Technical, economic and environmental effects and public perception of wind turbine blade life cycle management
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NCC	NCC OPERATIONS LIMITED	UK
MGE	MONDRAGON GOI ESKOLA POLITEKNIKOA JOSE MARIA ARIZMENDIARRIETA S COOP	ES
TNO	NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	NL
ULO	UNIVERSITY OF LEEDS	UK
NOR	NORDEX ENERGY GMBH	DE
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Executive summary

To achieve a climate-neutral Europe by 2050, energy must be generated from renewable energy sources with installations and operations that fit within a circular economy. This requires a transition in wind energy from linear to circular material use, with a special focus on eliminating (production) waste and reusing and recycling of wind turbine blades. The aim of this study, as part of the Horizon Europe project EoLO-HUBs, is to identify the challenges in circular End-of-Life (EoL) solutions for wind turbine blades. First, an inventory is made of all possible EoL routings and solutions with a prediction of future blade designs, materials and volumes. Next, the impact on costs and environment is analyzed for two Dutch offshore wind farm EoL scenarios. Finally, the Dutch public's perception is studied in detail to provide insights for socially aware decision-making in the blade EoL process.

Estimation of discarded blade volumes and materials. There is uncertainty about when and how much discarded blade material will become available for recycling. The reasons are that decisions about possible reuse of the blades or lifetime extension of a wind farm are made at a late stage. For future wind farms, also the mass and number of blades that will be installed are uncertain. Estimates can be made based on development trends. It is expected that the decommissioning of the offshore wind turbines will result in less uncertainty, because these decommissioned turbines will most likely not be reused and because the operational lifetime of an offshore wind farm is more defined than onshore wind farms. The design of the blade and the materials used are important in determining the optimal EoL route.

Blade EoL processing scenarios. To determine the effects of EoL solutions on costs, environment and public perception, the EoL flow diagram has been developed based on the cradle-to-cradle life cycle of present and future wind turbine blades. Developments in the size and design of turbines and blades are happening very quickly, which has a major impact on current and future EoL routes. For the current situation, the pre-processing of blades offshore is unlikely to happen due to the high costs and limitations on material emissions released during sawing or cutting. In the future, modular blades and/or solutions where the blade can be segmented at the site may result in lower costs and emissions when using smaller cranes and more efficient transport of blade material. For the cradle-to-cradle route, material from the blade is reclaimed and used in a new blade. Due to the high performance requirements of the composite material used in blades, the new glass fiber production and upgrading of carbon fibers used in current blade designs will be the preferred routes for achieving a fully circular process. Reversible resins or recycled chemical building blocks reclaimed from used resins can be reused, providing an example pathway for a new generation of circularly designed blades.

Scenario assessment. The Netherlands is focusing on developing wind power as much as possible offshore. Therefore, two Dutch offshore wind farm scenarios are studied, the old Princess Amalia Windpark (PAWP) and the upcoming IJmuiden (IJM) Ver farm, with the decommissioning port in Rotterdam and a recycling facility located in Moerdijk (NL) where all blades of the two farms are assumed to be sent. Shredding is required before the pyrolysis recycling process, and it is found to have the largest contribution to the total costs of pre-processing and transport from the port to the recycling facility. The transport of pre-processed blade material by water is preferable. When complete blades must be transported it will be considerably cheaper to transport with an inland vessel compared to the road where you need special transport. The most economical solution with the lowest emission footprint is found to be the transport of shredded material by inland vessel. The comparison between the PAWP (180 x 6.5 ton blades) scenario with the IJM Ver wind farm (400 x 65 ton blades) provides a

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clear idea of the scale difference, with the latter resulting in a total blade volume transport of 1700 standard 40ft containers compared to 76 of PAWP. With the larger blades, the crane lifting work will count less to the overall costs and the mass processed by the shredder will drive the total costs. Transport of complete blades with an inland vessel for the PAWP case is €180/ton and for IJM Ver €140/ton. For the transport of shredded blade material, the difference between transport by road or over water is less. For PAWP, the costs are €120/ton using a truck and €110/ton with an inland vessel. For the IJM Ver scenario, these costs are €116/ton and €107/ton respectively. The emission costs are about 10% of the total for the PAWP complete blade transport. In all other cases, the emission costs are less than five percent of the total costs. Note that only crane handling and transport are considered.

Public perception. Based on a survey investigating the perception of a representative Dutch target group of ~1500 respondents, it can be concluded that the general public's perception of the current EoL outlook of wind turbine and blade circularity in the Netherlands is rather positive. Concerns exist mainly about the recycling of composites and rare earth materials. There is a general preference for reusing wind turbine blades and parts of the composite material in the blades in new wind turbine blades compared to the other options offered. Owners of wind farms, manufacturers of wind turbines and the national government are seen as responsible for finding a proper solution for EoL wind turbine blades. There appears to be less preference for directly contributing to fully circular wind turbines, while there is mostly agreement on a governmental investment in circular solutions for EoL wind turbine blades via tax money.

Recommendations for future research include the optimization of the transport and pre-processing of wind turbine blades (e.g. investigating the potential benefits of cutting and shredding blades on the deck of a vessel or even cutting them while attached to the turbine); the assessment of life cycle costs and environmental impacts for future WTBs designed for circularity with circular materials and design solutions (e.g. reversible resins, modular designs, etc.); and the investigation of the public's perception in other countries such as Spain, UK, Denmark to expand and compare results from different European regions with a developed wind energy industry and gain insights on social differences and priorities.

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Glossary of terms, abbreviations, and acronyms

Abbreviation	Description
AEP	Annual Energy Production
CF	Carbon Fiber
CFRP	Carbon Fiber Reinforced Plastic
CTV	Crew Transport Vessel
EoL	End of Life
GF	Glass Fiber
GFRP	Glass Fiber Reinforced Plastic
JUV	Jack-up Vessel
LEE	Leading Edge Erosion
LEP	Leading Edge Protection system
LZV	Longer and heavier truck combination
OEM	Original Equipment Manufacturer
OWF	Offshore Wind Farm
PET	polyethylene terephthalate
PM_{10}	Particulate Matter with 10 micrometers or less in diameter
PVC	polyvinyl chloride
SOV	Service Operation Vessel
WTB	Wind Turbine Blade

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1 Introduction

To achieve a climate-neutral Europe by 2050, energy must be generated from renewable energy sources with installations and operations that fit within a circular economy. This requires a transition in wind energy from linear to circular, with the focus on limiting raw material use by eliminating (production) waste and reusing and recycling of the blades. For current wind turbine types about 85 – 90% can be recycled [1], nevertheless, the challenge to recycle the thermoset composite wind turbine blades will dominate until at least 2060.

The intended EU-wide landfill ban for composite blades in 2025 and the recent requirements from circular tenders for wind farms require circular solutions in design and End-of-Life (EoL). Incineration and cement co-processing are not suitable options for achieving the climate and environmental objectives. Processing the discarded wind turbine blades requires a supply chain with an economically (and energetically) viable recycling facility for large-scale processing of composite materials.

To make recycling of wind turbine composite materials feasible, in addition to regulations, the supply chain and investors must also be willing to make this possible. With the current situation, costs are still too high to compete with the use of new glass and carbon fibers in wind turbine blades. The bottlenecks are a lack of clarity about the expected material flows, both on the supply side of discarded blade material as well as on the supply side of recycled glass fiber material to end users for use in commercial end products. Moreover, the preliminary process for recycling the glass fibers starting from decommissioning with logistics and pre-processing of the blades until the EoL facility is still too expensive to compete with new virgin fiber material.

The aim of this study is to identify the challenges of the development and management of circular EoL solutions. First, an inventory is made of possible solutions. Next, for a selected number of scenarios the impact on costs and environment is analyzed. Finally, public perception is studied in order to support decision-making for the wind turbine blade EoL process.

The first part of the report (chapter 2) describes in the form of a flow diagram all possible EoL paths that can be followed over the entire cradle-to-cradle life cycle of a wind turbine blade from fabrication and commissioning to the end product fabricated with recycled fiber material. Information from the literature and input from the industry were used in this study. The second part (chapter 3) defines and analyzes EoL scenarios for two Dutch offshore wind farms, one near the end of its permit period, the Princess Amalia Windpark (PAWP), and one still under development, the IJmuiden (IJM) Ver. The focus of this study is on costs and emissions. Data has been obtained from literature, conversations with stakeholders from the industry and predictions based on models for transport and logistics developed by TNO. The third part (chapter 4) is the result of the study into the public perception of wind energy and wind turbine (blades) recycling. A target group's perception and knowledge are assessed via an informed survey about circularity in wind energy and recycling solutions for wind turbine blades.

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2 Inventory of waste streams, blade design and End-of-Life solutions

2.1 Wind turbine blade designs and materials

The wind turbine has developed rapidly over the past 20 years with a rated power of up to 15 MW for the current offshore turbine types (Figure 2.1). In terms of blades, the length has increased from about 25 m in 1995 to 120 m, with a mass increase from 3 tons to 50 tons, for the GE Haliade X 15 MW turbine.

Figure 2.1: Evolution of the wind turbine rotor size from 1995 until now (source DNV).

Until now, WTBs have been designed for optimal energy production performance at minimal cost. Only in recent years sustainable design solutions and recyclable materials have been applied by OEMs for commercial blade designs. It is expected that until 2060 the WTBs that will be dismantled are made of thermoset GFRP, whereas recent large blade designs have a relatively small amount of CF (max 9 wt%). An increased amount of CF is used to meet the stiffness requirements for the most modern large high-aspect-ratio turbine blades. A typical wind turbine blade design is given in Figure 2.2.

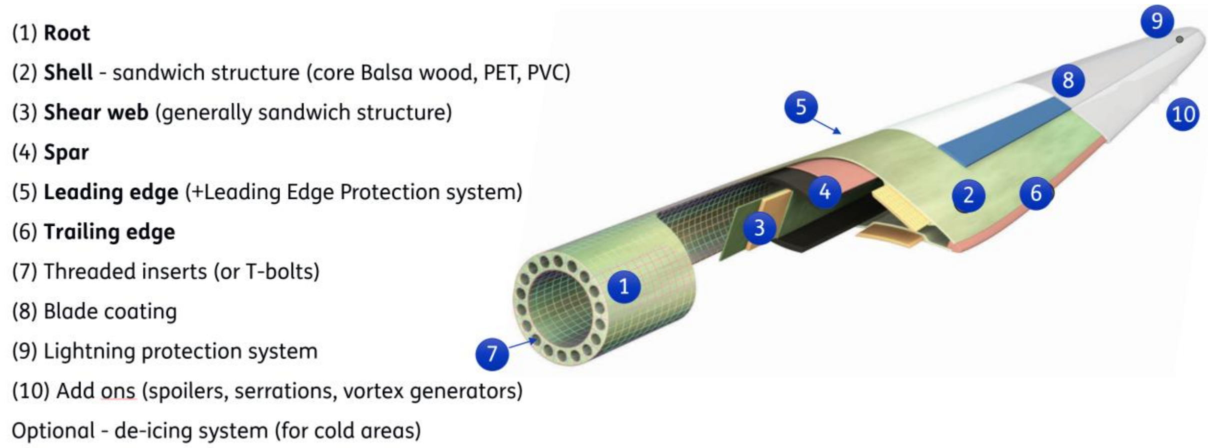

Figure 2.2: Wind turbine blade design parts and materials. Blade components (1) to (6) are made of composite material (based on image from www.gurit.com).

Five standard reference blade designs have been selected for this EoLO-HUBs project (Table 2.1) based on characteristic design and base materials used. Due to the limited accessibility of modern offshore

WTB designs and their material content, publicly available data from the NREL 5 MW [2] and 15 MW [3] reference wind turbines are used as references for modern offshore WTB designs.

Table 2.1: Selected reference WTB designs for EoLO HUBs project

ID	Description	Length [meters]	Mass [tons]	MW	Materials	Expected decommissioning
A1	**Onshore "before 2010"** "Nordex N80"	37,5	6,0	2,5	GFRP Epoxy shells GFRP Epoxy spar caps, webs Balsa core, PVC core PUR coating	up to 2030 (lifetime 20-25 yrs)
A2	**Onshore "2020"** "Nordex N175"	85,7	25	6	GFRP epoxy shells CFRP epoxy spar caps, webs PET core PUR coating	From 2030 (lifetime 30-40 yrs)
B1	**Offshore "2000-2010"** "Vestas V80"	40	6,5	2	GFRP polyester shell, webs GFRP polyester spar caps Balsa core PUR coating	From 2026 (lifetime 25 yrs)
B2	**Offshore "2010"** NREL 5 MW reference turbine [2]	62	18	5	GFRP epoxy shell CFRP epoxy spar caps, webs PET core PUR coating	From ~2040 (lifetime 30-40 yrs)
B3	**Offshore "2020"** IEA WIND 15 MW reference turbine [3]	120	65	15	GFRP epoxy shell CFRP epoxy spar caps, webs PET core PUR coating	From ~2050 (lifetime 30-40 yrs)

2.2 Expected volume of discarded wind turbine blade material

Several studies have been conducted to determine the amounts of discarded wind turbine blades for the coming period. The study into the forecast of discarded blades until 2050 in Europe [4] shows that the annual amount will increase to more than 300,000 tons in 2045 (Figure 2.3). The annual amount is expected to stabilize from 2045 onward.

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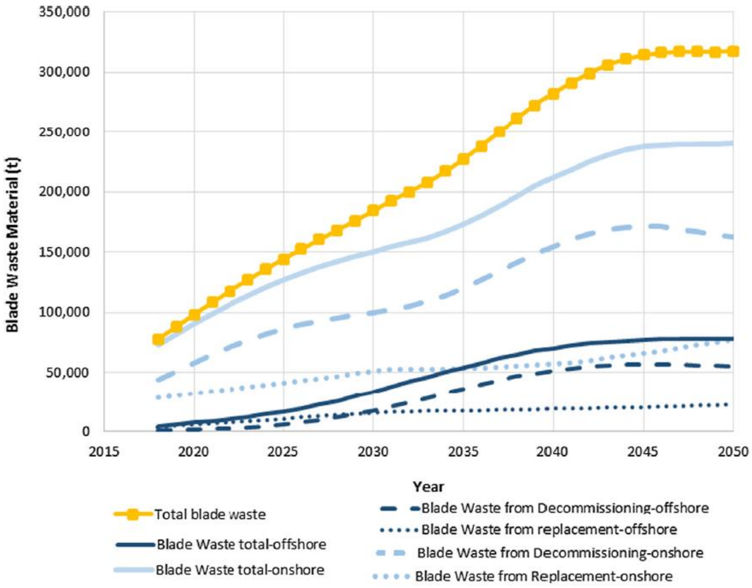

Figure 2.3: Blade waste material forecast from EoL wind turbines in Europe until 2050 [4].

2.2.1 Offshore compared to onshore

It is expected that there will be less uncertainty as to when an offshore wind turbine blade will be decommissioned and become available for an EoL process. Compared to onshore wind farms, the lifetime extension of blades of offshore wind turbines is expected to be less relevant for the following reasons:

- Offshore wind farm tenders set requirements for the period during which a wind farm is operational and when it must be removed;
- Current blade designs are better tailored for the desired operational time and turbine repowering is not expected to occur before the end of the permit period in an offshore farm due to high logistic costs;
- There is an increase in the operational lifespan, 20 years for a wind farm in 2006 (PAWF, NL) and 30-40 years for planned parks in 2028 (IJmuiden Ver NL);
- Offshore conditions are generally harsher than onshore locations, meaning blade quality is likely to deteriorate more quickly due to degradation such as leading edge erosion (LEE) damage, lightning strikes and surface degradation from UV radiation.

2.2.2 Expectation of discarded blades in the Netherlands and Denmark

For the Netherlands, an estimate of the expected number and mass of discarded blades from the Dutch North Sea wind farms is given in Figure 2.4. This estimate is based on the available data for the operational lifetime of the installed and future planned offshore wind farms until 2030 [5]. The expected size of the blades, mass and operational lifetime time are included in this assessment (the underlying calculation model is available on demand).

The large spread of the expected blades at the end of their life of the Dutch offshore wind farms is a result of:

- Increase in the expected operational lifespan (20 years in 2007 and 30-40 years from 2025);

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- Non-linear growth of length and mass of the blades (40-45 m length in 2007, 120+ m from 2025);
- Increasing the OWF capacity and the number of turbines (2007 OWF: 120 MW, 2025: 2 GW);
- The varying periods between the installation of the different offshore wind farms.

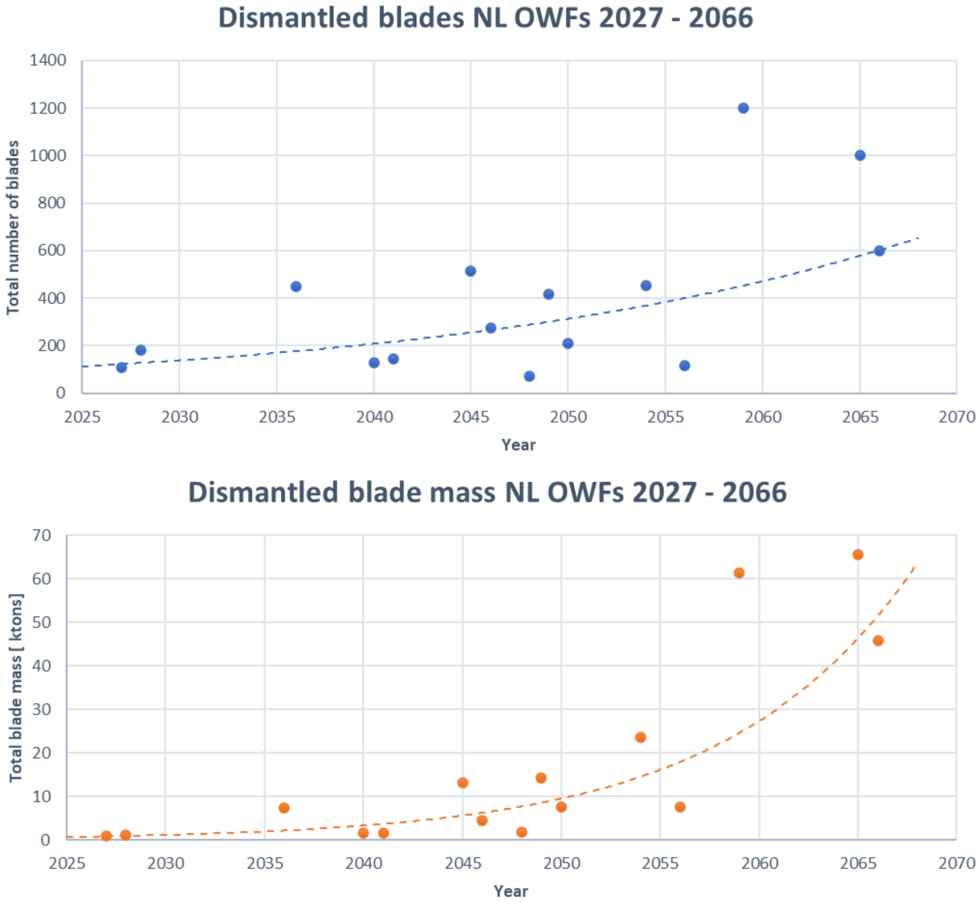

Figure 2.4: Estimate of the total mass and number of offshore wind turbine blades to be dismantled from offshore wind farms in the Netherlands in the period between 2027 and 2066.

The study into the predicted blade mass of discarded blades from the first installation of wind turbines in 1978 in Denmark also shows a scatter with the combined volumes of on- and offshore turbines (Figure 2.5) [6].

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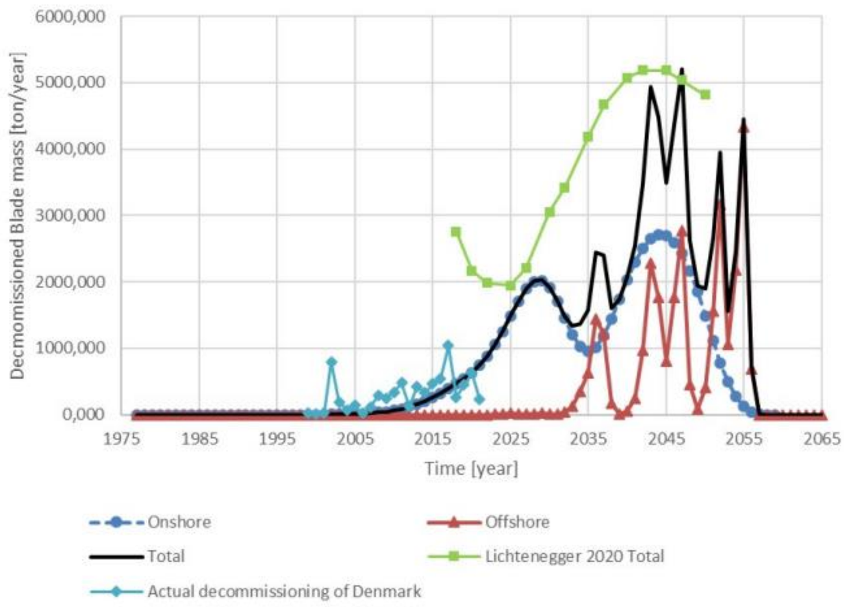

Figure 2.5: Estimate of decommissioned wind turbine blade mass of the wind turbines installed in Denmark from 1978 [6]. The green line is the predicted blade mass according to [7].

2.2.3 Reuse and lifetime extension prediction

The decision to extend the lifetime of a wind farm or reuse the blades for second-hand wind turbines or as spare parts are made during or at the end of the lifetime (Figure 2.6). Factors that influence the EoL or reuse decision are the energy price, the performance (AEP) and structural health of the wind turbines, subsidies, and policies. A recent study [8] has shown that in Denmark ~62% of blades will be reused after decommissioning, in Germany it is slightly lower ~48%. It is expected that the share of reuse of discarded blades will decrease in the coming decades. The older blade types, before ~2020, were in general more overdesigned and suitable for lifetime extension and reuse. This is more difficult with modern optimized blade designs given the current state of technology (design models, performance modeling and full-scale validation) and the increased loads with the current scale of wind turbines [9].

As mentioned before, it is expected that reuse of offshore wind turbine blades is not an option due to the more extreme conditions (wind, precipitation, salt, UV light). The present well-tuned designs are based on a longer design lifetime compared to the older generation blades. Besides that, offshore operations like installation and decommissioning are expensive. In the case of reuse, the dismantling and transport need to be handled with care, increasing the cost of decommissioning even more.

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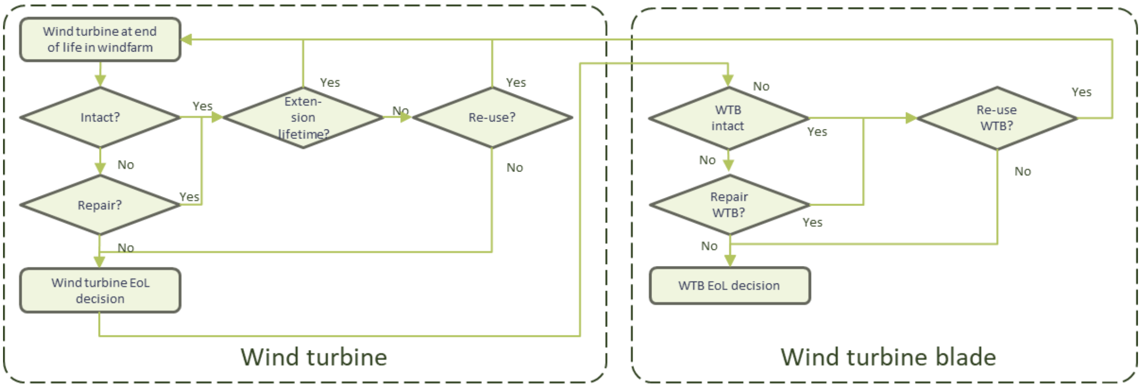

Figure 2.6: Decision-making process for a wind turbine and specifically the blade at the end of its operational life in a wind farm.

2.3 EoL flow diagram

The objective is to visualize the complex routing for EoL solution in a flow diagram for EoL scenarios of wind turbine blades onshore and offshore for use in cost, environmental impact and socio-economic analysis and data collection in the overall EoLO HUBs project.

The following process steps are identified in the EoL flow diagram as followed:

- **Processes:** pre-processing of the blades (cutting, shredding, grinding) and EoL processing (pyrolysis, solvolysis, cement co-processing, incineration, etc.);
- **Operations:** lifting, disassembling, etc.;
- **Logistics:** onshore and offshore transport with offshore or inland vessels, trucks, etc.;
- **End product applications:** recycled products for automotive, sports, etc., repurposed blade products, reused and refurbished blades as spare, etc.

The overview of the process steps is shown in Figure 2.7 and the complete diagram in Appendix A. End-of-Life flow diagram. The EoL flow diagram is a working document and has been defined based on experience with EoL and decommissioning scenarios for on and offshore wind turbines, literature, accompanying research projects and input from the industry.

For the assessment of the selected route of decommissioning and EoL processes and logistics, key data is required regarding:

- Emission (CO_2-eq, GHGs);
- Costs;
- Energy (the energy balance of the EoL processes);
- Process efficiencies (scraps and by-products)
- Material composition and shape/size (complete blade, blade sections, shredded, grinded particles, etc.);
- Material quality (in terms of purity, mechanical properties, etc. depending on the end application);
- The "material passport" status during the process;
- Public perception regarding wind energy circularity and EoL solutions (see chapter 4).

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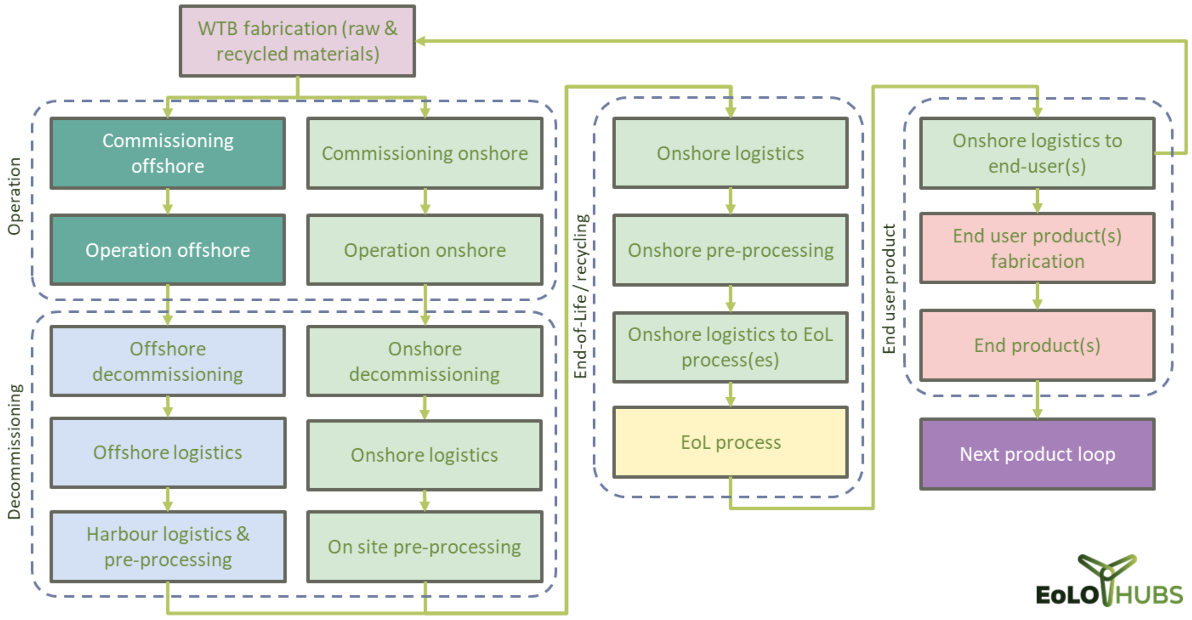

Figure 2.7: Main processes in the wind turbine blade EoL flow diagram.

2.3.1 Fabrication phase

During the fabrication process of a wind turbine blade, the raw materials and any recycled raw materials are used to produce semi-finished products like the pultruded unidirectional carbon fiber (CFRP) spar caps in modern blades. In addition to the fiber-reinforced composite materials (resin and fibers), metal parts are also used such as the copper wiring for the lightning protection system and metal inserts or T-bolts on the root section of the blade for the connection to the hub (see section 2.1, Figure 2.2). The balsa wood and/or PET foam core material is supplied and processed into the sandwich structure of the blade shells.

The wind turbine blade manufacturer fabricated the blade with the various parts and base materials mounted in a mold. After finishing the produced blade an additional coating system like the leading edge protection system (LEP) and for certain areas a required, red-colored signal coating is applied. Optional is the application of add-ons for performance improvement and noise reduction like vortex generators, gurney flaps, etc. which are mounted on the surface of the wind turbine blade.

