Part VII
Offshore Wind Decommissioning

Chapter 22
ODIN-WIND: An Overview of the Decommissioning Process for Offshore Wind Turbines

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Abstract The oldest offshore wind farms in Europe are now well over 2 decades old. Considering this fact, and the technological advancements in wind turbine technology, it is evident that decommissioning of wind farms will soon become a crucial topic of discussion. NIRAS have been at the forefront of offshore wind farm decommissioning, and have developed extensive expertise in the area. Recently, they released a tool—ODIN-WIND—to assist stakeholders with the decommissioning process. The current chapter describes the decommissioning process for wind farms, the inherent challenges that may be faced, and potential solutions. It also provides an overview of ODIN-WIND tool.

22.1 Introduction

Decommissioning has previously been seen as simply the reverse procedure of the commissioning of an offshore wind farm (OWF). In recent years the sector has seen a shift from looking at the challenge in this simplified way to viewing it as a more diverse and complex challenge. It is considered prudent to address the future challenge of offshore wind farm decommissioning in a much more detailed manner in order to avoid the situation currently being experienced in the Oil and Gas industry where the failure to consider the potential requirements for decommissioning at an early stage has resulted in significant underestimation of the costs associated with decommissioning.

This chapter presents the processes relevant for decommissioning of offshore windfarms. This is done from a planning/management perspective and a on a high level. It is briefly discusses when it is recommended to make such a decommissioning plan in order to be in due diligence and the obvious results from such an assessment are presented.

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Finally the ODIN-WIND tool is presented. ODIN-WIND is a decommissioning management tool that, in large, covers the phases of decommissioning as explained in this chapter.

22.2 Decommissioning Management

The planning and management of a decommissioning project must address the issue of decommissioning as a whole, considering the full process and all the associated sub-processes. By addressing and understanding the processes it is also possible to identify where there is a lack of knowledge and where contingencies and assumptions (known unknowns) should be made. Herby it is also possible to address the unknowns as they become known. The typical decommissioning process is explained further in Sect. 22.2.1, and can be seen in Fig. 22.1.

22.2.1 The Decommissioning Assessment

The assessment of the decommissioning process requires consideration on many levels and of many sub-processes. The typical processes of a OWF decommissioning which should be assessed are shown in Fig. 22.1. The assessment consists of three parts.

At the top, Fig. 22.1 shows the planning process which should asses all the process of decommissioning—i.e.—the decommissioning planning which is the work explained as a whole in this chapter.

Next, Fig. 22.1 illustrates the typical process of decommissioning: preparation, dismantling methods including cutting, lifting and detachment. Also included are considerations such as the used-vessels' capabilities and restraints; these restraints for vessels include weather on the site, challenges with transportation to the port and what the port capabilities are. All in all, this is essentially the offshore operation with an interface of the structure being lifted ashore.

In the middle part of the figure, the onshore operations are addressed, e.g. the treatment of the structural items including decontamination, striping and waste management.

The bottom part of Fig. 22.1 shows the main components of waste and recourses that are produced. The hierarchy of the four fractions—reuse, recycling, disposal and hazardous waste—is deliberate. The top two fractions are in favour while waste for disposal should be avoided as well as hazardous materials which should be minimised as far as possible.

