/h (prototype scale) (Liu et al., 2019), and the energy consumption is 0.16 – 0.27 MJ/kg (Gf and CF, respectively) for a feed rate of 150 kg/h (industrial scale) (Fonte and Xydis, 2021); [c] The end product ratio is 58.3% fibre and 41.7% powder by weight (Liu et al., 2022); [d] This material can be reprocessed once or multiple times and transformed into fibre and powder products (Liu et al., 2022); [e] Size of the WTB section at the entrance of the recycling process (Life ReFibre, 2024); [f] For instance, GFRP particles with a size <2 cm have been obtained in the Life ReFibre project (Life ReFibre, 2024); [g] For instance, fragment size of 14 µm contains 13% of GF and 87% of filler and organic material (Oudheusden, 2019).

Benchmark mechanical recycling requires an energy consumption (electricity) ranging from 0.1 to 4.8 MJ/kg (Jani et al., 2022, Liu et al., 2019, Rathore and Panwar, 2023, OGTC and ORE Catapult, 2021). These values depend on the machinery utilized and the scale of the recycling process. For instance, at a feeding rate of 10 kg/h (prototype scale), the energy consumption is estimated at 2.03 MJ/kg (Liu et al., 2019). On an industrial scale, with a feeding rate of 150 kg/h, the energy consumption is reported to be between 0.16 and 0.27 MJ/kg for GF and CF, respectively (Fonte and Xydis, 2021). The EoLO-HUBs project is in its early stage of execution; thus, energy consumption data for the mechanical recycling system is not yet available.

Some authors suggest that the benchmark mechanical recycling process produces three material streams (Liu et al., 2022, Fonte and Xydis, 2021, Jani et al., 2022): i) 21%-42% of a fibre-rich fraction utilized as reinforcement, ii) 30%-51% of resin-rich powder utilized as filler, and iii) 28% of coarse material requiring further reprocessing once or multiple times and transformed into fibre and powder products (Liu et al., 2022).

Finally, both the fibre-rich fraction and the resin-rich powder have a substitution rate ranging from 1% to 10% (Fonte and Xydis, 2021, Life ReFibre, 2024, Spini and Bettini, 2024, Jani et al., 2022). On the other hand, the mechanical recycling system designed in the EoLO-HUBs project specifies the following sizes at the outputs of its various stages (Per. Com., FHG, 2024): sections of 1 x 1 m in the cutting stage, particles with fibre lengths ranging from 6 to 30 mm in the shredding stage, and particles with an edge length of up to 50 mm in the classification stage.

4.2.1.2. Technical, economic, environmental and social characterization of mechanical recycling

This section presents the most relevant technical, economic, environmental, and social aspects of the benchmark mechanical recycling process and the EoLO-HUBs system (Table 28).

From a technical standpoint, mechanical recycling is currently the most extensively studied and applied recycling method so far (SusChem, 2018). It also has the highest TRL among recycling options: TRL 9 for GFRP and TRL 6-7 for CFRP (WindEurope, 2020a, OGTC and ORE Catapult, 2021). Mechanical recycling is a highly efficient process that provides high yields and processing capacities (WindEurope, 2020a, Per. Com., FHG, 2024, Life ReFibre, 2024). Additionally, it is a highly scalable and easily applicable process (Life ReFibre, 2024, Per. Com., FHG, 2024, Bunner, 2022, OGTC and ORE Catapult, 2021, Khalid et al., 2023). The most relevant aspect of mechanical recycling process is its high adaptability to the characteristics of each project regarding the requirements of the recycled material (DecomTools, 2024, Deremco, 2024). Mechanical recycling can be further optimized by developing portable crushing technologies for use directly in the wind farm (Life ReFibre, 2024).

In terms of material flow, alterations in the design and composition of the WTB do not affect the mechanical recycling performance (Life ReFibre, 2024). Mechanical recycling can be employed to reclaim both GF and CF (Jani et al., 2022), but the high cost of CF reinforcements renders mechanical recycling more suitable for GFRP blades (OGCT and ORE Catapult, 2021). Likewise, both fibres and resins, as well as composites (fibre-matrix), can be reclaimed (Liu et al., 2022, Pender and Yang, 2024, Fonte and Xydis, 2021). Mechanical recycling ultimately enables the production of granulated recycled material in different sizes (Per. Com., FHG, 2024), ensuring homogeneity across each size range. Moreover, there is potential for recovering additional blade materials such as metals and balsa wood (Per. Com., FHG, 2024, Life ReFibre, 2024, Life+Brio, 2024, Cordis, 2024c). Finally, in certain applications, recycled materials enhance the physical and technical properties of the final product, such as in the manufacturing of asphalt aggregates (Life ReFibre, 2024).

Table 28. Most relevant technical, economic, environmental and social aspects for the benchmark mechanical recycling and EoLO-HUBs system. Acronyms: EoL – End-of-Life; TRL – Technological Readiness Level; GF – Glass Fibre; CF – Carbon Fibre; GFRP – Glass Fibre Reinforced Polymer; CFRP – Carbon Fibre Reinforced Polymer; WTB – Wind Turbine Blade. Notes: (+) Advantages; (-) Disadvantages.

Aspect	Benchmark	EoLO-HUBs
Technical	• Technology adapted to the needs of the end user and easy to apply. (+) • High and easy scalability process. (+) • Versatility: the same technology can be used for shredding and grinding, including portable shredding and crushing technologies. (+) • The process has high throughput rates and treatment capacity. (+) • Produce recycled materials in various sizes to meet end-users needs. (+) • Homogeneity: produces uniform granulate-like materials. (+) • Possibility to recover other WTB materials: e.g., metals and balsa wood. (+) • Shredders should be adapted to accommodate different WTB geometry and weights. (-) • Crushing equipment suffers a lot of wear, many replacements are needed. (-) • The resulting product is a mixture of materials (fibres, polymer matrix, other) challenging to determinate the properties and leading to the lowest quality recycled material. (-) • The incorporation level of filler material is extremely limited (less than 10%). (-) • Risk of not meeting customers' specifications due to inferior performance. (-) • No substantial improvements are foreseen for mechanical recycling. (-)	• Technology adapted to the needs of the end user. (+) • Optimization of the shredding process for WTB: i) enlarging the length of the output fibres, ii) increasing the technology in terms of speed; ii) sorting different sizes of shredded parts. (+) • Two smart sorting technologies used to obtain single-origin fractions (GFRP and CFRP) and optimize this process. (+) • Easier separation of metal, wood and foam from FRP. (+) • Higher purity in material flows leads to higher quality in material output. (+) • Low technological development of the designed sorting system (induction heating and optical shape detection). (-) • No existing sorting technology is capable of sorting reinforced materials. (-) • Software's reliability for sorting could be critical. (-)
Economic	• Most economical and viable recycling process: low investment and low-cost process. (+) • No high-end technical equipment is needed. (+) • Automation can enhance throughput and lower operating costs. (+) • Mechanical recycling involves multiple steps: limiting potential cost reduction. (-) • Equipment suffers a lot of wear, many replacements are needed. (-) • Recycled materials' value decreases, making them commercially unviable. (-)	• Automated process. (+) • The implementation of EoLO-HUBs system is not considered to generate relevant additional costs. (+)
Environmental	• A process that consumes neither materials nor waste. (+) • Least energy-intensive and carbon emission process compared to other recycling methods. (+) • No hazardous fluids are released during the process. (+) • Mechanical recycling is identified as the most sustainable recycling technology currently available for GFRP blades. (+) • Microplastic and dust environment pollution. (-) • Metals and balsa wood are sent to landfill. (-) • There are particle emissions in the processes. (-)	• Improved process efficiencies (shredding and sorting) are expected to lead to lower energy use and environmental impacts (+) • Use of auxiliary materials in the classification process. (-) • There are particle emissions in the processes. (-)
Social	• Job creation. (+) • Dust generation: this material is not collected, and it is spread in the environment (need to use absorption equipment such as filters systems or carry out the process of closed protective area). (-) • Noise generation. (-)	• Reducing the dust compared to conventional processes. (+) • New techniques (e.g. smart sorting) can lead to the creation of new job posts (+) • Dust created in shredding can be dangerous for human health. (-)
Source	Bunner, 2022; C-Blade, 2024; Cordis. 2024a; Cordis, 2024b; Cordis, 2024c; DecomTools, 2024; Deremco, 2024; EPRI, 2018; Khalid et al., 2023; Life+Brio, 2024; Life ReFibre, 2024; Liu et al., 2022; Lund and Madsen, 2024; OGTC and ORE Catapult, 2021; REFRESH, 2024; Spini and Bettini, 2024; SusCehm, 2018; SusWIND, 2024	Per. Com., FHG, 2024

The mechanical recycling system (based on optimized shredding and smart sorting) designed for the EoLO-HUBs project incorporates several technical innovations compared to the benchmark process, in the crushing and sorting phases. The shredding technology being developed minimizes dust emissions (Per. Com., FHG, 2024). Firstly, the shredding process will be optimized to increase the length of the output fibres up to 6-30 mm, elevate the speed up to 50 cm/s, classify different particle sizes up to 500 mm edge length, and reduce dust compared to conventional processes. Secondly, a two-stages sorting process will be implemented, utilizing induction heating and thermography techniques and AI-based object identification algorithm software. This classification system will yield three distinct streams based on conductivity levels: high-conductivity materials (CFRP), medium-conductivity materials (metals), and low-conductivity materials (GFRP, balsa wood and foam). This approach enhances the purity and quality of the recycled materials obtained. In practical terms, the sorting system represents the most significant innovation that the EoLO-HUBs project will introduce to the mechanical recycling process. These innovations aim to increase efficiency concerning conventional material identification processes and thus improve the quality of the recycling process. The primary critical point of this process would be its optimization and efficiency since it will be essential to ensure that materials are classified correctly to avoid mixing materials with different compositions.

From a technical perspective, mechanical recycling presents certain negative aspects. Cutting and crushing equipment experience significant wear and require frequent replacements (Life ReFibre, 2024). On this matter, CFRP blade residue tends to be more abrasive due to the stronger fibres compared to GF. Unlike thermal and chemical processes, mechanical recycling does not yield clean fibres. Instead, the resulting product comprises a mixture of fibres and polymeric matrix in various forms, for instance, powders, fibre-particulate bundles, fibre tows and woven platelets, often containing other materials like wood. Consequently, determining the exact properties of the recycled fibre becomes challenging.

Ultimately, this recycling method produces lower-quality recycled material, compromising its mechanical and physical characteristics and resulting in varying performance due to differences in fibre content, lengths, and diameters, which impact tensile strength and stiffness. The physical and mechanical constraints result in a highly limited incorporation of filler material in the final product up to 10% (Spini and Bettini, 2024, Fonte and Xydis, 2021, Pender and Yang, 2024). This limitation hampers the market applications of recycled material, as it struggles to compete with virgin raw materials and carries the risk of failing to meet customer specifications or expectations due to inferior performance. As mechanical recycling is a well-established method, significant advancements in processes and technologies are not anticipated (Life Refibre, 2024).

The most notable drawback of the EoLO-HUBs system is the low technological maturity of the sorting phase (induction heating and optical shape detection) (Per. Com., FHG, 2024). The objective of EoLO-HUBs is to enhance the scalability of this process by optimizing the speed of the conveyor belt and improving the detection quality of the thermal camera. This requires larger machinery to increase performance and test more items simultaneously. According to the Per. Com., FHG (2024), no existing sorting technology is capable of sorting reinforced materials, especially fibre reinforced plastics. Therefore, the system developed by EoLO-HUBs represents an innnovative approach compared to the benchmark system.

From a logistical/economic perspective, operating a mechanical recycling plant optimally requires a continuous flow of WTB waste. Furthermore, identifying and quantifying the characteristics of this waste stream, such as material composition and quality and internal structure, can significantly improve the efficiency of the recycling process (Life ReFibre, 2024).

Considering the economic aspects, mechanical recycling is the most economical and viable recycling process (Life ReFibre, 2024, ACP, 2023, SusChem, 2018). This is because it requires low investment (OGTC and ORE Catapult, 2021) and does not require expensive high-end technical equipment, making it a low-cost process. Therefore (SusChem, 2018), mechanical recycling is cost effective process. For instance, mechanical recycling services can reduce the cost of waste handling and depositing blades to 25-30% (Cordis, 2024c). Futhermore, the process can be automated to improve throughput and further decrease operating costs (Cordis, 2024c), an aspect that is also highlighted in the EoLO-HUBs project

(Per. Com., FHG, 2024). Despite its low operation costs, mechanical recycling involves multiple steps (shredding, grinding and classification phases), and the equipment experiences significant wear and requires frequent replacements (Life ReFibre, 2024), limiting further cost reduction. Finally, this process reduces the value of the recycled materials obtained; therefore, this material is not commercially viable and not competitive (yet) due to the very low cost of virgin materials. Some authors consider mechanical recycling to be unviable if only a minimum amount of WTB waste is available, as a continuous flow of WTB waste is required for cost-effective operation of a mechanical recycling plant. Nevertheless, ensuring a constant supply of WTB waste of consistent quality can be highly challenging (Deremco, 2024). The implementation of the optimized crushing system and intelligent classification system developed by the EoLO-HUBs project is not considered to relevant generate additional costs.

With regard to the environmental considerations, the primary objective of mechanical recycling of WTB is to prevent waste material from being sent to landfills, thereby reducing the consumption of virgin material using recycled material obtained in this process (Life ReFibre, 2024, Cordis, 2024c, SusWIND, 2024). The processes involved in mechanical recycling do not consume additional raw materials or water (while electricity is consumed, no reviewed source indicates consumption of raw material or water), and these processes have low energy requirement (mechanical recycling utilized the least amount of energy among all the recycling techniques). Consequently, no waste streams are generated other than the materials contained in the blades: metal, balsa wood and foam (Per. Com., FHG, 2024, Life Refibre, 2024, Liu et al., 2022, OGTC and ORE Catapult, 2021, Oudheusden, 2019). As a result, it does not cause significant atmospheric or water pollution (though there may be microplastic and dust environment pollution, which must be avoid), releases hazardous fluids, or produces significant amounts of GHG emissions.

Finally, the most significant negative social aspect is the generation of dust and noise during the shredding and grinding stages (Life ReFibre, 2024, DecomTools, 2024, Per. Com., FHG, 2024). Shredding blades, regardless of technology used, produce dust and small material particles which will spread in the environment and consequently harm the environment and personnel (DecomTools, 2024). One solution to this problem is to collect dust and small particles using absorption equipment through bag filters system (Life ReFibre, 2024, Cordis, 2024c). Additionally, at the user level, inhalation of the dust can be mitigated through proper ventilation and personal protective equipment (DecomTools, 2024). Furthermore, carrying out these processes in enclosed spaces can prevent the spread of these particles (DecomTools, 2024). Conducting the mechanical recycling process in enclosed spaces can also help reduce environmental noise. Likewise, minimizing machine handling time (e.g., improving the process through automation) can decrease operators' exposure to noise (Life ReFibre, 2024, DecomTools, 2024, Per. Com., FHG, 2024).

On the other hand, the positive aspects of mechanical recycling include job generation, particularly in non-automated processed, and the generation of knowledge for stakeholders, for instance, specific processes are developed for each mechanical recycling project, fostering innnovation and expertise (Life ReFibre, 2024, REFRESH, 2024, DecomTools, 2024). Unlike thermal and chemical recycling, this method can be performed at room temperature and is non-toxic.

4.2.1.3. Quantitative analysis of mechanical recycling

This section presents the preliminary environmental footprint for the mechanical recycling system designed within the framework of the EoLO-HUBs project (optimized shredding and smart sorting), compared to benchmark mechanical recycling. The FU was defined as 1 kg of WTB (GFRP) of the Nordex

WT model N100 (60 m long). The preliminary inventory data of the benchmark mechanical recycling process and the EoLO-HUBs system are presented in Table 29 Currently, no data is available regarding the material balance and energy consumption of the mechanical recycling system designed for the EoLO-HUBs project as it is still in a laboratory and testing stage. Therefore, several assumptions have been made and are explained below.

Table 29. Resource inputs and outputs for the benchmark mechanical recycling and EoLO-HUBs system for the management of 1 kg of GFRP. Acronyms: N/A – not applicable; FU – Functional Unit; WTB – Wind Turbine Blade; GFRP – Glass Fibre Reinforced Polymer; rGF – recycled Glass Fibre.

FU: 1 kg WTB (GFRP) treated	Subprocess	Resource flow	Benchmark	EoLO-HUBs	GaBi process
Inputs	Shredding	Blade material (GFRP), kg	1	1	N/A
		Electricity consumption, low voltage, kWh	0.01 [a]	0.01 [a]	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
	Grinding	Electricity consumption, low voltage, kWh	0.06 [b]	Undetemined	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
	Sorting	Electricity consumption, low voltage, kWh	0.001 [c]	0.0003 [d]	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
Outputs	Sorting	Product (rGF), kg	0.75 [e]	0.96 [f]	N/A
		Waste (metal, wood and foam), kg	0.25 [e]	0.04 [f]	RER: treatment of inert waste, sanitary landfill ecoinvent 3.10

Notes: [a] Electricity consumption for the shredding technology is 0.04 MJ/kg (Liu et al.,2019); [b] Electricity consumption for the grinding technology is 0.22 MJ/kg (Liu et al., 2019); [c] Electricity consumption for the zig-zag classification of three repetitions technology is 0.005 MJ/kg (Pender and Yang, 2024); [d] Electricity consumption for induction heating and thermography technology and optical shape detection technology is 0.000922 MJ/kg (Nobile et al., 2023) and 0.00000213 MJ/kg (Gong et al., 2022, Per. Com., FHG, 2024), respectively; the data for optical shape detection has been calculated from 2.13 mJ/frame (Gong et al., 2022) and ~1000 images per shredded material (Per. Com., FHG, 2024); [e] Benchmark mechanical recycling yield is 58% (prototype scale) to 75% (industrial scale) (Sommer and Walther, 2021, Life ReFibre, 2024); [f] The EoLO-HUBs system yield is 90%-96% (commercial scale) (Per. Com., FHG, 2024).

The second benchmark mechanical recycling typology has been chosen for comparison with the EoLO-HUBs system (Figure 19), as it includes the classification stage of the recycled material obtained from the preceding crushing stages. The total energy consumption (electricity) of both the benchmark mechanical recycling and the EoLO-HUBs system was calculated based on the electrical consumption of each phase involved in the process.

In the benchmark process, the shredding stage consumes 0.01 kWh (Liu et al., 2019), the grinding stage consumes 0.06 kWh (Liu et al., 2019), and the classification stage consumes 0.001 kWh (Pender and Yang, 2024) per kg of WTB treated. The last stage corresponds to the energy consumption of a standard zig-zag classification system. Thus, the total electrical consumption of benchmark mechanical recycling is 0.071 kWh per kg of WTB treated. The EoLO-HUBs system comprises a shredding stage consuming 0.01 kWh (Liu et al., 2019), and a sorting stage consuming 0.0003 kWh per kg of WTB treated. The energy consumption of induction technology has been adapted from information provided by Nobile et al. (2023), while the energy consumption of the detection technology has been sourced from Gon et al. (2022), assuming that 1,000 photographs are taken per kg of recycled material (Per. Com., FHG, 2024). Therefore, the electrical consumption of the EoLO-HUBs system is 0.0103 kWh per kg of WTB treated.

The yield of the benchmark mechanical recycling system ranges from 58% to 75%, prototype scale and industrial scale, respectively (Sommer and Walther, 2021, Life ReFibre, 2024), whereas the EoLO-HUBs system exhibits a performance range between 90% and 96% (commercial scale) (Per. Com., FHG, 2024). The upper end of both ranges has been selected, as mechanical recycling is considered to be easily scalable (OGTC and ORE Catapult, 2021). Therefore, the total amount of material recovered from the benchmark system and EoLO-HUBs system is 0.75 kg (0.25 kg to landfill) and 0.96 kg (0.04 kg to landfill), respectively, for each kilogram of residual WTB entering mechanical recycling.

In summary, the technological innovation implemented in the EoLO-HUBs system reduces electrical consumption by 85%, improves process yield by 28% (recovering 28% more material), and reduces sending waste material to landfill by 84%, compared to the benchmark system.

A total of 16 environmental indicators have been calculated, as provided in Table 30.

Table 30. Preliminary environmental impacts for the benchmark mechanical recycling and EoLO-HUBs system (considering 1 kg WTB (GFRP) treated as FU).