The blades will be transported onshore with special transport by road and/or over inland waterways to the new location where they will be commissioned on another wind turbine. For the modern large turbines with blade lengths of 120 m and more, the factory is usually located near a sea harbor, since transport over the road is not possible or manageable (requiring special trucks, permits and costs).

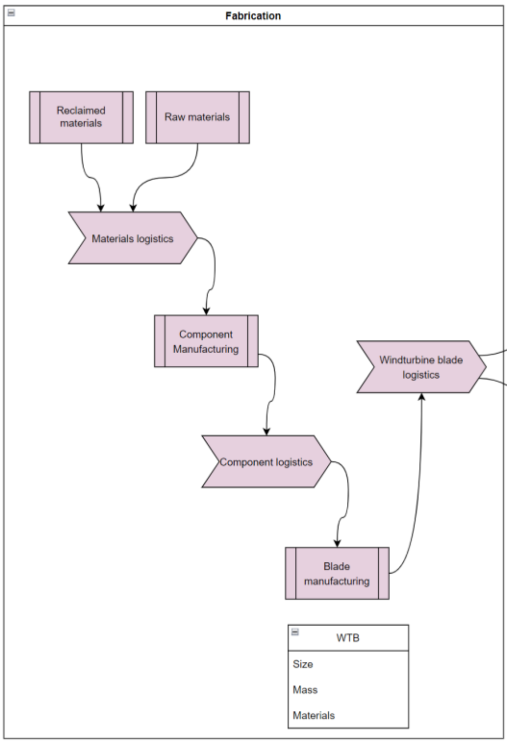

Figure 2.8: The wind turbine blade fabrication phase in the EoL flow diagram.

2.3.2 Commissioning and operation phase

Figure 2.9 shows the commissioning and operation phase with the different processes. A distinction is made between onshore and offshore wind turbines. For the analysis of the contribution to environmental impact and costs of a full life cycle, the impact of the commissioning and operational phase of offshore wind farms is larger than for wind turbines installed onshore.

For the installation of the wind turbine, the blades must be transported to the site. In the case of an onshore location, 1 or 2 cranes will be used to assemble the tower, nacelle, and blades. For offshore, a Jack-up Vessel (JUV) is generally used for the installation of the support structures and turbines of fixed-bottom wind farms with monopile support structures. For floating wind turbines in deeper seas, a crane installation vessel or transport from the harbor to the site with tug vessels can be used.

Onshore operation

Maintenance on onshore turbines is carried out using small vans or trucks for technical personnel, tools and materials and cherry pickers for maintenance at height. In some cases, a large crane must be used to lift large parts in the nacelle like gearbox replacement or replacement of complete blades.

Offshore operation

During the operational life of the offshore wind turbine, maintenance will be carried out using Crew Transport Vessels (CTVs), Service Operation Vessels (SOVs) and helicopters to transport maintenance personnel and materials. In the future, it is expected that cleaner fuels and also electrical propulsion will be used. As for the blades, repairs are mainly carried out on the outer surface in case of damage caused by water droplet impact erosion on the blade leading edge (LEE) and lightning strike impact. In rare cases, damage can lead to excessive structural damage and the blade must be replaced in its entirety by a new or used spare one.

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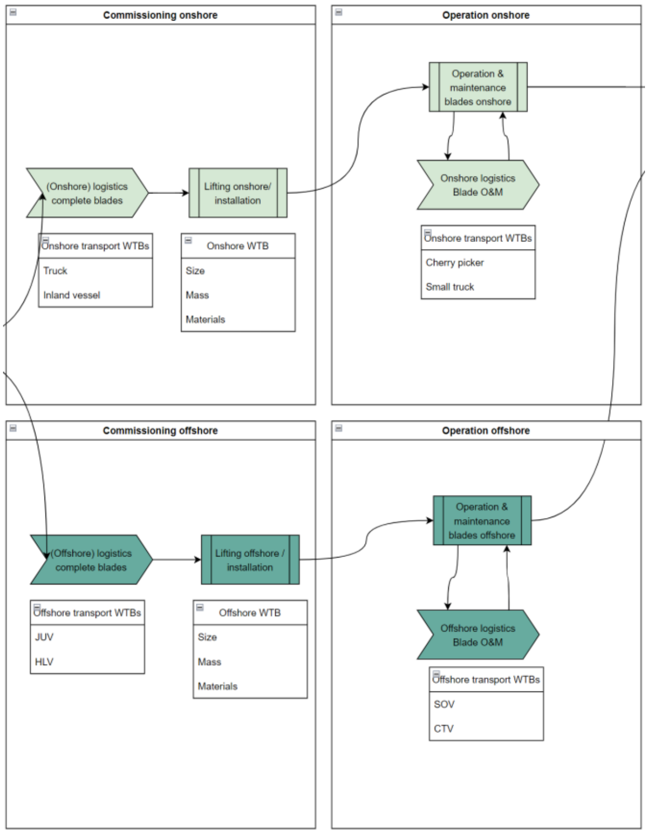

Figure 2.9: Commissioning and operation phase (on- and offshore) in the EoL flow diagram.

2.3.3 Offshore decommissioning phase

In the EoL flow diagram, the decommissioning processes are divided into three parts (Figure 2.10):

- The lifting operation offshore of the blades and wind turbines. Optional the pre-processing of the blade on the deck of a vessel with a water jet or saw cutter before transport;
- Logistic operations to transport the wind turbine and the blades to the harbor where a distinction is made between the transport of entire blades (handled with or without care) or segmented blade material;
- Logistics in the port. In practice, offshore construction, and ship recycling companies, such as Jansen Recycling in Vlaardingen (NL), are located in the port area where the water depth is too low for the heavy JUVs. In that case, the blades shipped by JUVs in the deeper port area are loaded onto smaller inland vessels.

It is expected that the offshore blades will not be reused due to the long operational duration and the tougher conditions in an offshore wind farm and also the responsibility of the contractor to ship the blades in the required condition to the harbor. In that case, careful handling could be waived for cost and insurance reasons.

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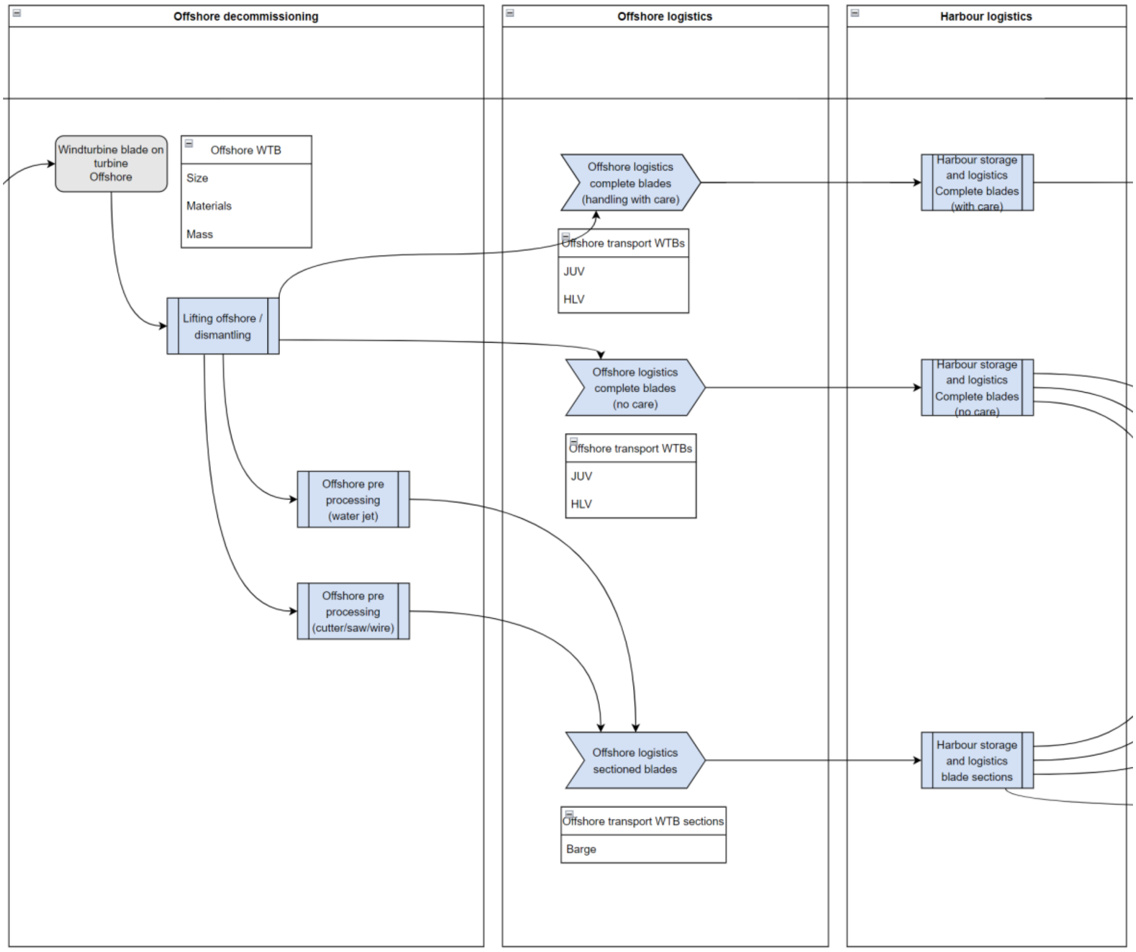

Figure 2.10: Offshore decommissioning phase in the EoL flow diagram.

Figure 2.11: The AEOLUS jack-up vessel (JUV) from Van Oord installing a wind turbine (source Van Oord).

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Figure 2.12: (Left) transport vessel with turbine blades (source Vattenfall); (right) transport on a barge with tug vessel (source North American Windpower).

2.3.4 Onshore decommissioning & pre-processing phase

The different routes for logistics and pre-processing are indicated in the EoL flow diagram (Figure 2.13). For offshore wind farms, the starting point of this phase will be the seaport where the wind turbines and blades arrive. Storage of blades and wind turbines in a port area is expensive and for that reason, it is desirable to transport the blades to a recycling facility as quickly as possible. This can be done by road or with inland vessels. When decommissioning wind turbines on land, accessibility and (local) restrictions and permits for, for example, environmental impact, windows for lifting operations and logistics determine the choice of the EoL route.

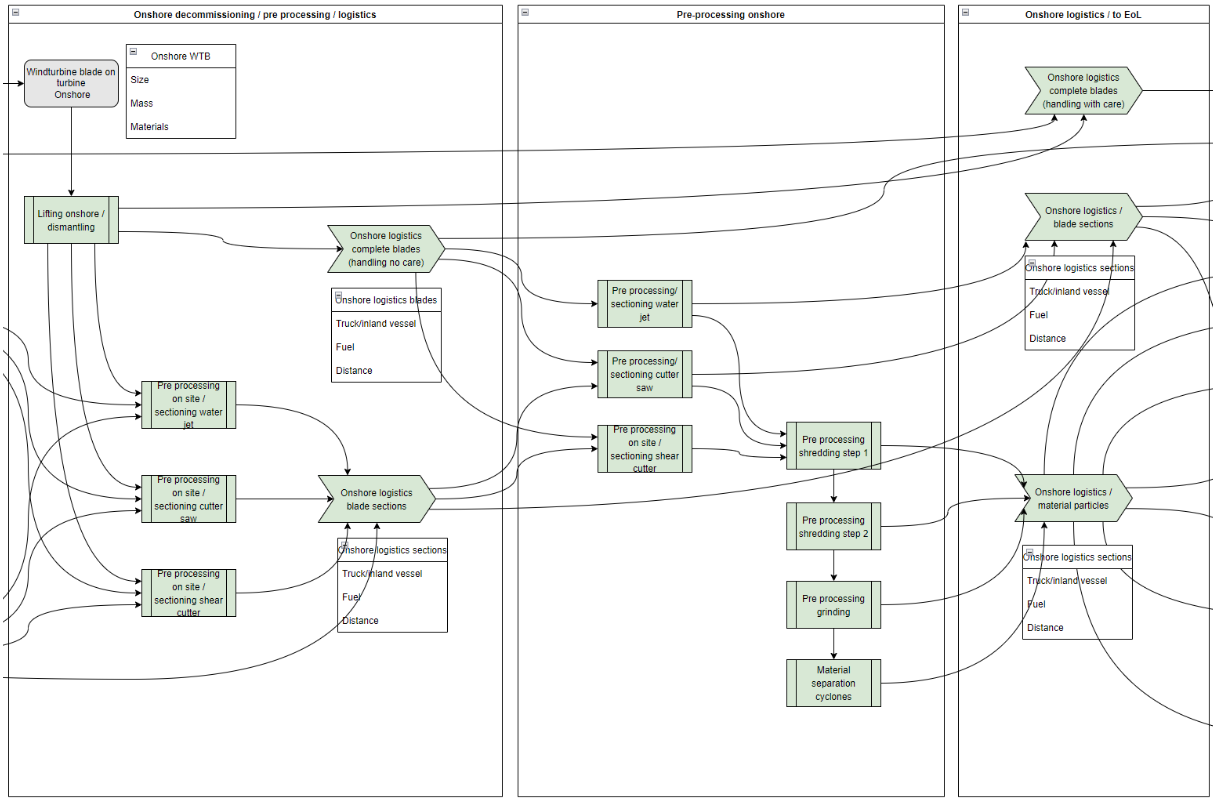

Figure 2.13: Onshore decommissioning and pre-processing phases in the EoL flow diagram.

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Onshore transport and logistics

For road transport, there are restrictions on the dimensions and weight of the load. In the Netherlands, a truck may not weigh more than 50,000 kg with a maximum length of 22 meters. If the blade does not have to remain intact for reuse, for example, it is better for economic and logistical reasons to pre-cut it into segments on-site. An additional option is to further process the material into smaller particles using a mobile shredder to be able to transport the blade material more efficiently in a truckload.

If the load is larger and/or heavier than permitted, special transport must be used, whereby the regulations for transport with large loads 'convoy exception' may differ per country. The costs are much higher because, in addition to heavier trucks, supporting vehicles and required permits, adjustments often have to be made to objects and barriers on the route.

The blade material can also be transported along the waterways by inland vessels. The advantage is that there are larger loading volumes, and more material can be transported with a single transit from for instance a harbor to a recycling facility.

Onshore decommissioning and lifting

Onshore decommissioning of a wind turbine is usually carried out with a crane. First, the blades and rotor are disassembled followed by the nacelle and tower. Depending on the EoL solution the components and blades may have to be handled with care for reuse. Usually, a second crane is required on-site: the wrecking crane (Figure 2.14). This smaller crane can be used for cutting, shredding, and lifting the smaller components and sections [10].

An alternative solution for decommissioning onshore turbines is cutting the tower root to break down the complete turbine as applied by the Danish company HJHansen. This reduces dismantling costs as no large crane is needed and less uncertainty for planning due to weather window for lifting operation [11]. This decommissioning method is not applicable for re-use since both the turbine and blades will be damaged.

Figure 2.14: Decommissioning of an onshore wind turbine (source Ramboll [10]).

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Pre-processing solutions

There are different methods to pre-process a blade to the desired dimensions for transport and the selected EoL solution (refer to EoLO HUBs report D2.1 [12]). To determine suitable routes, an assessment should be made based on:

- Dimensions and weight of the blade
- Desired shape in terms of segments and particle dimensions
- Separation of materials and components
- Local environmental and safety requirements
- Accessibility with on-site pre-processing (mobile installations)

Applicable blade pre-processing methods are:

- Sawing with a disc cutter or saw, operated by hand, or mounted on an excavator (Figure 2.15)
- Waterjet cutting (Figure 2.15)
- Cutting wire
- Shredding (Figure 2.16)
- Grinding

The EoLO-HUBs partner Advantis has developed a multi-wire cutting machine for smart cutting of a blade (Figure 2.17).

The different pre-processing methods are discussed and qualitatively compared in deliverable D2.1 [12]. Note that the pre-processing steps needed mainly depend on logistical considerations as well as the requirements of the specific EoL route selected.

Figure 2.15: (Left) cutting a WTB with a rotating cutter disk (source Echidna); (right) water jet cutting of a WTB (TNO).

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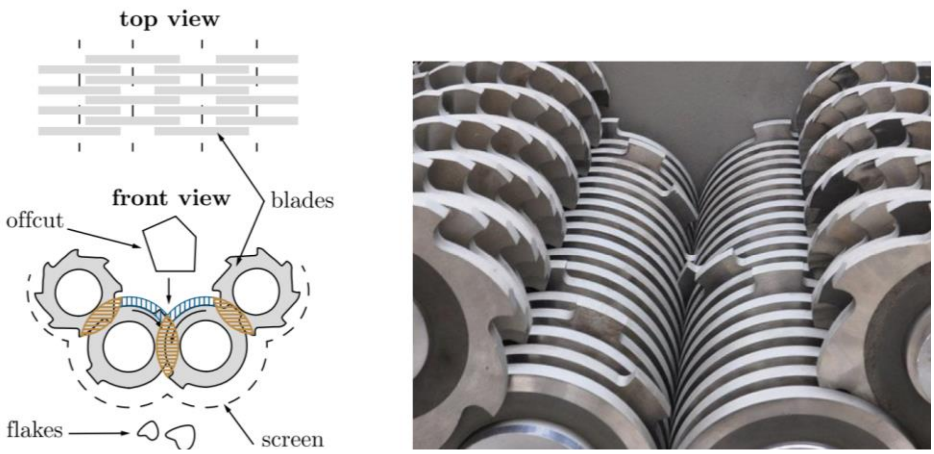

Figure 2.16: (Left) schematic representation of a shredder; (right) with the rotating steel cutting knives (from [13]).

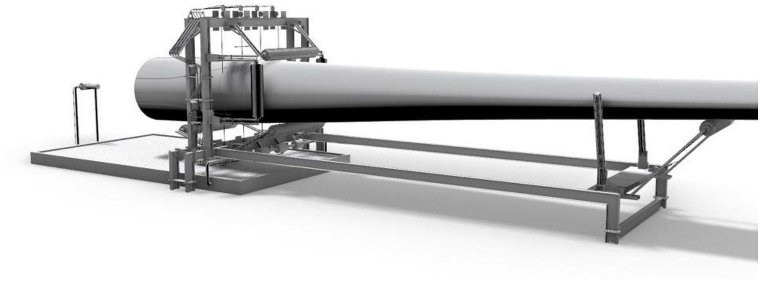

Figure 2.17: Advantis blade wire cutter concept (source: Advantis, EoLO HUBs).

2.3.5 EoL process phase

The end-of-life processes (Figure 2.18) are classified according to their degree of circularity: reuse, repurposing, recycling, recovery, and landfill. In practice, different processes will have to be carried out to make optimal use of a discarded wind turbine blade. For example, part of the blade can be used for a noise barrier with cut segments and the remaining parts can be pyrolyzed. An overview of different options is given in [14].

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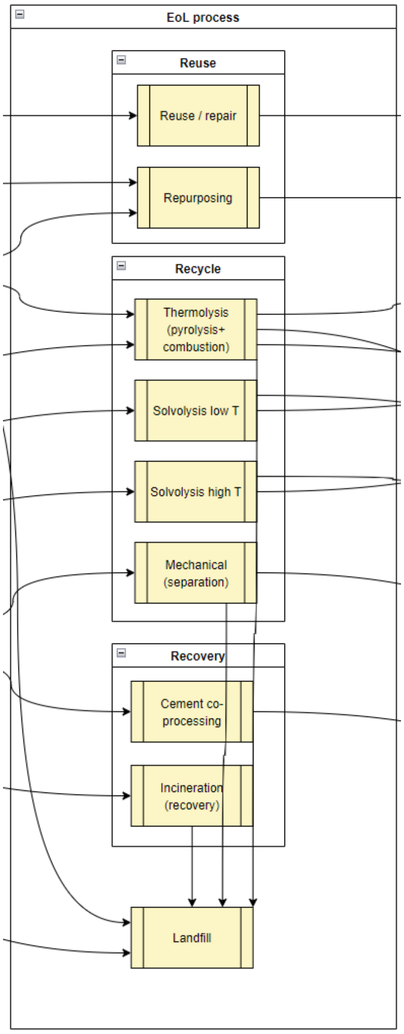

Figure 2.18: EoL process phase in the EoL flow diagram.

<u>Reuse</u>

The blade is still in good condition to use again as a repair blade or on a second-hand turbine. For reuse of wind turbines and blades, the complete chain from decommissioning, transport and re-commissioning must be tailored to handling the blades with care. Damage to the blades results in additional repair costs or rejection for safe use on a wind turbine.

<u>Repurposing</u>

With repurposing, the entire blades, or parts of them are used for another application. In practice, there are examples of repurposing on a limited scale in the form of bicycle sheds and playgrounds. However, for upscaling and economic added value, applications such as a road noise mitigating barrier solution of Blade-Made (https://blade-made.com/portfolio-items/blade-barrier/) or use as a building material are being considered.

It is essential to precisely cut out segments and parts of the blade (Figure 2.19). For structural constructions, the (residual) mechanical quality of the part must also be known [15].

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The goal is to repurpose large volumes of discarded blades and keep the value as high as possible. In that case, requirements are set for the original blade design, the materials used (materials passport), the current material quality and the (remaining) structural integrity for use as construction elements or other high-performance applications.

Depending on the application, the blade will have to be cut precisely, to cut the right segments into the required shape out of the blade, which means specific requirements on the cutting methods used and environmental permits.

In practice, a blade cannot be repurposed in its entirety and other processes will be used to process the complete blade, such as recycling and recovery.

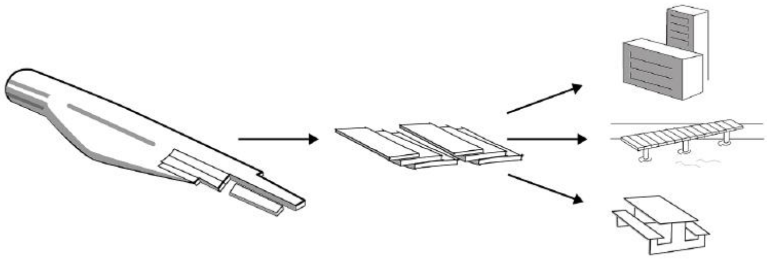

Figure 2.19: Segmenting the blade for repurposing in new products (from [15]).

Recycle

At the end of the cycle, the material will always have to be recycled. The focus of the EoLO HUBs project is on thermolysis and solvolysis. Based on the aimed end product, the processes can be adjusted, to keep the fiberglass as intact as possible for reuse, but the option of melting the glass for fabrication of new fiber material is also an option. The other recycling process is mechanical, where for instance fibers can be separated by mechanical grinding for reuse in new composite products like harbor piling. In this case, the quality of the fiber is degraded and has less value.

- Pyrolysis. The thermal recycling of fibers from composite materials is possible through pyrolysis, i.e. heating without the presence of oxygen. The pyrolysis treatment for plastic composite materials will be carried out at temperatures from 300 to 600 °C, in a nitrogen atmosphere. The resin is converted into oil or gas and the GF or CF remains behind. Residues of char adhered to the fiber surface are then removed with a combustion step in the presence of oxygen. This complete process is also called thermolysis.
- Solvolysis is a thermochemical recycling technology, where water, alcohols, acetic acid are examples to be used as solvent/reactants at high temperatures ranging from 200 to 450 °C and pressures from 50 to 250 bar for the degradation of organic materials such as polymers. The formed products depend on the input polymeric waste stream, solvent system, catalysts, temperature, pressure and reaction time [16].

Recovery

Recovery is a thermal treatment that converts the composite material into heat energy. For this study, two different recovery processes are applicable for the composite blade material:

- Incineration, a thermal waste treatment process converting into flue gas, ash, and heat energy. The added value is a combination of heat energy recovery and reduced waste volume.

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- Cement co-processing of GF composite material uses the combination of produced heat from the incinerated resin and core foam materials when entering the kiln for cement production with a source for raw mineral material [17]. The produced process heat results in a decrease in the required amount of coal to maintain high process temperatures, cement kilns operate at high temperatures above 1450°C. The inorganic components, like the GF, are incorporated into the cement clinker as part of the raw material, contributing to its mineral composition. Carbon fibers with very high melting temperatures (4000 °C) are not compatible with the cement production process and need to be excluded from the blade waste material for this process.

In this work, cement co-processing is considered a recovery process like incineration, since the main focus is on heat recovery to reduce fossil fuels like coal.

Landfill
Landfilling is added in the flow diagram as an EoL solution for blade material. However, it is expected that with the complete EU landfill ban aimed in 2025 this will not be an option anymore [18].

2.3.6 End user product and manufacturing phase

For this section of the EoL flow diagram (Figure 2.20), a distinction is made between the logistics process from the EoL location to the end user manufacturing location and the manufacturing processes for the end product.
The choice of transport of the recyclate and parts of the blades to the end user can have a major influence on the costs and environmental impact. It is not obvious that a manufacturer has its location near the recycling company. Particularly for large throughputs such as for the production of injection molded automotive parts, input materials must be continuously transported to meet the demand. This will mainly be transported by road.

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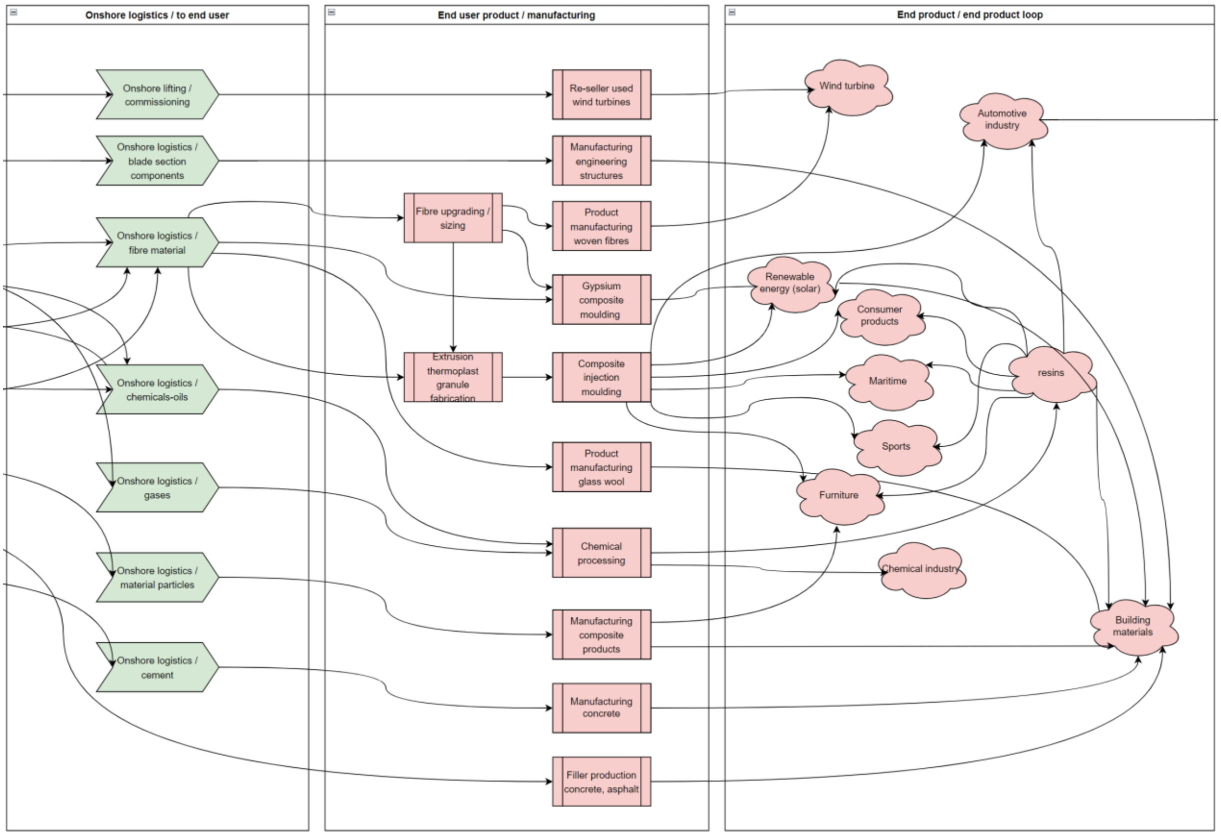

Figure 2.20: End user product and manufacturing phase in the EoL flow diagram.

2.3.7 End user product & next loop phase

The intended end product is essential for determining the optimal EoL route for a discarded wind turbine blade. The blades are currently recycled on a limited scale and there is no increase in value. Optimizing the economic value of the discarded blade must be tailored to the end users. The possible end products mentioned in the EoL flow diagram can be realized once the recycling process is optimized to upcycle the reclaimed glass fiber for use in new commercial composite products such as automotive interior parts. An important condition is that the volumes offered match the feedstock necessary for manufacturing the end products. This is a challenge as it requires good communication between stakeholders and clear agreements about when, where and how much material can be expected and processed (and at what cost).