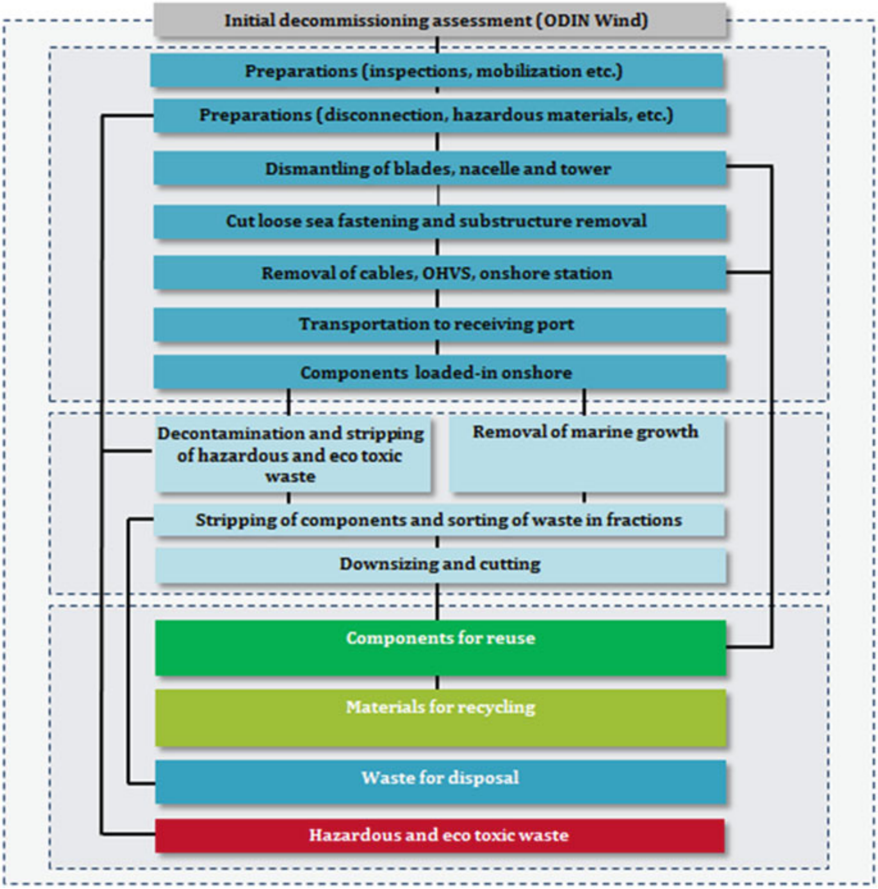

Fig. 22.1 Typical process decommissioning of an OWF from the ODIN-WIND tool (Gjødvad 2015)

After assessing the specific decommissioning project, the project should produce project output that can be used by the owner and the stakeholders involved. The focus and details of the output can vary, depending on which state the OWF is in: design, operation, or end of life. Typical outputs from such an assessment can be seen in Fig. 22.2.

It is of course the case that inadequate knowledge on the subject and equally inadequate or insufficient data, when using a tool as ODIN-WIND (Gjødvad 2015), obviously will result in results of equally poor quality.

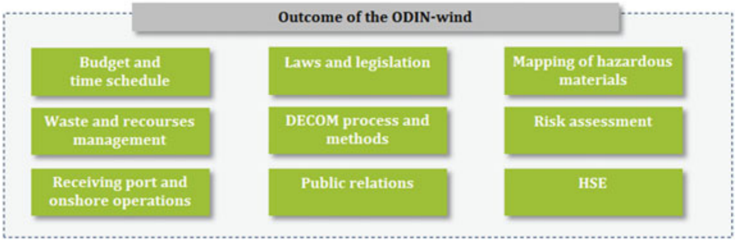

Fig. 22.2 Typical output from a decommissioning assessment the ODIN-WIND tool (Gjødvad 2015)

The mentioned method, considerations and other key elements of the decommissioning assessment are described in detail in Sects. 22.3–22.8. Starting with the actual decommissioning process including perpetrations, details on WTG (Wind turbine generator) and tower removal, substructure and OHVS (Offshore High Voltage Station) removal, cables removal, met mast removal followed by the vessel and port, weather and removal sequence, HSE and risk, waste and material management and finally cost estimation including budgeting and time schedule.

Managing an offshore decommissioning project requires involvement at an early state. This means the inclusion of a decommissioning assessment into a given offshore windfarm project as early as possible. The involvement of decommissioning in the different phases of an OWF is described shortly below.