Impact category	Unit	Benchmark	EoLO-HUBs	Difference
Acidification	[Mole of H+ eq.]	1.59E-04	2.47E-05	-84%
Climate Change - total	[kg CO_2 eq.]	2.56E-02	3.98E-03	-84%
Ecotoxicity, freshwater - total	[CTUe]	1.43E-01	2.23E-02	-84%
Eutrophication, freshwater	[kg P eq.]	2.70E-05	4.20E-06	-84%
Eutrophication, marine	[kg N eq.]	2.76E-05	4.30E-06	-84%
Eutrophication, terrestrial	[Mole of Neq.]	2.53E-04	3.95E-05	-84%
Human toxicity, cancer - total	[CTUh]	7.26E-11	1.13E-11	-84%
Human toxicity, non-cancer – total	[CTUh]	4.91E-10	7.63E-11	-84%
Ionising radiation, human health	[kBq U235 eq.]	1.50E-02	2.32E-03	-85%
Land Use	[Pt]	2.75E-01	4.34E-02	-84%
Ozone depletion	[kg CFC-11 eq.]	5.16E-10	8.02E-11	-84%
Particulate matter	[Disease incidences]	8.77E-10	1.38E-10	-84%
Photochemical ozone formation, human health	[kg NMVOC eq.]	8.65E-05	1.35E-05	-84%
Resource use, fossils	[MJ]	6.35E-01	9.85E-02	-84%
Resource use, mineral and metals	[kg Sb eq.]	3.29E-07	5.09E-08	-85%
Water use	[m^3 world equiv.]	2.17E-02	3.36E-03	-85%

The EoLO-HUBs system enhances performance across all impact categories, and it has 84%-85% lower environmental impact than the benchmark system. For instance, for climate change category the reduction would amount to 84%, saving 22 g CO_2 eq. per kg of WTB treated. This significant improvement in all impact categories is due to two factors.

First, the EoLO-HUBs system exhibits an 85% decrease in electricity consumption compared to the reference system (0.071 kWh and 0.0103 kWh per kg of WTB treated, respectively). Specifically, eliminating the grinding phase saves 0.06 kWh, which translates into 19 g CO_2 eq. per WTB; while optimizing the efficiency of the sorting process, which was specifically designed for this project, saves an additional 0.0007 kWh (0.3 g CO_2 eq. per kg of WTB treated).

Secondly, the EoLO-HUBs system demonstrates a 28% improvement in recycling efficiency, achieving a 96% recycling rate compared to the benchmark system's 75%. Therefore, the EoLO-HUBs system significantly reduces waste generation because 0.04 kg are sent to landfill compared to 0.25 kg of the benchmark system per kg of WTB treated, that is, waste generation is minimized by 84%. The mechanical recycling process efficiency improving alone saves 2 g CO_2 eq. Per kg of WTB treated.

A closer look at the results reveals that electricity consumption is the primary driver of environmental impact across the climate change, human toxicity (cancer and non-cancer), resource use fossils, resource use mineral and metals, and water use categories, for both the benchmark and EoLO-HUBs systems, as shown in Figure 20.

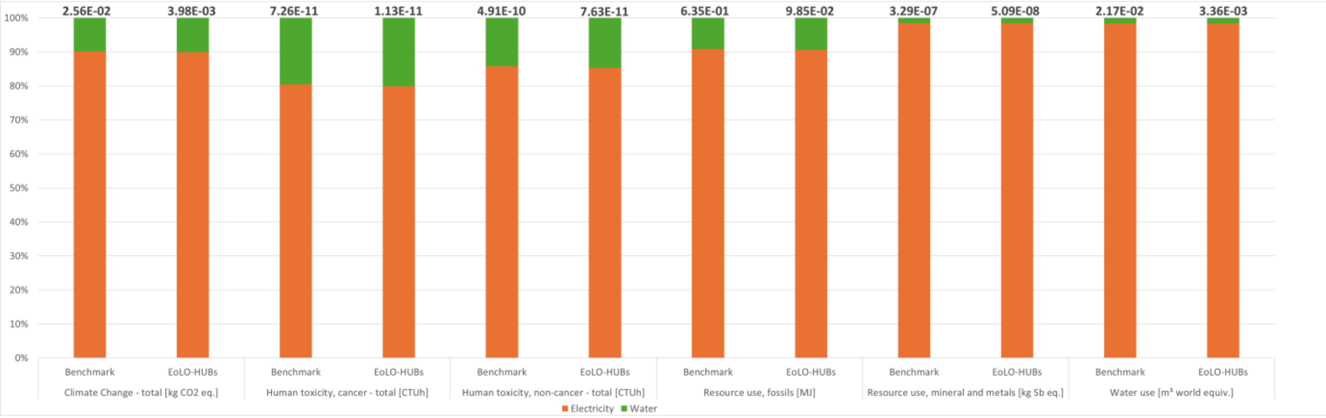

Figure 20. Comparison of the climate change ecotoxicity, ozone depletion and water use the benchmark mechanical recycling and EoLO-HUBs system (considering 1 kg WTB (GFRP) treated as FU).

In this way, electricity consumption explains between 80% and 98% of the impact in both systems (human toxicity, cancer and resource use, mineral and metals, respectively). The EoLO-HUBs system's 85% reduction in electrical consumption translates to a decrease in fossil fuel combustion for European electricity generation, thereby positively impacting these categories. Likewise, landfilling of recycling process waste contributes between 2% and 20% of the total environmental impact in the benchmark system and EoLO-HUBs system (Figure 21.) Landfilling the polymer contained in the composite leads to organic carbon leaching, which contributes to the landfill process' impact on the overall environmental footprint inboth systems, and its slow biodegradation can lead to environmental pollution.

4.2.1.4. Guidelines and opportunities for mechanical recycling

Mechanical recycling stands out as the most extensively researched recycling method, with a high TRL. It is easily scalable and straightforward to apply, relying solely on technology powered by electrical energy. Furthermore, the process can be adapted to obtain a product that adapts to the specific technical needs of each end user. However, the most significant drawbacks from a technical perspective are the process's low performance and the resulting low quality of the recyclates, which, with few exceptions, can only be used for downcycling applications. In terms of the first aspect, the optimization of the shredding process and the use of intelligent sorting technologies (with the latter still in an early stage of technological development) devised in the EoLO-HUBs project aims to enhance the efficiency of mechanical recycling. As for the second aspect, while no significant improvements are anticipated in the EoLO-HUBs system, the designed classification process will yield three distinct streams of recycled material. This facilitates better allocation for each stream obtained.

Mechanical recycling demands minimal investment and has low processing costs, rendering it the most economical, profitable, and feasible recycling method presently. Furthermore, the automation of the process facilitates further reduction in its economic requirements, a feature set to be implemented in the innovative sorting system conceived within the EoLO-HUBs project. Despite these positive aspects, mechanical recycling still faces economic barriers that need to be addressed. These include reducing the process phases (the EoLO-HUBs system reduces stages compared to the benchmark system), mitigating the high wear of crushing equipment, enhancing the value of recycled material to ensure commercial viability, and ensuring a continuous flow of blade waste.

In environmental terms, mechanical recycling stands out for its non-consumption of raw materials (particularly environmentally harmful products like solvents) and water. It is also characterized by the lowest energy requirement among recycling methods (as it solely consumes electricity, thus eliminating the need for combustion processes), and resulting in lower carbon emissions. However, unlike the benchmark, the EoLO-HUBs system may require auxiliary materials. The only environmental drawback is the current inability to recover metal or wood from blade waste. Hence, it presents a potential area for innovation in mechanical recycling.

Mechanical recycling is a job-creating activity (despite its potential for high levels of automation) that also contributes to knowledge generation (as mentioned previously, each recycling project has processes, technologies and equipment adapted to its characteristics). The primary social challenge lies in the generation of noise, dust, and microplastics during the crushing process. Nevertheless, solutions are being developed, such as advancing mechanical recycling in enclosed environments or employing aspiration systems to capture contaminants.

The EoLO-HUBs system significantly reduces electricity consumption by 85% and landfill waste by 84% (attributable to a 28% improvement in process performance) compared to the benchmark system. This translates to a performance improvement across all analyzed impact categories (84%-85%). Specifically, carbon savings reach 22 g CO_2 eq. per kg of WTB treated. However, further improvements in the efficiency of mechanical recycling, particularly in terms of energy consumption (electricity) and material recovery rates (rGF), could lead to a significant reduction in the process's carbon footprint.

4.2.2. WTB thermal recycling

The thermal treatment of WTBs is increasingly recognized for its high efficiency. This recycling approach includes techniques such as fluidized bed, microwave pyrolysis, and pyrolysis recycling (Zhang et al., 2023).

A fluidized bed involves suspending solid particles in an upward flow of gas, creating a fluid-like state that enhances heat and mass transfer efficiency (Pender and Yang, 2024). In WTB recycling, fluidized beds typically operate at temperatures ranging from 450°C to 550°C (Sorte et al., 2023a). This range effectively decomposes the polymer matrix while preserving the structural integrity of the GFs or CFs for possible reuse, being more effective for CFs as for GFs it can result in a significant loss of tensile strength (up to 50%) (Zhang et al., 2023). Residence times in the fluidized bed vary but are optimized to ensure complete matrix degradation and maximize fibre recovery. Environmental assessments indicate that processing WTB waste in fluidized beds reduces the global warming potential compared to conventional disposal methods to 0.57 kgCO_2 eq/kg GFRP (Pender and Yang, 2024), while results of 1.56-2.9 kg CO_2eq/kg are reported for CFRP (Tyurkay et al., 2024).

Another promising char-free thermal recycling system with minimal impact on their mechanical properties is microwave pyrolysis (Zhang et al., 2023). In this case, the organic material is exposed to electromagnetic microwaves instead of conventional heating methods, whereby most of the material is heated in its entirety and at the same temperature. Microwave pyrolysis is carried out in a chamber with a nitrogen atmosphere and is performed at temperatures between 300 and 600 °C, this temperature is usually lower than that of conventional thermal recycling methods as the use of microwaves allows the temperature during the process to be kept lower (Paulsen and Enevoldsen, 2021).

However, the most widely used and extended recycling technology to reclaim GFs and CFs from WTBs is conventional pyrolysis (Khalid et al., 2023). Pyrolysis (addressed within the EoLO-HUBs project) is a thermal recycling process where the polymer resins are depolymerized by heat with a temperature that could be between 450-1000°C based on the composition of waste material (Khalid et al., 2023; Xiong et al., 2022). In this way, the polymer resins are converted into vapor or gas and the fibres are recovered. In addition, the liquid and gaseous products generated at the same time as the fibres can be used as a heat source for pyrolysis processes (Xu et al., 2023a). The pyrolysis reaction can occur under different atmospheres, inert atmosphere, with O_2 or without O_2, among others (Jani et al., 2022; Xu et al., 2023a). This method is simple, but many pollutants such as SO_2, NO_x, hydrogen halides and dioxins are generated during the decomposition of resin, which requires the implementation of proper measures to handle emissions (Cong et al., 2023).

As reported in the literature, pyrolysis usually takes place at temperatures of 400-700 °C (Cooperman et al., 2021), with an energy requirement of 21.2-30 MJ/kg (Liu et al., 2019a). After this process, the strength of the GF is considerably reduced, while the CFs can retain their properties close to those of virgin carbon fibres (vCF). Liu et al. (2019a) give values of 50% of resistance for GF and 78% for CFs, compared to virgin fibres. Xu et al. (2023) performed different pyrolysis tests for WTBs composed of GF, the reaction was carried out at a temperature of 500°C and 1h of duration. Different reactive gases were tested in the study, such as pure N_2, 20% H_2O with N_2 and 20% CO_2 with N_2. After pyrolysis, the recovered solid products were post-oxidized at 500°C for 30 min under the same reagents to obtain clean GF. The effect of the temperature in the pyrolysis reaction was studied in several works by Yousef et al. (2023a,b), developing reactions at 500, 550 and 600°C at N_2 atmosphere. The higher yield for the solid fraction was obtained for the lower temperature reaction 500 °C, with a yield of almost 78%. Regarding the economic aspects, costs of €266/ton of gas and €300/ton of electricity have been reported for pyrolysis recycling process in literature (Jani et al., 2022). Table 31 shows the characteristics of the different pyrolysis processes found in the literature. The benchmark pyrolysis system (to compare the baseline/current and innovative EoLO-HUBs pyrolysis system by MCAM) has been defined by using the work of Yousef et al. (2023a,b), as it is a complete study.

Table 31. Characteristics of the pyrolysis processes found in the literature.

Author	Temperature	Time	Atmosphere	Energy	Data
(Cooperman et al., 2021; Liu et al., 2019b)	400-700 °C	*Data not available*	*Data not available*	21.2 MJ/kg	• Strength of the fibre 50% (GF), 75% (CF)
(Xu et al., 2023b)	500 °C	0.5, 1h	300 ml/min: N_2	Energy obtained 22.5-25.7 MJ/kg	• Gas: 6.32%, CH_4 (30.4 %), CO (24.6 %), CO_2 (31.5 %) • Oils: Phenolic compounds 14,88% • Solids: 78.8%
			H_2O/ N_2 20 %		• Gas: 7.89 % • Oils: 13.41% • Solids: 78.7%
			CO_2/ N_2 20 %		• Gas: 6.10% • Oils: 14.98% • Solids: 78.92%
(Fonte andXydis, 2021; Jani et al., 2022)	Reaction: 450-700 °C	*Data not available*	Without O_2	3-30 MJ/kg	• Gas: 1.2% • Oils: 31.3% • Solids: 67.4% • Cost: 284.99-325.16 Us$/ton
	Post Oxidation: 450-550 °C	*Data not available*	O_2		

Author	Temperature	Time	Atmosphere	Energy	Data
(Yousef, et al., 2023a; Yousef, et al., 2023b)	Reaction: 500°C Post Oxidation: 450°C	45-77 min	N_2 60 mL/min	7.2 MJ/kg	• Gas: 6.83% • Oils: 15.23% • Solids: 77.93% • GWP: 3.12 10^4 kg CO_2 eq
	550 °C			*Data not available*	• Gas: 9.65% • Oils: 13.57% • Solids: 76.78%
	600 °C			*Data not available*	• Gas: 10.42% • Oils: 12.96% • Solids: 76.62%

4.2.2.1. Qualitative analysis of thermal recycling

The simplified flow diagram for the benchmark and baseline (present) EolO-HUBs (MCAM) pyrolysis processes are presented in Figure 21, whereas Table 32 shows a summary of key operational aspects for both.

As can be seen in comparative Figure 21, while in the benchmark system liquid and gas are obtained in addition to fibres, in the baseline (MCAM) EoLO-HUBs system, in addition to fibres, only gas is obtained, which could be recirculated as an energy source within the same pyrolysis process (which will be addressed during the development of the project). In the EoLO-HUBs project, MCAM´s current pyrolysis system will be improved to develop a low-carbon pyrolysis process. MCAM will also adapt their large pyrolysis plant to the recovery of GF from WTB wastes as well, in order to make rGF economically viable through the implementation of energy recovery combustion systems. However, this has not been developed yet.

On MCAM premises, WTB waste is sorted according to waste origin, processing state and fiber quality (e.g. differentiating between CF residues, prepreg materials and end-of-life components) and shredded to a maximum size of 1 m (being the ideal size 9 cm x 9 cm aprox.). The resulting material is then steadily transported through the pyrolysis oven where the thermal breakdown of the materials takes place in a continuous flow oven at high temperature with thermoshock oxidation for easy char removal. Later on, a refinement process for the recovered fibers is required, which involves resizing and recoating of the fiber surface, converting them into a commercial product for use in the industry. Depending on individual customer requirements, a last step can include cutting the fibers into to a defined length or processing it further into semi-finished textile products through various fleece laying processes (Pers. Com. MCAM, 2024).

The novelty introduced by MCAM will be the implementation of a gas recovery system with the goal to reduce energy requirements by 80%. MCAM also plans to analyze the implementation of electrolyzers to produce hydrogen with the surplus of electricity (produced through a CHP plant) by using the gases not recirculated to support heating processes. This would add additional environmental credits to the system that are supposed to reduce further the impact compared to benchmark processes. In addition, MCAM will increase the capacity of the pyrolysis system significantly, optimizing performance (Pers. Com. MCAM, 2024). MCAM will also adapt their large pyrolysis plant to the recovery of GF (not only CF) from WTB wastes, in order to make rGF economically viable. All these changes (representing the EoLO-HUBs pyrolysis/MCAM innovation) will be evaluated as part of D2.5 (M42).

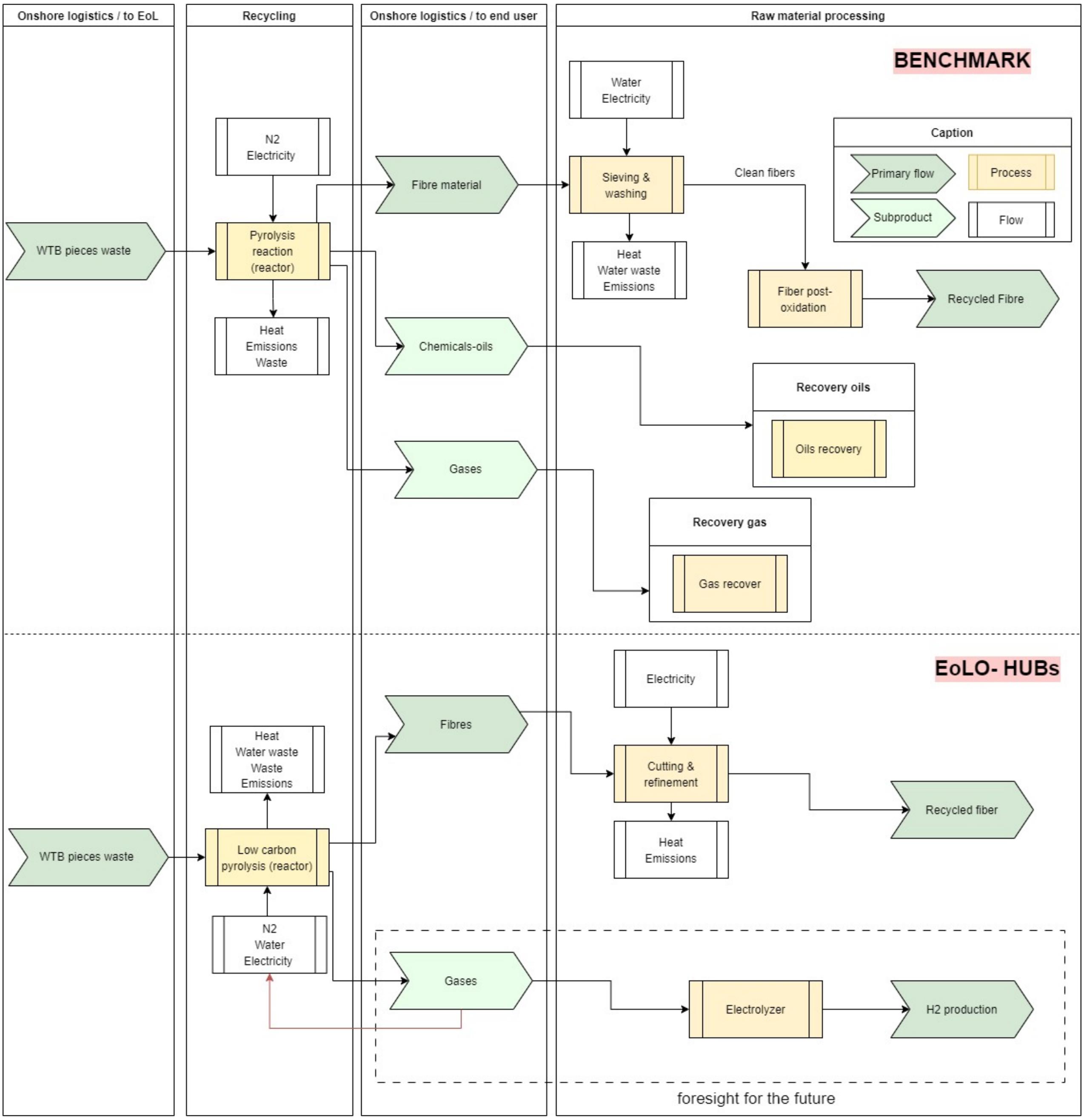

Figure 21. Flow diagram for the benchmark and baseline (MCAM) EoLO-HUBs pyrolysis processes. References: (Yousef et al., 2023a,b) and (Pers. Com. MCAM, 2024). Acronyms: WTB (Wind Turbine blade).

Considering operational aspects (Table 32), the main difference between the benchmark process and the baseline (MCAM) EoLO-HUBs process (without gas recirculation and hydrogen production) is the temperature at which pyrolysis takes place. The EoLO-HUBs pyrolysis process occurs a higher reaction temperature (800 °C) than the benchmark (500 °C) (Pers. Com. MCAM, 2024). It is important to highlight that one of the critical points of pyrolysis is the separation of the epoxy resin from the fibre, so it is essential to ensure that the resin is decomposed (Paulsen and Enevoldsen, 2021).

Table 32. Operational aspects of benchmark and baseline (current) EoLO-HUBs pyrolysis systems. FU= 1 kg of composite waste. References: (Yousef et al., 2023a,b; Pers. Com. MCAM, 2024).

Operational aspects	Benchmark	Baseline (MCAM) EoLO-HUBs
Temperature	Reaction: 500°C Post Oxidation: 450°C	800 ºC
Time	45-77 min	10 min
Atmosphere	N_2 60 ml/min	Inert atmosphere, N_2
Energy	7.72 MJ/kg (electricity)	Natural gas and electricity
Results	Gas: 6.83% Oils: 15.23% Solids: 77.93% GWP: 3.12 10^4 kg CO_2 eq	100% of fibres recovered, no char. 90-100% of the mechanical properties.