A major gain in the degree of circularity is when additional loops are created with an end product that can itself be reused or recycled after a useful life. However, this requires further investigation from a life cycle thinking approach to determine the actual net resource, environmental and cost savings.

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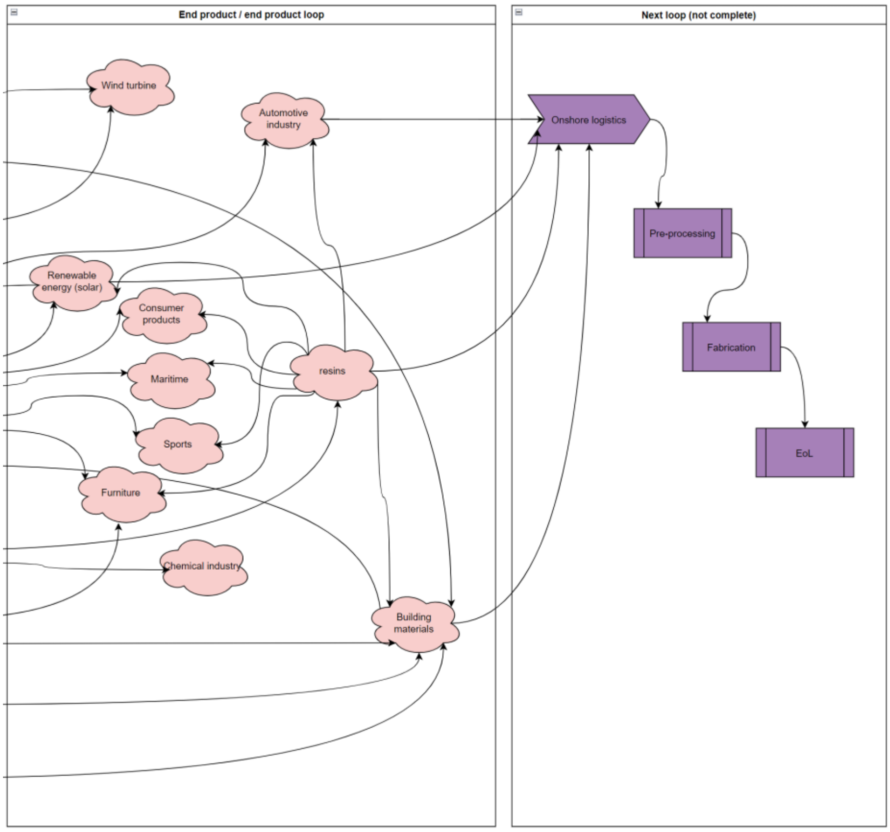

Figure 2.21: End user product and next loop phase in the EoL flow diagram.

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3 Scenario assessment

3.1 Introduction

In Chapter 2 an EoL flow diagram was presented from the fabrication phase until the end user product and next loop phase. In the current chapter, only a small part of the WTB life cycle management process is considered: pre-processing and logistics. It is assumed that all the WTBs decommissioned from a farm follow the same EoL route. Also, only the offshore case is considered starting with the blades still on board of the offshore vessel in the harbor. The scenario finishes at the start of the pyrolysis process. The reason for this choice is that pre-processing steps are involved in every EoL solution. Besides that, pre-processing has not received much attention in the literature [19]. [20]Activities during pre-processing are:

- Lifting, loading, unloading;
- Transport by truck or inland vessel;
- Cutting, shredding and optional grinding.

Ideally, an assessment should cover the following main themes:

- Economic;
- Technological;
- Environmental;
- Social.

In deliverable D2.1 [20] of the EoLO HUBs project these themes are discussed thoroughly based on preliminary and estimated data for some onshore WTB EoL processes, relying mostly on qualitative considerations. However, a quantitative approach is preferred for the scenarios. This limits the assessment to economic costs and the costs of emission of CO_2, NO_x and PM_{10}. The emissions of CO_2, NO_x and small particles (PM_{10}) during transport relate to the environment, while the same emissions also relate to the health of people in society.

In this chapter, the building blocks are developed to quantify the economic costs and emissions first. Next, the model is applied to two Dutch offshore wind farms. Finally, the results and limitations will be discussed.

3.2 Scenario building blocks

The aim is to assess the impact of the defined criteria preferably expressed in Euros. In the assessment, all the costs are in Euros for September 2024. In literature, however, values are given in US dollars and Euros, where the sources are published in different years. The year of publication is used as the reference year. The CPI Inflation Calculator [21] is used to account for the inflation since the year of publication, see Table 3.13.1. US dollars are converted to Euros using information from the European Central Bank [22]. For the currency exchange rate, the half-year average from 4 March 2024 to 2 September 2024 is taken, i.e. 0.9224 from US dollar to Euro.

Table 3.1: Inflation correction for the US dollar and Euro to 2024.

Year	US dollar	Euro
2015	1.33	1.28
2019	1.23	1.21

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2021	1.16	1.17
2022	1.07	1.07

Note that all the values reported in US dollars or Euros are as published. Only in section 3.5 where the scenarios are evaluated currency corrections are applied and everything is expressed in Euros for September 2024.

During transport and pre-processing there will be emissions that cause damage to the environment and social health. The emissions assessed in this report are CO_2, NO_x and small particles (PM_{10}). Emissions are calculated in mass. However, that makes it difficult to compare with the "economic" costs. Therefore, although there is no market, the impact of emissions on society is expressed in costs in Euros. In Table 3.2 of the CE-Delft report by De Vries et al. [23] the following pricing is presented for CO_2, NO_x and PM_{10} for a 2021 € per kilogram [20].

Table 3.2: Pricing of emissions based on CE-Delft report [23].

Chemical	Name	Lower €/kg	Central €/kg	Upper €/kg
CO_2	Carbon dioxide	0.050	0.130	0.160
NO_x	Nitrogen oxides	18.3	29.9	44.1
PM_{10}	Small particles	41.4	69.3	97.9

In the sections below the costs and emission rate will be discussed for:

- Lifting, loading, unloading;
- Transport by truck or inland vessel;
- Cutting, shredding and optional grinding.

3.2.1 Lifting, loading and unloading

Lifting operations of the full blade occur at the site when dismantling the wind turbine. At an onshore site, the cutting and shredding starts immediately after the lifting operation. For offshore sites, one more full-blade lift is expected when arriving at the quay of the selected decommissioning harbor. Once on the quay, the blade is first transported to a location on the yard where it is temporarily stored before the pre-processing starts. Another option is, that the blade is loaded on an inland vessel and transported to another location. There again the blade needs to be lifted and stored somewhere at the site.

Cooperman et al. [24] estimate the tear-down costs of a complete rotor at 26 $/kW for a hub height of 80 m with an adjustment of plus-minus 0.40 $/kW for each meter above or below 80 m. The same reference reports a crane cost of about 65,000 $ for a 2.5MW turbine, which is deemed quite high and will not be used. Instead, based on information on the internet [25] a rent of 1,500 euros a day will be used for a large mobile crane. For an excavator, 300 euro a day rent is taken based on internet information [26].

For emissions of crawler excavators, mobile cranes, crawler cranes internal TNO information [27] is used. See Table 3.3:. The emission classes are explained at dieselnet.com [28], [29]. In the assessment of the fleet average values will be used.

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Table 3.3: Crawler excavator, mobile crane and crawler crane emissions from internal TNO sources [27] and dieselnet.com [28].

Machine	Operating hours per year (fleet average)	CO_2 g/hour	NO_x g/hour	PM_{10} g/hour	Emission class	Power range
Crawler excavator	1270.875	22129.501	81.731	1.634	Fleet average	75 ≤ kW < 130
Crawler excavator	1270.875	21724.306	57.743	1.063	Stage IV	75 ≤ kW < 130
Crawler excavator	1270.875	23326.721	190.771	1.218	Stage IIIB	75 ≤ kW < 130
Crawler excavator	1270.875	24363.439	187.203	7.289	Stage IIIA	75 ≤ kW < 130
Mobile crane	1578.238	23207.420	193.387	3.930	Fleet average	300 ≤ kW < 560
Mobile crane	1578.238	21805.375	201.887	0.265	Stage V	300 ≤ kW < 560
Mobile crane	1578.238	22465.015	199.222	1.401	Stage IV	300 ≤ kW < 560
Mobile crane	1578.238	23434.475	105.584	1.600	Stage IIIB	300 ≤ kW < 560
Mobile crane	1578.238	24365.549	183.984	9.945	Stage IIIA	300 ≤ kW < 560
Crawler crane	1157.701	26280.724	190.295	6.753	Fleet average	75 ≤ kW < 130
Crawler crane	1157.701	24456.668	63.107	1.201	Stage IV	75 ≤ kW < 130
Crawler crane	1157.701	25464.216	208.837	1.333	Stage IIIB	75 ≤ kW < 130
Crawler crane	1157.701	26567.311	204.722	7.971	Stage IIIA	75 ≤ kW < 130

A distinction should be made between the duration of unloading all wind turbines and the duration of lifting a single blade. The lifting of a single blade is expected to take half an hour [30]. In this half hour, the crane is actually operating, and such a reference duration is used to estimate the amount of emissions. In case an excavator or crane is rented for a certain period, the operating hours per year reported in Table 3.2 are used as a basis for an estimate of the operating hours.

3.3 Cutting and shredding

Regardless of the selected EoL solution, with the exception of life extension and reuse, some pre-processing of the blade is needed. For instance, the transport of the complete blade onshore is very much expensive. Therefore, the blade is cut and possibly shredded on-site before further transport. In the literature, there is very limited information about the costs. Also, it is difficult to distinguish between cutting, shredding, or grinding, especially with regard to the type of machine used.

Cutting of the blade can be in about 10 m sections or by cutting the blade shell. In deliverable 2.1 [12] the circular saw, diamond wire, water jet and laser cutter are compared. Also, chainsaws are applied. In all cases, rules on emissions and safety should be taken into account. Unfortunately, information about the emissions of CO_2, NO_x and PM_{10} is not found.

As mentioned, the amount of data on costs of cutting is limited and often combined with other processes. For instance, the figures reported in the report by EPRI 2020 [31] include the cutting of a 37m blade in three pieces, a transport of 100 miles, and handling operations. The costs per blade are estimated between 1000 $ and 2000 $ in 2019. Cooperman [24] estimates the cost of transport at 14 $/mile. Assuming that cutting costs are 10% of 1500 $ seems reasonable. Therefore, the cost per cut of a blade cross-section is taken as 75 $/cut in the assessment.

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Next, depending on the selected end-of-life solution the blade is shredded to the desired fiber length. Before shredding, unwanted metals will be removed. Shredding takes place in several steps, each of them reducing the particle size. Two situations are considered:

1. The first shredding is done on-site using a mobile shredding unit. The reason behind this is that more blade material can be transported in one truck. At the site where the next step in the end-of-life stage occurs the blade material is shredded into the required size.
2. All the shredding takes place at the pyrolysis site.

Cutting and mobile shredding in one stage is estimated by Liu et al. [32] between 10 $/ton and 70 $/ton. An average of 40 $/ton will be used.

Referring to an interview with Thomas Wegman 2019 In EPRI 2020 [31], shredding in two stages to 1 - 3 cm costs between 90 $/ton and 120 $/ton. An average of $105/ton is used in this assessment. It should be noted that cutting to 1-3 cm is not needed for pyrolysis. However, no other data is available in the literature.

In the case of shredding before transport, mobile shredding costs are used together with half the costs of shredding to 1-3 cm.

3.4 Transport by truck or inland vessel

This section discusses the transport by truck or inland vessel of a full blade, blade sections and shredded blade material. Both the costs and the associated emissions will be determined. This depends on the travel distance and the amount of blade material to be transported.

It is expected that the size and volume of the blades will determine the number of trucks or vessels needed and not the blade mass. For the transport of a blade or blade segment, the blade root diameter is a driving parameter.

For shredded material, it is decided to take the volume of a 40-foot container as a measure. The outer dimensions (l x w x h) are 12.2 x 2.44 x 2.59 m, and the inner dimensions are 11.95 x 2.33 x 2.37 m. The inner volume is 67.8 m^3. Arjes Recycling Innovation [33] provided an estimate of the density of the shredded material 200-250 kg/m^3. A density of 225 kg/m^3 will be applied. This allows estimating the number of containers required to transport the shredded material.

In the next sections, the transport by truck will be discussed followed by the inland vessel.

3.4.1 Transport by truck

The transport costs used, are based on a public report for policy studies in The Netherlands KIMNET [34]. For transport by different trucks, the data is summarized in Table 3.4: (providing general information) and Table 3.5: (providing costs per km, ton-km and hour).

- The total annual costs are: fixed costs + variable costs + staff costs + mode-specific costs + general operating costs
- Costs per kilometer are: total annual costs / distance traveled (km)
- Costs per tonne-kilometer are: total annual costs / (distance traveled (km) * average tonnage)

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- Cost of waiting and (un)loading per hour are: (fixed costs + staff costs + general operating cost) / time in use (hr)

Table 3.4: Data on road transport [34], only miscellaneous goods.

Vehicle	Total annual costs €	Average tonnage tonne	Time in use hr/yr	Distance traveled km/yr	Utilization rate %
Truck	148165	5.1	2585	78000	39
Truck + trailer	173304	10.9	2585	78000	39
Tractor + trailer	174582	13.2	2585	78000	46
LZV	178186	18.7	2640	78000	46

Table 3.5: Costs for break bulk in euros per km, tonkm or hour [34].

Vehicle	Total costs per km	Total cost per tonkm	Loading costs per hour	Unloading costs per hour	Waiting costs per hour
Truck	1.90	0.375	40.54	40.54	40.54
Track + trailer	2.22	0.203	44.85	44.85	44.85
Tractor + trailer	2.08	0.153	45.20	45.20	45.20
LZV	2.28	0.122	44.23	44.23	44.23

Emissions of CO_2, NO_x and PM_{10} per km are presented based on inhouse TNO information [35] for different types of roads.

- City 30-50 km/hr
- Country road 60 – 80 km/hr
- Motorway 100-130 km/hr

Table 3.6: shows the emission factors for the EURO V standard. Table 3.7: for the EURO VI standard. About 75% of the trucks have the EURO VI standard and will be used in this report.

Table 3.6: Emissions from Euro V heavy transport for selected chemicals [35].

Type of road	CO_2 g/km	NO_x g/km	PM_{10} g/km
City 30-50km/hr	1621.68	7.32993	0.215326
Country road 60-80km/hr	1305.83	4.34628	0.138406
Motorway 100-130km/hr	1124.69	4.89046	0.126005

Table 3.7: Emissions from Euro VI heavy transport for selected chemicals [35].

Type of road	CO_2 g/km	NO_x g/km	PM_{10} g/km
City 30-50km/hr	1537.93	3.75756	0.139783
Country road 60-80km/hr	1194.68	2.58547	0.07501
Motorway 100-130km/hr	978.018	1.219174	0.077737

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A tractor + trailer is used for the scenario assessment.

3.4.2 Transport by inland vessel

For transport over inland waters, a number of different types of vessels are available. See Bureau Voorlichting Binnenvaart [36] and the report by Rijkswaterstaat [37].

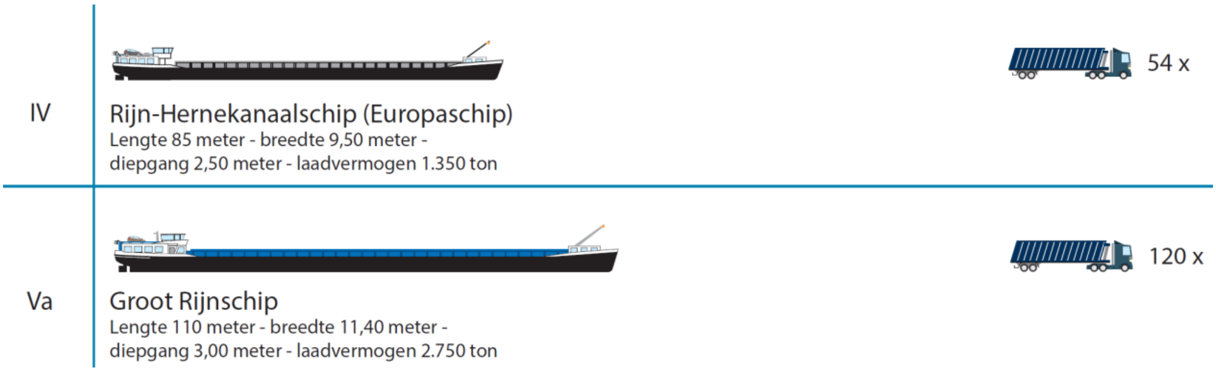

Figure 3.1: Snapshot of selected inland vessels, one truck represents one 40 feet container. Source Bureau Voorlichting Binnenvaart [36]

The Rhine-Herne Canal vessel (Rijn-Hernekanaalschip), CEMT class IV (AVV-type M6), and the Large Rhine vessel (Groot Rijnschip), and CEMT class Va (AVV-type M6) are considered in the assessment. See Figure 3.1.

The area of the cargo hold of a Rhine-Herne Canal vessel is three 40-foot containers wide and five containers long. A maximum of 54 x 40-foot containers is assumed. In the case of a Large Rhine vessel, the area of the hold is four containers wide and six and a half long, and a maximum of 120 x 40-foot containers is assumed.

As for road transport, the costs for transport by inland vessels in the KIMNET report [34] are used. For the Rhine-Herne Canal, vessel costs of a medium-sized ship of 12.07 €/km are taken. For the push convoy, costs for a large ship of 18.47 €/km are applied. Note that the values in the report for a push convoy are for four barges.

In practice, the quay length needs to be accounted for. In the assessment, it is assumed that this is possible for both ship types.

In Table 3.8 the CO_2 , NO_x and PM_{10} emissions for the two inland vessel types are given. The data is based on an in-house TNO analysis [38] of information available at the National Institute for Public Health and the Environment, RIVM [39].

Table 3.8: Emissions of the selected inhouse vessels.

Ship	AVV-type	CO_2 g/km	NO_x g/km	PM_{10} g/km
Rhine-Herne canal vessel	M6	17900.0	243.0	8.76
Large Rhine vessel	M8	24400.0	320.0	10.8

3.5 Two offshore scenarios

Now that the building blocks needed to evaluate the logistics and pre-processing of EoL solutions have been discussed, the reference scenarios can be defined. Unfortunately, not all aspects of EoL solutions can be captured in a mathematical assessment. This became clear in an EoLO-hubs workshop held in Amsterdam in October 2023, where the decommissioning of the Hartelkanaal wind farm was presented.

In 2003 the Hartelkanaal wind farm of Eneco became operational. The wind farm was located between the Hartelkanaal (Hartal canal) and the motorway A15, opposite the golfclub Kleiburg (see Figure 3.2: Location Hartelkanaal windfarm. Originally the wind farm consisted of nine Nordex N80 turbines. Four of them were removed in 2016, and the decommissioning of the remaining five turbines took place in 2021 [40]. The decommissioning project in 2021 was coordinated by Business In Wind (BIW).

Figure 3.2: Location Hartelkanaal windfarm.

One of the first decisions to be made during the preparation of the project was whether dismantling and transportation should be by road or over water. Due to the heavy traffic along the A15 it was decided to do both dismantling and transport at the Hartal canal. The dismantling depended on the wind conditions, but also the tide in the Hartal canal had to be taken into account.

Two barges were used for the dismantling and transport, the HEBO-Lift 2 and the Muller barge 10033-1. The HEBO barge stayed at the location. A telescopic crawler crane LR1100 and a crawler crane LR1600/2 were installed on this barge. The cranes were used to dismantle the turbine and to load the turbine parts in the Muller barge. After one complete turbine was loaded onto the Muller barge, it was transported to Jansen Recycling Group BV (JRG) in Vlaardingen. JRG recycles both ferrous and non-ferrous materials. The dismantling and transport of the five turbines was done in five days. Here the focus is on the blades and not the recycling of the metals of the N80 turbine.

At the quay of the yard in Vlaardingen the blades were unloaded from the barge by a rented mobile crane. The quay needed to be cleared for the arrival of the next turbine the day after. Therefore, the blades were pulled to a different location in the yard by an excavator crane. At this location, the blades were cut by an excavator with a hydraulic shear. The other excavator kept the blade steady in position. A shredder was rented to shred the cut blade parts for further transport in a kipper truck.

The choices in transport and pre-processing in the Hartel canal case will also be faced in other real-life scenarios. A lot has to do with practical solutions and common sense, which is difficult to model. The same holds for project management, communication between contractors, and legal issues and permits.

Two representative Dutch wind farms have been considered as reference scenarios in the EoLO-HUBs project:

1. The Prinses Amalia Wind Park (PAWP), Figure 3.3, section 3;
2. The IJmuiden Ver Beta wind farm (under development), Figure 3.3, section 6.

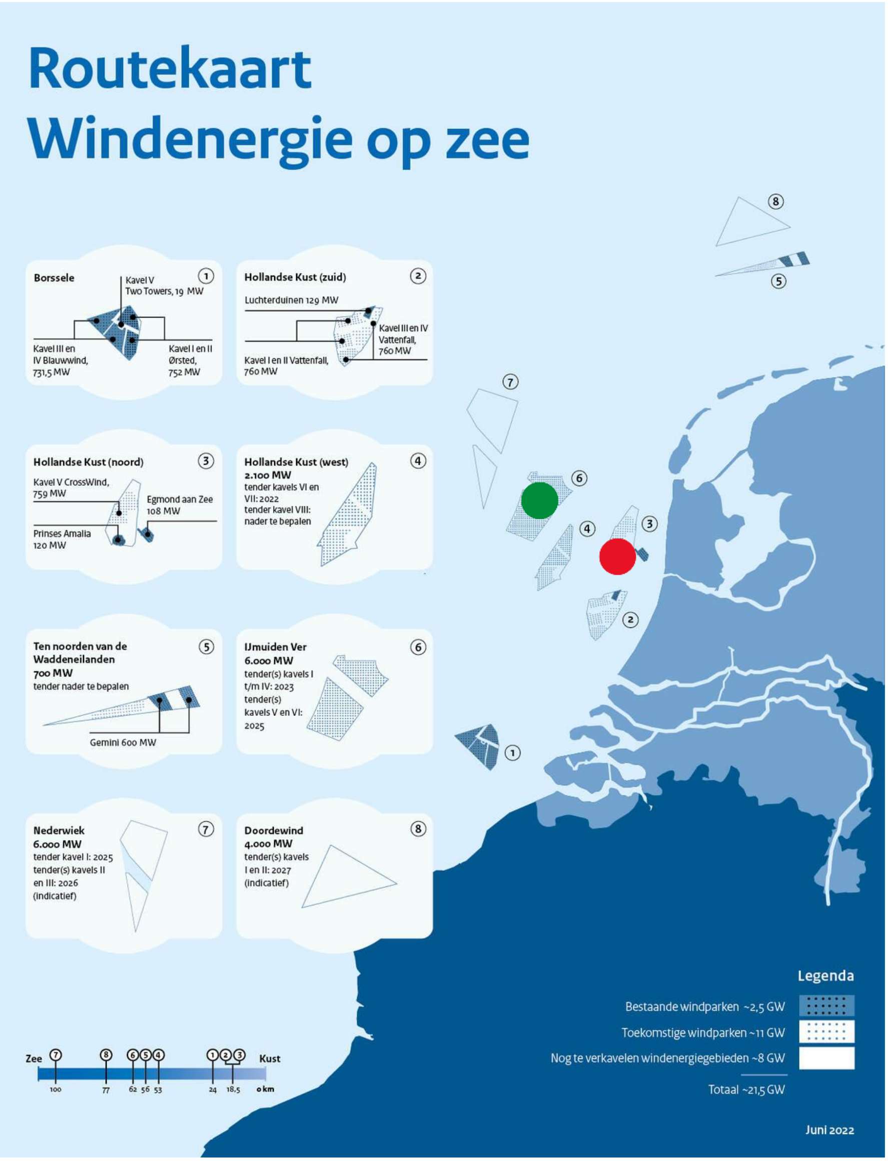

Figure 3.3: Dutch offshore wind future plans with red Prinses Amalia and green IJmuiden Ver [41].

The Prinses Amalia wind farm consists of 60 x Vestas V80 turbines representing a wind farm to be decommissioned before 2030. The IJmuiden Ver wind farm is under development, and it is assumed

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to consist of 133 x IEA 15 MW (blade B3 in Table 2.1). The IJmuiden Ver wind farm represents wind turbines to be decommissioned in the zero-emission society after 2050.

Although the two wind farms differ in size and time of decommissioning, the general EoL scenario will be the same. The scenario starts when the blades are still at a quay of the Maasvlakte of Rotterdam harbor. The scenario finishes at the start of the pyrolysis process. Transport by tractor + trailer and with inland vessels are considered. Figure 3.4 shows the route by road. Figure 3.5 the alternative route over water.

Figure 3.4: Transport by road. Total distance 75 km [42].

For each wind farm two sub-scenarios are defined:

1. At the quay the blade is loaded on an inland vessel and transported to Moerdijk, where pre-processing and pyrolysis steps take place.
2. The blade is unloaded at the Maasvlakte site where it is cut and pre-processed with a first stage of shredding before road transport. The next stage of shredding is performed at the pyrolysis site.

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Figure 3.5: Transport over inland waters, total distance 65 km [43].

3.5.1 Princes Amalia Wind Park (PAWP)

The selected blade for the PAWP is B1 (see Table 2.1). The length of the blade is a little less than 40m with a mass of 6.5 ton. It is assumed that five decommissioned wind turbines arrive at the Maasvlakte in the harbor of Rotterdam every two weeks and are transported next to the Moerdijk harbor where the pyrolysis facility is assumed to be. By ship, this is a distance of about 65 km. By truck, about 75 km. In total 180 blades are transported.

In the case of the complete blade sub-scenario, the blades are loaded in a Rhine-Herne canal vessel or a Large Rhine vessel. Every two weeks 15 blades need to be offloaded. It is assumed that the lift takes half an hour per blade.

It is assumed that a Rhine-Herne canal vessel can transport 6 blades at a time, in three rows of two blades. With a Large Rhine vessel, 8 blades can be transported in four rows of two. Hence, looking at 15 blades only, three Rhine-Herne ships are needed and two Large Rhine vessels. The number of Rhine-Herne vessels can be reduced to ten when three out of the 15 blades in a batch wait in Rotterdam until a ship can be completely loaded. Additional space is needed for this and also an extra crane lift for 12 blades. From the offshore vessel, the blades are first loaded onto the quay and then, after some weeks, loaded from the quay to the inland vessel. For the whole farm, this means thirty Rhine-Herne vessels or twenty-three Large Rhine vessels.

At the pyrolysis site, the blades are lifted onto the quayside of the facility. Then the blades are cut before shredding them in two stages.

The number of trips and total costs of transport are given in Table 3.9. The total costs are shown in Table 3.10. The difference in total costs has to do with transport and crane handling. In two trips only 12 blades can be transported on a Rhine-Herne vessel, leaving 3 still onshore. To avoid an additional

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trip with only three blades, additional crane handling is needed to store these blades temporarily. In total, 18 additional crane handlings are needed for the Rhine-Herne vessel. Although the Large Rhine is larger, the costs per km are higher while only two additional blades can be transported per trip. This makes it a more expensive choice compared to the Rhine Herne canal vessel.

Table 3.9: Number of trips and total transport costs for PAWP complete blade transport.

Vessel type	Number of trips	Total costs (k€)
Rhine-Herne canal vessel	30	28
Large Rhine vessel	23	32

Table 3.10: Overview of total pre-processing costs for the case of PAWP complete blade transport.