22.2.2 Decommissioning During the Design Phase

The decommissioning assessments in the design phase can commence early—ideally during the selection of substructures, arrays, location etc. This would mean that a decommissioning analysis is made considering different scenarios with variations of the variables and thereby feedback into the decision of what type of substructure, array type and installation and even location is optimal. Although experience shows that the input from decommissioning is not as important as other considerations—such structure, installation scenarios, etc. . . . — the decommissioning input can still have an important impact on the final decision.

If not included from the beginning the decommissioning analysis can be based on a selected scenario with defined parameters including substructures, arrays, location etc., taken into account. Here the decommissioning assessment feeds back in to the project with cost reductive design adjustments taking the future decommissioning in to consideration. This means that the existing design can be optimised by including the decommissioning input.

22.2.3 Decommissioning During the Operation Phase

A decommissioning plan can also be produced during the operation phase of an OWF. Making a plan at this stage can be done regardless of the existence of an decommissioning assessment from the design phase. It is recommended that the assessment should commence half way through the expected life time, typically 12–13 years after commissioning. If a decommissioning plan was made during the initial phases the assessment during the operation phase will naturally be an update. Otherwise the assessment should be made from scratch.

During the operation phase of the OWF, the estimation can be an important tool for the owner to decide what to do after end of operation; this enables the owner to set aside funding and also get a better picture of when the OWF should be taken out of operation. Furthermore the estimate can also be used for the purposes of life-extension and re-powering of the OWF.

The assessments will naturally be more detailed than the one made during the design phase. This is primarily because details of the OWF are actual 'as-built details', along with operation and maintenance information.

22.2.4 Decommissioning Prior to the End of Life

The final decommissioning assessment should be updated in good time prior to the actual decommissioning of the wind farm. The final assessments should be more detailed than the previous assessments, not only with actual details of the OWF in place. The final assessment also includes actual conditions at the time of decommissioning.

Even though such 'final assessments' get more precise the closer it is made to the planed time of decommissioning, it should not be left too late—and needs to be made at least 2–4 years ahead, depending on the quality of the previous decommissioning assessments made. As the time of decommission comes closer the assessment can then be used for EIA analysis, permitting and regulatory compliance as well as the actual tendering process.

Not only should the final assessment include details on the actual decommissioning, but also include plans for a post survey and a project close-out report.

22.2.5 The Regulatory Process for Decommissioning

Depending on which part of its life cycle the OWF is in—design, operation, or end of life—the regulatory process is a little different. Obviously the countries which first established offshore windfarms are most likely to be the ones that are furthest on the matter of decommissioning. This, combined with the level of environmental awareness that the respective countries holds, determines the state of regulations.

For the North Sea and most of the European waters, the regulations and guidelines that need to be fulfilled are international (from organizations such as IMO—International Maritime Organization), regional (from, for instance the OSPAR agreement), and national.

Regulations for the design phase, are at the present, only general rules of design such as Eurocode and environmental rules. Additionally, general rules of vessel operations and such should also be upheld. However, no *actual* rules of assessment of decommissioning of OWF or design input currently exist.

In many cases it is an authority requirement that decommissioning is considered during design, but the actual authority demand and the quality of the required assessment is very variable—and in most cases poor. Regulations for decommissioning assessments during operations are often driven by the fact that most European states require that the owner sets aside funding for the future decommissioning of the offshore structure.

The actual decommissioning for most of the European OWFs is at the present some time away, and therefore only few countries have actually made a fixed set of rules and procedures for decommissioning of offshore windfarms. Existing rules on O&G (oil and gas) are considered as starting points, and of course general regulations on HSE (Health, Safety & Environment) are to be upheld as well as general regulations on vessel operations.

22.3 The Decommissioning Process

For all the assessed methods the process should be considered with regards to HSE (Health Safety and Environment). The considerations of HSE requirements are equally as important as the cost and time consumption. Thus, potential risks related to offshore decommissioning projects must be understood and addressed. The mentioned considerations are as important as managing the project in a cost effective way. Indeed, addressing these matters can actually help to make the project more cost efficient.