As indicated above, the main novelty behind the innovate pyrolysis system to be developed within EoLO-HUBs by MCAM is the recovery and exploitation of the pyrolysis gases to overcome energy losses. At present, heat is recovered and recirculated within the process. However, within the EoLO-HUBs project, the remaining pyrolysis gases (purified through filtering systems) will be converted into electricity (CHP installation) and, if the electricity supply is greater than demand, the surplus will be used to produce hydrogen (installation of electrolysis modules). This would lead to cut the actual energy needs of the pyrolysis process to one third, significantly reducing the production costs and the carbon footprint of the recycled fibres. The use of high-temperature oxidation (800ºC) with thermo-shock oxidation for easy char removing will occur faster and demand less energy than state of-the-art oxidation. It will allow preserving 90-100% of the mechanical properties by a more gentile oxidation process. The resulting fibres from the process present a clean surface and do not suffer from negative property changes, the fibres can then be prepared for their subsequent commercial applications. on the CFRP improved pyrolysis process, MCAM will also develop process adaptations to recover GF as well, without compromising the mechanical properties (fibres with 70-90% mechanical strength and up to 100% stiffness).

Regarding the quality of the recycled fibres, it is almost in 100% for both cases, as they are clean. However, while the quality of rCF is equivalent to the quality of vCF, the tensile strength of rGF decreases considerably compared to virgin Glass Fibre (vGF), especially when the reaction temperature is high (Khalid et al., 2023). Nevertheless, the fibers quality can be improved through material upgrading processes (Section 4.3) and at this stage of the wind industry requirements, it is important to recover them and give them another use, avoiding landfill (Pers. Com. MCAM, 2024).

4.2.2.2. Technical, economic, environmental and social characterization of thermal recycling

Table 33 shows the most relevant technical, economic, environmental and social aspects for the benchmark and the baseline (MCAM) EoLO-HUBs pyrolysis systems.

The most relevant technical aspects in the case of pyrolysis are the reaction time and temperature, which affect energy consumption, and the corresponding economic costs and environmental impacts. To address this properly, it is crucial to know the WTB waste composition in advance to set up the operational parameters to ensure that the decomposition temperature is not too high to affect the degradation of the fibres, while optimizing the energy requirements, and therefore the process costs and impacts. In the case of the baseline (MCAM) EoLO-HUBs process, this will be further enhanced by applying heat recovery systems for the treatment of the pyrolysis gases, while implementing a combined heat and power plant to produce electricity with surplus heat and use the electricity to produce hydrogen. All this will optimize further the system energy, economic and environmental performance.

Another (social) issue for consideration is that high temperature decomposition of the epoxy releases toxic substances into the air that should be appropriately handled by applying security measures (Sommer et al., 2022). Relevant security measures such as the preventive monitoring of gas concentrations in the plant and reduction of emissions below the BImSCH limits by effective filter systems have been implemented and proven within earlier plant configurations and will be reapplied within the EoLO system.

Table 33. Most relevant technical, economic, environmental and social aspects of benchmark and baseline (MCAM) EoLO-HUBs pyrolysis recycling systems. References: (Yousef et al., 2023a,b and Pers. Com. MCAM, 2024). Acronyms: GWP (Global Warming Potential). Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark	EoLO-HUBs	Sources
Technical	• Lower temperature 500 °C (+) • 98% of fibre recovered (+) • Known residue leads to better optimization of reaction conditions (+) • Higher process time (45-77 min) (-)	• Lower process time (10 min) (+) • No char, almost 100% recovered (+) • High temperatures can reduce fibres mechanical properties (-) • Due to the unknown WTB waste composition, the reaction conditions could be overdimensioned (-)	(Yousef et al., 2023a,b) (Pers. Com. MCAM, 2024)
Economic	• By-products gas and oils (+) • Higher cost due to higher energy requirements (-)	• Lower cost due to lower energy requirement (reduced operation time) (+) • Near future: surplus energy used to produce electricity and hydrogen (+)	(Yousef et al., 2023a,b) (Pers. Com. MCAM, 2024) (Xu et al., 2023b) (Liu et al., 2019b)
Environmental	• Lower temperature (+) • Around 20 MJ of energy could be recovered (+)	• Lower energy consumption (+) • Up to 80% of energy could be recovered through gas recirculation (+) • Energy recovery plus electricity and hydrogen production can reduce GHG emissions substantially (+)	(Yousef et al., 2023a,b) (Pers. Com. MCAM, 2024) (Xu et al., 2023b) (Liu et al., 2019b)
Social	• Conventional social risks related to incineration plants	• Conventional social risks related to incineration plants	(Yousef et al., 2023a,b) (Pers. Com. MCAM, 2024) (Liu et al., 2019b)

4.2.2.3. Quantitative analysis of thermal recycling

Inventory data on the benchmark is provided in Table 34. No data for the MCAM baseline/current pyrolysis process cannot be provided due to confidentiality issues.

Table 34. Resource inputs and outputs for the pyrolysis recycling of 1 kg of WTB waste (FU). References: (Yousef, et al., 2023a,b; Pers. Com. MCAM, 2024). Acronyms: CFRP (Carbon fibre reinforced polymer), rCF (recycled carbon fibre), n.a. (no applicable)

<table>
<tr><th colspan="2">FU: recycling of 1 kg CFRP waste</th><th>Subprocess</th><th>Resource flows</th><th>Benchmark</th><th>Ecoinvent processes</th></tr>
<tr><td rowspan="8">Pyrolysis recycling</td><td rowspan="4">Inputs</td><td rowspan="2">Reaction</td><td>CFRP waste pretreated, kg</td><td>1</td><td>n.a.</td></tr>
<tr><td>Electricity, low voltage, MJ</td><td>7.2</td><td>ENTSO-E: market group for electricity, low voltage ecoinvent 3.10</td></tr>
<tr><td rowspan="2">Washing</td><td>Tap water, L</td><td>2</td><td>Europe without Switzerland: tap water production, conventional treatment ecoinvent 3.10</td></tr>
<tr><td>Electricity, low voltage, MJ</td><td>0. 56</td><td>ENTSO-E: market group for electricity, low voltage ecoinvent 3.10</td></tr>
<tr><td rowspan="4">Outputs</td><td rowspan="4">Recovered materials</td><td>rCF, kg</td><td>0.76</td><td>-</td></tr>
<tr><td>Chemical-oils, kg</td><td>0.15</td><td>Treatment no considered</td></tr>
<tr><td>Gases, kg</td><td>0.068</td><td>Treatment no considered</td></tr>
<tr><td>Waste, kg</td><td>0.019</td><td>Treatment no considered</td></tr>
</table>

The inventory data from the benchmark pyrolysis recycling process has been adapted based on the data provided by Yousef et al. (2023) for CFRP recycling. The impact of the management of byproducts and/or wastes (outcomes) was not contemplated due to the lack of information on the corresponding refinement and/or treatment processes.

Based on the data provided in Table 34 and the goal of MCAM to reduce energy consumption (reaction) by 80% through gas recirculation, this would mean that the energy demand by the innovative MCAM pyrolysis system would correspond to 1.44 MJ/kg. Also, salt water can be used in pyrolysis process to make it more efficient. Ions present in salt water can act as catalysts and facilitate certain chemical reactions during pyrolysis especially in the presence of eutectic salts, such as NaCl and KCl. This method reduces the initial pyrolysis temperature and increases the reaction rate, making it a more energy efficient and environmentally friendly process. (Su et al., 2019).

The preliminary environmental impacts for both the benchmark pyrolysis processes are presented in Table 35, where the resource flows contribution to the categories of climate change, human toxicity (cancer and non-cancer), use of fossil resources, use of mineral resources and metals, and water use, are shown in Figure 22. Impacts for the MCAM baseline/current pyrolysis process cannot be provided due to confidentiality issues.

Table 35. Environmental impacts for the benchmark pyrolysis recycling (1 kg of WTB waste) (FU).

Impact category	Unit	Benchmark
Acidification	[Mole of H+ eq.]	3.84E-03
Climate Change - total	[kg CO_2 eq.]	6.79E-01
Ecotoxicity, freshwater - total	[CTUe]	2.94E+00
Eutrophication, freshwater	[kg P eq.]	6.69E-04
Eutrophication, marine	[kg N eq.]	6.06E-04
Eutrophication, terrestrial	[Mole of Neq.]	5.25E-03
Human toxicity, cancer - total	[CTUh]	1.73E-09
Human toxicity, non-cancer – total	[CTUh]	1.23E-08
Ionising radiation, human health	[kBq U235 eq.]	4.37E-01
Land Use	[Pt]	3.88E+00
Ozone depletion	[kg CFC-11 eq.]	1.28E-08
Particulate matter	[Disease incidences]	1.34E-08
Photochemical ozone formation, human health	[kg NMVOC eq.]	1.74E-03
Resource use, fossils	[MJ]	1.69E+01
Resource use, mineral and metals	[kg Sb eq.]	9.48E-06
Water use	[m^3 world equiv.]	7.12E-01

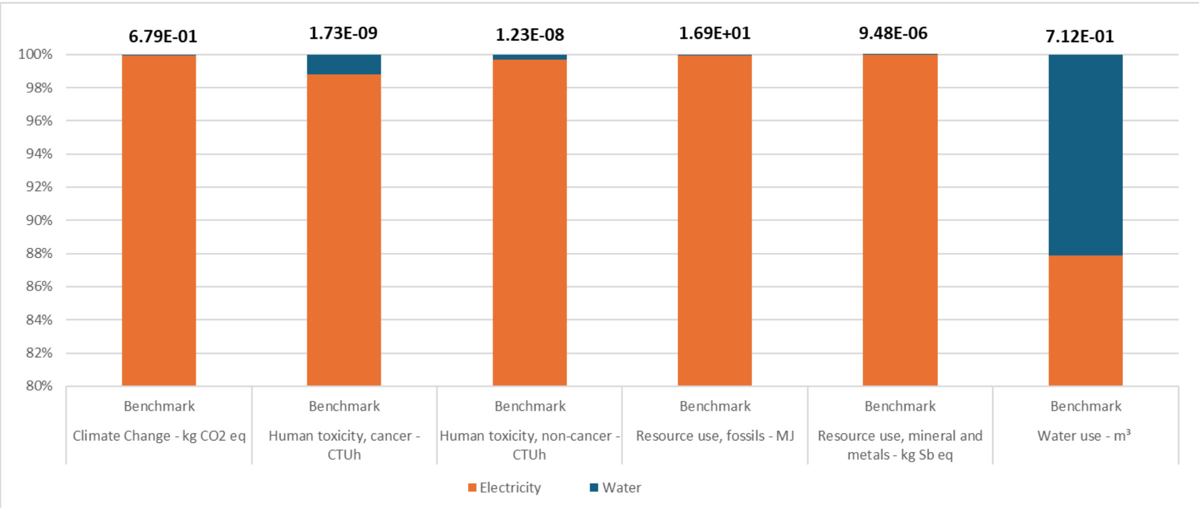

Figure 22. Preliminary contributions of electricity and tap water to the environmental impacts of the benchmark pyrolysis system for 1 kg of WTB waste.

It is clearly observed that the main contributor to environmental impacts is electricity, with the exception of the impact contribution to water use, as it has been already reported in the literature (Xayachak et al., 2023). The impact of electricity depends on the energy mix used. Therefore, the use of green electricity (produced by renewable energy technologies) could reduce the environmental impacts from electricity substantially, greening the entire pyrolysis process.

Focusing on the improved MCAM pyrolysis system (to be developed within the project), if energy demand is reduced by 80%, then the environmental impacts related to the thermal recycling of 1kg of WTB waste (relying on benchmark data as baseline and without considering equipment requirements and/or other processes changes) would be also reduced by 80% with the exception of water use that would be reduced by 70%.

4.2.2.4. Guidelines and opportunities for thermal recycling

One of the biggest problems faced by recyclers is the lack of information on the composition of the waste to be recycled. For a pyrolytic reaction to be adequate or successful, it is important to ensure the decomposition of the resin leading to a separation of the fibres. Thus, if the waste composition is unknown, higher temperatures could be required to ensure material separation, which can lead to higher energy use and/or damage of the recovered fibres. So, even though the baseline (MCAM) EoLO-HUBs system will be optimized by implementing gas recovery and electricity and hydrogen production systems, it could be also further improved if the composition of the wastes to be treated is known (obviously considering the case that only WTB waste is handled by specialized pyrolysis facilities).

Regarding the quality of the fibres obtained in the baseline (MCAM) EoLO-HUBs process, these tests have not been performed yet. But, according to the literature, thermal recycling is more suitable to recover CF than for GF due to their higher temperature resistance (Khalid et al., 2023). Heat treatments on GF could result in a significant loss of fibre strength (50% - 90%), limiting its application in high strength components. In any case, having a different pyrolysis set up for the recovery of GF will be explored within the EoLO-HUBs projects, which is expected to lead to successful results.

4.2.3. WTB chemical recycling

Chemical recycling of WTBs is a relatively new method, including hydrolysis, glycolysis and solvolysis, although solvolysis stands out (performance wise) above the others. Solvolysis is defined as a chemical decomposition of polymer matrix to recover fibres and other degraded materials, in this case resins (Khalid et al., 2023). Solvents, such as acids, ammonia, super or subcritical water, and alcohols are often used to degrade the cross-linked polymer resins (Mattsson et al., 2020a). Chemical recycling can be classified into solvolysis at low temperature <350 °C and supercritical solvolysis at higher temperatures, using supercritical fluids (e.g. water and alcohol) (Khalid et al., 2023). These supercritical fluids are usually characterized by their diffusivity and high solubility, resulting in the decomposition of composite residues.

A few studies have utilized WTB wastes to perform chemical recycling. Liu et al. (2019a) and Sorte et al. (2023a) indicate that WTB solvolysis energy consumption ranges from 19.2-21 MJ/kg, while Rathore and Panwar (2023) highlight that the tensile strength of rGF and rCF accounts for 58% and 95%, respectively. Moreover, Mattson et al.(2020a) propose the use of ethylene glycol, propylene glycol or water combined with alcohols as solvents and catalyzers at temperatures of 270-330 °C as promising solvolysis reaction conditions for GFRP degradation, obtaining degradations of up to 90 % in some cases.

In other works, the solvolysis of composite wastes has been carried out by using acetone together with chloric aluminum at a reaction temperature of 180 ºC for 6h with an energy consumption of 15.4 MJ/kg, obtaining a yield near to 100% (Butenegro et al., 2021; Wang et al., 2015, Sproul et al., 2023). Finally, Muzika et al. (2023) present an alternative method involving a small molecule assisted technique based on a dynamic reaction that dissolves waste composite materials containing ester groups to recycle the blades. For this, the authors use solvents such as ethylene glycol, N-Methyl-2-pyrrolidone (NMP), Tert-Butyl Alcohol (TBD) and require temperatures below 200 °C, effectively dissolving the resin

Table 36 summarize the performance of alternative solvolysis recycling processes found in the literature.

Table 36. Most relevant solvolysis processes found in the literature. Acronyms: GF (Glass fibre), CF (Carbon fibre), NMP (N-Methyl-2-pyrrolidone), TBD (Triazabicyclodecene), EPI (Epichlorohydrin), i-Pr (Isopropanol), $AlCl_3$ (aluminum chloride), H_2O_2 (hydrogen peroxide).

Author	Temperature	Time	Solvents	Energy	Results
(Mattsson et al., 2020)	270 °C	16h	Ethylene glycol	*Data not available*	Resin degradation 50-90%
	270 °C	16h	Propylene glycol		Resin degradation 40-80%
	330 °C	3h	Water, 1-propanol 20%, and KOH 10%		Resin degradation 10-64%
(Rathore and Panwar, 2023)	250-370 °C	*Data not available*	Alcohols, water, glycols	91 MJ/kg	Tensile strength 86-98%
(Liu et al., 2019; Sorte et al., 2023)	260-280 °C	*Data not available*	Water or organic solvents	19.2-21 MJ/kg	Process yield 95%, Fibre yield 100% Tensile strength 58% (GF), 95% (CF)
(Rani et al., 2021)	230 °C, MAC	*Data not available*	Acetic acid, H_2O_2	700 W	Max decomposition rate 97.2%
(Butenegro et al., 2021; Wang et al., 2015, Sproul et al., 2023)	180 °C	6 h	Acetic acid, $AlCl_3$	15.36 MJ/kg	Process yield up to 97.43 wt %
(Muzyka et al., 2023)	Reaction 100-190 °C	1-3 h	Ethylene glycol, NMP, TBD 1:1 mol ratio, 20 ml solution	*Data not available*	GF 64.34% Styrene/polystyrene 8.55% Ftalan oligomers 19.89 % Residue 7.12%
	Addition reaction: 67-70 °C	1,5 h	EPI 20 ml, i-Pr 10 ml, NaOH 17 ml	*Data not available*	*Data not available*

The work from Wang et al. (2015) has been considered to define a benchmark solvolysis system for WTB recycling as accurate and detailed as possible, based on the information provided by the authors. With regard to the preliminary EoLO-HUBs solvolysis recycling alternative, the preliminary information and data provided by MOSES for green solvolysis (laboratory scale) has been considered. In this case, the solvolysis reaction takes place in a close reactor at 80 °C using green solvents (e.g. acetic acid of biological origin) and H_2O_2 (from sustainable chemistry) for oxidation to remove char. After the solvolysis reaction, the recovered fibres are subjected to cleaning (in both cases: benchmark and baseline EoLO-HUBs alternatives) by using water and acetone. The solvents and the organic compound of the resin could also be recovered for further reuse.

4.2.3.1. Qualitative analysis of chemical recycling

A simplified flow diagram for the benchmark and preliminary (laboratory-scale) EoLO-HUBs solvolysis alternatives is provided in Figure 23, while Table 37 provides a summary of the operational conditions for each process.

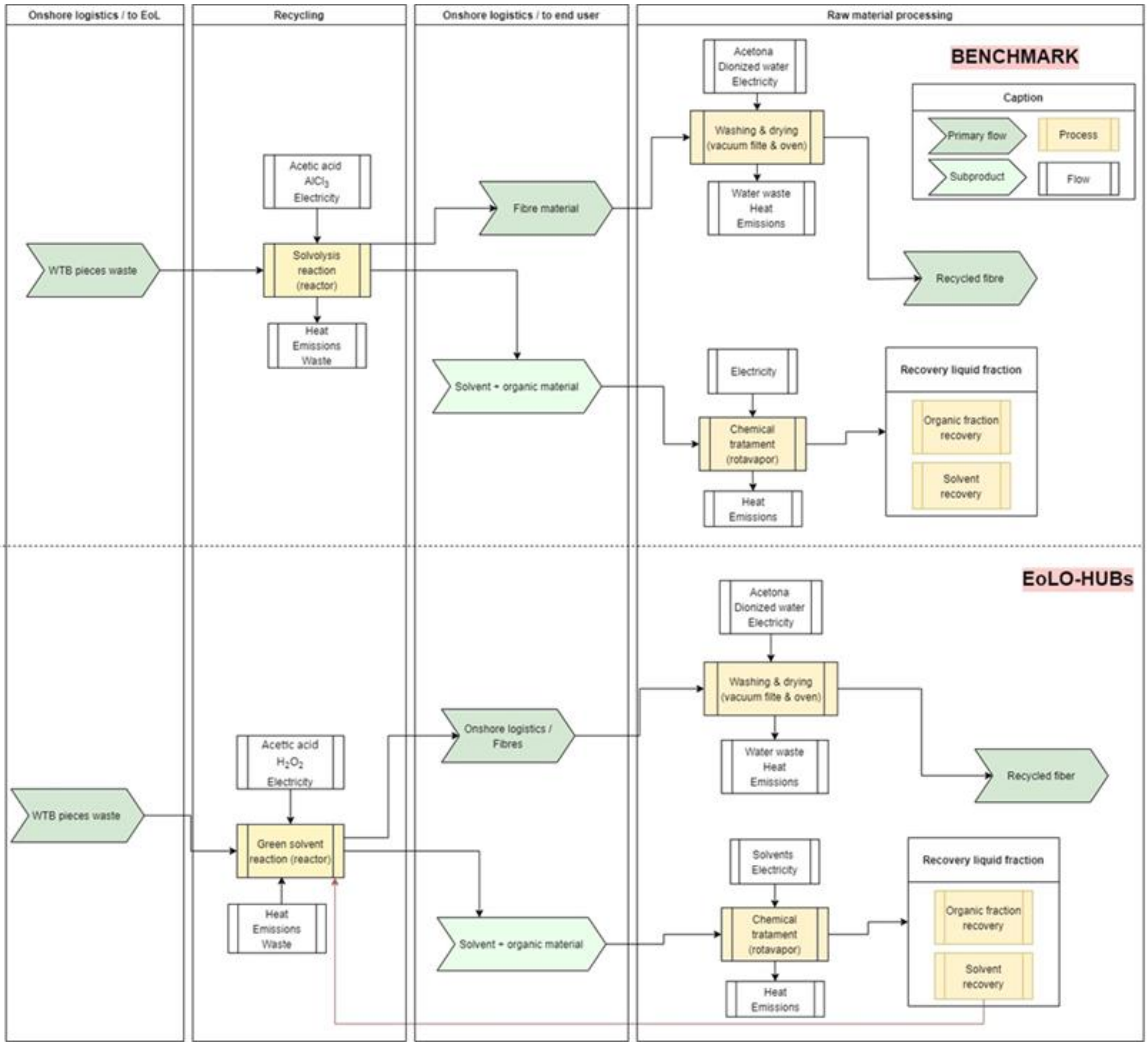

Figure 23. Flow diagram of benchmark and preliminary EoLO-HUBs solvolysis procesess. References: (Butenegro et al., 2021; Wang et al., 2015; Pers. Com. MOSES, 2024). Acronyms: WTB (Wind turbine blade), $AlCl_3$ (aluminum chloride), H_2O_2 (hydrogen peroxide).