Cost type	Rhine-Herne canal	Large Rhine
Transport (k€)	28	32307
Crane handling (k€)	12	11250
Cutting (k€)	31	30633
Shredding (k€)	139	139380
Total costs (k€)	209	213569
Cost per ton (€/ton)	179	183

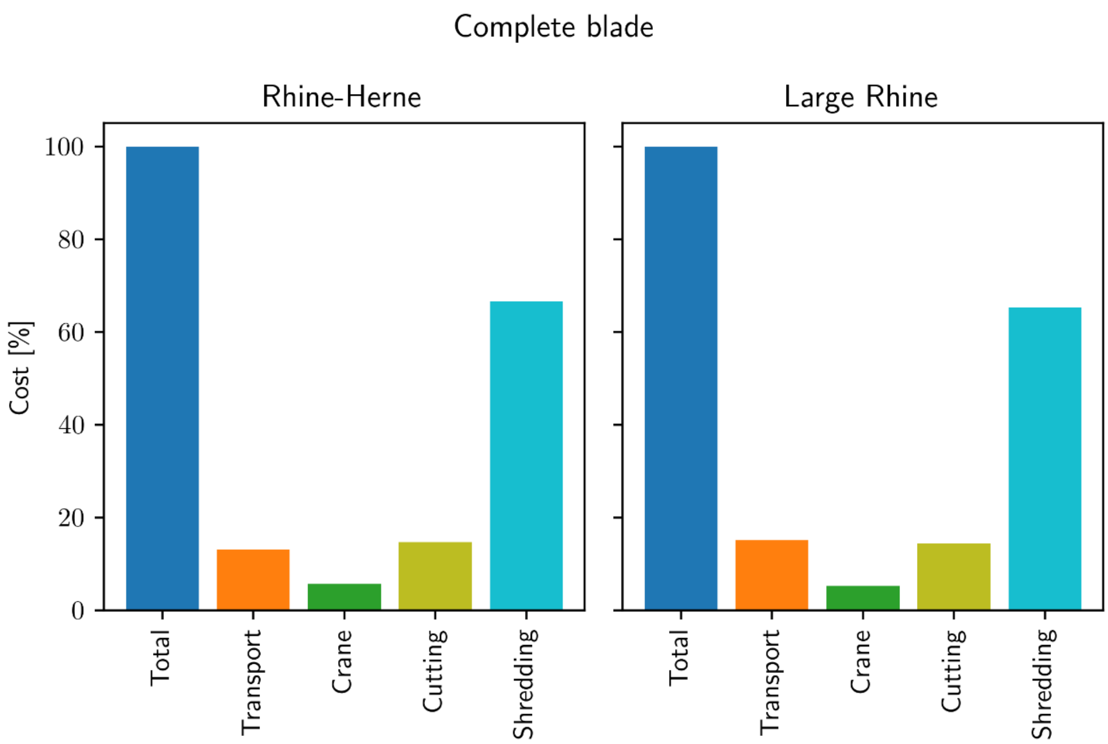

Figure 3.6: Costs in percentage for PAWP complete blade transport.

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In Table 3.10 the actual cost for complete blade transport is given. In Figure 3.6: Costs in percentage for PAWP complete blade transport. the contribution of the different activities in percentage of the total costs. Clearly shredding gives the highest contribution to the costs followed by cutting and transport.

Besides the economic costs, the costs associated with emissions are assessed for the crane handling and transport operations. The amount of CO_2 , NO_x and PM_{10} emissions for the different activities are depicted in Figure 3.7. The costs of the emissions are presented in Table 3.11. It is clear that the highest cost results from the NO_x emissions.

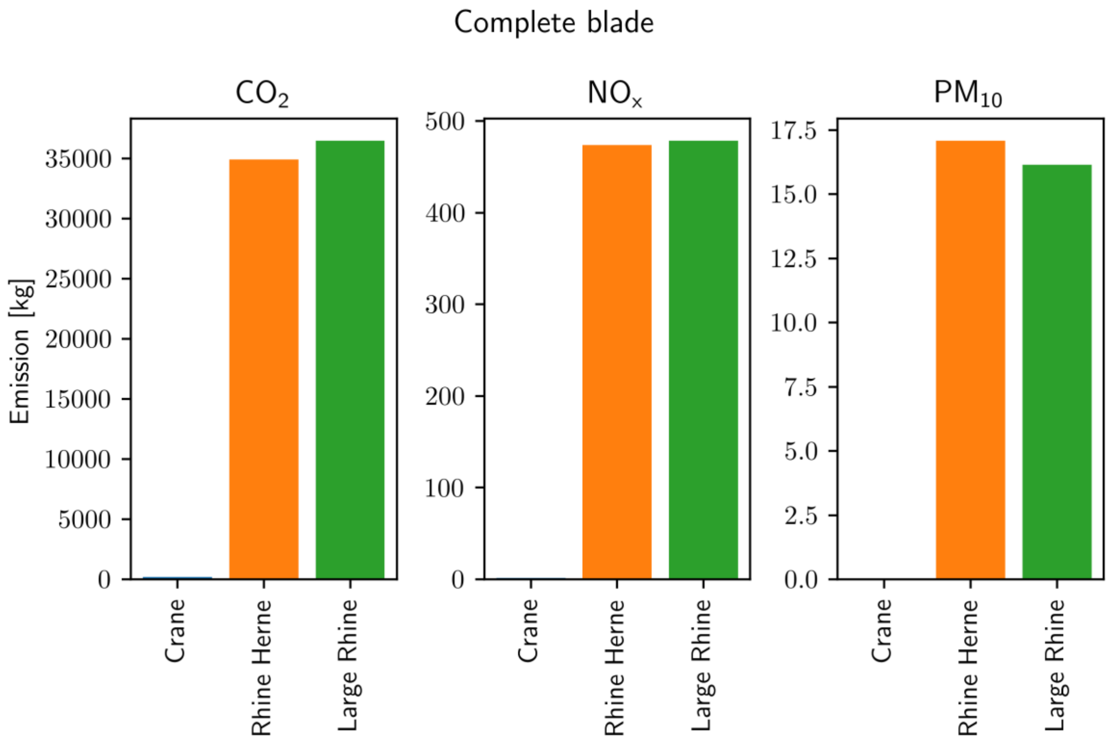

Figure 3.7: Emissions in kg for PAWP complete blade transport.

Table 3.11: Emission costs for PAWP complete blade transport.

Emission	Rhine-Herne canal (k€)	Large Rhine (k€)
CO_2	5	6
NO_x	17	17
PM_{10}	1	1
Combined	23	24
Percentage of total costs	11	11

In the case the blades are first shredded in the harbor the blade material is transported by 40-foot containers. Based on the density of the shredded material and the volume of the container, the total number of containers needed is estimated. It is assumed that the containers can be stored at the harbor waiting for transport. A total of 76 containers are needed for transport. Besides inland water transport, transport by truck is now also considered. Furthermore, it is assumed that a mobile shredder is used for the first stage of shredding. For the second stage, half the cost of shredding to 1-3 cm is applied. Loading and unloading of the containers are not included due to lack of information. Table 3.123 shows the cost of transport when the blade is first shredded. The number of trips for the vessels is reduced and therefore the transport costs. Transport by road is about an order of magnitude more expensive.

Table 3.12: Transport costs for inland water and road in case PAWP blades are shredded before transport.

Transport type	Number of trips	Total costs (k€)
Rhine-Herne canal vessel	2	2
Large Rhine vessel	1	1
Tractor + trailer	76	12

Table 3.13: Overview costs in case PAWP blades are shredded before transport.

Cost type	Rhine-Herne	Large Rhine	Tractor + trailer
Transport (k€)	2	1	12
Crane handling (k€)	6	6	6
Mobile shredding (k€)	53	53	53
Shredding 2nd stage (k€)	70	70	70
Total costs (k€)	130	130	140
Cost per ton (€/ton)	111	111	120

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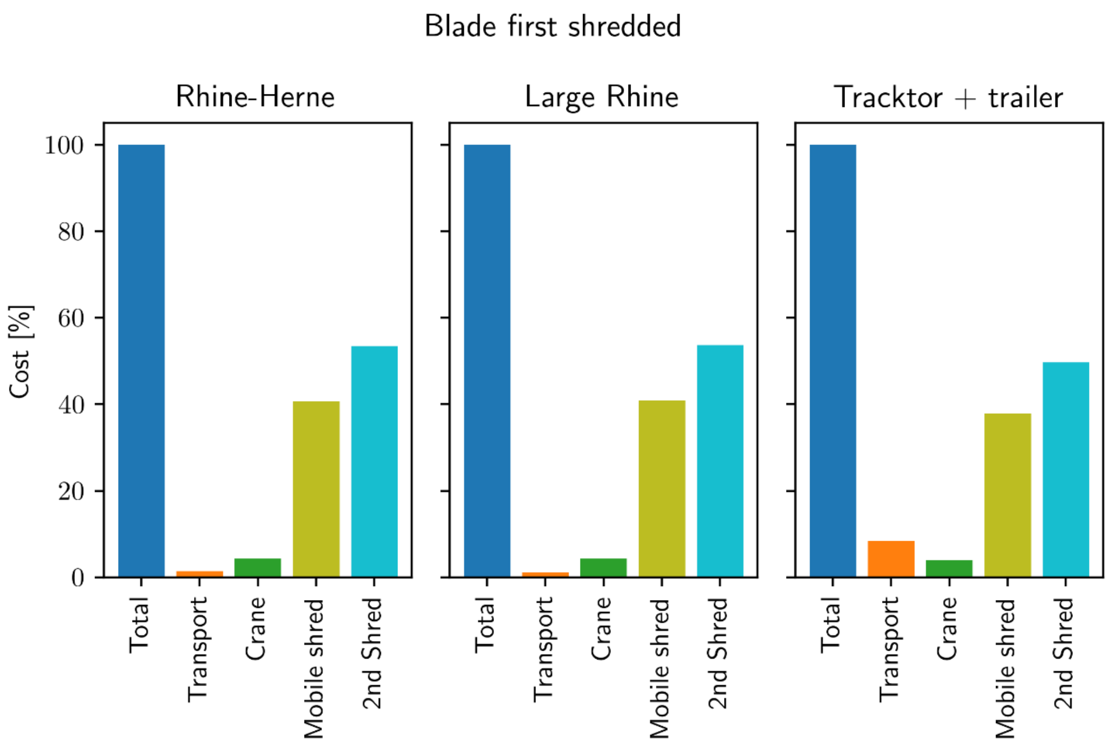

Figure 3.8: Overview of costs in percentage in case PAWP blades are shredded before transport.

Table 3.13 shows the costs when shredding first before transport. Now including transport by road. Figure 3.8 shows the contribution of the different activities to the total costs. Compared with the transport of a complete blade, the total costs are reduced. This is because the crane handling is half now since no crane handling occurs at Moerdijk. Note that no handling cost for the container to be loaded and unloaded is taken into account.

To have a better estimate there is a need for better information about the expected cost and duration of the different operations.

In Figure 3.9 the emissions in kg are given. Clearly, the CO_2 emission is dominated by tractor + trailer transport. The NO_x and PM_{10} emissions are most in case the Rhine-Herne canal vessel is used. In cost terms, NO_x emissions have the largest contribution to the total emission costs (see Table 3.14). Based on the number transport by road is the best from an emission point of view.

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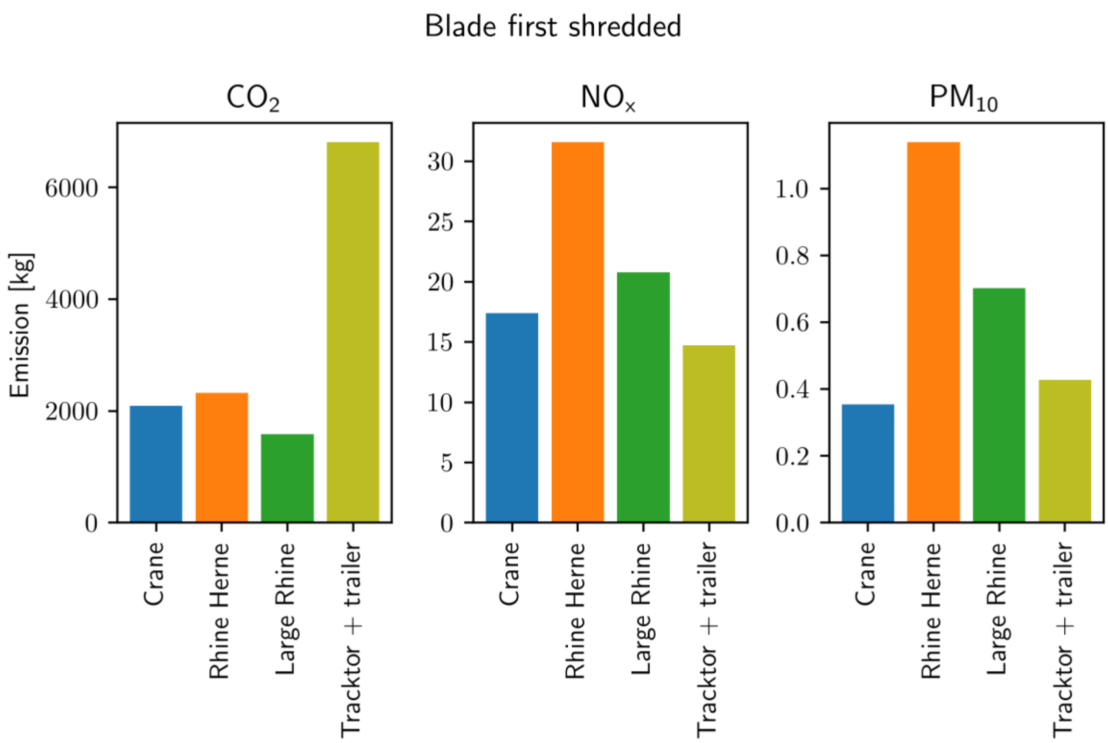

Figure 3.9: Emissions in kg for PAWP blades shredded before transport.

Table 3.14: Emission costs for PAWP blades shredded before transport.

Emission	Rhine-Herne canal (k€)	Large Rhine (k€)	Tractor + trailer (k€)
CO_2	1	1	1
NO_x	2	1	1
PM_{10}	0	0	0
Combined	3	2	2
Percentage of total costs	2	2	2

3.5.2 IJmuiden Ver Beta wind farm

The selected blade for the IJmuiden Ver Beta wind farm is B3 (see Table 2.1). The length of the blade is about 120m, and the mass is 65 ton. Besides the size of the blades, also the number of turbines (133) is larger than for the PAWP.

The same EoL scenario is considered for the IJmuiden Ver Beta wind farm as for the PAWP, again assuming that all WTBs of the farm follow the same EoL route. The most difficult part is that the wind farm will probably be decommissioned after 2050 in a zero-emission society.

Due to the blade length, it is impossible to ship the complete blade on an inland vessel. It should at least be cut in half. The blade root diameter of 5 m is about two containers wide. For transport, it is

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now assumed that a Rhine-Herne Canal vessel can transport two blades at a time, and a Large Rhine vessel a total of four.

In the scenario, the blade is unloaded on the quay where it is cut in half, and then each half is loaded on the selected inland vessel. Three crane handlings are needed for each blade in the Rotterdam harbor. In Moerdijk only two. Table 3.15 shows that the transport costs with a Large Rhine vessel are smaller but, due to the higher cost per km, less than the number of spared trips might suggest. Table 3.16 and Figure 3.10 clearly show that the total cost is dominated by the shredding process.

Table 3.15: Costs of inland vessel transport IJmuiden Ver complete blade.

Vessel type	Number of trips	Total costs (k€)
Rhine-Herne canal vessel	200	184
Large Rhine vessel	100	140

Table 3.16: Overview of total costs of complete blade transport IJmuiden Ver wind farm.

Cost type	Rhine-Herne	Large Rhine
Transport (k€)	184	140
Crane handling (k€)	62	62
Cutting (k€)	306	306
Shredding (k€)	3090	3090
Total costs (k€)	3641	3598
Cost per ton (€/ton)	140	139

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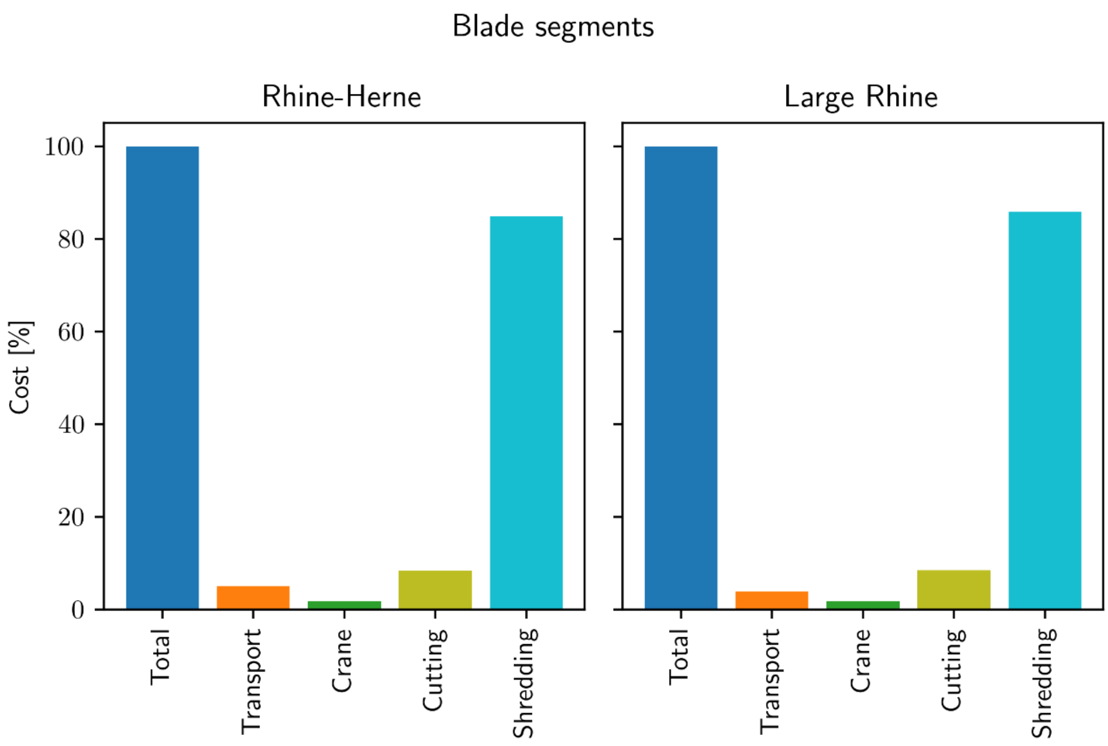

Figure 3.10: Overview of costs in percentage for IJmuiden Ver complete blade transport.

The emissions costs are given in Table 3.17. Figure 3.11.11 shows clearly that the emissions of the Rhine Herne canal vessel are the largest, and that transport by Large Rhine is preferred.

Table 3.17: Emission costs for IJmuiden Ver complete blade transport.

Emission	Rhine-Herne canal (k€)	Large Rhine (k€)
CO_2	36	24
NO_x	111	73
PM_{10}	9	6
Combined	156	103
Percentage of total costs	4	3

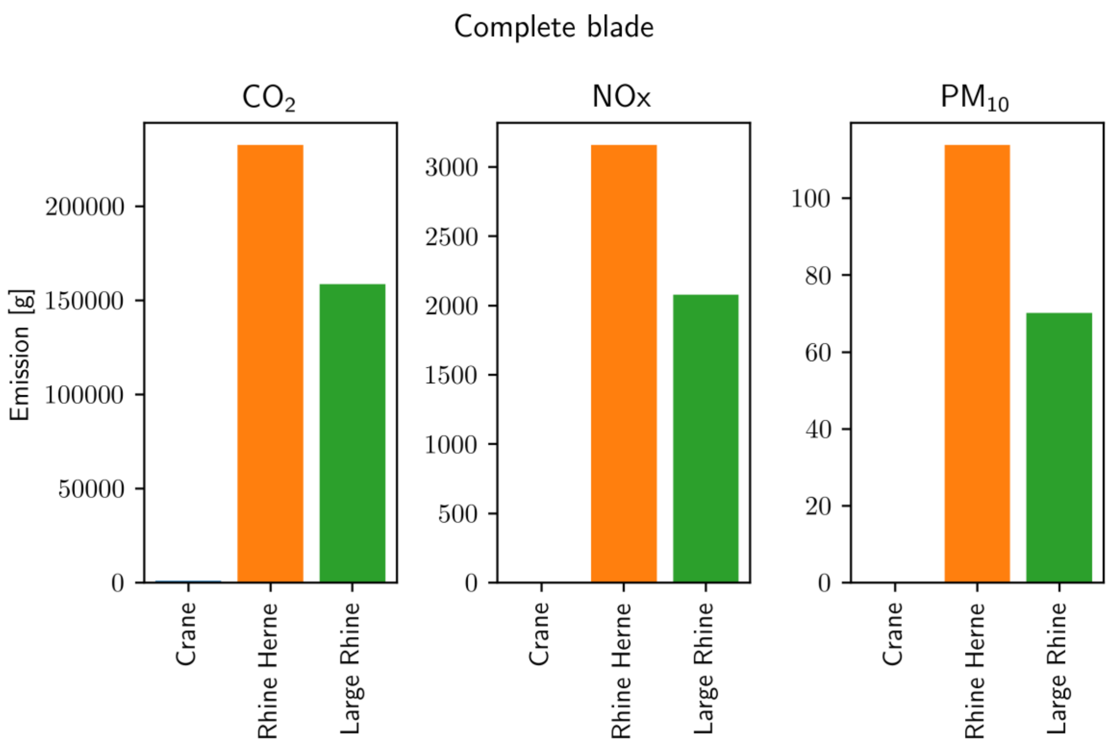

Figure 3.11: Emissions in kg for IJmuiden Ver complete blade transport.

In case the blade is first shredded before transport, a total of 1700 containers is needed. It is assumed that both vessel types can handle four layers of 40-foot containers. So, 54 containers on a Rhine-Herne vessel and 120 in a Large Rhine vessel. Again, shredding before transport is cheaper than transporting a complete blade. Table 3.18 shows that transport by tractor + trailer is ten times more expensive than transport by inland vessels. Table 3.19 and Figure 3.12 show that shredding adds most to the costs.

Table 3.18: Transport costs of IJmuiden Ver Beta wind farm blades in case of shredding before transport.

Transport type	Number of trips	Total costs [k€]
Rhine-Herne canal	32	29
Large Rhine vessel	15	21
Tractor + trailer	1700	265

Table 3.19: Overview of costs of Ijmuiden Ver Beta wind farm blades in case of shredding before transport.

Cost type	Rhine-Herne	Large Rhine	Tractor + trailer
Transport (k€)	29	21	265
Crane handling (k€)	12	12	12
Mobile shredding (k€)	1177	1177	1177
Shredding 2nd stage (k€)	1545	1545	1545
Total costs (k€)	2764	2755	2999
Cost per ton (€/ton)	107	106	116

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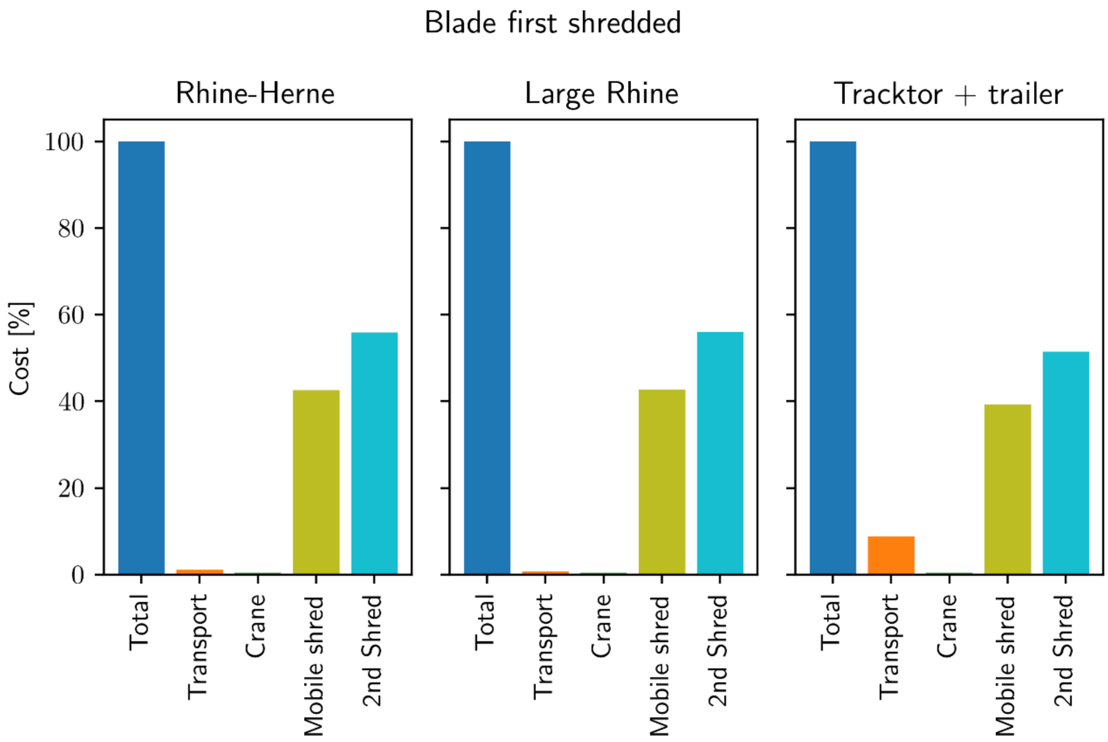

Figure 3.12: Cost in percentage for IJmuiden Ver blade shredded before transport.

Table 3.20: Emission costs for IJmuiden Ver blade shredded before transport.

Emission	Rhine-Herne canal (k€)	Large Rhine (k€)	Tractor + trailer (k€)
CO_2	6	4	23
NO_x	18	11	12
PM_{10}	1	1	1
Combined	25	16	36
Percentage of total costs	0.9	0.6	1.2

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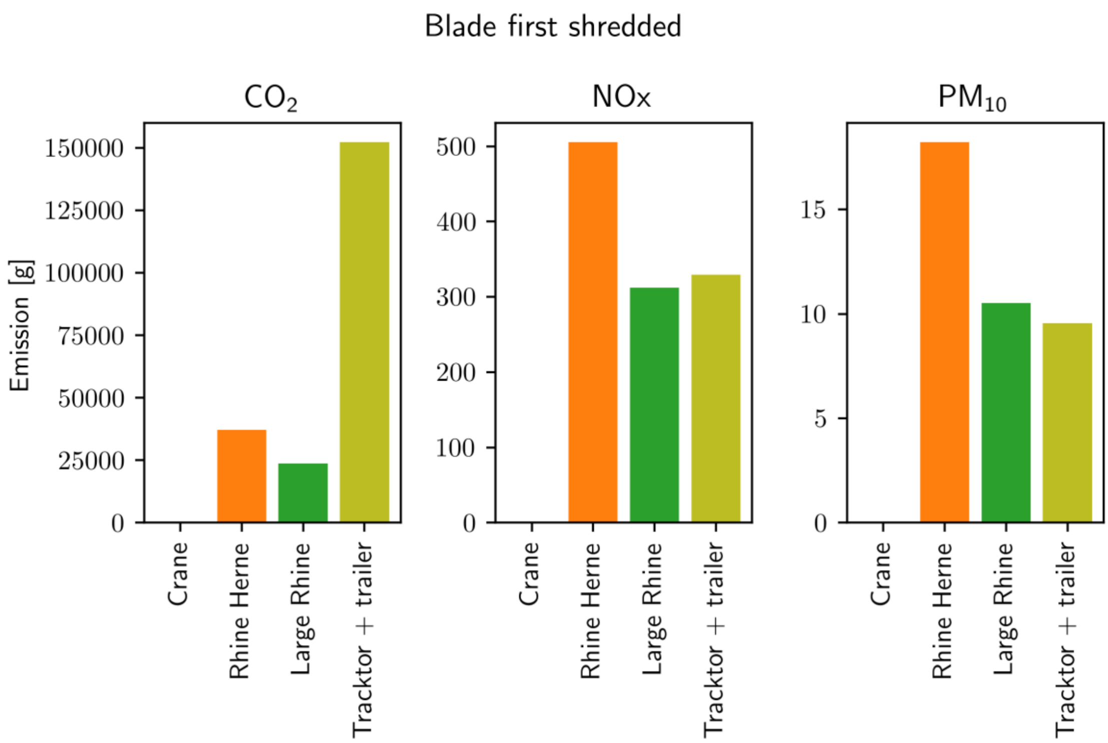

Figure 3.13: Emissions in kg for IJmuiden Ver blade shredded before transport.

Table 3.20 shows that, like in the PAWP case, the CO_2 emissions are dominated by tractor+trailer transport, while the NO_x and PM_{10} emissions are larger when the Rhine-Herne canal vessel is used.

3.6 Discussion

For the Dutch offshore wind farms PAWP and IJM VER, the turbines arrive in the harbour of Rotterdam and the blades are processed at the recycling facility located in Moerdijk (NL). Two cases are considered. One where the complete blade is transported to the recycling facility and one where the blades are shredded in the harbour of Rotterdam first.

The assessment is based on a calculation model to estimate the costs and the associated emissions. The model gives a first estimate and lacks detailed information about handling and related durations and costs. This is especially the case for the cutting and grinding process.

Based on the assessment of the two offshore wind farm scenarios the following conclusions can be drawn:

- If possible, transport of pre-processed blade material by water is preferred. Transporting complete blades will be considerably cheaper to transport with an inland vessel compared to transport over the road, where special transport ‘convoy exceptional’ is needed.
- Shredding has the largest contribution to the total costs of pre-processing and transport from the port to the EoL facility.
- There is limited practical data available on the costs and emissions of cutting and shredding of blades. Assumptions must be made about the duration, handling and use of types of equipment for certain processes.