22.3.1 Preparations

Comprehensive preparations are necessary prior to the commencement of the dismantling and removal operations both onshore and offshore. With regard to vessels, this includes providing sea-fastening, lifting yokes, mobilization of vessel in general, amongst other tasks. An upgrade of the receiving port is also often required—e.g.—reinforcement of quays.

Preparatory work at the site depends on the removal concepts. Prior to the WTG and tower dismantling, preparations usually include jack-up footing assessment of seabed, disconnecting of high voltage system and other installations, securing non-fixed structures, and structural integrity checks.

Preparatory work for substructures, topsides and cable recovery include tasks such as dredging prior to cutting operation, preparing access inside the piles for tool deployment and ROV's (Remotely Operated Vehicles), and removal cables and other equipment.

22.3.2 Wind Turbine and Tower Dismantling

The options of removal concepts typically considered are shown in Table 22.1:

These options follow the typical installation options, but in reverse order. Thus, the installation process for a wind farm should be properly documented during the installation stage, and studied closely in the decommissioning planning phase.

Typically WTIVs (Wind Turbine Installation Vessels) and HLVs (Heavy Lift Vessels) are used for installation of wind turbines, and the obvious choice for the dismantling is to use the same or a similar vessels. For minor near shore wind turbines other solutions are possible such as jack-up platforms or barges with a mobile crane.

Table 22.1 Wind turbine removal concepts

Removal concept	Description of lifts
Bunny ear and tower in 2 pieces	Single blade, nacelle, hub and two of the blades, tower in 2 pieces
Bunny ear and tower in 1 pieces	Single blade, nacelle, hub and two of the blades, tower in 1 piece
Rotor and tower in 2 pieces	Hub and three blades, nacelle, tower in 2 pieces
Rotor and tower in 1 pieces	Hub and three blades, nacelle, tower in 1 piece
Five pieces separately	All three blades individually, nacelle and hub, tower in one piece
Six pieces separately	All three blades individually, nacelle and hub, tower in two pieces
Removal in 1 piece	Blades, hub, nacelle and tower in one single lift

22.3.3 *Transition Piece and Substructure Removal*

The key factor to be considered removing substructures is whether the installation is to be removed entirely or if any parts are to be left behind. The baseline of international law and obligations—e.g.—OSPAR convention and UNCLOS—is complete removal of offshore installations, with exceptions according to the IMO guidelines. The IMO guidelines list 6 key components that should be considered when making decommissioning decisions regarding how much—if any—of a platform or a structure should be left on the seabed.

The substructure design and installation concepts must be taken into consideration when planning the decommissioning. Typical substructure designs include: Monopile, 4 legged jacket, 3 legged jacket, tripod, gravity based. Typical installation and design concepts include: transition piece grouted onto top of pile, driven or drilled (grouted), or suction bucket (monopod).

22.3.3.1 Monopiles, Jackets and Tripods

The common practice for removal of monopiles, tripod and jackets at other offshore installations has been to cut piles just under the seabed. Concepts for complete removal are yet to be field tested in full scale. The feasibility of the concepts and methods vary depending on the installation method—namely suction buckets and type of pile installation used. Various decommissioning concepts for monopiles, jackets and tripods are shown in Table 22.2.

Table 22.2 Decommissioning concepts for Monopiles, Jackets and Tripods

Decommissioning concept	Description
Partial removal	Substructure with TP in one piece cut below seabed level
Partial removal	Substructure and TP in separate pieces cut below seabed level and TP
Complete removal	Removal of monopiles, tripod or jackets with suction buckets by reversing the suction process. Field proven on met mast leaving the seabed unmarked
Complete removal	Removal of the monopile, tripod and jacket piles in its full height using water pressure. Novel concept which not yet have been field tested
Complete removal	Removal of the monopile in its full height by removing sand around the pile. Considerable impact on the benthic ecologic and challenging. The impact and challenge increase proportional with the substructure depth

If the substructure is to be partially removed selecting the correct cutting concepts and methods is crucial for the operation to be successful. There are several cutting methods concepts, including:

- Internal pile cutting tool. The cutting tool is lowered inside the MP after clearance of internal parts and necessary seabed excavation
- External cutting. The cutting tool is installed after dredging soil around piles

The best solution of cutting tool and dredging method depends on the site conditions. In many cases it is preferable to minimize the use of divers which can cause safety risks and long downtimes. Cutting tools include flame cutting (oxy-fuel cutting); wire cutting; abrasive water jet cutting; cutting using linear shaped charge (explosives); blade sawing; and laser cutting. Explosives can be placed and detonated safely in regard to personnel health but are usually wrongly counted out due to environmental concerns.