As can be seen in Figure 23, the main difference between the benchmark and the preliminary EoLO-HUBs solvolysis systems is the solvent mixture. While acetic acid and aluminum chloride ($AlCl_3$) are used in the benchmark, hydrogen peroxide is used in the preliminary EoLO-HUBs alternative. $AlCl_3$ is corrosive and can cause serious effects on human health, including skin and respiratory tract irritation, and its handling requires strict precautions. Besides, it has a GWP impact of 5.62 kg CO_2 eq/kg (Ecoquery, 2024). In contrast, hydrogen peroxide decomposes into water and oxygen, leaving no harmful residues with minimal risk to ecosystems (Ofoedu et al., 2021) and presents a much lower GWP of 1.15 kg CO_2 eq/kg (Ecoquery, 2024). Therefore, it could be anticipated that the preliminary EoLO-HUBs solvolysis process is more environmentally friendly, since it uses more ecological solvents.

Table 37. Operational parameters of benchmark and preliminary (lab-scale) EoLO-HUBs solvolysis recycling for 1 kg of composite waste (FU). References: (Butenegro et al., 2021; Wang et al., 2015, Sproul et al., 2023) and (Pers. Com. MOSES, 2024).

Operational aspects	Benchmark	EoLO-HUBs
Temperature	180 °C	80 °C
Time	6 h	16 h
Solvents	Acetic acid and $AlCl_3$	Acetic acid and H_2O_2
Energy	15.36 MJ/kg	*Lower energy requirements expected*
Results	Process yield up to 97.4 wt %	*Higher yield expected*

Moreover, the preliminary EoLO-HUBs solvolysis is carried out at very low temperatures for 16h, whereas in the benchmark process, lower reaction times are observed but at higher temperatures (180 °C) (Table 37). Consequently, the preliminary EoLO-HUBs process would reduce energy consumption.

As the solvolysis process for WTBs in the EoLO-HUBs project is still under research and development by MOSES, the solvolysis process outcomes, such as yields and material quality, are yet unknown. However, as in the case of pyrolysis recycling (Section 4.2.2), higher tensile strength and mechanical performance is estimated for the recovered GF and CF fibres.

4.2.3.2. Technical, economic, environmental and social characterization of chemical recycling

The most relevant technical, economic, environmental and social aspects between the benchmark and preliminary (lab-scale) EoLO-HUBs solvolysis process are summarized in Table 38.

From a technical perspective, both the fibre and organic compounds as well as the solvents used in the reaction could be recovered in both systems. However, the reaction conditions are very different:

- Benchmark solvolysis is carried out in a short period of time but at a higher temperature and by using fossil-based chemicals
- Preliminary EoLO-HUBs solvolysis is carried out in a longer period of time but at a much lower temperature and by using green chemicals.

These major differences in temperature, process times and type of chemicals used determine the energy requirements, costs and the corresponding environmental impacts. For instance, within EoLO-HUBs, as the process is carried out at 80 °C for 16 hours it is estimated that it could consume less energy than those carried out at 180 °C for 6h. Taking that into account this, it has been estimated that the energy consumption for the preliminary EoLO-HUBs green solvolysis process could range from 5 to 10 MJ/kg, in this case 10 MJ/kg has been use. This estimate is consistent with the consideration that processes at lower temperatures, although having a longer duration, require less energy overall due to the reduced need to maintain high temperatures for shorter periods (Chen et al., 2023; Kooduvalli et al., 2022). Besides, a reduction of environmental impacts is expected in the EoLO-HUBs solvolysis process (compared to the benchmark) thanks to the use of environmentally friendly solvents, avoiding toxic products such as aluminum chloride, helping to improve the well-being of workers and the local population (by reducing risks), as well.

Table 38. Most relevant technical, economic, environmental and social aspects of the benchmark and preliminary (lab-scale) EoLO-HUBs solvolysis recycling systems. Acronyms: GF (glass fibre), CF (carbon fibre). Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark	EoLO-HUBs (MOSES)	Sources
Technical	• Lower time (6h) (+) • Process yield up to 97% (+) • Tensile strength 58% (GF), 95% (CF) (+) • Recovery of resin and fibre components (+) • Higher temperature 180 °C and therefore energy use (-)	• Lower temperature (80 °C) (+) • Higher potential yield (+) • High fibres mechanical properties (+) • Recovery of resin and fibre components (+) • Higher process time (16h) (-)	(Liu et al., 2019) (Sorte et al., 2023) (Butenegro et al., 2021) (Wang et al., 2015) (Pers. Com. MOSES, 2024)
Economic	• Higher cost due to higher energy use (-)	• Lower cost due to lower energy use (+) • Higher cost of green solvents (-)	(Liu et al., 2019) (Sorte et al., 2023) (Pers. Com. MOSES, 2024)
Environmental	• Material recovery (+) • Higher temperature (-) • Hazardous solvents (-) • Higher impact (-)	• Material recovery (+) • Lower energy use (+) • Green solvents (+)	(Liu et al., 2019) (Sorte et al., 2023) (Butenegro et al., 2021) (Wang et al., 2015) (Pers. Com. MOSES, 2024)
Social	• Workers safety issues due to the use of chemicals (-)	• Reducing solvent toxicity improves worker well-being (+)	(Liu et al., 2019) (Sorte et al., 2023) (Pers. Com. MOSES, 2024)

4.2.3.3. Quantitative analysis of chemical recycling

Preliminary inventory data for the benchmark and EoLO-HUBs processes is presented in Table 39. Some data have been estimated or taken from the literature. Data for the EoLO-HUBs process hwas provided by MOSES, but since it is a process still under study, data is preliminary and some data have been estimated or taken from the literature.

As shown in Table 39, the major difference is the larger amount of solvent used in the case of Eolo-HUBs carried out by MOSES (+56%). As the composition of the WTB waste received by MOSES is unknow, they are focusing for now on ensuring they achieve a full decomposition of the resin, so they are using a large amounts of solvents (Pers. Com. MOSES, 2024). Therefore, the process is not yet optimized.

Another important difference is the lower energy requirement (-51%) by the preliminary EoLO-HUBs solvolysis process compared with the benchmark. Although the reaction time is longer, the temperature is much lower, leading to a reduction in energy use (as explained in the previous section). However, for the washing of the fibres the consumption of water and acetone is much higher (+ 700%) for the preliminary EoLO-HUBs system to ensure a good cleaning of the fibres to neutralize them, although the process water efficiency will be optimized as the project develops (Pers. Com. MOSES, 2024). Finally, 100% recovery of fibres is expected to be achieved in the EoLO-HUBs solvolysis alternative. Considering the data provided by MOSES for WTB waste (61% of fibre and 39% of resin), 0.61 kg of fibres are estimated to recover in the preliminary EoLO-HUBs system and 0.59 kg for the benchmark (Table 37), having the preliminary EoLO-HUBs system, therefore, a 3% higher productivity.

Table 39. Resource inputs and outputs for the benchmark and Epreliminary (lab-scale) oLO-HUBs solvolysis recycling of 1 kg of WTB waste (FU). References: (Butenegro et al., 2021; Wang et al., 2015; Sproul et al., 2023) and (Pers. Com. MOSES, 2024). Acronyms: CFRP (Carbon fibre reinforced polymer), $AlCl_3$ (aluminum chloride), H_2O_2 (hydrogen peroxide).

FU: recycling of 1 kg WTBs waste		**Resource flows**	**Benchmark**	**EoLO-HUBs**	**Ecoinvent processes**
Solvolysis	**Inputs**	CFRP waste pretreated, kg	1	1	n.a.
		Acetic acid, kg	5.31	8.75	GLO: market for acetic acid, without water, in 98% solution state ecoinvent 3.10
		$AlCl_3$, kg	0.93	-	GLO: market for aluminium chloride ecoinvent 3.10
		H_2O_2, kg	-	1	RER: market for hydrogen peroxide, without water, in 50% solution state
		Electricity, low voltage, MJ	15.36	10	ENTSO-E: market group for electricity, low voltage ecoinvent 3.10
	Outputs	Dirty Fibre, kg	0.61	0.61	*Excluded (further treatment required)*
		Solvents, kg	6.25	9.75	*Excluded (further treatment required)*
		Resin compounds, kg	0.39	0.39	*Excluded (further treatment required)*
Washing	**Inputs**	Tap water, kg	5.00	40	Europe without Switzerland: tap water production, conventional treatment ecoinvent 3.10
		Acetone, kg	1.25	10	RER: market for acetone, liquid ecoinvent 3.10
	Outputs	Dry fibres, kg	0.59	0.61	*Excluded (further treatment required)*
		Waste, kg	0.02		*Excluded (further treatment required)*

Based on all these considerations, Table 40 presents the preliminary environmental impacts for the benchmark and the preliminary EoLO-HUBs solvolysis processes. The current preliminary EoLO-HUBs solvolysis alternative (at lab scale) has a significantly greater impact (49% and 310% higher) than the benchmark solvolysis process. The biggest impact difference is on human toxicity (cancer) related to the larger use of acetone (8 times higher), together with the higher amount of acetic acid. Although the energy consumption is lower for the preliminary EoLO-HUBs solvolysis process, this is not enough to compensate the impacts for the greater use of solvents. The contribution of the resource inflows to the environmental categories of climate change, human toxicity (cancer and non-cancer), use of fossil resources, use of mineral resources and metals, and water use are shown in Figure 24.

Table 40. Preliminary environmental impacts for the benchmark and preliminary (lab-scale) solvolysis recycling of 1 kg of WTBs waste (FU).

Impact categories	Unit	Benchmark	EoLO-HUBs	Difference
Acidification	[Mole of H+ eq.]	1.18E-01	1.88E-01	**+59%**
Climate Change - total	[kg CO_2 eq.]	2.63E+01	4.98E+01	**+89%**
Ecotoxicity, freshwater - total	[CTUe]	2.54E+02	4.97E+02	**+96%**
Eutrophication, freshwater	[kg P eq.]	8.44E-03	1.30E-02	**+54%**
Eutrophication, marine	[kg N eq.]	2.17E-02	3.57E-02	**+65%**
Eutrophication, terrestrial	[Mole of Neq.]	2.20E-01	3.63E-01	**+65%**
Human toxicity, cancer - total	[CTUh]	1.05E-07	4.31E-07	**+310%**
Human toxicity, non-cancer – total	[CTUh]	5.36E-07	9.52E-07	**+78%**
Ionising radiation, human health	[kBq U235 eq.]	2.39E+00	3.56E+00	**+49%**
Land Use	[Pt]	6.75E+01	1.30E+02	**+92%**
Ozone depletion	[kg CFC-11 eq.]	5.15E-07	1.14E-06	**+122%**
Particulate matter	[Disease incidences]	1.26E-06	2.04E-06	**+61%**
Photochemical ozone formation, human health	[kg NMVOC eq.]	9.80E-02	2.04E-01	**+108%**
Resource use, fossils	[MJ]	5.22E+02	1.10E+03	**+111%**
Resource use, mineral and metals	[kg Sb eq.]	1.41E-04	2.93E-04	**+108%**
Water use	[m^3 world equiv.]	1.35E+01	2.61E+01	**+94%**

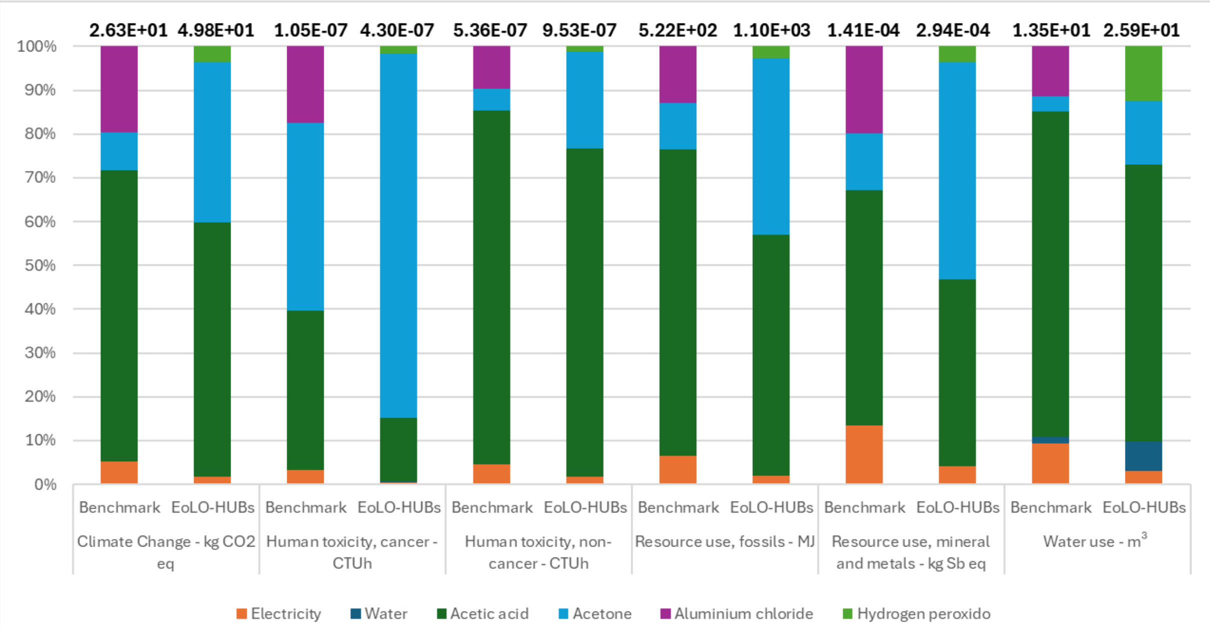

Figure 24. Preliminary impact contributions of electricity, tap water, acetic acid, acetone, aluminum chloride and hydrogen peroxide consumptions to the benchmark and preliminary (lab-scale) EoLO-HUBs solvolysis systems for 1 kg of WTB waste (FU)

A closer examination of the results reveals that acetic acid consumption, followed by acetone consumption, are the main contributors of environmental impact in all impact categories analyzed. With respect to climate change, it is noted that the oxidant used as a benchmark (aluminum chloride) has a 20% contribution to this impact compared to the 4% contribution of hydrogen peroxide in the preliminary EoLO-HUBs system. The same trend is observed for the other impact categories except for water use. For the human toxicity impact category (both cancer and non-cancer), the contribution of aluminum chloride is 17% and 10% respectively, compared to the contribution of hydrogen peroxide for the preliminary EoLO-HUBs system which is 2% and 1%. On the other hand, for the resource use impact category for fossils, minerals and metals, the contribution of aluminum chloride is 13% and 20% respectively, compared to the 3% and 4% contribution of hydrogen peroxide for the preliminary EoLO-HUBs system. This is because, as mentioned above, aluminum chloride has a higher environmental impact compared with hydrogen peroxide, 5.62 kg CO_2 eq for $AlCl_3$ against 1.15 kg CO_2 eq for H_2O_2 (Ecoquery, 2024).

Consequently, in terms of the type of solvents used, the preliminary EoLO-HUBs system is more environmentally friendly recycling process. However, as the process is over dimensioned (testing at lab scale), the potential savings from implementing green solvolysis are not yet noticeable, compared to benchmark systems. This is why it is important to optimize and adjust the reaction parameters (knowing the WGTB waste composition in advance) to avoid the excess use of solvents.

It should also be taken into account that in solvolysis recycling systems the solvents are almost 100% recoverable and could be recycled for continuous solvolysis reactions, but this solvent recovery requires an energy consumption that is unknown at this time, as the project progresses these data will be updated and adjusted. Likewise, the fibre cleaning process can be optimized to avoid high consumption of acetone and water. Finally, higher productivity yields are expected in the EoLO-HUBs solvolysis process, which can generate environmental credits that compensate for the impacts. For instance, if by recovering acetic acid and hydrogen peroxide, MOSES could reduce by 30% the use of solvents, while reducing 70% the consumption of water and acetone, the environmental impacts would be similar to the benchmark with a climate change of 27 kg CO_2eq/kg of recycled waste. However, these aspects and scenarios were not yet explored as data was not yet available.

4.2.3.4. Guidelines and opportunities for chemical recycling

One of the main challenges of solvolysis is the recovery of the materials (matrix and fibre) without degrading them. For this purpose, it is important to optimize reaction times and temperatures, but standardizing recycling processes is challenging considering the diversity of WTB wastes. The presence of materials, other than resin and fibre ,can affect the operation conditions and the quality of the solvolysis process. The best case scenario would be to have WTB waste mixtures composed only of resin and fibre, but this would probably not happen in practice due to the nature of the sector (Pers. Com. MOSES, 2024).

In the meantime, it is important to optimize the solvolysis process, taking into account the energy parameters and using solvents of biological origin that contribute to the reduction of the use of natural resources, avoiding the oversizing of solvents as discussed above. It is also important to improve the overall efficiency of the process, both in terms of fibre recovery and recovery of organic components such as solvents used in the reaction for future reactions or for other processes yet to be defined.

As experts point out, the challenge is to make recycling processes economic and competitive with the manufacture of virgin fibres, because if the recycling process is more expensive than manufacturing virgin fibre, it will not be an economically viable process (Pers. Com. MOSES, 2024). Thus, for solvolysis to be a promising recycling method, a comprehensive cost-benefit balance needs to be performed. This could be also challenging due to the fluctuation prices of green solvents as well as energy and WTB wastes solvents as well as market demands.

4.2.4. Comparison of mechanical, pyrolysis and solvolysis recycling

Table 41 shows the most relevant technical, environmental, economic and social aspects of the mechanical (shredding and sorting), thermal (pyrolysis) and chemical (solvolysis) recycling systems analyzed in sections 4.2.1 to 4.2.3.

Table 41. Most relevant technical, economic, environmental and social aspects of mechanical (shredding and sorting), thermal (pyrolysis) and chemical (solvolysis) recycling systems. References: (Liu et al. 2019, 2022; cefic et al. 2020; Mattsson et al. 2020; Diez-Cañamero and Mendoza 2023; Khalid et al. 2023; Rybicka et al., 2016). Acronyms: TRL (Technology Readiness Levels). Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Mechanical	Pyrolysis	Solvolysis
Technical	• No post-processing necessary (+) • TRL 9 (+) • Product obtained is a mixture of fibres and polymer matrix (-) • Low quality secondary application (-)	• Gas and liquid recovered useful for energy (+) • TRL 7-8 (+) • Low-medium quality secondary applications (+) • Post-oxidation needed (-) • Segregation depends on reaction parameters (-)	• Complete segregation of fibres and resins (+) • High quality secondary applications (+) • Cleaning with organic solvent required (-) • TRL 5-6 (-)
Economic	• Low cost: \$100/t - \$300/t (+) • Low investment need (+)	• Low cost, \$214.1/t (+)	• High cost, \$713.6/t (-)
Environmental	• No consumption or raw material and water (+) • Consumption of least amount of energy (+) • Lower carbon footprint (+)	• Formation of undesirable organic components (-) • Higher energy consumption (-) • Higher GWP impact (-)	• Lower energy consumption (+) • Lower GWP impact (+) • Use of aggressive chemicals (-)
Social	• Dust and noise generation (-)	• Low-medium investment need (+)	• High investment need (-)
Critical issues and challenges	• Dust collection • Noise level reduction • Design of portable shredding and sorting technologies	• Better control of the reaction parameters and avoid by-products emission • Design a more optimum process	• Use of environmentally friendly solvents • Design a more optimum process

From a technical standpoint, each method has unique operational characteristics and results. First, each recycling method has a different technological development: TRL 9 for mechanical recycling, TRL 7-8 for pyrolysis, and TRL 5-6 for solvolysis (Rybicka et al., 2016). On the one hand, mechanical recycling produces a mixture of fibres and polymeric matrix, which leads to lower quality secondary applications. However, it benefits from not requiring post-processing in most cases. On the other hand, solvolysis excels in achieving complete segregation of fibres and resins, leading to high quality secondary applications (Liu et al. 2019). However, this method requires cleaning with organic solvents, which adds complexity to the process. Pyrolysis, on the other hand, is highly dependent on reaction parameters for efficient segregation. The recovered gases and liquids can be reused for energy production, but the quality of secondary applications is usually low to medium, and post-oxidation is required to complete the process.

Focusing on the economic aspects, in addition to the costs, the value of the recycled material must be taken into account. Mechanical recycling is the most profitable, with costs ranging from \$150 to

$300/ton, and requires a low investment, which makes it attractive for wider implementation (cefic et al. 2020). However, as already mentioned, the recycled material is a mixture of fibres, of lower quality and therefore of lower economic value. On the other hand, pyrolysis offers an average cost of $214.1 per ton, in this case the fibre obtained is of higher quality. Even so, it must be taken into account that depending on the type of GF or CF fibre, the price varies greatly, since the properties of the fibres are different. In general, GFs have a lower resistance to pyrolysis, so they can degrade, decreasing their economic value (Fayyaz et al. 2023). However, solvolysis does not damage the fibre and the quality of the material obtained for both fibres is very high (Liu et al. 2019); however, although it produces high value products, it has a high cost of $713.6 per ton, which is a major barrier to widespread adoption.