- For the decision to transport complete plates or shredded blades, the most economical solution with the lowest emissions is shredding before transport by inland vessel.
- Comparison between the PAWP (180 x 6.5 ton blades) and IJM Ver wind farm (400 x 65 ton blades) the total blade volume for transport is respectively 76 compared to 1700 40 ft containers. With the larger blades, the crane lifting work will count less and the mass processed by the shredder will determine the total costs. Transport of complete blades with an inland vessel for the PAWP case is € 180/ton and IJM Ver € 140/ton. For the transport of shredded blade material, the difference between transport by road or over water is less. For PAWP, the costs are € 120/ton for using a truck and € 110/ton with an inland vessel. For the IJM Ver these costs are €116/ton and €107/ton respectively.
- The emission costs are about 10% for the PAWP complete blade transport. For the other cases, the emission costs are less than five percent of the total costs. Note that only crane handling and transport are considered.

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4 Public perception

4.1 Introduction

4.1.1 Background

Wind energy has grown into one of the leading sources of sustainable electricity [44], [45], [46]. The expected growth for the coming years will result in an increasing amount of wind turbines to be commissioned [47]. The wind energy sector has matured over the last few decades and consequently, research on and recycling of wind turbines, and specifically turbine blades, has increased [48]. However, as stated in the general introduction, the challenge to recycle the thermoset composite wind turbine blades will remain for the coming decades. The recycling of wind turbine blades from decommissioned wind turbines has therefore become a priority to maintain the sustainable reputation of wind energy [47].

Broad international attention on possible tens of thousands of old turbine blades that could end up in landfills has recently caused public resentment [49], [50]. Especially, the pictures of the Casper Regional Landfill in Wyoming from 2019 showing buried wind turbine blades and Bloomberg's following complaint in 2020 caught the public's attention [51]. The media play an important role in creating a public image of the sustainability of wind energy and wind turbines [48]. Furthermore, the responsibility of wind turbine producers is emphasized in the possible public backlash and damage to the reputation of wind energy as a clean energy technology, if the challenge of handling decommissioned wind turbines is not properly tackled [52], [53].

With growing attention in the Dutch media on the importance of recycling wind turbine blades [54], [55], [56], this research decided to focus on the public perception of the topic in the Netherlands. Wind turbines are expected to account for a large share of the 35 TWh of onshore sustainably produced electricity in the Netherlands in 2030 [57]. Especially onshore wind farms have been met with public resistance and have received much attention in the Dutch energy transition [58]. The public perception of a more circular approach to wind energy could provide valuable insights for the wind industry [59]. This, in turn, could lead to a better alignment among stakeholders such as policymakers, wind turbine owners and manufacturers, and the public.

Whilst the full life cycle assessment and the recycling of wind turbines have become a growing concern among the public and policymakers [60], [61], [62], the academic literature is mainly focused on the resistance toward the local development of wind farms as the main social-political challenge of wind farms [48]. So far two studies found only small effects of the recycling of wind turbines on the public perception and acceptance [63], [64]. In a survey in the Czech Republic, [63] found that recycling of wind turbines in general was not considered a major factor in the acceptance of wind farms. Furthermore, [64] showed the perception of the impact of wind turbines on the environment to be less strong than for the infrastructure of other energy technologies, such as nuclear power. However, considerations and questions on waste management and recycling are likely to play an increasingly important role in public perception in the near future due to the more frequent decommissioning of old wind farms.

The wind industry has been devoting more and more attention (and investments) toward circularity. Quite some research has been focusing on developing circular EoL solutions (e.g., [18]). Until now though, little research has considered the opinion of citizens on several possible stages of circularity

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or the possible reuse solutions of the composite materials of wind turbines and wind turbine blades, for example for bridges, playgrounds or furniture. To the best of our knowledge, only one study has so far found a positive effect on people's opinion of furniture that was made from blade composite material [48].

4.1.2 Aim and research questions

This research aims to identify the general and informed public perception of the current EoL outlook of wind turbine (blade) circularity in order to provide support in making decisions for the EoL process for a specific wind farm. Insights into whether people perceive the current EoL outlook of wind turbine (blade) circularity as positive or negative, people's knowledge on the topic, how relevant they think it is, and who should be responsible for circular solutions can provide additional knowledge to limited literature so far. Since there is a considerable knowledge gap on the complex topic of the recycling of wind turbine blades, we investigate the public perception in the Netherlands with an informed questionnaire. This method has derived from the methods of the informed opinion and informed choice questionnaire (e.g., [65], [66], and has been used previously in a similar study on green hydrogen [67]. In this type of questionnaire, respondents read extensive parts of factual and balanced information that have been reviewed by experts on a certain topic, before answering questions and expressing their opinions about that topic. When it comes to complex topics, uninformed opinions are thought to be unstable and possibly influencing the assessment, whereas informed opinions are more stable and predictive of future opinions [65], [66], [68].

Central to this research are the following research questions:

1. How do Dutch citizens perceive the current EoL outlook of wind turbine (blade) circularity?
2. What characteristics can explain Dutch citizens' public perception?

Next to answering these main research questions, we aim to address the following sub-questions:

3.1 To what extent are Dutch citizens aware of the present situation on wind turbine (blade) circularity?
3.2 Is wind turbine (blade) circularity important to Dutch citizens?
3.3 What would be Dutch citizens' preferred EoL routings for wind turbine blades?
3.4 Who do Dutch citizens think should be responsible for implementing wind turbine blade circularity?
3.5 Would Dutch citizens be willing to (financially) contribute to wind turbine blade circularity?

Gaining more knowledge regarding the public perception of the current EoL outlook of wind turbine (blade) circularity is important for several reasons. First, these insights can inform involved stakeholders in the wind industry and provide support in making decisions for the EoL process for a specific wind farm. Second, the insights from this research can indicate how possible risks resulting from negative public perception can be mitigated, as a negative public opinion about wind turbine (blade) circularity can have negative consequences for the development and implementation of circular strategies to reduce CO_2 emissions. Third and last, the Dutch general public can be informed about the present outlook of wind energy, its circularity, the different EoL options for wind turbines and wind turbine blades, and the open challenges associated with circular solutions.

4.1.3 Chapter outline

Section 4.2 presents the research method, including the development of the informed questionnaire. This is followed by a description of the empirical results in Section 4.3. Section 4.4 discusses our findings and comes to conclusions by addressing the research questions.

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4.2 Research method

This section describes the research method used in this study, covering its design, the recruitment of respondents including sample descriptions, and the methodologies followed to develop and conduct the questionnaire. The post-processing steps that have been performed to obtain the results are also presented.

4.2.1 Study design

An informed questionnaire has been developed to identify the public perception of the current EoL outlook of wind turbine (blade) circularity. A questionnaire enables an empirical investigation of the research questions, as it is suited to investigate the perception of a larger group of citizens and allows for a representative picture of the perception of Dutch society. In an informed questionnaire, respondents are prompted to read extensive parts of factual and balanced information, which have been reviewed by subject matter experts, before answering questions and expressing their opinions about that topic. Although the project team aimed to ensure the information was as balanced and factual as possible, we recognize that the text supplied might have resulted in a slight (positive) bias due to the project team's active involvement in the energy transition. For transparency, an English translation of the full questionnaire text has been reported in Appendix B. Informed questionnaire on public perception of wind turbine (blade) circularity (English version translated from Dutch).

4.2.2 Participants

From 13 June to 1 July 2024, market research agency Norstat[1], commissioned by TNO, conducted an online informed questionnaire among a representative sample of the Dutch population regarding gender, age, educational background and region. A total of 1522 panel members completed the questionnaire. After excluding the data of 49 respondents due to straightlining[2], the final sample consisted of 1473 respondents. See Table 4.1 for a comparison of the demographic characteristics of the sample with the Dutch population, from which we can conclude that the sample is sufficiently representative of the Dutch population.

Table 4.1: Gender, age, educational background, and region of residence of the Dutch population and the sample (n = 1473).

Demographic		Dutch population	Sample
Gender	Male	49%	47%
	Female	51%	53%
Age	*Mean*	42,6	49,5
	Standard Deviation	-	17.0
Educational background	Practical	20%	24%
	Intermediate	39%	33%
	Theoretical	41%	43%
Region of residence	North	10%	10%
	East	21%	19%
	West	45%	50%
	South	24%	21%

[1] https://norstat.co/nl

[2] (Nearly) identical answers to sub questions using the same response scale that included both positive and negative statements.

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4.2.3 Questionnaire development

Through conversations with different subject matter experts and a (grey) literature review, the project team gathered information on several topics related to the current EoL outlook of wind turbines and wind turbine circularity. The collected information was processed into brief information blocks understandable for lay people, and reviewed again by 11 experts among TNO staff and EoLO-HUBs partners with a multidisciplinary background to ensure accuracy. In addition, a graphic designer prepared several images that accompanied the information blocks to enhance comprehensibility. The questions were then developed and combined with the information blocks and images. The full questionnaire translated into English[3] is reported in Appendix B. Informed questionnaire on public perception of wind turbine (blade) circularity (English version translated from Dutch).

4.2.4 Data analysis

The data from the informed questionnaire were statistically analyzed using R [69]. Analyses to arrive at descriptive statistics have been carried out first. Subsequently, the differences in means of perception before and after information have been examined with paired samples *t*-tests.

Linear regression analysis has also been performed to analyze which predictors significantly explain variance in the perception of wind turbine circularity and wind turbine blade circularity. In the regression models, the after-information perception has been used as the dependent variable. The independent variables tested are: gender; age; educational background; objective knowledge; concern about climate change; attitude toward the energy transition; perception of onshore wind energy and offshore wind energy; stated importance of recycling; the effect of recycling wind turbines (blades) on climate change; responsibility of parties for implementing wind turbine blade circularity; and the willingness to (financially) participate. The model with the highest explained variance has been searched for based on the R^2-value.

Finally, the answers to the open-ended questions have been approached qualitatively, by inductively coding the responses according to a number of themes.

4.3 Results

This section presents the results of the informed questionnaire. The respondents' perception of onshore and offshore wind energy, circularity, and the recycling of wind turbines and wind turbine blades is analyzed first. It is then investigated whether these perceptions differ before and after information on the topics was provided. Finally, this section assesses to what extent respondents are aware of the present situation of wind energy circularity.

4.3.1 Perception before and after information provision

The following paragraphs present the respondents' perception of onshore wind energy, offshore wind energy, circularity, the recycling of wind turbines, and the recycling of wind turbine blades before and after information provision. In addition, for each topic it is investigated whether the information provision affected these perceptions by comparing responses before and after information blocks using paired samples *t*-tests.

[3] We translated the original Dutch version of the questionnaire, including the text blocks, to English with an online translator. Mind that this is a basic translation from Dutch and the quality of the text may be affected.

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4.3.1.1 Onshore and offshore wind energy

Before information was provided, almost two-thirds of the respondents (63%; see Figure 4.1) were (very) positive about onshore wind energy, whereas 14% were (very) negative. After information provision, 60% of the respondents (see Figure 4.1) were (very) positive about onshore wind energy, whereas 16% were (very) negative.

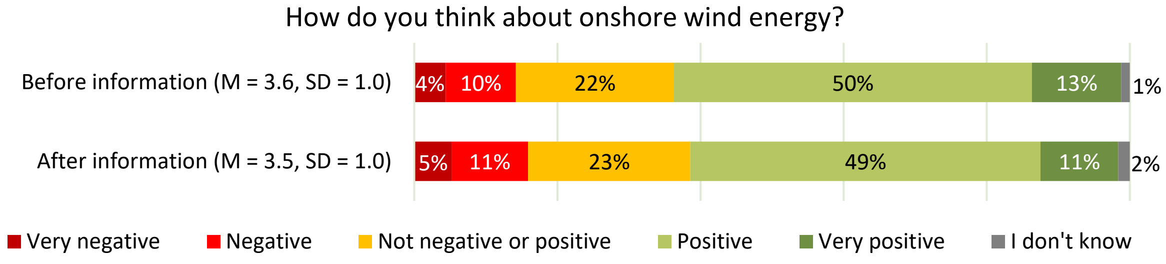

Figure 4.1: Perception of onshore wind energy before and after information (n = 1473).

The perception before and after information differed minimally but significantly, $t(1436) = -3.09$, $p = .002$, $d = -0.06$. The perception of onshore wind energy was slightly less positive after the information, compared with the perception before the information provision.

Before the information provision, three-quarters of the respondents (75%; see Figure 4.2) were (very) positive about offshore wind energy, whereas 11% were (very) negative. After information provision, still 75% of the respondents (see Figure 4.2) were (very) positive about offshore wind energy, whereas 10% were (very) negative.

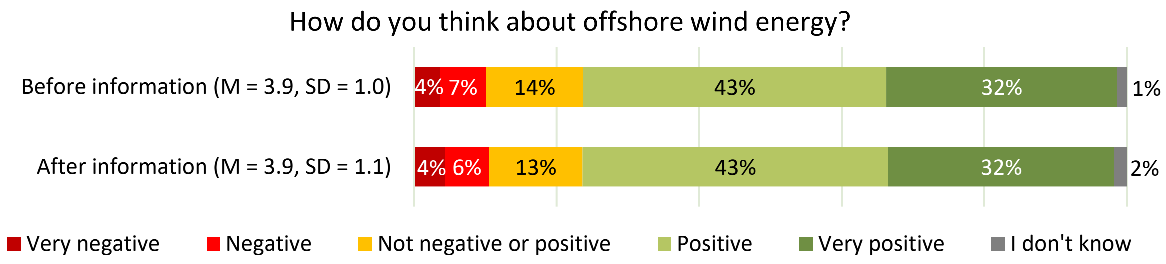

Figure 4.2: Perception of offshore wind energy before and after information (n = 1473).

No significant difference in the perception of offshore wind energy before and after information was found, $t(1430) = -1.10$, $p = .272$, $d = -0.02$.

4.3.1.2 Circularity

Before information was provided, two-thirds of the respondents (66%; see Figure 4.3) were (very) positive about circularity, whereas only 2% were (very) negative. Furthermore, 16% of the respondents did not know whether they were positive or negative about circularity. After information provision, 84% of the respondents (see Figure 4.3) were (very) positive about circularity, whereas still 2% were (very) negative. Only 4% of the respondents still did not know whether they were positive or negative about circularity.

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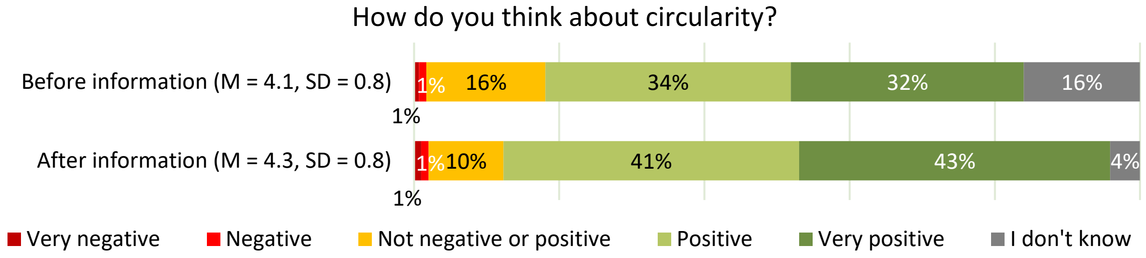

Figure 4.3: Perception of circularity before and after information (n = 1473).

The perception before and after information differed significantly, $t(1215) = 7.12$, $p < .001$, $d = 0.20$, indicating respondents were more positive about circularity after information was provided, compared with how they perceived circularity before the information provision.

4.3.1.3 Recycling of wind turbines and wind turbine blades

Before the information provision, 82% of the respondents (see Figure 4.4) were (very) positive about the recycling of wind turbines, whereas only 3% were (very) negative. After the information provision, 83% of the respondents (see Figure 4.4) were (very) positive about the recycling of wind turbines, whereas 4% were (very) negative.

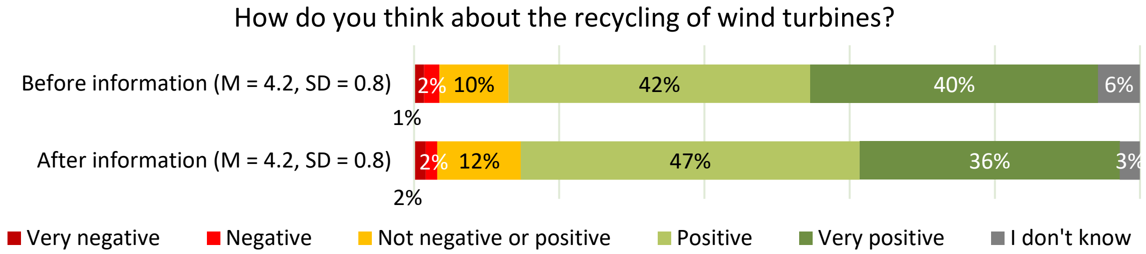

Figure 4.4: Perception of wind turbine recycling before and after information (n = 1473).

The perception before and after information differed minimally but significantly, $t(1363) = -2.74$, $p = .006$, $d = -0.07$. The perception of the recycling of wind turbines was slightly less positive after the information, compared with the perception before the information provision.

Before information was provided, 81% of the respondents (see Figure 4.5) were (very) positive about the recycling of wind turbine blades, whereas 4% were (very) negative. After the information provision, 78% of the respondents (see Figure 4.5) were (very) positive about the recycling of wind turbine blades, whereas 6% were (very) negative.

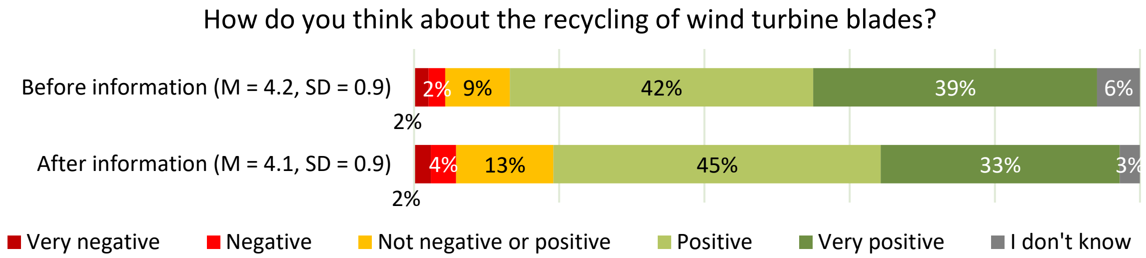

Figure 4.5: Perception of wind turbine blade recycling before and after information (n = 1473).

The perception before and after information differed significantly, *t*(1361) = -6.01, *p* < .001, *d* = -0.17, indicating respondents were less positive about the recycling of wind turbine blades after information was provided, compared with how they perceived wind turbine blade recycling before information provision.

Overall, respondents' perception of onshore wind energy was more negative than offshore wind energy, although both are perceived fairly positively in general. Onshore and offshore wind energy and the recycling of wind turbines and wind turbine blades were perceived slightly more negatively after receiving information on the topic, whereas respondents' perception of circularity was more positive after receiving the information.

4.3.2 Awareness of present situation on wind energy circularity

A small majority of the respondents (61%) estimated to have at least some knowledge of wind energy (see Figure 4.6). In contrast, many respondents estimated their own knowledge as (very) little on wind turbines (59%), circularity (55%), the recycling of wind turbines (84%) and the recycling of wind turbine blades (85%).

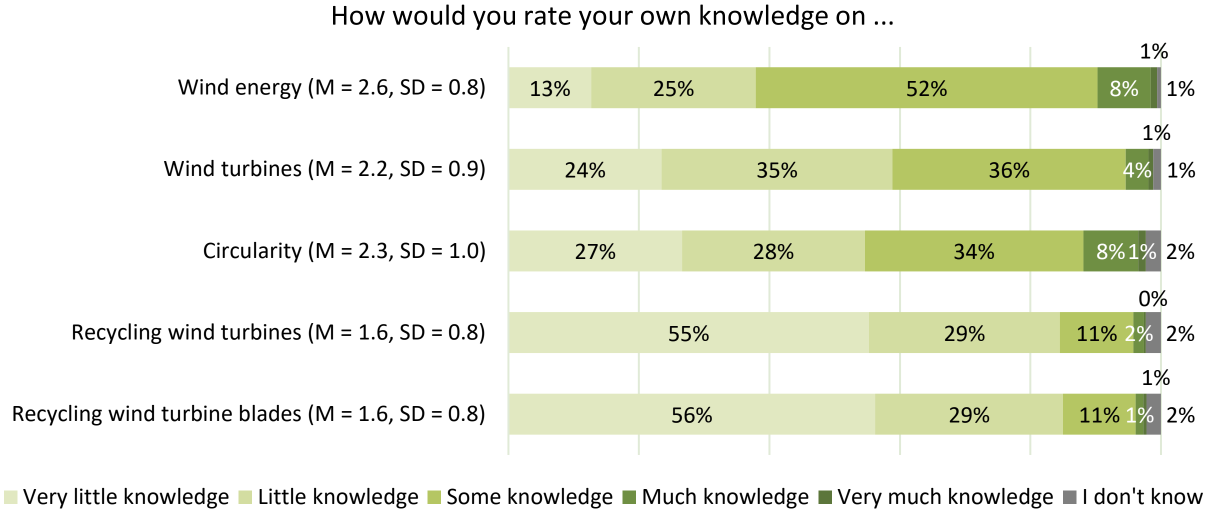

Figure 4.6: Subjective knowledge of wind energy, wind turbines, circularity, and wind turbine (blade) recycling (n = 1473).

Respondents estimated the recyclability of wind turbines very differently (see Figure 4.7): more than two-thirds of the respondents thought 50% or more could be recycled, and even a quarter thought more than 80% could be recycled. In addition, 3% of the participants thought wind turbines are fully recyclable, whereas 1% thought wind turbines are not recyclable at all.

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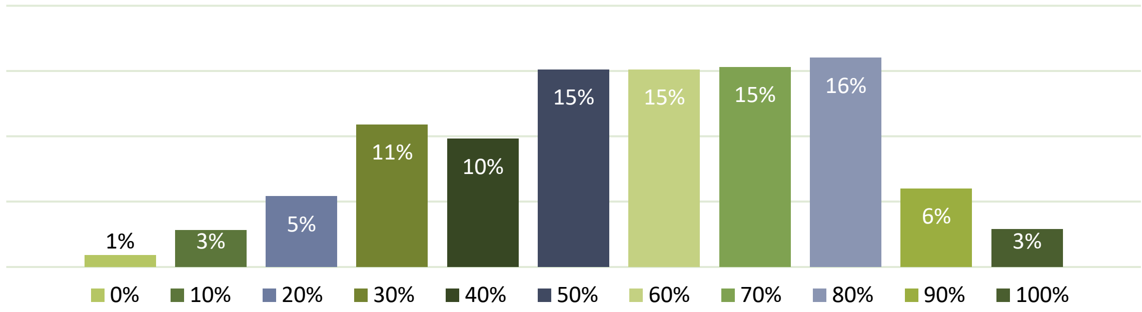

Figure 4.7: Objective knowledge on wind turbine recyclability: "What percentage of wind turbine components do you think is recyclable?" (n = 1473).

A large majority of respondents were not familiar with what happens with EoL wind turbines (77%, see Figure 4.8) and EoL wind turbine blades (85%, see Figure 4.9).

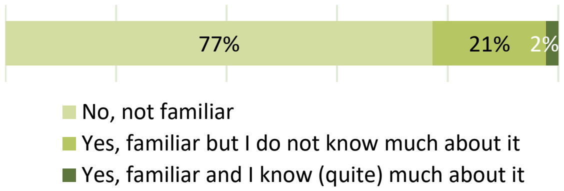

Figure 4.8: Familiarity with what happens to EoL wind turbines (n = 1473).

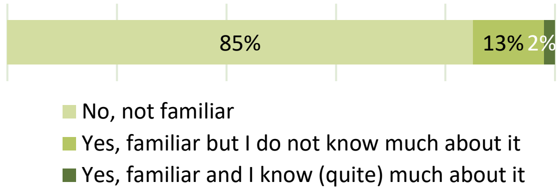

Figure 4.9: Familiarity with what happens to EoL wind turbine blades (n = 1473).

Overall, the estimated and actual knowledge level of respondents on wind turbines, circularity, the recycling of wind turbines and the recycling of wind turbine blades is rather low, as well as the familiarity with what happens with EoL wind turbines and wind turbine blades.

4.3.3 Importance of energy transition, wind energy and (wind) circularity

4.3.3.1 Attitudes toward climate change and the energy transition

Respondents were in general concerned about climate change (70%) and thought the impact of climate change on people in the Netherlands will be negative (67%). In addition, more than two-thirds of the respondents (73%) were positive about the energy transition (the shift from fossil fuels such as natural gas and coal to renewable energy sources such as solar and wind energy).

4.3.3.2 Role of wind energy in future energy system

A large majority of the respondents (78%) thought wind energy should have a reasonable to large role in the energy system of the future, whereas 3% thought it should have a small role (see Figure 4.10).

Figure 4.10: Role of wind energy in the energy system of the future.

When asked to elaborate on their opinion on the role of wind energy in the energy system, respondents were divergent in their responses. Despite open questions being optional, most

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participants provided an answer and five groups of respondents with consistent opinions have been identified:

- The first and fairly large group (n = 635) saw a large role for wind energy in the energy transition. They mentioned a combination of reasons: high wind energy potential in the Netherlands, higher energy demand in the future, wind is free to use and the best alternative when moving away from fossil fuels.
- The most commonly shared perspective of the second group (n = 395) was that wind energy would be a part of a mix of technologies. Many respondents in this group also saw disadvantages in wind energy, such as the financial costs, the waste even after recycling, the costs for nature, and birds specifically, and horizon pollution. They mainly see wind energy in addition to solar energy and or as a temporary solution until nuclear energy and hydrogen mature. Some have a preference for offshore wind energy instead of onshore.
- A third and small group (n = 22) did not express a strong opinion. Some mentioned that they lacked sufficient knowledge on the topic. Others saw an equal number of pros and cons, and they could not decide on which role wind energy should have in the future energy system.
- The fourth considerably large group (n = 133) was slightly negative. They mostly mentioned other technologies, mainly nuclear energy, as a more sustainable alternative for the future. Wind energy would take up too much space, there is too much dependency on wind and the fluctuation of energy damages the electricity grid. Some in this group distrust the government that favors wind energy with high subsidies, and some are living near a wind farm.
- The last and small group (n = 35) does not see any role for wind energy. There is no belief in the recycling of wind turbines, no trust in the energy transition in general, and the common opinion is that the costs would be too high, and it would only bring horizon pollution.

4.3.3.3 Importance of value retention and circularity

Value retention and circularity were important to most respondents: they (strongly) agreed with the statements that the depletion of raw materials should be prevented (93%), that the negative environmental impacts from the growing demand for raw materials must be avoided (90%), and that more attention needs to be given to repairing and recycling items (91%). To a lesser extent they thought it is important that the value of raw materials lasts as long as possible: 66% (strongly) agreed, whereas 15% (strongly) disagreed and 7% did not know. Moreover, a large majority of 82% indicated to take a positive view on the transition from a linear economy to a circular economy, compared with 5% that did not.

4.3.3.4 Importance of wind turbine (blade) circularity

Respondents highly valued the circularity of wind turbines and wind turbine blades: 90% of the respondents thought it is important that a proper solution is found for EoL wind turbines, and 91% thought the same about wind turbine blades. Similarly, 88% of the respondents (strongly) agreed that recycling wind turbines is an innovative way to make wind turbines more sustainable, and 80% (strongly) agreed on this regarding wind turbine blades. Furthermore, 59% of the respondents (strongly) agreed that recycling wind turbines helps to tackle climate change, whereas 14% (strongly) disagreed. Likewise, 58% thought recycling wind turbine blades helps to tackle climate change, whereas 11% (strongly) disagreed.

We see a more varied view on whether respondents thought recycling wind turbines takes comparatively a lot of effort for what it yields: 25% (strongly) disagreed, whereas also 25% (strongly) agreed, 30% neither agreed nor disagreed, and 21% did not know. A somewhat similar pattern is found for the recycling of wind turbine blades: 34% (strongly) disagreed on recycling taking comparatively a lot of effort for what it yields, whereas 13% (strongly) agreed, 29% neither agreed nor disagreed, and 24% did not know.

Respondents also varied in their satisfaction with how EoL wind turbines are currently handled (see Figure 4.11): 23% of the respondents (strongly) agreed on being satisfied, whereas 16% (strongly) disagreed, 29% neither agreed nor disagreed, and 32% did not know. Regarding the current handling of EoL wind turbine blades, only 8% indicated being satisfied, whereas 41% indicated not being satisfied, 30% neither agreed nor disagreed on being satisfied, and 21% did not know.