In terms of environmental aspects, the best performing process could be mechanical recycling, due to the fact that it does not consume raw materials or water and requires the least amount of energy. In contrast, solvolysis, while also having lower energy consumption, involves the use of chemicals that can be aggressive and pose environmental risks if not properly managed (Liu et al. 2019; Diez-Cañamero and Mendoza 2023). On the other hand, pyrolysis, although it can recover gases and liquids useful for energy, has higher energy consumption and a higher GWP impact (Liu et al. 2019; Diez-Cañamero and Mendoza 2023). In addition, it also generates undesirable organic components, which require careful environmental management. However, mechanical recycling is not a suitable option to recover suitable fibers for industrial use, beyond using the fillers as additive for construction products. Thus, it represents an intermediate solution until suitable (efficient and low impact) pyrolysis and solvolysis systems are developed and deployed.

Focusing on social aspects, mechanical recycling is well known and therefore easier to apply and accept. However, it generates dust and noise, which can affect workers, environment and nearby communities. Pyrolysis, on the other hand, despite being a well-established method, as a relatively new method, has the potential to incorporate modern safety improvements, such as the control of harmful emissions to protect worker safety. Solvolysis, as a relatively new method, involves hazardous solvents that pose health risks to workers and therefore requires strict safety measures. However, this can be mitigated with the use of green solvents.

Thus, the optimal recycling method for WTBs will depend on the composition of the blades themselves and the requirements of the end-users of the recyclates.

4.3. Upgrading of recovered materials and industrial use

After recovery of the fibres by pyrolysis or solvolysis, the fibres are subjected to upgrading as a previous step to the end-use of the fibres in the industry.

TNO is working on a laboratory scale using the recovered fibres from the pyrolysis and solvolysis processes to blend the material with PP, PA6 and PA6.6 thermoplastics into recycled long-fibre thermoplastic granules (reLFT). The process will be optimized to retain as much fibre length as possible, including the potential use of additive additives to improve the fibre/matrix interface. After the testing processes, including injection molding, about 50 kg of the most promising thermoplastic composite pellets will be sent to CRF for the production of injection molding automobile parts.

In addition, FHG, together with NCC, are working at laboratory scale using the previously recycled fibres to manufacture nonwoven material/organosheets (FHG) and composite sheets (NCC). Around 200 kg of nonwoven textiles will be processed into organosheets at FHG and then sent to NCC which will use the organosheet material to perform isothermically forming and overmolding trials to produce automotive parts with a high quantity and quality by CRF. Finally, a share of the recovered fibres will be also sent to SGP to substitute the use of vGF in the production of gypsum panels and use rGF as additive to substitute the use of sand in the production of glass wool.

Taking into account the expectations of the partners involved in the end-user phase, three different end products have been defined from the literature as reference to analyze (later on) the potential sustainability improvements by using rGF in industrial production. The manufacture of air intakes has been considered as a benchmark product for the automobile sector (CRF), while the manufacture of gypsum panels and glass wool (SGP) has been considered as a benchmark product for the construction setcor, as discussed in the following sections.

4.3.1. WTB-based manufacture of automobile components

The main plastics used for the production of automotive components are PP and PA and all these materials can be filled (e.g. 10% to 30%) with short GF for higher mechanical and thermal performance. In a single car there are about 150 kg of plastics, of which 20% are composites with an average of 25% GF and about 30 kg of components filled with about 7.5 kg of GF (Pers. Com. CRF, 2024). With the help of TNO, CRF intends to manufacture different car parts to avoid and/or reduce the use of vGF (e.g. a pedal bracket with PP and GF30, a radiator fan and front cooling module with PA66 with GF30, and an air intake manifold with PA6 and GF30).

The study from Delogu et al. (2015) on an LCA of an air intake system (PA6 thermoplastics with 30% GF) has been selected as benchmark process. The air Intake plays a vital role in a car engine's system, distributing air to each individual cylinder (Delogu et al., 2015). Historically, this compound was primarily manufactured from aluminum or magnesium alloys, using either a sand-casting process or a multi-tube brazing process. The introduction of thermoplastic polymers in the production of air intakes in the 21st century brought significant advantages, such us, weight and cost reduction and improved engine performance (Delogu et al., 2015).

4.3.1.1. Qualitative analysis of automobile components manufacturing

The flow diagram of the benchmark and EoLO-HUBs (CRF) manufacturing process for an car air intake is illustrated in Figure 25. However, as the EoLO-HUBs (CRF) process will be developed/tested later on the project there is no operational data yet available.

In summary, the manufacturing process involves first the production of the compounder or thermoplastic compound, which is a mixture of PA6 and 30% GF. Next, the thermoplastic undergoes vacuum delivery and drying, where cold water and electricity are consumed. The thermoplastic is then returned to vacuum before the injection molding process, which, in addition to energy, also consumes oil. Finally, the product is injected molded to generate the air intake. In the case of EoLO-HUBs (CRF), as a preliminary estimate, 15% of vGF and 15% of rGF would be mixed with the thermoplastic needed to manufacture the air intake. No major changes at the industrial manufacturing scale are expected, when rGF is used instead of vGF. If the technical performance of the rGF is equivalent to the vGF (up to 10% reduction in mechanical performance as maximum) it is estimated that 1:1 substitution could be achieved hence reducing the GWP of the GF content by 50% (vbeing the GWP/kg of vGF equivalent to 1.5 kg CO_2) (Pers. Com. CRF, 2024). In addition to the use of rGF, CRF is considering the use of recycled plastics to further reduce the CO_2 emissions and costs. However, today recycled polymers and vGF are being used, so the effect of changing from this to the use of rGF and virgin polymers (to maintain the car parts performance) should be carefully evaluated from an environmental and economic standpoint.

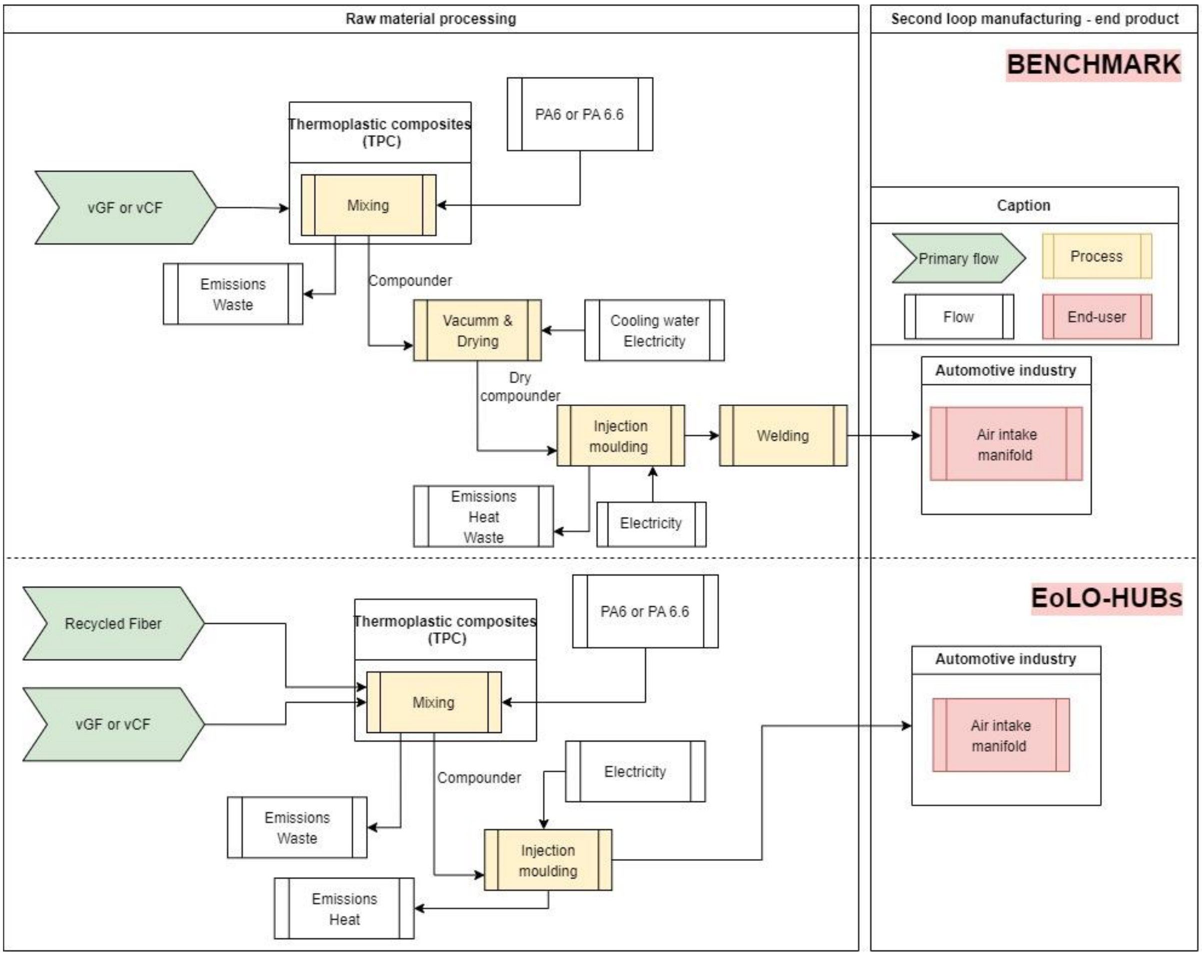

Figure 25. Flow diagram for the benchmark and EoLO-HUBs (CRF) air intake manufacturing process. Acronyms: PA6 (polyamide 6), PA6.6 (polyamide 6.6) vGF (virgin glass fibre), rGF (recycled glass fibre), vCF (virgin carbon fibre), rCF (recycled carbon fibre).

It is important to note that CF and rCF could be used by the industry, without expecting any alteration in the process (Pers. Com. CRF, 2024). The problem in this case is the high economic value of this material, which makes the use of GF more economically viable.

4.3.1.2. Technical, economic, environmental and social characterization of automobile components manufacturing

The most relevant technical, environmental, economic and social aspects between the benchmark and EoLO-HUBs (CRF) process for the production of a car air intake are summarized in Table 42.

From a technical point of view, the use of rGF instead of vGF presents both challenges and opportunities. Although recycled fibre can exhibit a reduction in mechanical properties compared to virgin fibre, up to 10% reduction is considered acceptable within the performance limits required for the air intake manifold (Pers. Com. CRF, 2024). The mixture of recycled GF with virgin PA6 can maintain the necessary mechanical properties for automotive use, with minimal impact on the efficiency of the final component. This process does not require significant changes in existing manufacturing techniques, allowing recycled fibres to be integrated without major adjustments in production lines (Pers. Com. CRF, 2024).

Table 42. Most relevant technical, economic, environmental and social aspects for the production of car air intakes. Acronyms: PA (polyamide), PP (polypropylene), vGF (virgin glass fibre), rGF (recycled glass fibre). Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark	EoLO-HUBs	Sources
Technical	• Compounder: virgin polymer and virgin fibre (-)	• Compounder: virgin polymer, 50% virgin fibre and recycled fibre 50% (+) • Substitution rGF/vGF 1:1 (+)	(Delogu et al., 2015) (Pers. Com. CRF, 2024)
Economic	• Higher cost due to higher price of vGF (-)	• Lower cost due to lower consumption of vGF (+) • Big economic opportunities having several kg of rGF in vehicle (+) • No reduction expected for manufacturing cost of products (=)	(Delogu et al., 2015) (Pers. Com. CRF, 2024)
Environmental	• vGF 1.5-1.7 kg CO_2/kg (-)	• Fibre impact cut 50% due the rGF (+)	(Pers. Com. CRF, 2024) (Pers. Com. SGP, 2024)
Social	• Well known method (+)	• Method under study (-)	(Pers. Com. CRF, 2024)

The environmental benefits of using recycled GF could be significant for the industry (considering the amount of composite materials used anually), including potentially lower GHG, if the resource requirements (Sections 4.1 and 4.2) for the production of recycled fibres is lower than those required to produce virgin fibres. It also essential to ensure that rGF is cheaper or equivalent to the cost of vGF.

From a societal perspective, the adoption of rGF in manufacturing can lead to positive outcomes, such as job creation in the recycling and composites sectors, and the promotion of a circular economy. Innovation in recycling practices and the use of sustainable materials can also improve the public image of automotive manufacturers, attracting a more environmentally conscious consumer base.

4.3.1.3. Quantitative analysis of automobile components manufacturing

Since the production of car parts by using recovered fibres from the EoLO-HUBs project innovations has not yet started, some general inventory data is provided in Table 43, considering the study of Delogu et al. (2015) as benchmark and the feedback provided by CRF.

Table 43. Resource inputs and outputs for the manufacturing of 1 car air intake manifold (FU) References: (Delogu et al., 2015; Pers. Com. CRF, 2024). Acronyms: PA6 (polyamide 6), vGF (Glass fibre), rGF (recycled Glas fibre), AIM (air intake manifold).

FU: 1 unit air intake manifold		Resource flows	Benchmark	EoLO-HUBs
Raw material	**Input**	PA6, kg	1.25	1.25
		vGF, kg	0.53	0.27
		rGF, kg	-	0.27
	Output	Raw material for AIM, unit	1	1

As presented in Table 43, the virgin fibre content to produce an air intake manifold can be reduced by 50% through the use of rGF, which is assumed to not affect the process paramenters (e.g. energy requirements, etc). However, as the rGF produced through the implementation of the EoLO-HUBs innovations is yet unknown, it is uncertain at this point if the use of rGF in the car industry would be economically and environmentally profitable. To be profitable, the cost should be lower than €1.5-2.5/kg, while the environmental footprint should be lower than 3 kg CO_2 eq/kg of fibre production.

4.3.1.4. Guidelines and opportunities for automobile components manufacturing

The replacement of vGF with rGF should lead to a maximum of 10% reduction in the car parts performance and comply with all the (technical and safety) testing standards from the car industry. However, it is crucial that the cost and environmental burden of rGF is lower than the one from vGF to facilitate the adoption of the reclaimed fibres in the car industry.

4.3.2. WTB-based manufacture of construction materials

SGP plans to use rGF to manufacture two end products: i) gypsum plasterboards, and ii) glass wool.

Gypsum plasterboard is composed of gypsum, a soft, brittle material with 21% water in its composition, laminated between two sheets of specially designed paper, which gives it most of its mechanical performance. The gypsum core is reinforced with vGF that increase its mechanical performance (in both bending and screw pull-out tests) and fire resistance. These vGF can be substituted with the use of rGF, if their technical performance is adequate.

Glass wool is used for thermal insulation in buildings, and the use of rGF (up to 1% if the glass wool mass) can substitute the use of sand, generating environmental benefits, while improving performance if it is technically adequate.

4.3.2.1. Gypsum plasterboards manufacturing

Gypsum plasterboard is a material widely used in the construction industry as dry wall component for interior partitions and ceilings (Quintana et al., 2018). Their use enables efficient spatial distribution inside buildings, improving living conditions and safety (Alameda et al., 2016).

As reported in the work of Quintana et al. (2018), to produce gypsum plasterboard first the gypsum rocks must be extracted from the quarry with a maximum diameter of 5 cm. Then, once in the production plant, they are ground and heated to 160 °C. During this process, the gypsum loses about 70% of its moisture and is transformed into stucco. It is then mixed with water and other chemicals and converted into slurry, which is poured onto a large layer of cellulose that is unrolled through a longboard machine. In the same way, another layer of paper is unrolled over the board, which then passes through a system of different rollers that compact the core to the right thickness. In a short time, the slurry begins to harden and is ready to be cut to the desired size. Finally, the boards are placed in an oven to remove any remaining moisture (Quintana et al. 2018). Fibres are added to the dosing system together with the gypsum.

In the EoLO-HUBs project, SGP will be responsible for the manufacture of gypsum plasterboards by adding a small proportion of rGF in the form of chopped strands to increase their mechanical and fire resistance (Pers. Com. SGP, 2024). This would allow to substitute the use of vGF, which in the case of the production of gypsum plasterboards can represent a relevant share of their weight (much more considering the annual EU production of gypsum panels).

The most optimal for the process would be to achieve a 1:1 (rGF/vGF) substitution, but rGF may not have the same performance as vGF, which would entail using a larger amount of rGF (e.g. 1.2:1 or 1.5:1) to reach the same level. Importantly, the introduction of a higher amount of rGF could lead to the use of a higher quantity of water and energy in the process (Pers. Com. SGP, 2024) that should be carefully considered when data becomes available during the industrial tests.

4.3.2.1.1. Qualitative analysis of gypsum plasterboard manufacturing

The flow diagram for the production of benchmark vs EoLO-HUBs (SGP) gypsum plasterboards is presented in Figure 26. As the industrial testing processes have not yet started, there is no operational data yet available.

The difference between the benchmark and the EoLO-HUBs process is related to the addition of recycled fibres in the dosing process. It is expected that the rest of the industrial processes will remain the same. In the manufacturing of gypsum panels by using rGF, it is estimated a 1.2:1 substitution ratio with vGF. These rGF must have a sizing pretreatment consisting of the addition of organic compounds to promote dispersion and bonding with the gypsum (Pers. Com. SGP, 2024).

Dosing is the key to this process as it is important that the conditions in which the fibres arrive to the industrial plant are good enough for dosage and that the fibres flow properly through the dosing system. Otherwise, the dosing system would have to be changed wih represents an important capital investment that would not be addressed within the EoLO-HUBs project. Once the dosing is done, there will be the mixing stage with other compounds and then the hydration stage and finally the drying stage to remove all the remaining moisture from the plasterboard.

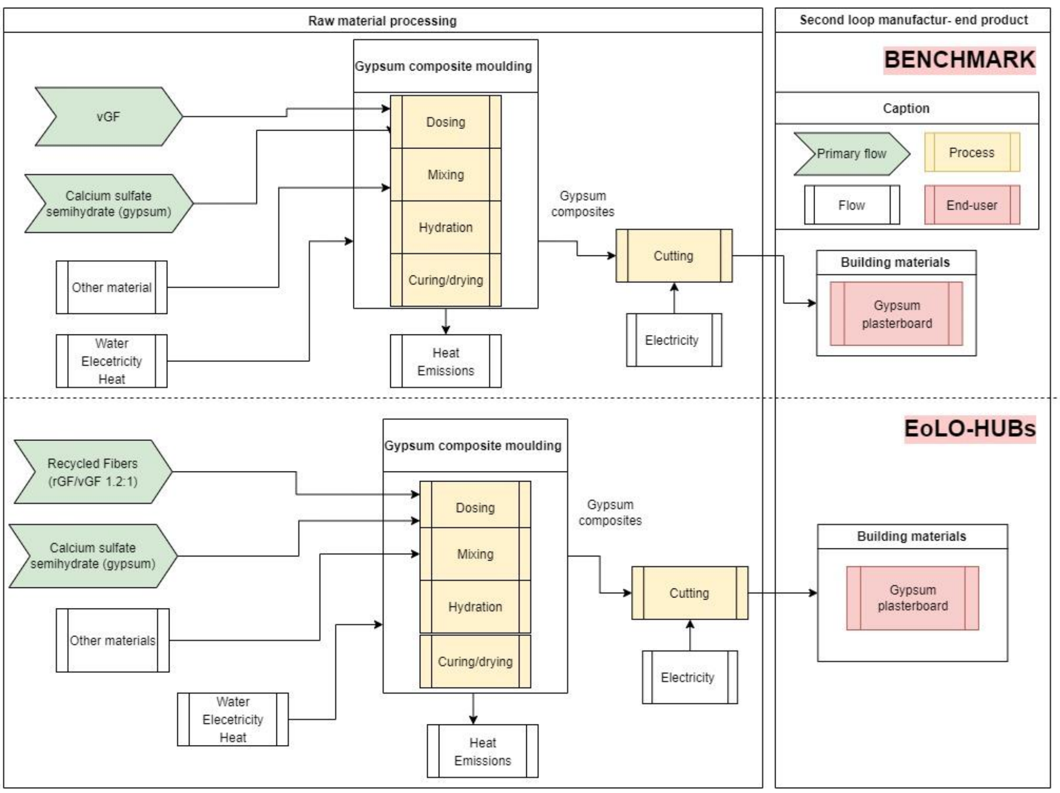

Figure 26. Flow diagram of benchmark and EoLO-HUBs gypsum plasterboard manufacturing. Acronyms: vGF (virgin glass fibre), rGF (recycled glass fibre).

4.3.2.1.2. Technical, economic, environmental and social characterization of gypsum plasterboard manufacturing

The most relevant technical, environmental, economic and social aspects between the benchmark and EoLO-HUBs process for the production of gypsum plasterboard are summarized in Table 44.

In the conventional gypsum plasterboard manufacturing process, the vGFs are perfectly integrated into the gypsum matrix, ensuring consistent quality and mechanical properties (Rajak et al., 2019). According to data provided by SGP, each gypsum plasterboard, averaging 8 kg, contains around 40 g of vGF (Pers. Com. SGP, 2024). In contrast, the use of rGF introduces complexities to the processes due to possible entanglement of the fibres, which can disrupt the dosing system. Ensuring that the rGF flows well during dosing is therefore critical.