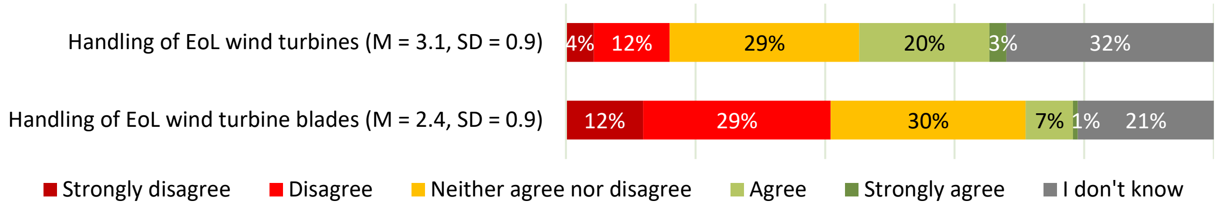

Figure 4.11: Satisfaction with current EoL solutions for wind turbines and wind turbine blades (n = 1473).

Specifically on the current handling of wind turbine blades, 66% of the participants (strongly) agreed with the statement that until there is a proper solution to handle the wind turbine blades, it is better to store the blades, rather than burn them or dump them in a landfill. To this statement, 7% (strongly) disagreed, 19% neither agreed or disagreed and 9% did not know.

4.3.3.5 Concern about recycling materials of wind turbines

Respondents had considerably fewer concerns about the recycling of concrete, steel, aluminum and copper, compared with the recycling of composites and rare earth materials. A small majority of the respondents indicated having (very) few concerns about the recycling of concrete (55%), steel (60%) and aluminum and copper (57%). In contrast, half of the respondents indicated to have many or lots of concerns about the recycling of composites (47%) and rare earth materials (50%).

When the respondents who answered to have many or lots of concerns were asked why they are concerned about the recycling of those materials, they provided divergent responses. However, five main themes were mentioned. Respondents indicated these concerns were due to the **perceived difficulty of recycling** all the materials and the **perceived high financial and energy costs** involved in recycling aluminum and copper, composites and rare earth materials, and because they think the use of concrete, steel, aluminum and copper, and composite materials **is polluting and leads to a lot of emissions**. Also, respondents said to have concerns because they **know too little about the recycling** of concrete, composites and rare earth materials. For aluminum and copper and rare earth materials respondents indicated these concerns were due to these **materials running out**.

4.3.3.6 Importance in composite material processing solution

When asked whether financial costs or a sustainable solution is most important regarding methods for processing composite materials from EoL wind turbine blades, most respondents preferred either an equal balance between financial costs and sustainability (50%) or a sustainable solution (44%; see Figure 4.12). Only few respondents (6%) thought financial costs are more important.

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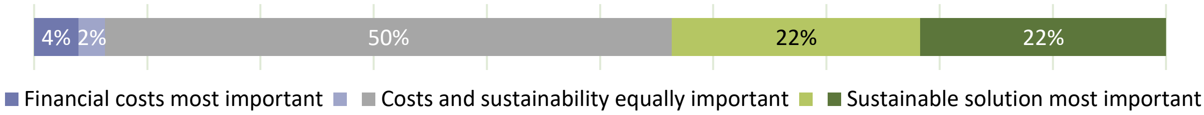

Figure 4.12: Importance of financial costs vs. sustainable solution in processing methods for composite materials (n = 1473).

Overall, respondents foresaw a fairly large role of wind energy in the energy system of the future, as part of a mix of technologies, due to the high wind energy potential in the Netherlands, being free to use and a good alternative when moving away from fossil fuels. Furthermore, value retention and circularity were found to be important, and the circularity of wind turbines and wind turbine blades is highly valued. Respondents were divided on whether recycling wind turbines and wind turbine blades takes comparatively a lot of effort for what it yields, and varied in their satisfaction with how EoL wind turbines and wind turbine blades are currently handled. Most respondents would rather store EoL wind turbine blades than burn them or dump them in a landfill until a proper handling solution is found. Respondents were most concerned about the recycling of composites and rare earth materials and had considerably less concerns about the recycling of concrete, steel, aluminum and copper. Most preferred an equal balance between financial costs and sustainability or a sustainable solution regarding methods for processing composite materials from EoL wind turbine blades.

4.3.4 Preferred EoL routings for wind turbine blades

A large majority of respondents thought noise barriers along highways (85%), bicycle racks (80%), and components of a bridge (75%) are good solutions for reusing EoL wind turbine blades (see Figure 4.13). Fewer respondents, but still a majority, (strongly) agreed that components in playgrounds (64%) and designer furniture (58%) would be good solutions for reusing EoL wind turbine blades.

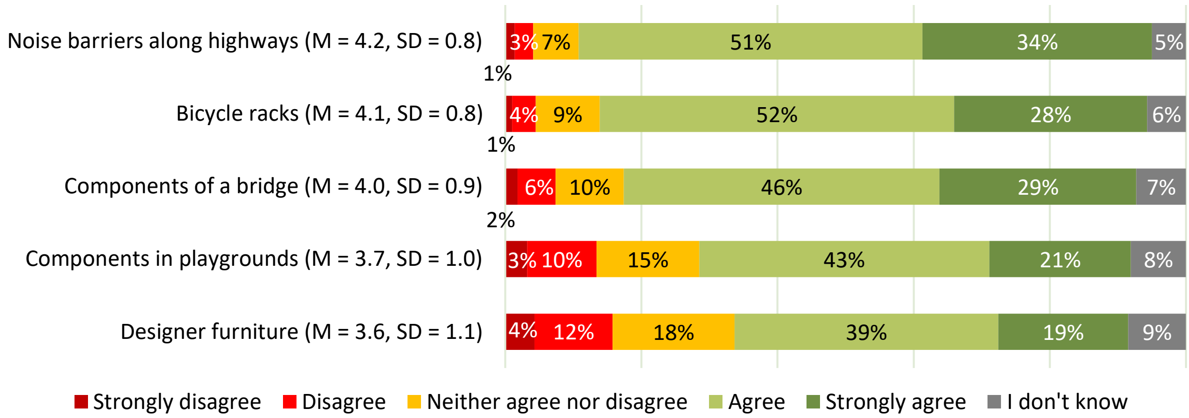

Figure 4.13: Perception of proposed solutions for repurposing EoL wind turbine blades (n = 1473).

In addition, when asked whether respondents themselves have original solutions for reusing EoL wind turbine blades, they proposed to reuse them for new wind turbine blades or use the wind turbine blades in the construction sector, in means of transport (plane, car, boat, bicycle, surfboard), for infrastructure (highways, crash barriers, bridges, road signs), as art or for artists, in outdoor spaces (benches, playgrounds, bus shelters, planters, garden furniture, skate parks), as partitions or fences, for the reinforcement or raising of dykes or sheet piling, and as canopy or roofing.

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Moreover, a large majority of respondents thought it is a good solution to reuse parts of the composite material from wind turbine blades (after grinding, chemically dissolving, or thermally separating them) for new wind turbine blades (88%), car components (74%) and smartphone cases (71%; see Figure 4.14). Fewer respondents, but still a majority, (strongly) agreed on reusing parts of the composite material from wind turbine blades for sailing boats (68%Figure 4.13), as part of cement (63%) and packaging material (58%).

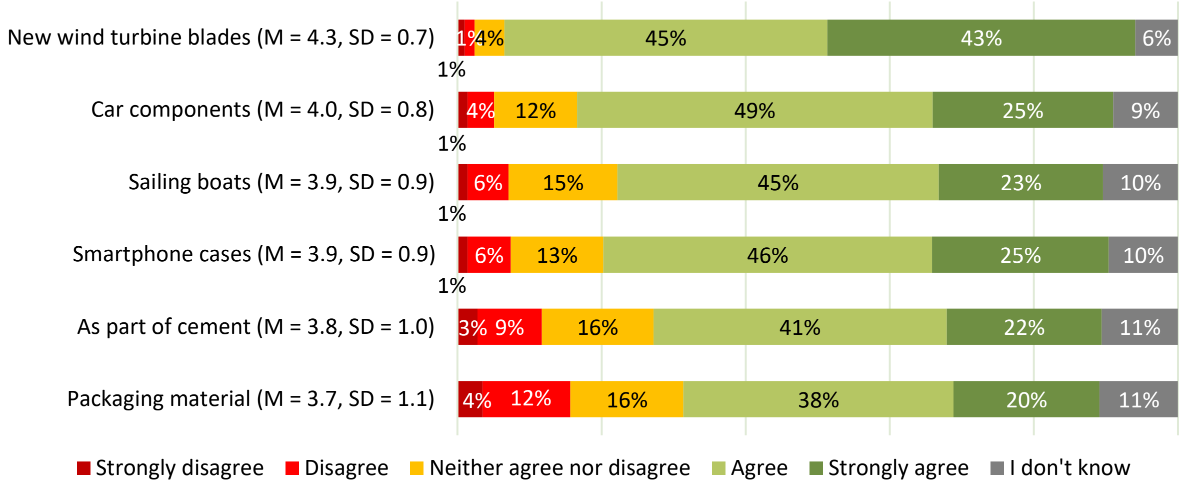

Figure 4.14: Perception of proposed solutions for composite material of EoL wind turbine blades after grinding, chemically dissolving or thermally separating.

4.3.5 Responsibility for implementing wind turbine blade circularity

Respondents did not think one specific stakeholder is fully responsible for finding a proper solution for EoL wind turbine blades. A large majority of respondents thought owners of wind farms (81%), manufacturers of wind turbines (80%), and the national government (76%) are the most responsible (see Figure 4.15). Fewer respondents, but still a majority, (strongly) agreed that energy suppliers (68%) and the European Union (68%) are responsible, while universities and research institutes (52%) were thought of as the least responsible for finding a proper solution for EoL wind turbine blades.

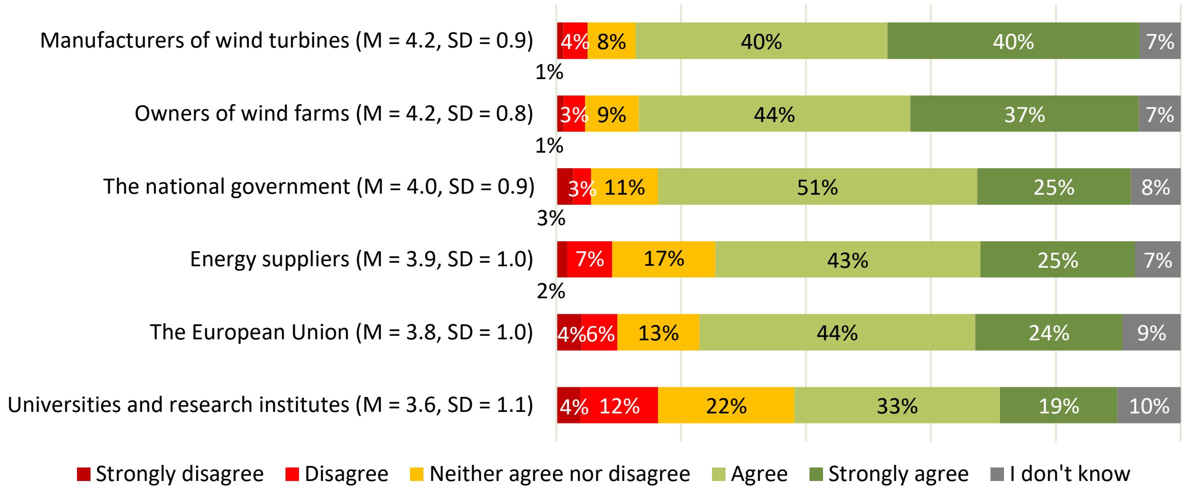

Figure 4.15: Perception of the responsibility for finding a proper solution for EoL wind turbine blades (n = 1473).

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4.3.6 Willingness to (financially) contribute to wind turbine (blade) circularity

Almost half of the respondents (46%) would not be willing to pay a higher price for electricity generated by fully circular wind turbines, whereas 24% would be and 26% neither agreed nor disagreed on willing to pay a higher price. Furthermore, a majority of 66% of respondents was fine with the government using their tax money to invest in finding a solution for EoL wind turbine blades, whereas 13% (strongly) disagreed and 18% neither agreed nor disagreed on being fine. Also, almost half of the respondents (46%) would not prefer the government spend money on installing more wind turbines rather than recycling wind turbines, whereas 11% would be ok with it and 37% neither agreed nor disagreed.

After respondents went through all the information blocks, 30% of the respondents indicated to be willing to accept wind turbines near their town or village, 23% would like to buy shares of electricity generated by a wind turbine, and 13% would like to join an energy cooperative (see Figure 4.16).

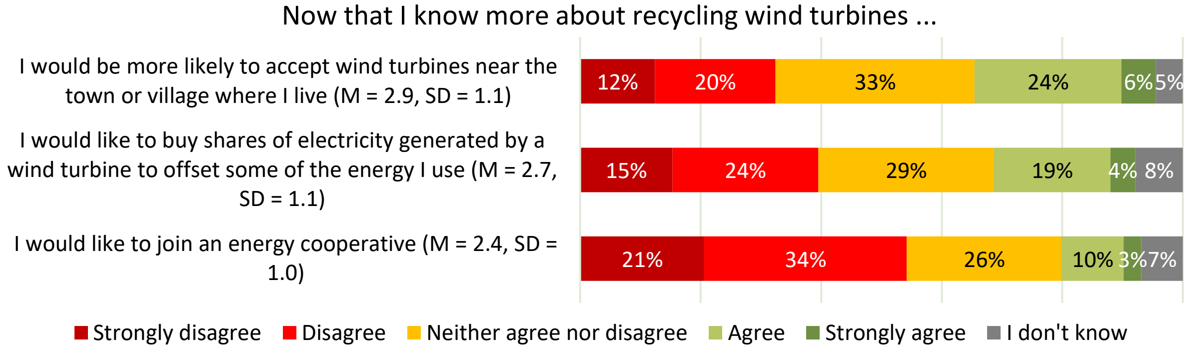

Figure 4.16: Willingness to contribute when knowing more about recycling wind turbines (n = 1473).

4.3.7 Characteristics explaining perception of wind turbine (blade) circularity

Two linear regression analyses have been performed considering the variables listed in Section 4.2.4. However, the outcome is inconclusive as it was not possible to determine with reasonable certainty which characteristics could explain the perception of wind turbine circularity and wind turbine blade circularity. For the interested reader, the full results of the regression analyses investigating the relationship between the perception of wind turbine circularity and wind turbine blade circularity, and the possible explanatory variables are presented in Appendix C.

4.4 Discussion and conclusions

This section discusses the main findings from the questionnaire and addresses the research questions defined at the beginning of this study (see Section 4.1.2). The role of possible explanatory variables of perception is also discussed along with the main limitations of this study and suggestions for follow-up research.

4.4.1 Answering the research questions

4.4.1.1 Public perception of the current EoL outlook of wind turbine (blade) circularity

How do Dutch citizens perceive the current EoL outlook of wind turbine (blade) circularity? – It has been found that the public perception is quite positive in general. This holds for both wind turbine recycling and wind turbine blade recycling, with minor changes before and after information on the topics was provided.

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Interestingly, although information does not have a large impact on how respondents perceive wind turbine (blade) circularity, a slight change toward a less positive perception of the topic after the information provision has been observed. Possibly just by learning more about how difficult recycling currently in fact is, the challenges involved and the issues regarding different materials, respondents might have actually become a bit more negative. It is notable that the level of knowledge about wind energy seemed quite high in the sample, whether due to the information given or not, which in general presumably allowed respondents to argue well-informed on the topic and express well-reasoned opinions.

4.4.1.2 Characteristics explaining public perception of the current EoL outlook of wind turbine (blade) circularity

What characteristics can explain Dutch citizens' public perception? – Unfortunately, a confident answer to which characteristics explain the perception of wind turbine circularity and wind turbine blade circularity has not been found. Based on two linear regression analyses, the measured variables in our dataset were only able to explain 30% of the variance in the perception of wind turbine circularity, and 29% of the variance in the perception of wind turbine blade circularity (see Appendix C). Approximately 70% of the variance remains unexplained, indicating that there may be still many unmeasured factors that could better explain the perception (see Section 4.4.2.4).

4.4.1.3 Awareness of present situation on wind energy circularity

Respondents are to a large extent not aware of the present situation of wind energy circularity, and how EoL wind turbines and blades are currently handled. Although respondents stated to have at least some knowledge of wind energy, the estimated knowledge of wind turbines, circularity, and the recycling of wind turbines and wind turbine blades is generally little. A large majority said not to be familiar with the recycling of EoL wind turbines and blades. Only a quarter of the respondents knew indeed that more than 80% of wind turbines can be recycled. The respondents that seem to be familiar with the current EoL practices were, however, mainly negative about the current handling of wind turbines and their blades: almost a quarter of respondents are satisfied with the current handling of EoL wind turbines, while for wind turbine blades this is only 8%.

4.4.1.4 Importance of circularity and wind turbine (blade) circularity

In general, value retention and circularity are considered important, as almost all respondents agree on preventing the depletion of raw materials and think more attention is needed for repairing and recycling items. In addition, transitioning from a linear to a circular economy is viewed positively.

Furthermore, the circularity of wind turbines and wind turbine blades is considered relevant and important. Almost all respondents stress the importance of finding a good solution for EoL wind turbines and blades, and a large majority of respondents think recycling wind turbines and blades is an innovative way to make them more sustainable.

Overall, there is not much concern about the recycling of concrete, steel, aluminum and copper, whereas there is much concern about the recycling of composites and rare earth materials. Concerns were mainly due to the perceived difficulty of recycling the materials, the perceived high financial and energy costs involved in recycling, the materials running out, because using the materials is polluting and leads to a lot of emissions, or knowing too little about the recycling.

Half of the respondents believe financial costs and sustainability are equally important when choosing between methods to process composite materials from wind turbine blades, while a large portion of the other half prefers sustainability over financial costs.

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4.4.1.5 Preferred EoL routings for wind turbine blades

Respondents preferred EoL routings for repurposing wind turbine blades are: noise barriers along highways, bicycle racks and components of a bridge, whereas components in playgrounds and designer furniture are somewhat less popular solutions (among those provided). Other, self-conceived solutions include reusing the blades in new turbines, using the wind turbine blades in the construction sector, for infrastructure, as art, in outdoor spaces, as partitions or fences, for the reinforcement or raising of dykes or sheet piling, and as canopy or roofing.

Recycled elements of the composite material from EoL wind turbine blades are preferred to be used in new wind turbine blades. Reusing the composite material parts in car components, sailing boats, smartphone cases, as part of cement, and in packaging material is somewhat less favored.

4.4.1.6 Responsibility for implementing wind turbine blade circularity

Although not one specific stakeholder is considered fully responsible for finding a proper solution for EoL wind turbine blades, the national government, owners of wind farms and manufacturers of wind turbines are seen as most responsible for implementing wind turbine circularity. The European Union and energy suppliers are perceived as less responsible, while universities and research institutes are thought of as least responsible.

4.4.1.7 Willingness to (financially) contribute to wind turbine (blade) circularity

There seems to be a rather low willingness to contribute to wind turbine (blade) circularity. With more knowledge on the recycling of wind turbines and blades, the acceptance of wind turbines in the neighborhood, and the willingness to buy shares of wind-generated electricity and to join an energy cooperative are still quite low. Almost half of the respondents are not willing to pay more for electricity generated by fully circular wind turbines, while they prefer the government to spend money on recycling wind turbines rather than installing more wind turbines. Two-thirds of respondents agree with the government using tax money to invest in finding a solution for EoL wind turbine blades.

4.4.2 Research limitations and future research

4.4.2.1 Length and intensity of questionnaire and respondents' understanding of information

The questionnaire demanded a lot from respondents as it included lengthy text sections dense with information and a considerable number of questions requiring critical thinking. Possibly this has been difficult for multiple respondents. A potential drawback of this research method is therefore the difficulty in ensuring that respondents have thoroughly read and understood the information provided. To mitigate the risk of respondents ignoring the information blocks, a minimum reading time was set before allowing respondents to proceed to the questions. Also, several sanity checks have been performed on the data to ensure quality. A qualitative but encouraging fact is the relatively high response rate to the optional open questions and the rational answers provided by the vast majority of respondents. Despite all, it is important to consider the possibility of incomplete comprehension by respondents when interpreting the results.

4.4.2.2 Lack of detailed information on topics

The environmental impact of the recycling process of wind turbine blades has not been quantified and was thus not part of the information in the questionnaire. Also, expert information on existing technologies and methods used for recycling wind turbine blades (e.g. grinding, chemically dissolving, or thermally separating the composite materials) was deliberately withheld, as it was anticipated that it would be too complicated to understand. Moreover, to mitigate the dropout risks of a long questionnaire, information on certain topics was limited to the essentials. This lack of information might not allow respondents to fully assess the extent to which they think recycling wind turbine (blades) is necessary, positive or negative, etc. Hence, it is suggested to further investigate the public perception again regarding several aspects of recycling wind turbine blades (perhaps with a different method) to validate the findings of this study and gather information on the perception of different technologies and methods used, which were not part of the current questionnaire.

4.4.2.3 Measurement of (informed) perception

Small but significant differences in the measurements of perception before and after providing the information have been found, indicating that the results vary when perception is measured with or without prior information. Causal inference that respondents' perception changed *because* of the expert information cannot be made. No experimental setup was used to ensure participants were not influenced by other factors than the expert information. An experimental setup and conducting longitudinal research where perception is monitored over a longer period to determine how it changes over time, are suggestions for future research. The latter might be important as people state they do not know much about the recycling of wind turbines and their blades, implying that for example media coverage could potentially influence the responses.

4.4.2.4 Unexplained variance in perception

The regression analyses performed on the perception of wind turbine circularity and wind turbine blade circularity showed that only 30% and 29% of the variance, respectively, could be explained by all independent variables together. This means there is still approximately 70% of unexplained variance. Although the results appear to be relatively robust, tested by adding and removing several independent variables measured in our dataset, it is anticipated that the regression outcomes may alter when incorporating additional relevant variables not measured. Examples of variables that could play a role are the political orientation, as well as the distribution of costs and benefits of wind turbine circularity, or the trust in organizations related to the recycling of EoL turbines and blades, as was found in similar research on green hydrogen [67]. A suggestion for further research would be to examine how people view the costs and benefits of wind turbine (blade) recycling, as well as the distribution of the costs and benefits. Moreover, it would be interesting to measure the extent to which people trust the stakeholders involved in wind turbine (blade) recycling and their capabilities to achieve a more circular industry. In future research, conducting interviews with citizens before or during the development of the questionnaire could provide a deeper ex-ante understanding of the factors that influence their thinking.

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5 Conclusions and discussion

Based on the study of technical, economic, environmental, and social challenges and opportunities of WTB life cycle management from cradle to cradle, the following conclusions can be drawn:

5.1 Estimation of discarded blade volumes and materials

- There is uncertainty about when and how much discarded blade material will become available for recycling. The main reason is that decisions about the possible reuse of the blades, lifetime extension or decommissioning of a wind farm are made at a late stage. For future wind farms, also the mass and number of blades that will be installed are uncertain and estimates should be based on the latest development trends;
- It is expected that the decommissioning of offshore wind turbines will result in less material flow uncertainty, because these decommissioned turbines will most likely not be reused and because the operational lifetime of an offshore wind farm is more predictable than onshore wind farms;
- The design of the blade and the materials used are important in determining the optimal EoL route. The older generation of blades (1970s) contains PVC, which is a limitation for pyrolysis. Modern blades use carbon fiber, which provides added value in terms of environmental impact (carbon footprint) and sales price when recycled, but it requires complex material separation in the EoL process to guarantee recyclability;
- Future circular blade designs will see a greater diversity of materials applied with a specific EoL solution. This can be a limitation when setting up large-scale EoL facilities based on standard designs.

5.2 EoL process diagram

- To determine the effects of EoL solutions on costs, environment and social perception, the EoL flow diagram has been developed based on the cradle-to-cradle life cycle of present and future wind turbine blades. There is still limited practical experience and data available, especially with the decommissioning of large offshore wind farms;
- Developments in size and design of turbines and blades are happening very quickly, which has a major impact on current and future EoL routes. The EoL flow diagram maps the possible processes and logistics routes currently applied or being developed for large-scale use;
- For the current situation, pre-processing of blades offshore is not realistic due to the high costs and the limitations concerning material particles released during sawing or cutting. In the future, modular blades and/or solutions where the blade can be segmented onsite would result in lower costs and emissions when using smaller cranes and more efficient transport of blade material to the port;
- For the cradle-to-cradle route, material from the blade is reclaimed and used in a new blade. Due to the high performance requirements of the composite material used in blades, the new production of glass fibers and upgrading of carbon fiber of current blade designs will be the preferred routes. Reversible resins or recycled chemical building blocks reclaimed from the used resins can be reused, providing an example pathway for a new generation of circularly designed blades.

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5.3 Scenario assessment

Based on the assessment of the two offshore wind farm (PAWP and IJM Ver) scenarios the following conclusions can be drawn:

- If possible, transport of pre-processed blade material by water is preferable. Transporting complete blades will be considerably cheaper with an inland vessel compared to transport over the road where special transport permits ('convoy exceptional') are needed;
- Shredding has the largest contribution to the total costs of pre-processing and transport from the port to the EoL facility;
- There is limited practical data available on the costs and emission footprint of blade cutting and shredding activities. Assumptions must be made about the duration, handling and use of types of equipment for certain processes;
- For the decision to transport complete or shredded blades, the most economic solution with the lowest emissions is shredding before transport by inland vessel;
- Comparing the PAWP (180 x 6.5 ton blades) and IJM Ver wind farm (400 x 65 ton blades), the total blade volume to be transported in units of 40 ft containers is 76 compared to 1700, respectively. With the larger blades, the crane lifting work will count less and the mass processed by the shredder will determine the total costs. Transport of complete blades with an inland vessel for the PAWP case is €180/ton and IJM Ver €140/ton;
- For the transport of shredded blade material, the difference between transport by road or over water is less. For PAWP, the costs are €120/ton using a truck and €110/ton with an inland vessel. For the IJM Ver these costs are €116/ton and €107/ton respectively;
- The emission costs are about 10% for the PAWP complete blade transport. For the other cases, the emission costs are less than five percent of the total costs. Note that only crane handling and transport are considered.

5.4 Public perception

The following conclusions can be drawn based on the public perception study amongst a representative sample of Dutch citizens:

- The public perception of the current EoL outlook of wind turbine and blade circularity in the Netherlands is rather positive;
- Concerns exist mainly about the recycling of composites and rare earth materials;
- There is a general preference for reusing wind turbine blades and parts of the composite material in the blades in new wind turbine blades to other offered options;
- Owners of wind farms, manufacturers of wind turbines and the national government are seen as most responsible for finding a proper solution for EoL wind turbine blades;
- There appears to be less preference for directly contributing (financially) to fully circular wind turbines, while there is mostly agreement on a governmental investment in circular solutions for EoL wind turbine blades via tax money.

5.5 Recommendations for future research

- To optimize transport and preprocessing of the wind turbine blades, it must be investigated whether cutting and shredding can also be carried out offshore on the deck of a vessel or even cut the blade attached to the turbine;
- Assessment of costs and environmental impacts for future WTBs designed for circularity with circular materials and design solutions (reversible resins, modular designs, etc.);

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- Explore in more detail the different cutting and shredding methods for WTB applications;
- Expanding and comparing the research on public perception with data from other countries such as Spain, UK, Denmark, etc.

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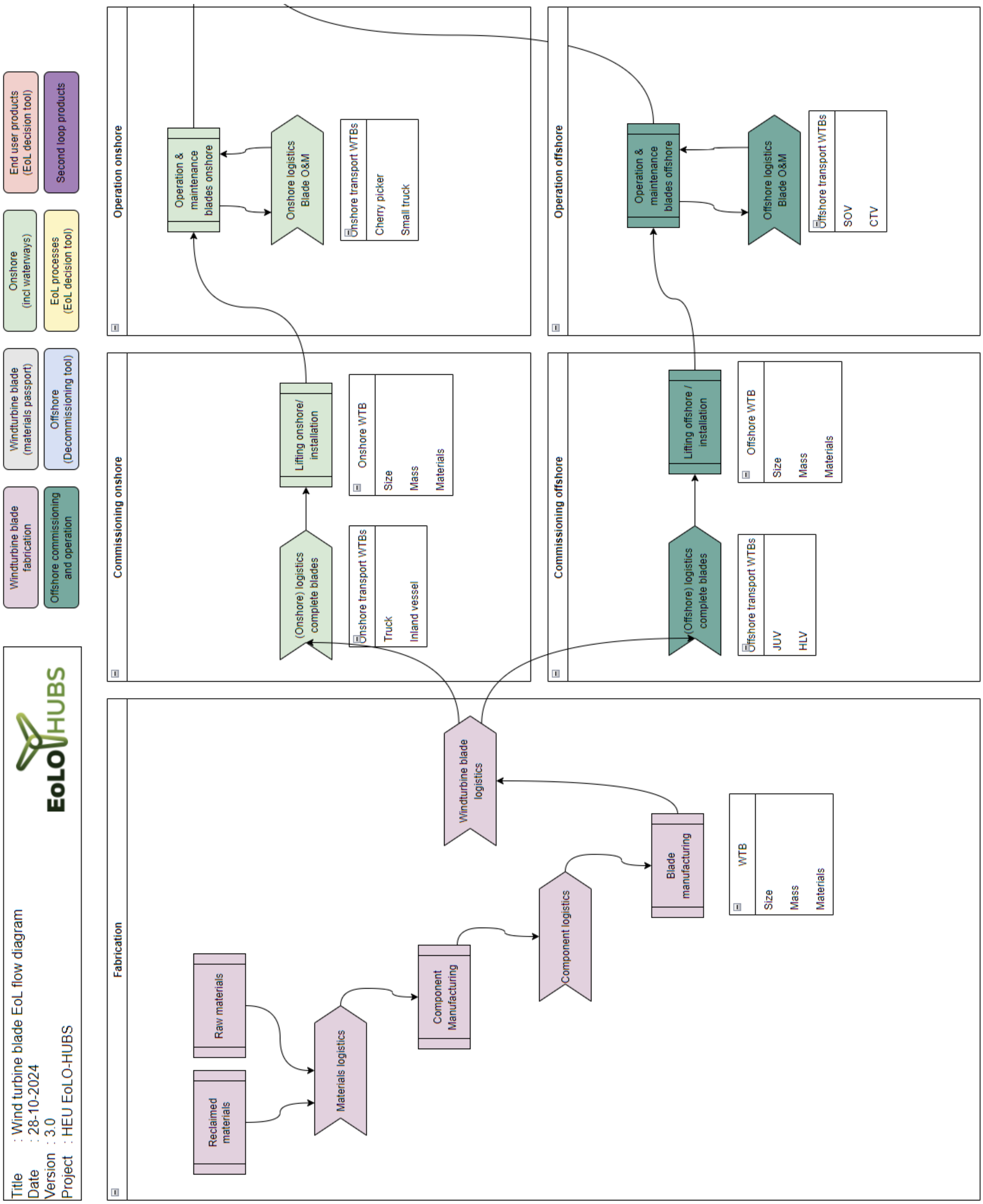
Appendix A. End-of-Life flow diagram



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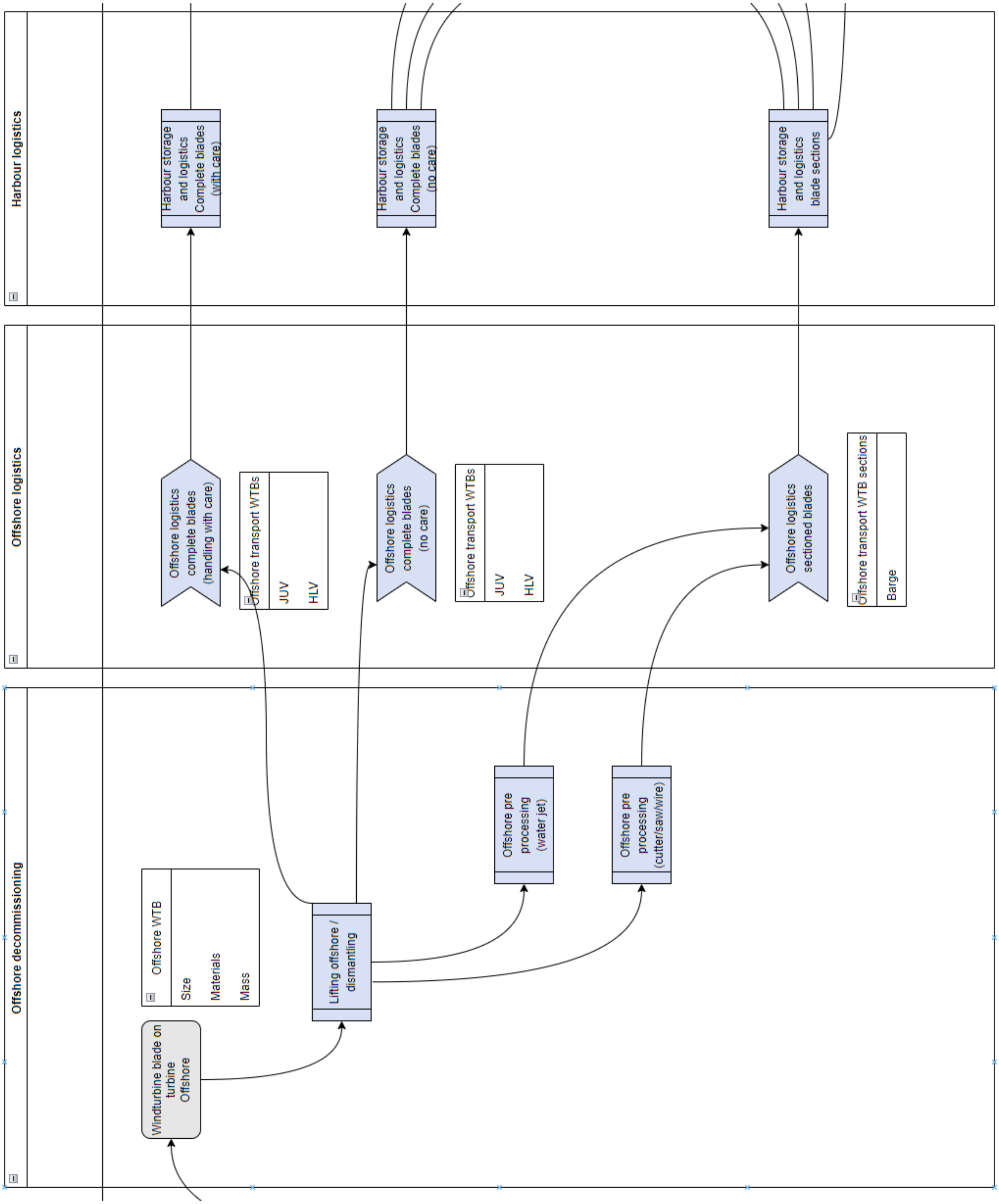

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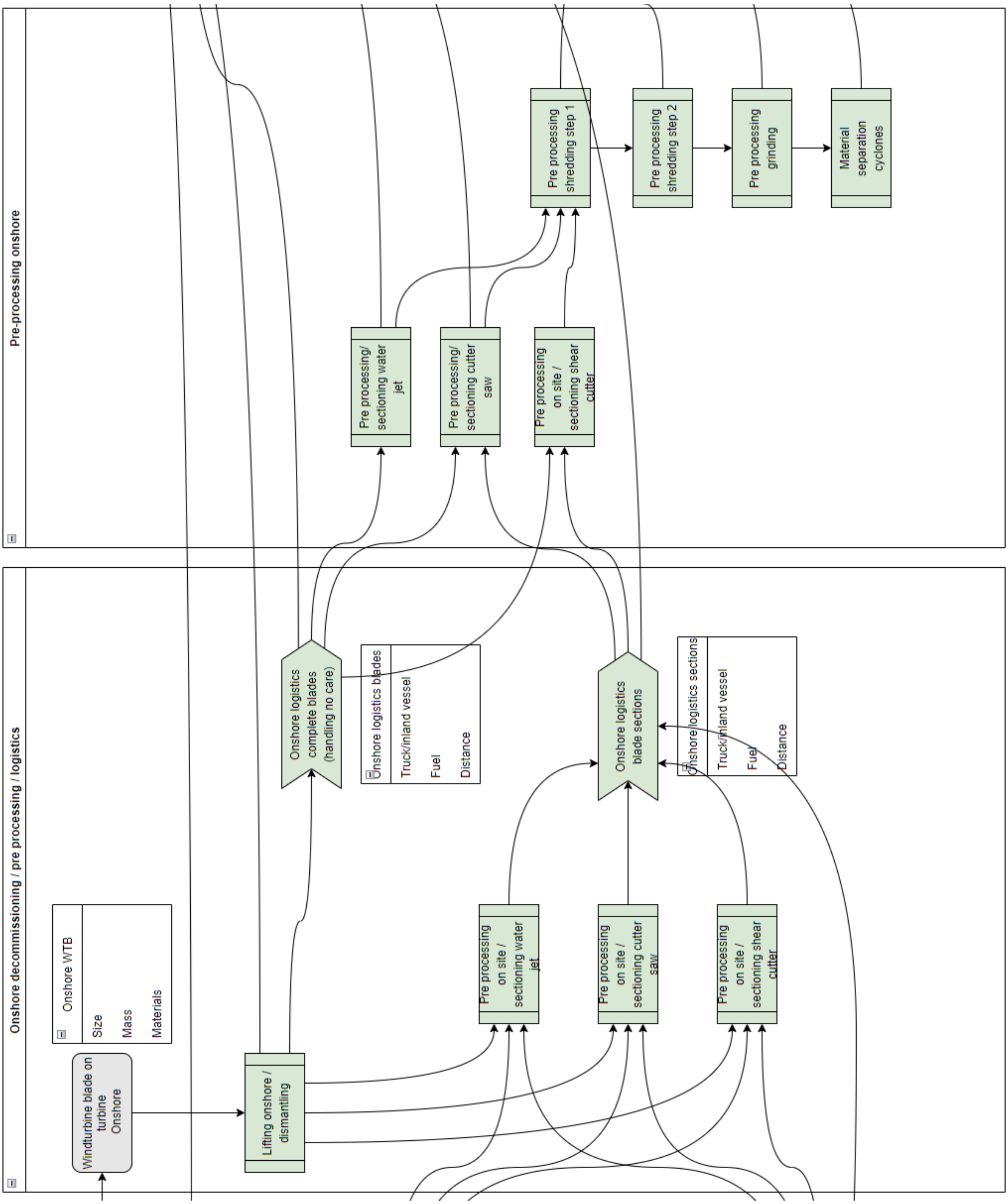

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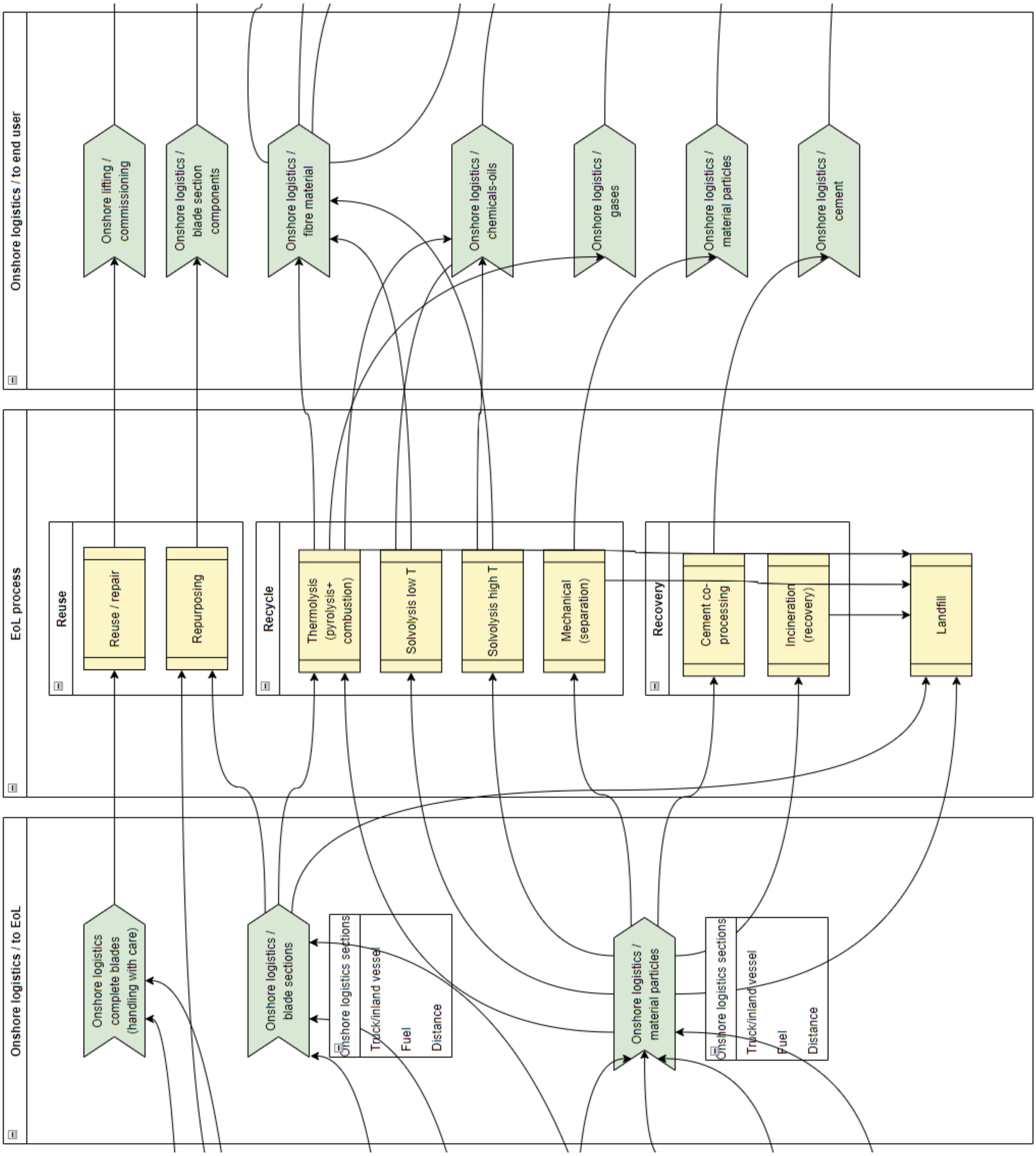

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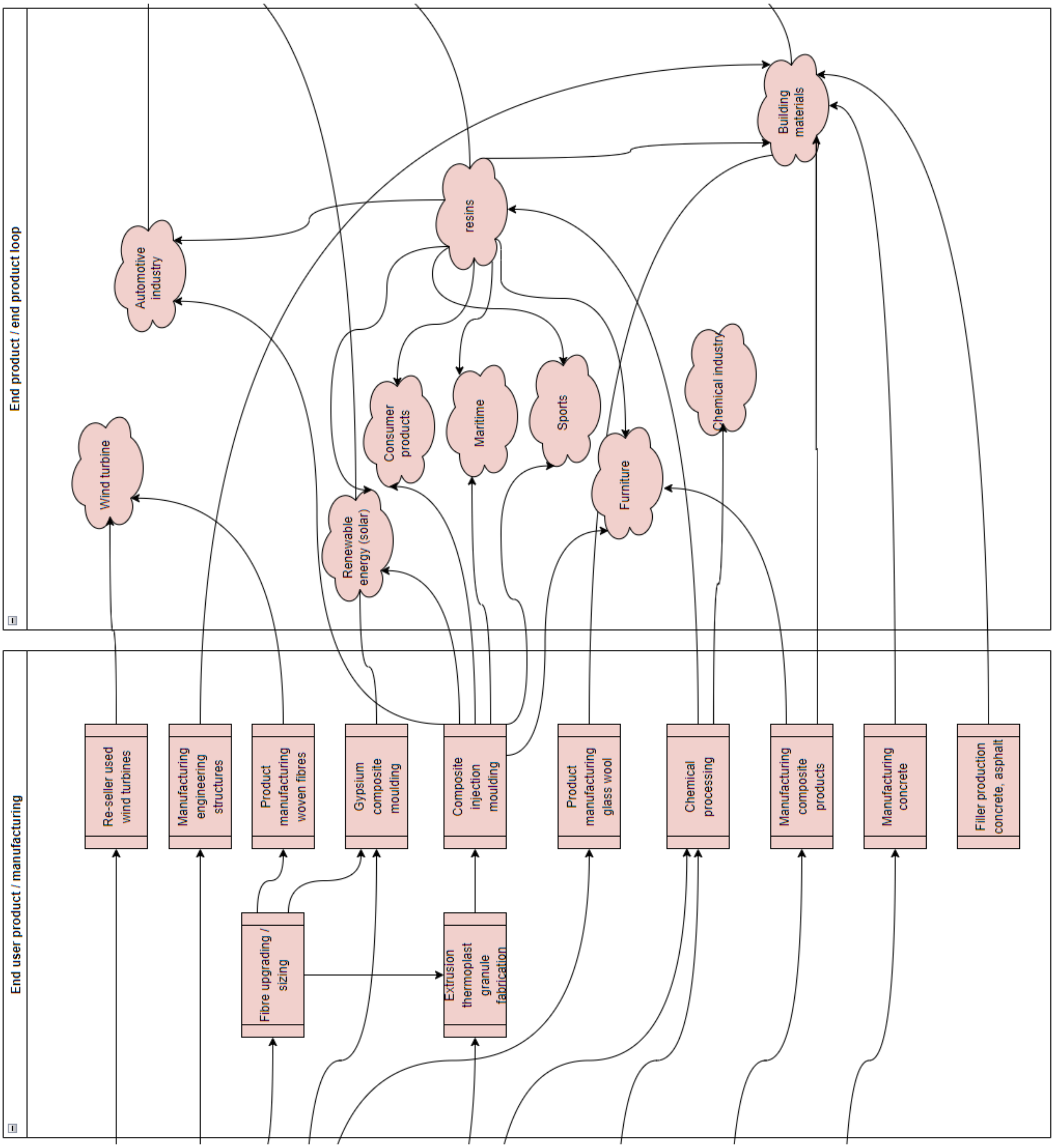

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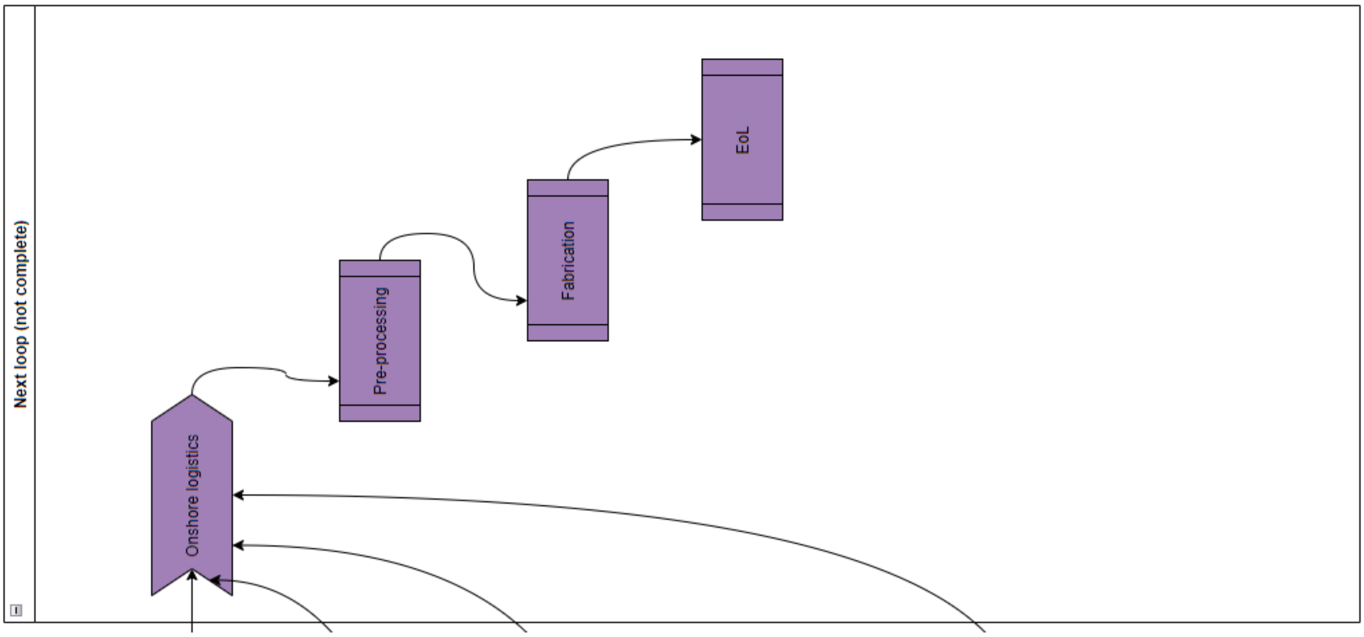

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Appendix B. Informed questionnaire on public perception of wind turbine (blade) circularity (English version translated from Dutch)

Introduction

Welcome to this questionnaire about the circularity of wind turbines developed by TNO. By circularity, we mean that the negative effects of products on the environment are minimal because products are used longer and reused, and waste becomes the raw material for new products. Circularity is a part of sustainability.

In this questionnaire, we ask for your opinion on wind energy, wind turbines, and what happens to wind turbines and wind turbine blades when they reach the end of their useful life. Recycling is an example here. Your opinion on this subject is important because recycling of wind turbines is gaining more attention but is new for most people. Therefore, it is still unknown what people know about it and what they think.

Even if you are not familiar with what happens to wind turbines and wind turbine blades at the end of their useful life, your opinion is important. Before we ask for your opinion, we will first give you information about the topic, collected together with various experts. To give you time to read everything properly, these screens with information will 'freeze' for a while. You can then click through to the next page after a while. There are no right or wrong answers. Your personal opinion is what truly matters.

Completing the questionnaire will take about 25 minutes. A large part of this time is for reading information about wind energy, wind turbines, and the end of the life of wind turbines and wind turbine blades. You can stop participating in the survey at any time during the questionnaire.

Thank you very much in advance for your cooperation.

General questions

We understand that it might be difficult to answer the following questions if you are not familiar with the mentioned topic. Still, we kindly ask you to answer based on your perception of the topic. If you really have no idea, you can fill in 'I don't know'.

1. How would you rate your own knowledge on the topics below?

	Very little knowledge	Little know-ledge	Some know-ledge	A lot of know-ledge	Very much knowledge	I don't know
Wind energy	☐	☐	☐	☐	☐	☐
Wind turbines	☐	☐	☐	☐	☐	☐
Circularity	☐	☐	☐	☐	☐	☐
Recycling of wind turbines	☐	☐	☐	☐	☐	☐
Recycling of wind turbine blades	☐	☐	☐	☐	☐	☐

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2. What percentage of the components of a wind turbine do you think can be recycled?
Please try to make an estimation.

0%	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
☐	☐	☐	☐	☐	☐	☐	☐	☐	☐	☐

Information and questions

Hereafter follows information about wind energy, wind turbines, and what happens to wind turbines and wind turbine blades at the end of their useful life. We understand it's a lot of information. Yet we ask you to read the information carefully. After the information, a number of questions will follow.

Climate and energy transition

To tackle global warming, we need to emit fewer greenhouse gases such as CO_2. Most of our CO_2 emissions come from the use of fossil fuels:

- For generating electricity.
- For various processes in industry and factories.
- As fuel for transport.
- For heating buildings.

Therefore, in 2019, the Dutch government, organizations, and companies signed the national Climate Agreement. This includes goals to emit 55% less greenhouse gases by 2030 compared to 1990 and to stop emitting CO_2 altogether by 2050. To achieve these goals, the coming years will be characterized by an energy transition. In this transition, fossil fuels (such as coal, oil, and natural gas) will be replaced as much as possible by sustainable and low-carbon energy sources (such as solar and wind energy, hydropower, and geothermal energy).

Questions on climate change and energy transition

3. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
I am concerned about the effects of climate change.	☐	☐	☐	☐	☐	☐
I think the impact of climate change on people in the Netherlands will be negative.	☐	☐	☐	☐	☐	☐
I have a positive view on the energy transition (the shift from fossil fuels such as natural gas and coal to renewable energy sources such as solar and wind energy).	☐	☐	☐	☐	☐	☐

4. What are your thoughts on the following topics?

	Very negative	Negative	Neither negative,	Positive	Very positive	I don't know

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			nor positive			
Wind energy generated on land	☐	☐	☐	☐	☐	☐
Wind energy generated at sea	☐	☐	☐	☐	☐	☐
Circularity	☐	☐	☐	☐	☐	☐
Recycling of wind turbines	☐	☐	☐	☐	☐	☐
Recycling of wind turbine blades	☐	☐	☐	☐	☐	☐

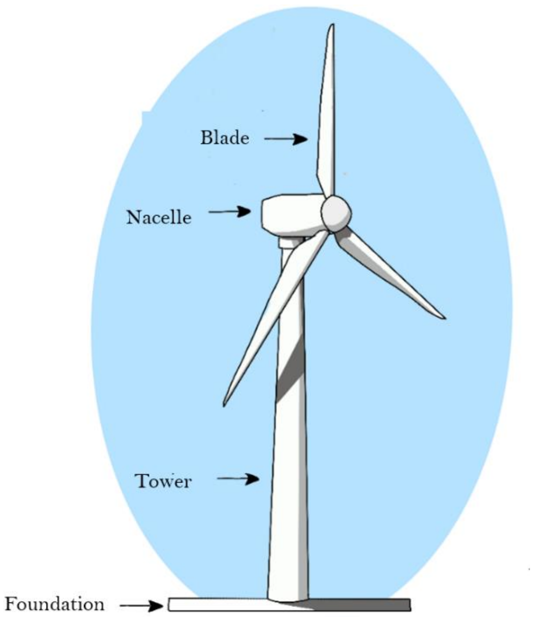
Wind energy and wind turbines

Windmills convert wind energy into power for tasks like grinding grain, sawing wood, pressing oil, and draining entire polders. This technology is over a thousand years old, and windmills are an important part of the Dutch landscape. Modern windmills are called wind turbines and convert wind energy into electricity. A group or collection of wind turbines is called a wind farm.

The main components of a wind turbine are:

- The blades or vanes that convert the force of the wind into a rotating motion.
- The nacelle, which houses a generator that converts the rotation of the blades into electricity.
- The tower or mast to which the nacelle is attached.
- The foundation in the ground that keeps the whole structure upright.

See the image below for the parts of a wind turbine.



Wind turbines are placed both on land and at sea. Generally, larger wind turbines can generate more electricity and thus do so more cheaply than smaller turbines. Larger wind turbines are usually installed offshore instead of onshore. The wind also blows harder at sea, generating more electricity. However, the costs for maintenance and connection to the electricity grid are higher for offshore wind turbines than for those on land. Another advantage of onshore wind turbines is that there is sometimes the opportunity to participate financially (for example, by becoming a co-owner of a wind

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turbine). On land, larger wind turbines can lead to more resistance from local residents. This is usually due to concerns about how the wind turbines are integrated into the landscape and nuisances like horizon pollution, shadow flicker, and noise pollution.

Wind energy can be important for the energy transition and achieving the goals of the Climate Agreement. This is because it is a cheap and widely available energy source that emits far fewer greenhouse gases, such as CO_2 and nitrogen, than coal or gas power stations that produce electricity. On the other hand, there are also drawbacks related to wind energy generation; the production of electricity is dependent on the strength of the wind and the electricity has to be expanded considerably.

Questions on wind energy and wind turbines

5. What role do you think wind energy should play in the energy system of the future?

Small role: we definitely do not need wind energy		Neither a small nor a large role: we only need wind energy to a moderate extent		Large role: we definitely need wind energy to a greater extent
☐	☐	☐	☐	☐

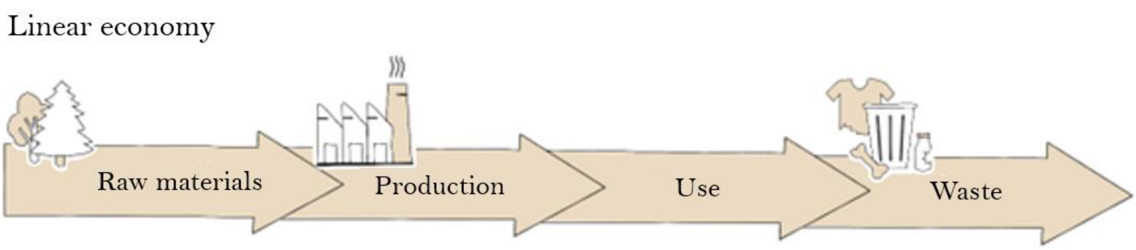
6. Could you elaborate on your answer to the previous question about the role of wind energy in the energy system of the future?

☐ I do not know / No answer

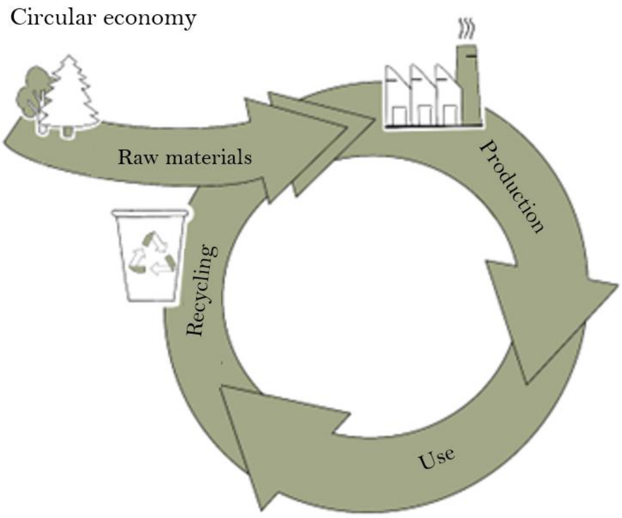
Value retention and circular economy

Building wind turbines requires various raw materials. There is a growing demand worldwide for materials such as wood, sand, oil, gas, aluminum, copper, and tin. Wind turbines specifically require materials like steel, aluminum, and copper. This growing demand means some raw materials are becoming harder to find and are slowly running out, making them more expensive. Additionally, the growing demand for raw materials has negative effects on the environment.