Economically, the price of vGF is approximately €1.5-2.5/kg. SGP has an annual GF consumption of about 11,000 tons in Europe, the cost of raw materials is significant, so replacing vGF with rGF, even if the substitution is 1.2:1, the economic savings could be potentially significant, assuming that rGF would be cheaper (Pers. Com. SGP, 2024). Material savings could also be significant. However, these savings must be balanced against the possible increase in water and energy costs due to the higher moisture content and the need for additional drying of rGF gypsum plasterboards.

Table 44. Most relevant technical, economic, environmental and social aspects for gypsum plasterboard manufacturing (FU). Acronyms: vGF (virgin glass fibre), rGF (recycled glass fibre). Note(-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark	EoLO-HUBs	Sources
Technical	• vGF is use (-)	• Substitution rGF/vGF 1:1 ideal, estimated 1.2:1 (+) • rGFs need to be handled just like vGFs, so they need to be sized and packaged in such a way that they can flow through our dosers (-) • May require higher consumption of water and energy (-)	(Rajak et al., 2019) (Dalchem; Venta et al., 1997) (Pers. Com. SGP, 2024)
Economic	• Lower cost due to higher water and energy requirements (+) • Higher cost due to higher price of vGF, (rGF could have a cost close, if not lower, than the vGF) (-)	• Lower cost due to lower consumption of vGF, (rGF could have a cost close, if not lower, than the vGF) (+) • Higher cost due to higher water and energy requirements (-)	(Rajak et al., 2019) (Quintana et al., 2018) (Pers. Com. SGP, 2024)
Environmental	• Lower energy and water consumption (+)	• Implementation of rGF must obtain lower environmental impacts (+) • Higher impact of energy and water consumption (-)	(Pers. Com. SGP, 2024)
Social	• Well known method (+)	• Method under study, dosing is the big limitation (-)	(Pers. Com. SGP, 2024)

From an environmental point of view, the production of vGFs is energy-intensive and generates significant emissions. The use of rGF could reduce the environmental impact of vGF plasterboards, if they have a lower environmental burden than vGFs. However, the use a a higher use of rGF to compensate the technical loss by substituting vGF can also lead to greater water and energy use with the corresponding additional environmental impacts. This should be carefully considered during the environmental calculations to ensure even if there is an increase in the use of water and energy, there is an environmental savings compared to the use of vGF.

From a social perspective, the use of rGFs in gypsum plasterboard production promotes sustainability by encouraging recycling and waste reduction, which enhances the company's reputation and aligns with society's environmental goals.

4.3.2.1.3. Quantitative analysis of gypsum plasterboard manufacturing

Table 45 provides general inventory data for the benchmark and EoLO-HUBs (SGP) gypsum plasterboard manufacturing processes. The data on the manufacturing of benchmark gypsum plasterboards has been taken from different sources, such as environmental product declarations (Pers. Com. SGP, 2024) and academic literature (Dalchem; Venta et al., 1997). For the case of EoLO-HUBs alternative, no data has been gathered as the industrial testing processes have not yet started. So, it has been assumed based on the use of 1.2 units of rGF per unit of vGF, and assuming a linear additional consumption of water and energy based on benchmark data.

Table 45. Resource inputs and outputs for the manufacturing of 1 m^2 of gypsum plasterboards (FU). References: (Pers. Com. SGP, 2024; Dalchem; Venta et al., 1997). Acronyms: vGF (virgin glass fibre), rGF (recycled glass fibre).

FU= 1m^2 gypsum plasterboard		Resource flows	Benchmark	EoLO-HUBs
Gypsum plasterboard	Input	vGF, g	72	-
		rGF, g	-	86.4
		Calcium sulfate semihydrate (gypsum), kg	12.6	12.6
		Other materials, kg	1.4	1.4
		Energy, MJ/m2	17.4	20.8
		Water, L	9.4	11.3
	Output	Gypsum Plasterboard, m^2	1	1

As in the case of the manufacture of the car air intake manifold (Section 4.3.1), since the environmental impact of the EoLO-HUBs´ rGF is yet unknown, the LCA calculations cannot be performed as they would be misleading. So, Table 45 only aims at providing a general overview of the potential effect of the use of rGF in the inventory data for the gypsum plasterboards, which could lead to a 8% increase in material use, and 20% increase in water and energy use, consindering a linear extrapolation of the benchmark data based on the use of 1.2 units of rGF per unit of vGF, which should be validated by running the corresponding tests. In any case, any additional impact based on a higher use of materials, water and/or energy could be offset in practice by the use of rGF in substitution of vGF depending on their lower environmental burden.

4.3.2.1.4. Guidelines and opportunities for gypsum plasterboard manufacturing

According to SGP, the most critical technical aspect for the manufacturing of gypsum panels by using rGF is the dosing. So, fibres should arrive in the right way (in terms of disposition and packaging) and their length has to be between 6-12 mm with a diameter ideally from 13-17 µm and a moisture content between 7-10%. Moreover, rGF tends to thicken the gypsum mixture, leading to increased water and energy consumption. This could increase operating costs, although more testing is needed to confirm these impacts.

On the other hand, the EoLO-HUBs project can contribute significantly by providing high quality recycled fibres that meet these technical and cost specifications, thus supporting the circular economy and reducing the environmental footprint.

4.3.2.2. Glass wool manufacturing

Glass wool is a thermal insulation and sound absorption material used in buildings as it has good insulating properties and it is resistant to corrosion and fatigue damage. Glass wool is traditionally produced by burner blowing, vertical steam blowing and centrifugal winding. However, the centrifugal winding method is the main production technology at present, which has low energy consumption and is free of dross balls and contamination (Zhao et al., 2018).

To manufacture glass wool, raw materials such as quartz powder, dolomite, soda and borax are thoroughly mixed. This mixture is then heated in an electric furnace to produce melted glass. The melted glass is then expelled through the nozzle of a high-speed centrifuge, which runs on a combination of fuel gas and air. As it exits the centrifuge's exhaust ports, the glass forms primary fibres. These primary fibres are then stretched into superfine fibres inside a circular combustion chamber. The final stage is to process these superfine fibres through various techniques, such as molding, settling and collection, to create glass wool (Zhao et al., 2018).

Currently, glass fibres (either virgin or recycled) are not used for the production of glass wool. Therefore, one the EoLO-HUBs innovations is to facilitate the incorporation of rGF (up to 1% in mass) in the manufacture of glass wool in substitution of silica sand or glass cullets. To this purpose, SGP plans to use 1000 kg of rGFs, with a ground fibre size of 5-6 mm in length and 10 mm maximum in their glass furnace to produce glass wool.

4.3.2.2.1. Qualitative analysis of glass wool manufacturing

The process flow diagram for benchmark and EoLO-HUBs (SGP) glass wool manufacturing is provided in Figure 27. However, as the industrial testing processes have not yet started, no operational data is available.

The only difference between the two cases is the use of recycled fibre in the melting stageto substitute the use of a share of silica sand and/or glass cullet's. The remaining parameters, such as energy requirements, are assumed to remain constant. Cost are also assumed to be not affected if the cost of the rGF is equivalent to the materials substituted (Pers. Com. SGP, 2024).

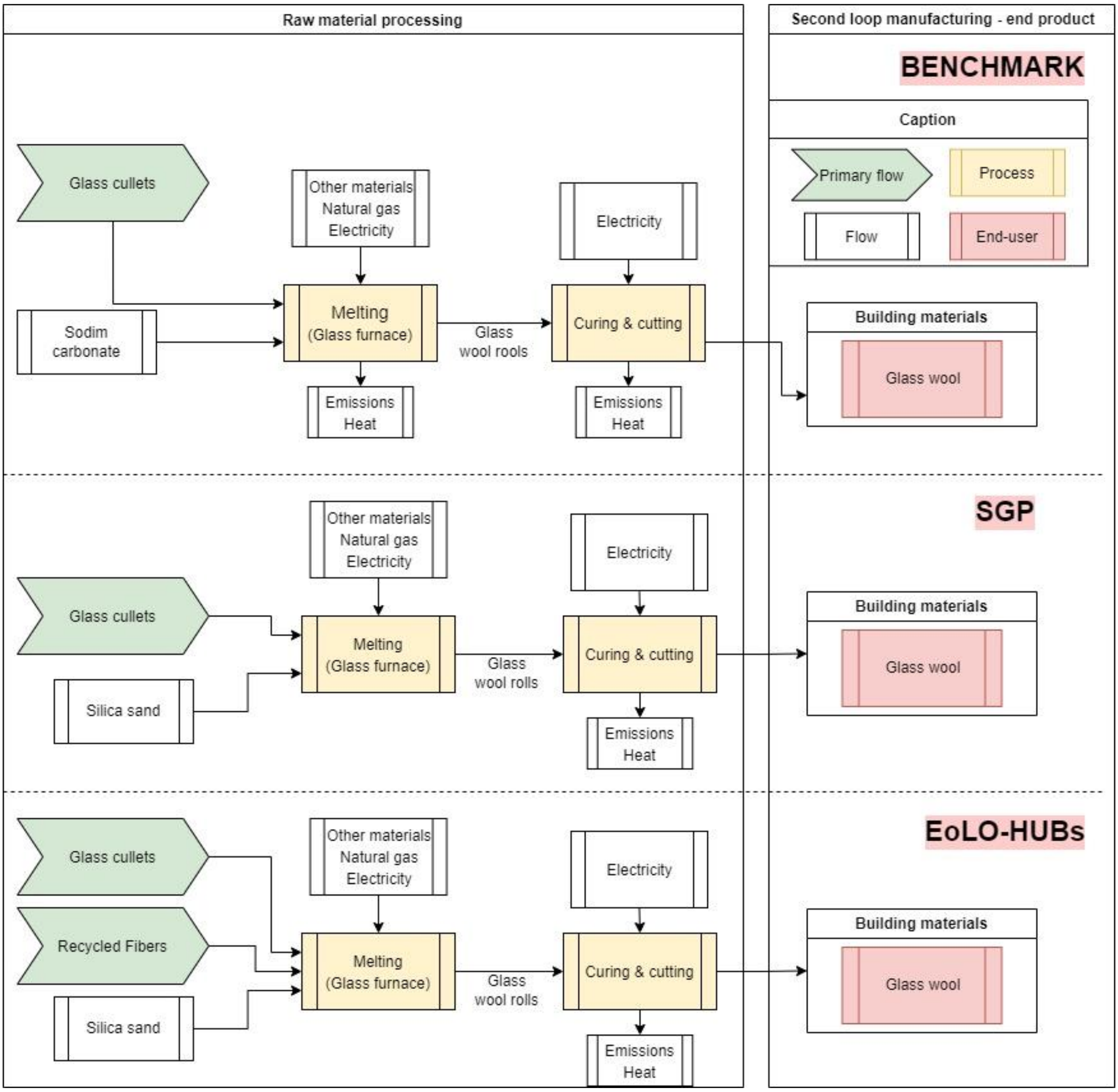

Figure 27. Comparative flow diagram for glass wool manufacturing process between benchmark, SGP and EoLO-HUBs processes. Acronyms: rGF (recycled glass fibre), rCF (recycled carbon fibre)

4.3.2.2.2. Technical, economic, environmental and social characterization of glass wool manufacturing

The most relevant technical, economic, environmental and social aspects between the benchmark and EoLO-HUBs (SGP) process for the production of glass wool are summarized in Table 46.

Table 46. Most relevant technical, environmental, economic and social aspects of benchmark and EoLO-HUBs for glass wool manufacturing. Acronyms: rGF (recycled glass fibre). Note: (-) refer to negative aspects, (+) refer to positive aspects.

Sustainability aspects	Benchmark	EoLO-HUBs	Sources
Technical	• Glass cullets and sodium carbonate is use (-) • Higher melting temperature 1500 °C (-)	• Incorporation of 1% rGF reducing consumption of glass cullets or silica sand (+) • Lower melting temperature 1200 °C (+) • Requirement that rGF be free of any materials that melts above 1150 °C (-)	(Cantini et al., 2022) (Pers. Com, SGP, 2024)
Economic	• Higher cost due to lower consumption of cullet or sand, if rGF cost is cheaper than both (-)	• Lower cost due to lower consumption of cullet or sand, if rGF cost is cheaper than both. (+)	(Pers. Com, SGP, 2024) (WRAP 2024)
Environmental	• Higher expected impact due to the use of more silica sand and/or glass cullets (-)	• Expected lower impact due to that 1% of rGF use, substituting silica sand and glass cullet´s (+)	(Pers. Com, SGP, 2024)
Social	• Well known method (+)	• Method under study, as of today, there is no certainty that rGF will replace sand or cullet (-)	(Pers. Com, SGP, 2024)

Considering technical aspects, 1% of rGF will be introduced in substitution of silica sand or glass cullet, depending on the glass wool formulation. Although 1% rGF may not seem relevant, it is estimated that 765 kt of glass wool was produced in Europe in 2020. Therefore, the use of rGF in the production of glass wool could lead to significant material and cost savings at the EU level (Pers. Comm. SGP, 2024). However, a critical requirement is that the rGF must be free of any impurities that melt above 1150 °C to ensure the integrity of the production process (Pers. Com. SGP, 2024). This innovative method shows potential for reducing energy consumption and material costs, though it requires rigorous quality control of the recycled materials.

Regarding the environmental aspects, the potential environmental savings that can be actually achieved require careful consideration because rGF would be used to substitute silica sand (virgin material or reused) or glass cullet's (that already represent a waste stream). From an economic perspective, taking into account that the price of a glass cullet is around €26/kg and that the price of silica sand can be 5 times lower (around €5/kg) (WRAP 2024), the cost of the rGF should fit within these ranges to be profitable.

4.3.2.2.3. Quantitative analysis of glass wool manufacturing

The information provided by Zhao et al. (2018) has been used to define the benchmark system for the production of glass wool and adapted to the EoLO-HUBs alternative considering only the use of rGF in substitution of silica sand (Table 47). It has been estimated the same energy consumption for both cases as no major changes at the industrial level are expected.

Table 47. Resource inputs and outputs for 1 kg glass wool manufacturing (FU). References: (Zhao et al., 2018; Ecoinvent, 2024, Pers. Com. SGP, 2024). Notes: [1]Ecoinvent glass wool.

FU: 1kg glass wool		Benchmark	Benchark	EoLO-HUBs
Melting	Input	Glass cullet, kg	0.70	0.70
		Sodium carbonate, kg	-	-
		Silica sand, kg	0.12	0.11
		Other material and additives, kg	0.18	0.18
		rGF, kg	-	0.01
		Natural gas MJ	6.60[1]	6.60[1]
		Electricity, kWh	2.32[1]	2.32[1]
	Output	Glass wool, kg	1	1

The main differences between the processes is the use of rGF instead of a share of silica sand. Taking into account that the GWP of silica sand (0.028 kg CO_2/kg) and knowing that the European production of glass wool was 765 kt in 2020, this 1% saving in silica sand could represent a saving of 25,704 t CO_2 per year and almost 40 million euros (Pers. Com. SGP, 2024). However, as in the case of the manufacture of gypsum plasterboards (Section 4.3.2.1), since the environmental impact of the EoLO-HUBs´ rGF is yet unknown, the LCA calculations cannot be performed as they would be misleading. Thus, these environmental and cost savings by reducing the use of silica sand, could be compromised depending on the environmental impact and cost of the rGF used in glass wool manufacturing, which should be carefully considered.

4.3.2.2.4. Guidelines and opportunities for glass wool manufacturing

The biggest challenge for the production of glass wool by using rGF is that the fibres should be at leeast 5-6 mm in length and be free of metals, wood, plastic, any material that melts above 1150 °C, such as CF, opal glass and ceramics, contaminants such as PbO, F, SrO, BaO, Sb_2O_3, Cl, CoOHg, As_2O_3, Hg. The organic content should be a maximum of 0.3% and the moisture level should not exceed 2.5% (Pers. Com. SGP, 2024). The cost of the rGF should be also competitive and they must have a reduced environmental footprint. If all these requirements are fulfilled, annual cost and environmental savings for the industry could be significant.

5. INTEGRATED ASSESSMENT OF THE CIRCULARITY AND SUSTAINABILITY PERFORMANCE OF EoLO-HUBs INNOVATIONS

Within the EoLO-HUBs project, two large-scale demonstrators, covering the full WTB recycling value chain (from dismantling to material recovery and recirculation in the industry) will be deployed and analyzed (Figure 7).

Both recycling systems will handle WTB-EoL wastes through a novel combination of cost-efficient and versatile decommissioning processes and tools, including a software decommissioning tool for logistics management as well as flexible and efficient inspectioning, cutting, decoating and material shredding and sorting technologies (Section 4.1) to optimize the entire WTB recycling system (Section 4.2) from dismantling to the end-use of the recovered materials in the (automobile and construction) industry (Section 4.3). Accordingly, the WTB pyrolysis and solvolysis recycling outcomes (recyclates and byproducts) will be refined and upgraded for use as raw materials in industrial manufacturing sectors (automotive and construction).

One demonstrator (Spain) will be focused on the implementation of a zero-pollution smart mobile system for cutting and decoating dismantled onshore WTBs with the subsequent material recycling by means of green solvolysis. To do so, the green solvolysis plant (Section 4.2.3) will be upgraded to reach a 400t/year of WTB-EoL waste management capacity in order to produce 56 t of high-quality rGF (110kg/t) and rCF (30kg/t) as well as 24t of chemical building blocks (60kg/t) for industrial applications. Another demonstrator (Germany, Denmark and The Netherlands) will be focused on the thermal recycling of WTBs through pyrolysis (Section 4.2.2) in order to obtain high quality rGF and rCF in a zero-waste approach for both onshore and offshore WTBs. A large low carbon pyrolysis plant with a capacity to treat up to 5,000 t/year of WTB-EoL wastes will be developed to produce 2,500 t of rGF.

The deployment of the EoLO-HUBs innovations in the different demonstrators are aimed at generating the following major improvements compared to benchmark systems:

- 50% time reduction in WTB decommissioning processes thanks to automation processes by means of the portable cutting and decoating systems
- 40% reduction in WTB cutting time thanks to the new cutting technologies
- 10% cost reduction in WTB decommissioning and management per installed MW
- 75% reduction of the cost of rGF to make it competitive with vGF
- Over 80% reduction of GHG emissions associated to the transport of WTBs due to the lower transport operations thanks to better cutting processes
- 80% energy recovery by burning pyrolysis gases and over 85% lower GHG emisions from low-carbon pyrolysis having 15 times faster process speed compared to benchmark pyrolysis systems
- 60% reduction of process time, higher fibres mechanical properties retention (70-90%), 50% material recovery rate and 30% reduction in energy consumption from green solvolysis
- Over 90% WTB waste reduction thanks to material recycling and recirculation strategies

Importantly, EoLO-HUBs´ end-users also foreseen to incorporate the rGF in their production processes. For instance, CRF attempts to use up to 80 kt/y in the production of automobile (injection molding) parts and SGP up to 11 kt/y in the production of construction materials (gypsum plasterboards and glass wool), assuming the technical properties of the fibres are adequate and their cost is competitive, while the environmental burden of rGF is lower than vGF.

To determine the potential circularity and sustainability performance of the EoLO-HUBs recycling demonstrators compared to the benchmark there are two options : i) compare the entire EoLO-HUBs WTB recycling systems to other benchmark WTB management systems, and/or ii) compare specific EoLO-HUBs WTB recycling processes to other benchmark WTB recycling processes. The same applies for the comparison of one EoLO-HUBs demonstrator over the other.

Focusing on the first option, in practical terms, the WTB management systems already in place (alternative to landfilling) with a high TRL 8-9 (commercial scale) (Paulsen and Enevoldsen 2021) include:

- mechanical recycling (i.e. shredding and milling or grinding the WTB into smaller pieces and/or particles to be used as fillers, reinforcement or additives in composite materials or the development of other products),
- cement co-processing (i.e. using WTB wastes as an alternative energy and material source in cement kilns to substitute fossil fuels and virgin materials, such as sand and limestone), and

- repurposing (i.e. finding new structural uses for decommissioned WTBs beyond their original function).

However, they are placed at different levels of the 10R circular economy solutions hierarchy (Potting et al. 2017), where structural repurposing is at level R7, mechanical recycling is at level R8, and cement co-processing ranks between levels R8 and R9 (Lund and Madsen 2024). This means that they have a different circularity and sustainability improvement potential compared to linear WTB management systems (e.g. landfilling) (Lund and Madsen 2024).

For instance, structural repurposing can be useful for the production of furniture, playgrounds, bridges, and housing projects. However, industrial upscaling is difficult because the processing steps largely depend on the specific WTB composition, geometry and state, and also there could be a mismatch between the supply of residual WTBs and the demands of repurposed products based on WTBs (Mendoza et al. 2022). Finally, cement co-processing is considered a low-cost and easily scalable process for WTB-EoL management that can contribute to reduce the environmental footprint of the cement production. However, research indicates that it is a less attractive solution compared to structural repurposing or mechanical recycling due to the lower material circularity potential (Lund and Madsen 2024). All these alternatives will be extensively analyzed in deliverable D2.2.