Resources are depleting because our economy is almost entirely linear. In a linear economy, raw materials are extracted and turned into products. After use, these products are thrown away and either burned as waste or dumped. The raw materials are only used once, causing pollution.



We can prevent the depletion of resources and reduce environmental harm by gradually transforming our linear economy into a circular economy. In a circular economy, there is almost no waste, and resources and products are reused as much as possible. The value of these resources is preserved because they are reused in other products, components, and materials. Thus, in a circular economy, it is much less often necessary to continually extract new resources. The goal is to maintain the value of resources for as long as possible.



In a circular economy, we use less, and products that are not needed are not made or used. Or we use resources more intelligently and sparingly by reducing the amount used during production. Also, products are designed in such a way that they can be used longer. If a product (like a wind turbine) breaks, it is repaired. If it can no longer be repaired, the product is recycled, and new products are made from it. If no new products can be made, then the product eventually becomes waste.

Transitioning from a linear to a circular economy can lead to higher costs in the short term. For example, recycling is sometimes still more expensive than extracting new raw materials. Additionally, changes are needed in how people and companies think and operate. For instance, designing products that can be made with fewer raw materials and have a longer lifespan.

Repairing and recycling are examples of circular approaches. These approaches aim to save resources or ensure that the value of resources is maintained. They strive for a more sustainable economy. To describe these approaches, we use a ladder. See the ladder image below. The ladder shows *how* circular an approach is. An approach higher on the ladder uses fewer new resources and is therefore more circular.

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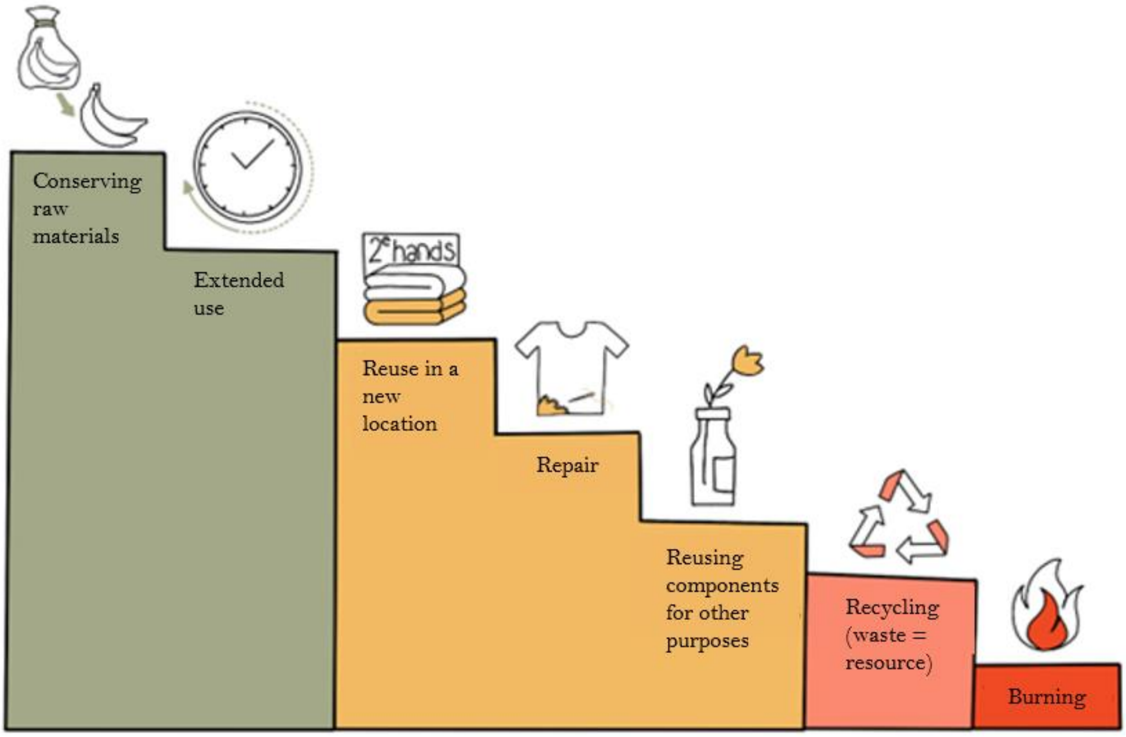

Questions on value retention and circular economy

7. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
Preventing the depletion of resources is necessary.	☐	☐	☐	☐	☐	☐
The negative environmental impacts from the growing demand for resources must be prevented.	☐	☐	☐	☐	☐	☐
I think it is unimportant that the value of resources is preserved as long as possible.	☐	☐	☐	☐	☐	☐
I have a negative view on the transition from a linear to a circular economy.	☐	☐	☐	☐	☐	☐
More attention needs to be given to repairing and recycling items.	☐	☐	☐	☐	☐	☐

EoL wind turbine components

To conserve the resources of a wind turbine, it is crucial to keep the turbine operating as long as possible. This is aimed for already as modern wind turbines are designed to last 25 to 30 years, which is much longer than the older turbines that lasted about 20 years. Regular maintenance and repairs are needed for a longer lifespan. Next to that, a wind turbine or its parts can often be used in other locations or even for different purposes when the turbine reaches the end of its useful life. Being

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resource-efficient with a wind turbine also involves recycling its parts. A large portion of the wind turbine (about 85-90% of the weight) is quite easily recycled. These parts mainly include the foundation, the tower, and the nacelle. These components are largely made of concrete and metals that are easy to recycle, such as steel, aluminum, and copper.

The rest of the wind turbine includes magnets in the generator and composite materials. These components are primarily found in the turbine blades and the exterior of the nacelle. The magnets in the generator are partly made from rare earth materials (about 1-2%). Compared to other sustainable energy technologies (such as solar power), wind turbines use a relatively large amount of these rare earth materials.

Composite is a material made from various parts glued together with resin. The composite materials in wind turbine blades are fiberglass or carbon fiber and balsa wood or plastic foam, bonded in resin. The fiberglass or carbon fiber is for strength, the balsa wood or plastic foam for firmness, and the resin to hold everything together. Composite materials are thus used for wind turbines because they are lightweight and stiff but can also withstand weather and wind under heavy loads for many years. These materials cannot be melted and are therefore less recyclable. As it is difficult to separate the parts and the resin, this process demands energy and money.

In the next parts of the questionnaire, we will further explore the challenge of finding a solution for the composite material in the blades.

Questions on EoL wind turbines

8. Were you already aware of what happens to EoL wind turbines?

- ☐ No, not familiar
- ☐ Yes, familiar but I do not know much about it
- ☐ Yes, familiar and I know (quite) much about it

9. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
Recycling wind turbines is an innovative way to make them more sustainable.	☐	☐	☐	☐	☐	☐
Recycling wind turbines involves a lot of effort for what it yields.	☐	☐	☐	☐	☐	☐
Recycling wind turbines does not help to reduce climate change.	☐	☐	☐	☐	☐	☐
I am satisfied with how wind turbines are currently handled at the end of their useful life.	☐	☐	☐	☐	☐	☐
I think it is important that a good solution is found for what happens to wind turbines at the end of their useful life.	☐	☐	☐	☐	☐	☐

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10. To what extent are you concerned about recycling the following materials from wind turbines?

	Very little concern	Little concern	Neither little nor much concern	Much concern	Very much concern	I don't know
Concrete	☐	☐	☐	☐	☐	☐
Steel	☐	☐	☐	☐	☐	☐
Aluminum and copper	☐	☐	☐	☐	☐	☐
Composites	☐	☐	☐	☐	☐	☐
Rare earth materials	☐	☐	☐	☐	☐	☐

11. Why are you concerned about the recycling of [if 'much concern' or 'very much concern' answer from Q10]?

☐ I don't know / No answer

EoL wind turbine blades

As mentioned, wind turbine blades are lightweight due to the composite materials used. The weight of the blades is only a small portion of the total weight of the entire wind turbine. Yet, the blades are large components of the wind turbine. For an average onshore wind turbine (2 megawatts), the blades are about 40 meters long and weigh approximately 7,000 kilograms. For large modern wind turbines that will be placed in the North Sea in the coming years (15 megawatts), the blades can be more than 120 meters long and weigh 60,000 kilograms.

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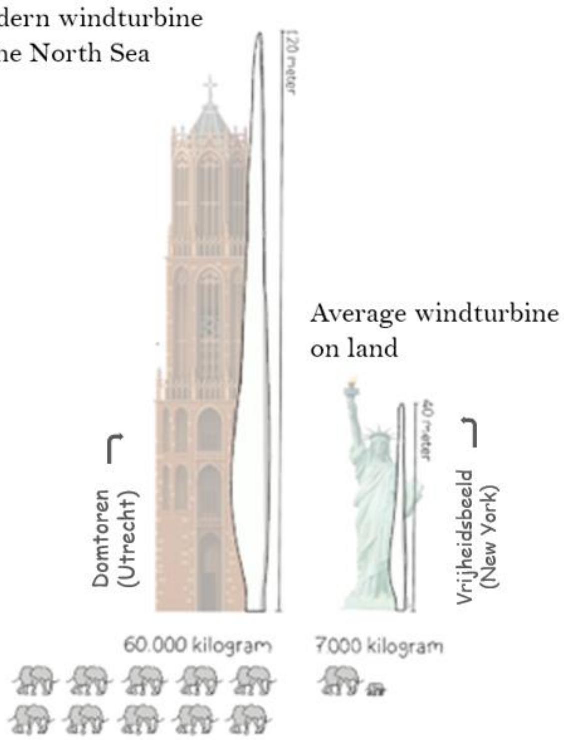

Currently, there are not many wind turbines at the end of their useful life. However, this number will increase with the turbines that are currently standing and those yet to be installed. The blades of wind turbines are now difficult to reuse or recycle. Reusing is challenging due to the high costs of transporting the large parts in one piece. Due to their large and unique shape, the blades can also be difficult to redeploy for other uses.

Because reusing or recycling the blades is difficult, there are currently only a few ways to deal with wind turbine blades at the end of their useful life. Currently, the blades are often ground into small pieces and dumped in landfills, burned, or processed into cement. These approaches are relatively non-circular because they do not preserve the value of the raw materials and components well. On the circularity ladder, this means going directly from one of the top steps to the bottom, skipping steps in between. Research is now looking into finding more circular solutions for the wind turbine blades, higher up on the ladder.

Questions on EoL wind turbine blades

12. Were you already aware of what happens to EoL wind turbine blades?

- ☐ No, not familiar
- ☐ Yes, familiar but I do not know much about it
- ☐ Yes, familiar and I know (quite) much about it

13. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know

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Until a good solution is found for dealing with the blades, it is better to store wind turbine blades, rather than burning them or dumping them in a landfill.	☐	☐	☐	☐	☐	☐
I am satisfied with how wind turbine blades are currently handled at the end of their useful life.	☐	☐	☐	☐	☐	☐
I think it is important that a good solution is found for what happens to wind turbine blades at the end of their useful life.	☐	☐	☐	☐	☐	☐
Recycling wind turbine blades is an innovative way to make wind turbines more sustainable.	☐	☐	☐	☐	☐	☐
Recycling wind turbine blades requires a lot of effort for what it yields.	☐	☐	☐	☐	☐	☐
Recycling wind turbine blades helps to reduce climate change.	☐	☐	☐	☐	☐	☐

14. Who do you think is responsible for finding a good solution for what happens to EoL wind turbine blades?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
The European Union	☐	☐	☐	☐	☐	☐
The national government	☐	☐	☐	☐	☐	☐
Owners of wind parks	☐	☐	☐	☐	☐	☐
Manufacturers of wind turbines	☐	☐	☐	☐	☐	☐
Energy suppliers	☐	☐	☐	☐	☐	☐
Universities and research institutes	☐	☐	☐	☐	☐	☐

Circular solutions for EoL wind turbine blades

More and more research is being conducted to better preserve the value of wind turbine blades and use them for purposes other than as raw material for cement or asphalt. Based on the circularity ladder, there are solutions that are more or less circular:

Conserving raw materials

Make the blades with as few new resources as possible, for example, using fewer materials or recycled materials.

Extended use

Extend the life of the blades as long as possible through maintenance and proper use.

Reuse in a new location

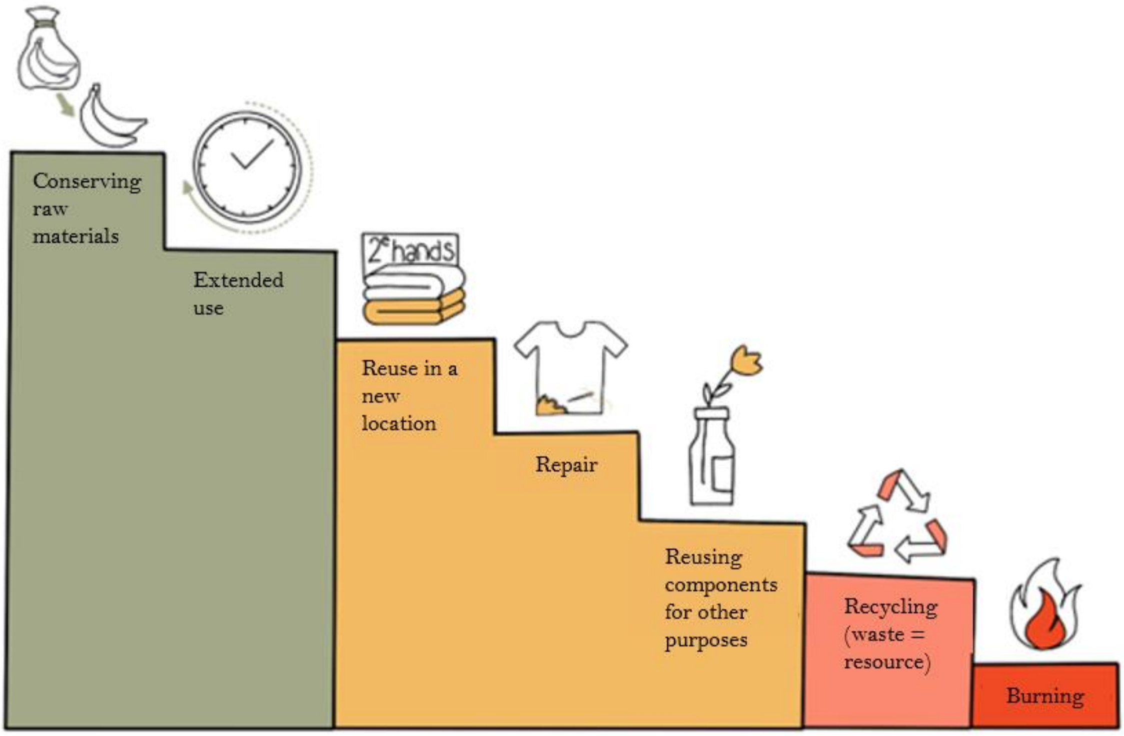
Reuse the blades at a new location after they are removed from their original site.

Repair
Repair the blades for reuse, such as in second-hand wind turbines.

Reusing components for other purposes
Transform the blades into other products, like noise barriers along highways, components in playgrounds, and bike racks.

Recycling (waste = resource)
In addition to using blades for cement or asphalt, there are solutions to use the materials from the blades in a more circular way, which the text under this ladder discusses.

Burning
Use the materials from the blades as fuel.



The wind turbine industry pays close attention to resource conservation and extending the lifespan of wind turbine blades. However, old wind turbines of 20-25 years old will soon need to be replaced because they can no longer be repaired or reused. Recycling is one of the steps for which better and more circular solutions for wind turbine blades can be found.

Producing new carbon fibers requires a lot of energy and money, which has a significant environmental impact. Therefore, it may be more cost-effective to extract the carbon fibers from existing wind turbine blades, in order to reuse them.

To reuse the materials in the blades in the most circular way possible, the various composite materials must be separated. This can be done by grinding the composite materials, chemically dissolving them, or thermally (with heat) separating them into different materials.

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The choice of method for separating the composite materials depends on several factors:

- The amount of energy required for the separation.
- Whether the (good) properties of the materials are preserved.
- The price at which the recycled material can be sold.

Questions on circular solutions for EoL wind turbine blades

15. Imagine that (a part of) the wind turbine blades can be reused. Which of the following purposes do you think are good solutions for what happens to EoL wind turbine blades?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
Noise barriers along highways	☐	☐	☐	☐	☐	☐
Components in playgrounds	☐	☐	☐	☐	☐	☐
Bicycle racks	☐	☐	☐	☐	☐	☐
Components of a bridge	☐	☐	☐	☐	☐	☐
Designer furniture	☐	☐	☐	☐	☐	☐

16. Do you think there are other good solutions for what happens to EoL wind turbine blades, and if so, what?

☐ I don't know / No answer

17. Imagine that parts of the composite material from wind turbine blades can be reused by grinding, chemically dissolving, or thermally (with heat) separating them. Which of the following goals do you think are good solutions?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
New wind turbine blades	☐	☐	☐	☐	☐	☐
Sailing boats	☐	☐	☐	☐	☐	☐
Car components	☐	☐	☐	☐	☐	☐
Smartphone cases	☐	☐	☐	☐	☐	☐
As part of cement	☐	☐	☐	☐	☐	☐
Packaging material	☐	☐	☐	☐	☐	☐

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18. When you can choose between methods to process composite materials from EoL wind turbine blades, what is more important to you?

Financial cost is most important		Cost and sustainability are equally important		Sustainable solution is most important
☐	☐	☐	☐	☐

19. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
I would not be willing to pay a higher price for electricity generated with fully circular wind turbines.	☐	☐	☐	☐	☐	☐
I think it is good that the government uses my tax money to invest in finding a solution for what happens to wind turbine blades at the end of their useful life.	☐	☐	☐	☐	☐	☐
I would prefer that the government spend money on installing more wind turbines rather than recycling them.	☐	☐	☐	☐	☐	☐

General questions about wind farms

20. Do you live near a wind farm?

☐ No, and there are no plans to build a wind farm → Q23
☐ No, but there are plans to build a wind farm → Q23
☐ Yes → Q21

21. Do you notice any positive or negative effects from the wind farm?

☐ No → Q23
☐ Yes → Q22

22. To what extent do you experience the following impacts from the wind farm?

	None	Little	Some	Much	Very much	I don't know
Biodiversity loss	☐	☐	☐	☐	☐	☐
Danger to birds and other animals	☐	☐	☐	☐	☐	☐
Financial benefits (e.g., income because I am a co-owner of the wind park or can obtain cheaper energy)	☐	☐	☐	☐	☐	☐

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Decrease in (house) property value	☐	☐	☐	☐	☐	☐
Deterioration of health of people living nearby	☐	☐	☐	☐	☐	☐
Positive contribution to the goals for sustainable energy on land	☐	☐	☐	☐	☐	☐
Horizon pollution	☐	☐	☐	☐	☐	☐
Deterioration of the quality of life of people living nearby	☐	☐	☐	☐	☐	☐

General questions

23. What do you think about the following topics after reading the information in the questionnaire?

	Very negative	Negative	Neither negative, nor positive	Positive	Very positive	I don't know
Wind energy generated on land	☐	☐	☐	☐	☐	☐
Wind energy generated at sea	☐	☐	☐	☐	☐	☐
Circularity	☐	☐	☐	☐	☐	☐
Recycling of wind turbines	☐	☐	☐	☐	☐	☐
Recycling of wind turbine blades	☐	☐	☐	☐	☐	☐

24. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
My opinion about wind energy has changed due to this questionnaire.	☐	☐	☐	☐	☐	☐
Now that I know more about the recycling of wind turbines, I would be more likely to accept wind turbines near the town or village where I live.	☐	☐	☐	☐	☐	☐
Now that I know more about the recycling of wind turbines, I would like to join an energy cooperative.	☐	☐	☐	☐	☐	☐
Now that I know more about the recycling of wind turbines, I would like to buy shares of the electricity generated by a wind turbine to offset the energy I use.	☐	☐	☐	☐	☐	☐

25. To what extent do you agree or disagree with the following statements?

	Strongly disagree	Disagree	Neither disagree nor agree	Agree	Strongly agree	I don't know
The information in the questionnaire was clear.	☐	☐	☐	☐	☐	☐
The information in the questionnaire was trustworthy.	☐	☐	☐	☐	☐	☐
The information in the questionnaire was biased.	☐	☐	☐	☐	☐	☐

26. If you would like to be informed about the outcomes of this research, you can indicate that below.

☐ Yes, I would like to be informed about the outcomes of this research
☐ No, I would not like to be informed about the outcomes of this research

27. If you would like to participate in follow-up questionnaires on this subject, you can indicate that below.

☐ Yes, I would like to participate in follow-up questionnaires on this subject
☐ No, I would not like to participate in follow-up questionnaires on this subject

28. If you have any questions or comments on the questionnaire, you can mention them here.

☐ No comments

These were all the questions. Thank you very much for your cooperation!

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Appendix C. Results of regression analyses on characteristics explaining the perception of wind turbine (blade) circularity

Characteristics explaining the perception of wind turbine circularity

The linear regression analysis revealed a statistically significant model, $F(22, 1019) = 21.7$, $p < .001$, adjusted $R^2 = .30$. The results showed that 30% of variance in the perception of wind turbine circularity was explained by: the perception of onshore wind energy and offshore wind energy, attitude toward the effect of recycling wind turbines in tackling climate change, attitude toward the needed attention for repairing and recycling items, attitude toward the energy transition, age, and attitude toward the responsibility of wind turbine manufacturers for implementing wind turbine blade circularity.

The perception of wind turbine circularity was not significantly predicted by gender, educational background, region of residence, stated knowledge on wind turbine circularity, concern about climate change, concern about the recycling of composite materials and of rare earth materials, attitude toward the responsibility of the national government and wind farms owners for implementing wind turbine blade circularity, the willingness to pay a higher price for electricity of fully circular wind turbines, the preference of installing more wind turbines over recycling wind turbines, and the proximity of living near to a (planned) wind farm.

The analysis showed that the perception of offshore wind energy, the effect of recycling wind turbines on tackling climate change, and the needed attention for repairing and recycling items were the most important explanatory variables of respondents' perception (see Table C.1). When respondents had a more positive perception of offshore wind energy, believed recycling wind turbines helps to tackle climate change, and thought more attention is needed for repairing and recycling items, their perception of wind turbine circularity was more positive.

These explanatory variables of perception were followed by the perception of onshore wind energy, attitude toward the energy transition, age and attitude toward the responsibility of wind turbine manufacturers for implementing wind turbine blade circularity. When respondents had a more positive perception of onshore wind energy and a more positive attitude toward the energy transition, were younger and regarded wind turbine manufacturers responsible for implementing wind turbine blade circularity, their perception of wind turbine circularity was also more positive.

Table C.1. Regression coefficients, standard errors, betas and p-values for measures predicting the perception of circularity of wind turbines.

Measure	B	*SE* B	β	*p*
Intercept	1.05	.25		<.001
Perception of offshore wind energy	.16	.03	.21	<.001
Attitude toward the effect of recycling wind turbines on tackling climate change	.15	.02	.19	<.001
Attitude toward needed attention for repairing and recycling items	.14	.03	.13	<.001
Perception of onshore wind energy	.09	.03	.11	.001
Attitude toward the energy transition	.09	.03	.11	.002
Age	.01	.00	.10	<.001

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Responsibility of wind turbine manufacturers for implementing wind turbine blade circularity	.07	.03	.08	.011
Gender	.07	.05	.04	.110
Educational background	.01	.03	.01	.639
Region: East (reference category: North)	-.05	.08	-.02	.589
Region: West (reference category: North)	-.05	.07	-.03	.467
Region: South (reference category: North)	-.06	.08	-.03	.439
Stated knowledge of wind turbine circularity	-.02	.03	-.02	.544
Concern about climate change	.03	.03	.04	.333
Concern about the recycling of composite materials	.01	.03	.01	.766
Concern about the recycling of rare earth materials	-.01	.02	-.02	.567
Responsibility of the national government for implementing wind turbine blade circularity	.02	.03	.02	.565
Responsibility of wind farm owners for implementing wind turbine blade circularity	.02	.03	.02	.498
Willingness to pay a higher price for electricity from fully circular wind turbines	-.02	.02	-.03	.326
Preference for installing more wind turbines over recycling wind turbines	-.04	.02	-.04	.114
Not living near a wind farm, no plans (reference category: living nearby wind farm)	.03	.07	.01	.700
Not living near a wind farm, plans (reference category: living nearby wind farm)	-.04	.09	-.02	.638

Note. Explanatory variables are regarded as significant with *p*-value <.05 (two-sided).

Characteristics explaining perception of wind turbine blade circularity

The linear regression analysis revealed a statistically significant model, $F(23, 1003) = 19.5$, $p < .001$, adjusted $R^2 = .29$. The results showed that 29% of variance in the perception of wind turbine blade circularity was explained by: attitude toward the effect of recycling wind turbines in tackling climate change, the perception of onshore wind energy and offshore wind energy, attitude toward using composite materials from old wind turbine blades in new blades, attitude toward the government using tax money for wind turbine blade recycling, age, gender, and attitude toward the needed attention for repairing and recycling items.

The perception of wind turbine blade circularity was not significantly predicted by educational background, region of residence, stated knowledge of wind turbine circularity, concern about climate change, attitude toward the energy transition, concern about the recycling of composite materials and rare earth materials, attitude toward the responsibility of the national government, wind turbine manufacturers and wind farms owners for implementing wind turbine blade circularity, the willingness to pay a higher price for electricity of fully circular wind turbines, the preference of installing more wind turbines over recycling wind turbines, and the proximity of living to a (planned) wind farm.

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The analysis showed that the effect of recycling wind turbines on tackling climate change, the perception of offshore wind energy, attitude toward using composite materials from old wind turbine blades in new blades, and age were the most important explanatory variables of respondents' perception (see Table C.2). When respondents believed recycling wind turbines helps tackle climate change, had a more positive perception of offshore wind energy, were more positive about using composite materials from old wind turbine blades in new blades, and were younger, their perception of wind turbine blade circularity was more positive.

These explanatory variables of perception were followed by attitude toward the government using tax money for wind turbine blade recycling, the perception of onshore wind energy, gender, and attitude toward the needed attention for repairing and recycling items. When respondents were positive about the government using their tax money to invest in finding a solution for EoL wind turbine blades, had a more positive perception of onshore wind energy, were women and thought more attention is needed for repairing and recycling items, their perception of wind turbine blade circularity was also more positive.

Table C.2. Regression coefficients, standard errors, betas and p-values for measures predicting the perception of circularity of wind turbine blades.

Measure	B	*SE* B	β	*p*
Intercept	.64	.30		.034
Attitude toward the effect of recycling wind turbine blades on tackling climate change	.20	.03	.23	<.001
Perception of offshore wind energy	.14	.03	.16	<.001
Attitude toward using composite materials from old wind turbine blades in new blades	.15	.04	.12	<.001
Age	.06	.00	.12	<.001
Attitude toward government using tax money for wind turbine blade recycling	.09	.03	.10	.005
Perception of onshore wind energy	.09	.03	.10	.004
Gender	.13	.05	.07	.015
Attitude toward needed attention for repairing and recycling items	.08	.03	.07	.022
Educational background	.02	.03	.02	.539
Region: East (reference category: North)	-.13	.10	-.06	.172
Region: West (reference category: North)	-.13	.09	-.07	.124
Region: South (reference category: North)	-.11	.09	-.05	.257
Stated knowledge of wind turbine blade circularity	-.01	.03	.00	.876
Concern about climate change	-.00	.03	-.01	.883
Attitude toward the energy transition	.05	.03	.05	.177
Concern about recycling of composite materials	-.06	.03	-.07	.064
Concern about the recycling of rare earth materials	-.01	.03	-.02	.619

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Responsibility of the national government for implementing wind turbine blade circularity	-.00	.03	-.01	.798
Responsibility of wind farm owners for implementing wind turbine blade circularity	.05	.03	.04	.165
Responsibility of wind turbine manufacturers for implementing wind turbine blade circularity	.02	.03	.02	.504
Preference for installing more wind turbines over recycling wind turbines	-.05	.03	-.05	.062
Not living near a wind farm, no plans (reference category: living nearby wind farm)	.05	.08	.02	.479
Not living near a wind farm, plans (reference category: living nearby wind farm)	.08	.10	.03	.437

Note. Explanatory variables are regarded as significant with *p*-value <.05 (two-sided).

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