Focusing on WTB recycling through pyrolysis (TRL 7) and solvolysis (TRL 5-6) (Paulsen and Enevoldsen 2021), they are at lower TRL than mechanical recycling, cement co-processing and repurposing. Thus, comparing WTB-EoL technologies that are not at the same TRL and circularity level is a complex issue, especially when the assessed future solutions that are not yet in operation (such as those related to the EoLO-HUBs project). On the one side, the data available for WTB-EoL management technologies at a lower TRL is either lacking or less mature than for those with higher TRL levels, making it problematic to compare technologies. On the other hand, technologies should be upscaled to actually compared functionally-equivalent processes, being the functionally-equivalence here the industrial-scale management of residual WTBs.

In the case of the EoLO-HUBs project, all the technology innovations and developments are under development and have not been fully implemented yet. Likewise, some technology developments are at different TRL than others. Consequently, in order to determine the potential circularity and sustainability performance of each demonstrator (preliminary partial assessment based on the current stage of the project development and data availability) and compare it with the benchmark systems, it is relevant to understand first the potential circularity and sustainability performance of each specific WTB-EoL management process (as it has been addressed in Section 4) that will later on be upscaled and linked to other upstream and/or downstream processes (evaluation to be fully addressed in D2.5, M45).

However, in practice, it is the end-use applications for the recovered fibres what are going to determine if WTB recycling can be profitable for the future and contribute to sustainability (e.g. if there is no industrial market for the recyclates, there is no reason in practice to deploy WTB recycling processes). Accordingly, some important aspects for the production of automobile parts and construction materials are discussed here.

Within the EoLO-HUBs project, only the use of rGF in the automobile and construction industry is contemplated in the demonstrator cases, which in practice represents the major challenge to be addressed as GFRP is the predominant composite material used in WTBs and the quality and cost of the rGF obtained through today´s conventional processes is not yet competitive with vGF. For instance, Spini and Bettini (2024) indicate that WTB pyrolysis is a mature technology capable of recycling both GFRP and CFRP composites. However, for GFRP recycling, the major challenge is the reduction in the strength of GFs when exposed to high temperatures, hindering their successful reuse for new composites production. Also, the tensile fracture stress can be lowered by 50–80%, depending on the temperature and heating time. Although regeneration techniques can lead to improved mechanical performance of rGFs, these treatments require additional steps to reclaim valuable reinforcements, leading to increased costs and impacts.

Focusing on GFRP recycling through solvolysis, it can lead to recovering high-quality GFs retaining over 95 % of the fibres' original tensile strength. However, solvolysis is more expensive than pyrolysis. Thus, recycling GFRP is particularly challenging because GF are low-cost materials (€1.5-2.5/kg). On the other hand, CFRP are expensive as their price ranges from €15-60/kg, depending on the type. Likewise, vCF production is an energy-intensive (198–595 MJ/kg) and polluting process, compared to CF recovery, that can have a cost of €5/kg, which is about 15 % of the price of virgin fibre. For this reason, end-user applications explored in EoLO-HUBs are ostly focused on the industrial use of rGF.

Focusing on the manufacture of automobile parts using rGF (Section 4.3.1):

- CRF expects to introduce up to 100% rGF in Stellantis production, if the fibres have the right technical performance, cost and environmental profile.
- Today the mass of vGF used in a single passenger car can account for 5-10 kg/car (*personal communication*), having a cost between 1.3-1.5€/kg and an environmental impact of 2.91 kgCO2eq./kg (Pender and Yang 2024)
- The total annual Stellantis production passenger cars at the EU level accounts for about 13 million
- Assumming that rGF could have a conservative 15% lower cost and CO2 emissions compared to vGF, the use of rGF in the automobile industry in the EU can lead to up to €20M and 43kt CO2 of savings as average, considering only the Stellantins passenger car production volume.
- However, using rGF could be at the cost of using virgin polymers (PP and PA) instead of recycled polymers, which cound offset some of these potential savings. Always considering that the rest of the industrial processes and the performance of the products are preserved.

Focusing on the manufacture of construction materials using rGF (Section 4.3.2):

- SGP will test the substitution of vGF with rGF for the production of two products, gypsum plasterboards and glass wool.
- In the case of the production of gypsum plasterboards, all the amount of vGF used in the panels could be substituted by using rGF if it is provided in a way that can be appropriately dosed and dispersed at plant, while the fibres having a good technical performance. However, substitution might not be 1:1 and a higher amount of rGF (e.g. 1.2:1 or 1.5:1) could be required to compensate the quality losses.
- In the case of the production of glass wool, rGF could be used as a new input in production (as there is no use of vGF at the moment) in substitution of silica sand inputs.
- It is estimated that the annual production in SGP for gypsum plasterboards corresponds to 11,000 t, while the annual production for glass wool corresponds to 765 kt, where 0.5% (40 g) for gypsum plasterboards and 1% (10 g) for glass wool (assuming in both cases a 1:1 substitution) could corresponds to 440 t and 7.65 kt of rGF, respectively.

- Assumming that rGF could have a conservative 15% lower cost and CO_2 emissions compared to vGF, the use of rGF in the construction industry to produce gypsum plasterboards and glass wool in the EU can lead to up to €92,400 for gypsum plasterboards and €29.1M for glass wool (considering the price of silica sand vs 15% the price of vGF) of economic savings, whereas environmental savings could account for 192,160 kg CO_2 eq. avoided for gypsum panels (without accounting for any potential changes in energy and water requirements in industrial processes). However, as the environmental impact of silica sand is quite low (0.028 kg CO_2 eq./kg) the use of rGF in substitution of 1% of silica sand to produce glass wool, could lead to increase GHG emissions by 18.7 kt annually (without considering any potential changes in energy and water requirements in industrial processes).

It is therefore essential to mitigate the impact of rGF as much as possible, while accounting for all the potential environmental credits that can be achieved at a system level for using rGF in the industry instead of virgin materials. This requires considering the entire supply chain from WTB decommissioning to material recovery for industrial use, as analyzed in Section 4.

5.1. EoLO-HUBs system-level hotspots assessment

The development of each WTB upstream, core and downstream process, involves the use of specific equipment, technologies and facilities (including professional staff), which determine the processes resource inflows and outflows, and therefore their corresponding economic and environmental impacts.

Building upon the information and results provided in Section 4, a summary of the relationship between resource inflows and outflows and EoLO-HUBs processes, as well as the potential circularity solutions already under consideration or with interest for exploration by the project partners, is provided in Table 48. Likewise, Table 48 provides an overview of the scope of each of the demonstrators to be deployed within the EoLO-HUBs project, and their potential hotspots for consideration to optimise their circularity and sustainability performance through further innovation and/or the implementation of corrective measures as the project develops.

As shown in Table 48, both demonstrators involve the development of common WTB management processes to reduce the WTB size (through cutting) and facilitate material separation (also through cutting as well as through decoating, shredding and sorting) to optimise the subsequent WTB recycling. Likewise, whereas WTB recycling systems will be optimised, material upgrading processes are required to be performed to ensure recyclates can be used in subsequent industrial production processes.

Accordingly, the main differences between demonstrator 1 and demonstrator 2 relate to the type of WTB pre-treatment alternative implemented, the core WTB recycling system developed, and the material upgrading process applied for use of the recovered materials in the automobile and construction industries. However, these differences in the type of processes implemented at each demonstrator is what will actually determine what the most resource efficient, economically profitable, environmentally sustainable and socially responsible strategy (or route) can be for the effective management of the EoL of WTBs.

The following subsections discuss the most relevant aspects related to the relationship between resource flows and WTB life cycle management processes.

Table 48. Major (potential) EoLO-HUBs hotspots based on the relationship between resource flows and the WTB life cycle management processes. Note (*): emissions refer to direct emissions (e.g. by fuel combustion) and not indirect emissions (e.g. by electricity production and consumption); (X): it depends on the dust collection method used (wet vs dry).

Resource flows	Type of resource flows	WTB decommissioning and pre-treatment										WTB recycling		Material upgrading			End-use applications		
		Decom.	Insp.	Cutting			Decoating			Shredding and sorting		Pyr	Solv	Nonw	Comp	r-LFT	Car parts	Construction materials	
				Diamond wire	Waterjet	Laser	Mech	Chem	Ther	Shred	Sort							Gyp.	Glass wool
Energy	Diesel	X		X															
	Electricity		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
	Natural gas											X						X	
Water	Tap water/Cooling water			(X)	X	X	X						X	X			X	X	
Materials	Equipment	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	
	Air											X		X					
	Salt water (molten salts)											X							
	Helium					X													
	Brass-sapphire nozzles					X													
	Nitrile globes					X													
	Diamond wires			X															
	Roadplates			X															
	Abrasives/mineral grit				X		X												
	Chemicals							X					X						
	Additives													X	X	X	X		
	Thermoplastics													X	X	X	X		
	Gypsum																	X	
	Paper																	X	
	Glass cullets																		X
	Sand																		X
	Recovered (glass) fibres													X		X	X	X	X
Wastes	Scraps	X		X	X	X				X	X				X	X			
	Dust			X															

	Worn abrasives/grit				**X**		**X**												
	Residual chemicals							**X**											
	Filtered particles											**X**							
	Neutralized dissolution												**X**						
	Wastewater							**X**						**X**					
Byproducts	Collected dust (in dry or wet form)			**X**	**X**														
	Oils											**X**							
	Gases											**X**							
	Recovered coatings						**X**	**X**	**X**										
	Recovered resins												**X**						
	Cut WTB parts (not necessary or suitable for recycling)			**X**	**X**	**X**													
Emissions*	CO2	**X**		**X**								**X**						**X**	**X**
	Gases	**X**		**X**								**X**						**X**	**X**
	Particles	**X**		**X**	**X**		**X**			**X**		**X**						**X**	**X**
	Fumes					**X**			**X**										
	Organic volatile compounds							**X**					**X**						
	Water vapour											**X**							
Other	Land use	**X**		**X**															
Economic costs	Equipment	**X**	**X**		**X**					**X**	**X**								
	Energy	**X**		**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**	**X**
	Materials			**X**	**X**		**X**	**X**					**X**				**X**	**X**	**X**
	Workers	**X**																	
Toxicity and social risks	Machinery injuries	**X**																	
	Dust inhalation	**X**		**X**	**X**		**X**			**X**		**X**		**X**				**X**	**X**
	Radiation exposure		**(X)**																
	Eye and skin burns					**X**			**X**			**X**							
	Chemical hazzards							**X**					**X**						
	Fumes inhalation					**X**			**X**			**X**							

Circularity solutions	Sharing/pooling platforms			X										X					
	Recycled/secondary materials			X						X	X			X		X	X	X	X
	Non-toxic & benign materials				X		X	X	X				X				X	X	X
	Lean manufacturing & cleaner production			X			X	X	X	X	X	X	X	X	X	X	X	X	X
	Restorative sourcing (use former 'wastes' as input)																X	X	X
	Manufacturing closed-loop recycling and recovery				X		X	X	X				X					X	X
	Product longevity			X															
	Low consumables			X	X		X	X	X										
	Prevent excess use			X								X	X					X	X
	Improve efficiency and circularity potential	X		X						X	X	X	X				X	X	X
	Upgrade			X															
	Repair and maintenance			X															
	Reuse	X												X					
	Recycling	X					X	X	X	X	X	X	X						
	Cascading resource use (from higher-grade to lower-grade)																	X	X
	Recovery	X					X	X	X				X						
DEMONSTRATORS																			
DEMO 1 (ES)																			
DEMO 2 (DE)																			

5.1.1. Energy consumption

Energy consumption is a critical factor determining the economic cost and life cycle environmental impact of industrial processes and products as it correlates with resource depletion and GHG emissions as well as other environmental impacts (Sharif et al. 2019). In some industries, energy use can account for up to 80% of the environmental impacts (Wernet et al. 2011). Thus, understanding the relationship between energy use and environmental and economic impacts is essential for developing more circular and sustainable industrial practices.

Three major types of energy sources are required in WTB recycling, including upstream, core and downstream processes (Table 48):

- Diesel (used basically to power the heavy machinery employed in decommissioning processes),
- Electricity (used in all the WTB recycling processes), and
- Natural gas (used mostly the WTB pyrolysis process and the production of gypsum plasterboards as an EoLO-HUBs use case for the uptake of rGF in the construction industry)

Within the EoLO-HUBs project, innovations are not targeting the improvement of the WTB decommissioning process on site (e.g. the actual WTB dismantling from the WTs and transportation – if required – to processing plants), where much of the diesel use for the management of EoL-WTB takes place due to the use of cranes, liftrucks, etc. This stage will be common for benchmark and EoLO-HUBs systems. However, diesel could also be used in diesel generators to produce electricity (on site) for the use of the diamond wire cutter but it represents an optional resource consumption, which in any case its use should be minimised and/or optimised as much as possible to mitigate GHG emissions. Regarding to diesel used in transportation activities (from site, e.g. cut WTB sections, to processing plants, e.g. further cutting or decoating or shredding), the improved EoLO-HUBs cutting processes are expected to optimise transportation operations and therefore reduce the transport diesel use and environmental impacts.

Focusing on natural gas, it is mostly used in WTB pyrolysis process and the production of gypsum plasterboards, which in the case of EoLO-HUBs it will involve using rGF in substitution of vGF. However, in WTB pyrolysis, natural gas it is only required for re-heating purposes when the pyrolysis oven has been stopped for maintenance and it should be re-started or to ensure post-combustion of waste gases (if no pyrolysis gas is available). Therefore, it is not a continuous energy requirement.

Consequently, the environmental impact of the energy consumed to perform the EoLO-HUBs WTB recycling processes will be mostly determined by the amount and type of electricity mix used to undertake the different industrial activities.

The environmental impacts of electricity production and consumption are primarily driven by the reliance on fossil fuels (e.g. coal, gasoil, and natural gas) as energy sources. The use of fossil fuels for electricity generation not only leads to local air pollution but also exacerbates global issues such as climate change, acidification, and resource depletion (Li et al. 2022). On the other side, renewable energy sources (e.g. hydropower, wind, and geothermal) have a reduced environmental impact contribution compared to conventional sources, although some renewable energy sources are more favourable than others (Atilgan and Azapagic 2016). Thus, improving the processes energy efficiency and ensuring green electricity sources are used for WTB-EoL management is key to mitigate the environmental impacts related to energy use.

5.1.2. Water consumption

Water is required to support WTB cutting processes (either for cooling purposes – laser, dust collection – diamond wire, or to perform the actual cutting - waterjet), mechanical decoating (sandblasting), solvolysis (as a solvent), nonwoven production (for fibre suspension and distribution, bonding and entanglement and removal of impurities), the production of injection molding car parts (control mold temperature) and the production of gypsum plasterboards (for material kneading) (Table 48).

Industrial water consumption has significant environmental impacts, primarily through the depletion of freshwater resources (leading to water scarcity issues) and the generation of wastewater (leading to the contamination of natural water bodies and the subsequent effects on human health and ecosystems) (Zacchaeus et al. 2020). Thus, even though the contribution to the life cycle environmental impact of products and processes by water use is usually lower than the contribution related to energy use, effective water management techniques (e.g. reuse and recycling) are crucial to reduce for freshwater as well as reducing water pollution, thereby mitigating the corresponding environmental impacts. This is relevant especially in water-scarce regions.

5.1.3. Material consumption

Different materials are required to develop the WTB upstream, core and downstream recycling processes (Table 48). However, only a few materials could be relevant both from an economic and environmental standpoint within the EoLO-HUBs project: helium, brass-sapphire nozzles, diamond wires, abrasives/mineral grit, chemicals, and additives.

Focusing on WTB laser-based cutting processes, on the one hand, laser-cutting technologies are energy-intensive, contributing to energy-related impacts (Yilbas et al. 2017). On the other hand, it requires the use of helium due to its high thermal conductivity and ability to generate high shear stress, which results in narrow heat-affected zones and low dross formation. This is particularly beneficial to achieve clean and precise cuts with minimal thermal damage to the material being processed (Wang et al. 2019). Additionally, the high heat convection capabilities of helium contribute to efficient heat dissipation, further enhancing the cutting process's effectiveness and stability. Finally, the inert nature of helium prevents unwanted chemical reactions during the cutting process, further enhancing the cuts quality and consistency (Liu et al. 2020). However, helium is scarce and its extraction and purification is energy-intensive and costly; aspects that require careful consideration to determine the appropriate balance between the performance benefits and the cost and potential environmental impacts of laser cutting (Velmurugan et al. 2021).

Focusing on the brass-sapphire nozzles, also used in laser cutting, they could add an additional environmental impact as brass, a metallic alloy of copper and zinc, requires significant energy for extraction and refinement, contributing to resource depletion and environmental impacts (Sari et al. 2023). Sapphire, a form of aluminum oxide, while durable and effective to support cutting processes, is also energy-intensive to produce and requires the use of chemicals that can be harmful (Xie et al. 2020, Carpena-Nuñez e al. 2017). Also, the EoL phase for the nozzles presents challenges, as the combination of different materials complicates recycling processes. For instance, recycling sapphire is challenging due to its hardness and the potential contamination from other materials. Therefore, optimizing the design and durability of these products is relevant to reduce their environmental impact.

With regard to diamond wire cutting, on the one hand, it is an energy-intensive process. On the other hand, the use of diamond wires (e.g. around 100m are used in the ADV cutter) is expensive, considering that the cost is around €65-100/m and their lifetime is short (they can support the cutting of 10-20 WTBs, therefore, it can be assumed that around 5-10m (€325-€1000) are required to cut a single WTB (4-5 cuts)) (Pers. Comm. ADV). Thus, even though diamond wire cutting can improve significantly the efficiency of WTB cutting processes (Feng et al. 2019), they can contribute a relevant environmental impact that should be properly analyzed. For instance, the extraction and processing of diamonds for the manufacture of the diamond wires involve substantial environmental degradation, including habitat destruction and carbon emissions (Kumar and Melkote 2018).

Focusing on abrasives and mineral grits, their use in waterjet cutting and blasting processes can have relevant environmental impacts for consideration, depending on the type of abrasives used (e.g. environmental burdens related to abrasives manufacturing) and the ways they are handled at the EoL. For instance, waterjet cutting technologies often employ mineral abrasives (such as garnet) that can generate substantial waste with the corresponding environmental impacts (Jerman et al. 2021). However, the reuse of abrasives can improve the quality of the processed surfaces, while reducing the need for virgin materials, thereby offering both economic and environmental advantages (Schnakovszky et al. 2014). On the other hand, grit blasting with alumina particles (or other mineral grits), while effective, could be less environmentally friendly compared to abrasiveless waterjet peening, which eliminates the need for abrasive particles altogether, although it may result in higher mass loss and lower compressive residual stresses (Lieblich et al. 2026).

Regarding chemicals and additives, they are used in chemical decoating, solvolysis, nonwoven production, composite sheets production and the production of reinforced thermoplastics and car parts. It is well known that chemicals and additives can determine a large share of the economic cost and environmental burden of processes and products (Hahladakis et al. 2018). For instance, the WTB exposure to various chemical solvents can lead to the degradation of the coatings but this can result in the leaching of harmful substances to water and the environment (Kord et al. 2017). Regarding solvolysis, organic solvents, such as acetone, while can effectively degrade fibre-reinforced composites, they pose sustainability challenges due to their high costs and potential environmental toxicity. Although, the recycling of these solvents through consecutive recycling batchescan significantly reduce the environmental impacts and lead to the production of valuable bulk chemicals (Sokoli et al. 2017). With regard to additives (e.g. sizing and compatibilizer agents used in the production of reinforced thermoplastics to improve the adhesion between fibres and the polymer matrix and enhance the compatibility between hydrophobic polymer matrices and hydrophilic fibres) can be also pollutant and should be considered carefully in the assessment of the corresponding environmental impacts (Hahladakis et al. 2018).

Finally, salt water (molten salts) is also used in pyrolysis systems to enhance the efficiency and quality of the pyrolysis products (e.g. better carbonization, prevention of metal atom aggregation, efficient degradation of epoxy components, reduction of pyrolysis temperature and enhancing the stability of biochar as well as improving the chemical composition of pyrolysis products) (Li et al. 2021, Su et al. 2019, Wo et al. 2018, Lee yet al. 2017, Das and Sarmah 2015). The production and disposal of molten salts can pose environmental challenges, including the potential release of harmful by-products and the need for high temperatures, which require significant energy input. Overall, while molten salts can enhance the efficiency and quality of pyrolysis processes, their life cycle environmental impact must be carefully managed to mitigate potential negative effects (Tang et al. 2018, Yang et al. 2020). Thus, while molten salts can enhance the efficiency and quality of pyrolysis processes, their life cycle environmental impact must be carefully monitored to mitigate potential negative effects.

Regarding the materials embodied in the equipment, technologies, facilities and infrastructure used in the different processes, they are not considered to have a large environmental impact contribution per functional unit (e.g. EoL management of a WTB) based on their long lifespan. In any case, some technologies might contribute to relevant environmental impacts, such as the implementation of carbon capture units in the WTB low-carbon pyrolysis recycling processes; while they are effective in reducing CO_2 emissions, environmental trade-offs require careful consideration to ensure a net positive environmental outcome (García-García et al. 2020). This will be carefully evaluated during the project.

5.1.4. Wastes, emissions generation, byproducts and other aspects

The type of wastes that can be generated during the WTB-EoL management processes correspond to material scraps, dust, worn abrasives, residual chemicals, filtered particles, neutralized dissolutions and wastewater (Table 48). From an environmental perspective, the most critical wastes for prevention/minimization, reuse/recycling and/or proper handling are the residual chemicals, worn abrasives, and wastewater due to their potential impact to the environment and the human health.

Focusing on the most relevant direct emissions (Table 48), they correspond to CO_2 and gases (due to direct combustions in diesel-based machines, the pyrolysis and gypsum production processes), particles and dust (from WTB cutting and material treatment in industrial processes), fumes (mostly from laser cutting and thermal decoating), and organic volatile compounds (mostly from solvolysis but also from chemical decoating). The impact of all these emissions will be carefully analyzed as data becomes available (as the EoLO-HUBs project develops) considering their potential harm to the environment and the human health.

Other aspects for consideration will include the impacts on land and the contribution to land use change between EoLO-HUBs innovations and the benchmark, as they can change significantly. For instance, while a share of the soil (e.g. 10 cm high) should be removed for the deployment of conventional WTB cutting machinery and logistics, this can be avoided with the use of more efficient cutting technologies, such as diamond wire cutters that can be located and secured by using roadplates on the terrain.

Finally, byproducts can be generated in different WTB recycling processes, such as decoating, pyrolysis and solvolyis, should be refined and upgraded for use in the industry. So, the refinement requirements as well as the potential use in industry applications will be carefully analyzed to determine the environmental credits to be allocated to the EoLO-HUBs innovations by applying a system expansion or substitution approach (Heijungs et al. 2021).

5.1.5. Economic costs

As indicated in Table 48 and discussed in the previous sections, the most relevant costs related to the upstream, core and downstream WTB recycling processes will be determined by the type and amount of energy and materials required. Also, technology investments and staff requirements will play a key role.

For instance, the long-term operational costs, such as the frequency of replacing consumable and spare parts, such as diamond wires, can significantly impact the overall cost-effectiveness of the chosen technology. Also, costs are influenced by other factors, such as the technologies´ efficiency, the material geometry and composition to be handle and the operators skills Lund et al. 2023).

It is also important to highlight that WT teardown costs are the largest contributor to the EoL costs of WT, and therefore WTB, decommissioning due to the need to use large cranes and heavy machinery. Therefore, it is essential that WTB-EoL management processes, including cutting and recycling, are optimised as much as possible to compensate for the WTB dismantling costs that can range from €17-36/kW (Cooperman et al. 2021).

All these will be carefully evaluated when data becomes available as the project develops.

5.1.6. Toxicity and social risks

There are various processes that can cause harm to human health in the form of machinery injuries, dust and fumes inhalation, radiation exposure (only if X-rays are used in WTB inspection), skin burns, chemical hazards (Table 48). All these social risks will be mitigated by applying the corresponding safety and security measures during the project. In any case, these will be integrated in the life cycle sustainability assessment of the project innovations as the project develops and data becomes available.

5.1.7. Circularity potential

As shown in Table 48, the EoLO-HUBs project partners selected a number of circularity solutions that are being currently implemented or with a potential and/or interest for exploration and/or implementation during or beyond the project.

Following, the most relevant circular economy solutions (16 out of 35) (Blomsma et al. 2019) (see Section 3), ranked according to the number of times there were selected by the project partners, are presented:

1. Lean manufacturing & cleaner production (14), understood as the implementation of techniques to use less energy and materials, treat wastes, etc
2. Improve efficiency and circularity potential (9), understood as consuming fewer natural resources or energy, aimind for 'gentani' (the absolute minimum input required to run a process)
3. Non-toxic and benign materials (8), to facilitate re-absorption in natural cycles
4. Recycling (8), understood as the extension of materials lifespan by processing them in order to obtain the same or comparable quality
5. Closed-loop recycling and recovery (manufacturing waste) (7), understood as the internal recirculation of manufacturing waste to substitute virgin materials
6. Recycled/secondary materials (6), understood as to extend material lifespan by processing them in order to obtain the same or comparable quality
7. Low consumables (5), of energy, water and materials during product use and operation
8. Prevent excess use (5), understood as improving process efficiency in logistics operations, aim for 'gentani' (minimum input into a process
9. Recovery (4), of materials and energy
10. Restorative sourcing (use former 'wastes' as input) (3), understood as the use of former 'wastes' from other industries as input

11. Sharing/pooling platforms (2), understood as satisfying user needs without transferring ownership of physical products.
12. Reuse (2), understood as to extend the products lifespan to new use cycle by reusing a part/product (discarded/not in use) that is still in good condition and can fulfil its original function in a different use context (new customer/user)
13. Cascading resource use (from higher-grade to lower-grade) (2), understood as a subsequent use that significantly transforms the chemical or physical nature of the material
14. Product longevity (1), understood as enabling product longevity through high product integrity and robustness.
15. Upgrade (1), understood as extending existing use cycle by adding value or enhancing the function of a product in respect to previous versions
16. Repair and maintenance (1), understood as extending existing use cycle by countering wear and tear, and correcting faulty components of a defective product/part to return it to its original functionality.

Each partner selected the corresponding circularity solutions based on the nature, context and potential hotspots and opportunities of their industrial activities. The effect of implementing some and/or a combination of these strategies within the EoLO-HUBs project will be evaluated to determine the potential circularity and sustainability improvements that can be achieved by addressing the EoLO-HUBs hotspots through further innovation.

5.2. Key variables and aspects affecting the circularity and sustainability performance of the WTB recycling processes

Apart from the processes and technology aspects discussed in the previous section, the circularity and sustainability performance of the EoLO-HUBs, as well as the general, WTB recycling systems can be constrained by several key issues that will be carefully considered as the EoLO-HUBs project develops (within WP2 and WP3):

- Design and material composition challenges (Carnicero et al. 2023, Joustra et al. 2021 Delaney et al. 2021, Lund and Madsen 2024):
  - WTB designs (e.g. type and amount of materials used) significantly influence their future recyclability. The diversity in of WTB models, entail the development of tailored WTB decommissioning and EoL management plans, adding complexity to the standardization of EoL recycling process and the identification of the most promising circular and sustainable strategies.
  - Thus, design for circularity (e.g. by using new materials and new resins) is crucial to facilitate WTB-EoL management processes. This includes material innovation as well as facilitating understanding on the material composition and structure of WTBs for the design of efficient EoL management value chains.
- Technical challenges in composite recycling (Woo and Whale 2022, Rahimizadeh et al. 2019, Psomopoulos et al. 2019, Korniejenko et al. 2021), Fayyaz et al. 2023, Jensen and Skelton 2018):
  - Current WTB recycling technologies are limited and some of them have a low TRL, making it difficult to effectively recycle large volumes of upcoming residual WTBs
  - The environmental benefits of WTB recycling processes can be offset by the high energy requirements and GHG emissions, if the processes are not optimized

- The high-end material quality requirements by the industry for the uptake of rGF and rCF in products manufacturing processes is not fully fulfilled by existing recycling processes, as the technical performance (e.g. lower lenght and/or strenght) of WTB recyclates are usually lower than virgin materials, constraining their industrial uptake.
    - The dynamic nature of WT technologies, including WTBs, means that EoL management practices should continuously adapt to accommodate new future developments, which can be resource-intensive and challenging
    - Achieving a homogeneous WTB waste mass is difficult, requiring many processing steps, which increases costs, energy use, and time requirements, affecting the profitability of the WTB recycling business case
- Logistical and operational challenges (Woo and Whale 2022 Delaney et al. 2021):
    - The size and weight of WTBs pose significant logistical challenges for sectioning, cutting and transportation to recycling facilities, which entail the use of heavy machinery, increasing the overall cost and environmental footprint
    - The geographical and time variability in the quantity of potential WTB waste generation over time generates high uncertainty for the deployment of efficient WTB recycling systems
    - Also, the dynamic and complex nature of WTB-EoL management processes require the consideration of multiple, often conflicting factors, such as such as optimizing the management of current waste streams while having flexibility to accommodate new technology developments
- Economic and market barriers (Carnicero et al. 2023, Woo and Whale 2022, Upadhyayula et al. 2022, Rentizelas et al. 2021, Psomopoulos et al. 2019):
    - There are few proven business cases available demonstrating the profitability of WTB-EoL managements strategies, where material quality issues, logistical challenges, and market constraints for recycled products represent key aspects for consideration.
    - Also, there is a lack of established markets for WTB recyclates, which reduces the economic incentive for recycling and limits the development of a circular marketplace for WTB recyclates.
    - The economic viability of WTB recycling is yet uncertain, as mechanical (but specially) thermal (e.g. pyrolysis) and chemical (e.g. solvolysis) processes are often energy-intensive and costly with low financial returns, which discourages new investment in recycling technologies and infrastructures.
- Regulatory and policy Issues (Korniejenko et al. 2021, Chen et al. 2021, Whoo and Whale 2022, Stecher and Salgado 2023):
    - Existing policies and regulations are not necessarily promoting WTB recycling systems due to the way residual WTBs are targeted
    - The lack of standardized regulations across different regions complicates the implementation of effective WTB recycling practices
    - Also, the lack Extended Producer Responsibility (EPR) (OECD 2024) policies for WTs, and therefore WTBs, hinders the development of effective EoL management strategies
    - There is a need for technology-specific regulations and incentives to support more sustainable WTB-EoL management processes. Also, clear guidelines and policies can drive innovation and provide the necessary support for scaling up recycling operations.
    - Designing for circularity, stakeholder collaboration, and the development of circular business models and technology-specific regulations are essential to improve the sustainability of WTB-EoL management systems

- Data availability to perform circularity and LCA studies (Sproul et al. 2023, Liu et al. 2019, Lund et al. 2023, Lund and Madsen, 2024):
    - Current limited data availability on WTB design and life cycle management processes, can constraint circular innovation and sustainability-oriented decision-making processes as it affects the development of comprehensive and comparable assessments.
    - The TRL and market penetration of some WTB recycling technologies vary significantly, affecting the robustness of life cycle environmental impact assessments.
    - The environmental sustainability benefits of WTB recycling systems are highly dependent on the specific materials used in the manufacture of the WTBs and the efficiency of the recycling technologies.
    - The financial performance of different WTB recycling options, is also critical to evaluate circularity and economic sustainability but it is often uncertain and variable.
    - The degradation of recyclate, particularly the reduction in tensile strength of recycled fibres, affects the value and usability of the recycled material by the industry, complicating the calculation of circularity and sustainability indicators.
    - Assessment models should be based on data from published literature and discussions with industry experts to ensure accuracy and relevance to current practices
- Sustainability assessments (Fayyaz et al. 2023, Sproul et al. 2023, Lund et al. 2023):
    - Obtaining reliable and comprehensive data for all relevant criteria, such as environmental impact, economic costs, and social implications, is challenging, as some aspects often rely on expert judgment rather than empirical data
    - Environmental, economic and social impacts cannot be directly compared to evaluate WTB-EoL scenarios without relying on multi-criteria decision-making (MCDA) methods (Sahoo and Goswami 2023), calling for active stakeholder engagement to provide feedback and weighting factors
    - The lack of standardized integrated circularity and sustainability assessment methodologies, and specially focused on this sector, adds further uncertainty to the comparison of alternative WTB-EoL management processes

Consequently, while addressing all these limitations through collaboration between industry professionals, economic actors, policymakers, and researchers, it is crucial to define alternative scenarios incorporating these considerations to analyze how the resource efficiency and sustainability performance of WTB recycling systems can be optimized. In this process, it is crucial to pay particular attention to understanding and use operational frameworks to quantify quality of recycling. Improving quality of recycling is essential to increasing the amount of recycled materials that can be used in new products (Roosen et al. 2023).

According to Grant et al. (2020), quality of recycling can be defined as the extent to which, through the recycling chain, the distinct characteristics of the material are preserved or recovered so as to maximize their potential to be reused in the circular economy. As discussed by Roosen et al. (2023), in this process, it is crucial the preservation of the functionality of materials (i.e., the quantity of material that is "actually" useful to displace virgin production) as it allows achieving a maximum of substitutions across the multiple markets where the material can possibly be applied at a certain point in time. The environmental dimension of quality of recycling is also relevant as recycling processes producing high-quality recyclates may have a higher environmental burden than processes with lower-quality outputs, due to energy consumption or material losses. Finally, quality of recycling can also be understood as the path that ensures the longest durability of the material in the economy, to show how much of a certain material is still functional in society over a given timeframe. Generally, the higher the substitution potential and in-use occupation of materals, the lower the environmental impact of recycling pathways (Roosen et al. 2023).

Thus, a lack of clarity on what quality for recycling means represents a crucial obstacle to the conception of robust policy measures addressing recycling in the circular economy context as well as a tool to achieve the highest possible resource efficiency (Tonini et al. 2022). To do this, it is also important to consider the following material- and system-level aspects related to quality of recycling:

- Impurity content: Content of untargeted materials and/or substances in a targeted waste stream destined to recycling/reprocessing (material-specific concept).
- Technical quality: Example for plastics: the technical quality of plastics is a result of mostly mechanical properties, typically complemented with a property that describes the flow behaviour of the melt phase (material-specific concept).
- Technical characteristics (properties): Properties that give the material the ability to fulfil the required functions. For example, for plastics the properties are generally divided into mechanical and processability characteristics (material-specific concept).
- Function/Functionality: Physical and chemical properties that made the material desirable in the first place (material-specific concept).
- Functional recycling: Recycling in which the physical and chemical properties that made the material desirable in the first place are retained for subsequent use (system-wide concept).
- Resource dissipation/Dissipative flows: Dissipative flows of abiotic resources are flows to sinks or stocks that are not accessible to future users due to different constraints. These constraints prevent humans to make use of the function(s) that the resources could have in the technosphere (system-wide concept).
- Substitutability: The degree of functional equivalence between alternative resources/products for a specific end-use. Also called substitution ratio or displacement/substitution factor (material-specific concept). For example for plastics: a measure of the functionality of the recycled plastic divided by the functionality of the substituted virgin plastic.
- Circularity potential: The ability of individual recycled fractions to fulfil quality demands in a steady-state market representing a closed material loop situation (system-wide concept).
- Downcycling vs Upcycling: Recycling process whereby the recycled material is used for a lower-quality market application than that of the previous life cycle, normally defined by a lower market value, as opposite to upcycling (system-wide concept), defined for plastics as: 'the use of plastic waste, post-industrial or postconsumer, as a feedstock for the synthesis of value-added products, being polymers, molecules, or materials'
- Closed-loop vs Open-Loop Recycling: Closed loop is a recycling process whereby the recycled material is reused for the same market application as that of its previous life cycle (system-wide concept). Open loop is a recycling process whereby the recycled material is used for a different market application than that of the previous life cycle (system-wide concept).

All these aspects will be considered as the EoLO-HUBs project develops and data from testing processes becomes available.

6. CONCLUSIONS AND RECOMMENDATIONS

This report has provided the preliminary findings from the qualitative and partial/simplified quantitative analysis of the circularity and sustainability performance of the WTB recycling innovations under development within the EoLO-HUBs project. This assessment was performed at four major levels:

- EoLO-HUBs upstream recycling processes, involving decommissioning, inspectioning, cutting, decoating and material shredding and sorting (Section 4.1)
- EoLO-HUBs core recycling processes, including pyrolysis and solvolysis (Section 4.2)
- EoLO-HUBs downstream recycling processes, involving the upgrading of the recyclates for use as raw materials in industrial manufacturing sectors (automotive and construction) (Section 4.3), and
- The EoLO-HUBs system-level integrated hotspots assessment and recommendations for improvement (Section 5), including a discussion of key variables and aspects affecting the circularity and sustainability performance of WTB recycling systems, to complete the assessments performed at the process-level.

In all cases, the potential sustainability performance of the EoLO-HUBs process and technology innovations was compared to benchmark systems. However, as all the EoLO-HUBs solutions are currently under development, the information and data shared is preliminary and does not demonstrate yet the improved performance as some of the processes are not yet optimized as they are at the laboratory scale (e.g. WTB inspectioning, cutting, decoating and solvolysis). Likewise, there is no data yet available on the industrial tests related to the use of rGF and/or rCF in the manufacture of automobile and construction products. Therefore, a comprehensive and final assessment of the circularity and sustainability performance of each of the EoLO-HUBs innovations and the different demonstrator cases, will be provided in deliverable D2.5 to be submitted in month 45 (September 2026) of the project development.

To address the limitation on the lack of information and data readily available, a practical action research methodology, involving exploratory, qualitative and quantitative analytical steps, has been applied to determine the potential resource, environmental and socio-economic hotspots and improvements of EoLO-HUBs innovations compared to the benchmark as well as the definition of some guidelines and recommendations for consideration as the project develops. Accordingly, the action research methodology involved i) the definition and characterization of WTB recycling systems (through an systematic literature review coupled with two cycles of stakeholder engagement) (Section 3.1), ii) a qualitative circularity and sustainability assessment (to identify the processes´ most relevant hotspots and potential areas for intervention) (Section 3.2) and iii) a simplified quantitative circularity and life cycle environmental assessment (through the preliminary calculation of LCA impact indicators to optimize resource efficiency and mitigate negative impacts) (Section 3.3).

The study allowed to identify some relevant potential hotspots and areas for intervention to optimize the EoLO-HUBs processes and system performance. However, the results are not conclusive as they are based on the use of preliminary (and mostly at a laboratory level) data. In any case, unsurprisingly, optimizing energy efficiency (in all processes), while minimizing the use of some environmentally sensitive materials, such as chemicals and additives (e.g. WTB decoating and solvolysis), abrasives (WTB decoating and waterjet cutting) and helium as well as optimizing the use of diamond wire (for cutting purposes) is considered critical to reduce the environmental burden and the cost of recovered carbon and glass fibres. Likewise, some relevant emissions for consideration and mitigation are the emission of CO2 emissions (by all processes) and particularly (considering safety and health issues) the emission of dustand particles (e.g. in WTB cutting and shredding processes), fumes (e.g. in laser cutting and thermal decoating) and organic volatile compounds (e.g. in chemical decoating and solvolysis). Focusing on technical and economic aspects, even if the recovered glass and carbon fibers could have a lower environmental footprint than virgin fibres, they end-use ultimately depends on meeting the technical specificities of industrial end-users (e.g. automobile and construction industries), in terms of physico-chemical properties, mechanical performance, safety and costs.

Consequently, evaluating the technical, economic, environmental and social opportunities and trade-offs of different recycling approaches at an early stage of development is critical to ensure that the solutions are optimized to increase the market uptake and the overall circularity and sustainability performance of the sector. This requires the development of detailed process and system models to track resource flows (including physical and monetary flows) for each recycling approach by relying on expert real business cases, expert consultations and academic and industrial literature.
In this regard, the most relevant concerns highlighted by the technical EoLO-HUBs partners (NOR, TNO, JRG, MTC, ADV, AIT, FHG, MCAM, MOSES, TNO, NCC, CRF, and SGP) for the development of optimized cradle-to-cradle WTB recycling systems (discussed in Section 4 and Section 5) include:

- Improve the cost efficiency of the entire WTB-EoL management processes, as it is not profitable at present.
- The storage of residual WTBs consume a large space on yards, which can represent a logistical challenge
- WTB cutting and shredding are unhandy, time consuming, noisy and expensive activities, contributing to dust generation and environmental impacts. Thus, they must be improved by making them quicker and more efficient
- Different WTB cutting systems will have specific requirements with regard to planning and plotting the cutting paths and the manner of extracting the recyclable materials. This will determine the speed and accuracy requirements of the prior inspection processes, which can lead to simplification and/or increase in its complexity. Likewise, the point at which inspection could take place during WTB-EoL management could have a substantial impact on the infrastructure and resource requirements.
- For WTB cutting, decoating and recycling it is essential to identify in advance (e.g. through prior inspectioning and/or having access to robust material passports with desaggregated data on material types, thicknesses and amounts) is crucial to optimize the processes and achieve purer high-valuable material outcomes.
- In some cases and for some processes (e.g. WTB cutting) profitability will be site-specific.
- Robust low-cost and low-impact WTB recycling processes, able to accept scrap from multiple industries (beyond the wind sector) is crucial since the volumes in the wind industry might be low and too uncertain to justify future investments.
- An issue with recycling WTB waste lies in their heterogeneity, as each manufacturer utilizes an unique and specific composition. Therefore, it is crucial to identify, assess and quantify this anticipated WTB waste stream (considering its quality, material composition, and internal structure) to ensure appropriate management.
- Likewise, the technical properties, price and environmental performance of recycled glass and carbon fibres must be competitive with virgin fibres and their use should be adapted to the process requirements of the end-user industry.
- Even if the technical qualities, cost and environmental performance of the recovered fibres is acceptable, end-users must have a certain and stable and constant supply of large volumes of good quality recycled compounds. In this context, recycling processes could be developed in response to demand, aligning the solution with the actual needs of the market.

All these aspects along with those discussed in Section 5.2 (on WTB design, logistics, market acceptance, policy requirements, data availability and assessment models) will be carefully considered in the definition and assessment of alternative scenarios and alternatives to be performed under WP2 and WP3 within the EoLO-HUBs project.

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