22.3.3.2 Gravity Based Substructures (GBS)

In the Oil & Gas sector partial removal or leave wholly in place (reefing) are conceivable solutions in some case for large concrete GBS situated on deep waters. GBS for wind turbines are in most cases situated at shallow water depths and typically minor constructions than the ones used for oil rigs. GBS' are not piled and therefore they do not have the issue of cutting and leaving the piles partly in the seabed hence most likely complete removal is the only acceptable solution. Decommissioning concepts for GBS are shown in Table 22.3.

The weight of GBS' is substantial by design, and moving the GBS is a challenging operation. Conceivable options are shown in Table 22.4.

22.3.4 Substation (Offshore High Voltage Station) Removal

Substructure concepts for substations are the same as for wind turbines and can in general be decommissioned applying the same measures as for wind turbines

Table 22.3 Decommissioning concepts for GBS

Decommissioning concept	Description
Offshore disposal	Moving the GBS further off shore and dumping it on greater depth
Demolition at other location	Moving the GBS inshore at location with wider and cheaper options for deconstruction
Demolition on site	Demolition on site and removal of debris/pieces
Onshore demolition	Moving the GBS onshore for conventional demolition

Table 22.4 Options for moving GBS

Options for moving GBS	Description
Single heavy lift in one	The lift requires very large vessels with large draughts for the heavy lift. The feasibility of the solution is dependent on the water depth and the weight
Heavy lift in two pieces	Dividing the GBS by wire cutting or sawing will reduce required lifting capacity significantly and enabling more vessels do carry out the lift. The cutting operation is very sensitive to weather conditions due to underwater operations. Feasibility is dependent on the GBS design
Floating	Floating the GBS supported by salvage pontoons and filling it with ballast on site is usually used for the installation and it is obvious to reuse the method if the design allows pumping out sufficient ballast weight to enable buoyancy.

Table 22.5 Overview of removal concepts for substation topsides

Removal concept	Description
Single heavy lift	Removal of topsides by heavy lift vessels.
Float-over	Float-over is the removal by lifting the topside of the substructure with semisubmersible heavy lift vessels or dual barges with jack-up systems. No crane lift is required for this method.
Skidding	The method is the reverse of skid-on where the topside is transferred to a vessel by drifting on rails from the substructure.
Modular	Lifted in modules reverse of the installation process.

substructures. The substructures for substations however, are typically bigger than wind turbine substructures. The logical solution for removing the topside is using the same concept as is used for the installation. Self-installing (jack-up) concepts have been used at other offshore installations but most offshore high voltage station (OHVS) topsides have been installed using the single full topside concept. The concepts for removal of substation topsides are shown in Table 22.5.

Independent of the removal concepts, the separation of the topside and substructure requires a cut at stabbing pipe sleeves and all welded connections. A OWF typically only includes one OHVS and therefore opting to use a lifting vessel already at the site is likely to be cost-effective.

22.3.5 Cable Removal

The installation concepts for inner array cables and export cables are given in Table 22.6.

At the time of decommissioning seabed conditions may have change dramatically from the installation phase due to current and sand waves. Hence a thorough

Table 22.6 Installation concepts for offshore cables

Installation concepts	Description
Buried	Typically buried 1–2 m under seabed in a trench and possible partly scour protected
Covered	Typically covered with 0.5–1.0 m of rock boulders

Table 22.7 Overview removal methods for cables

Recovery	Storing on CLB or CLV
Jetted up on seabed (if buried) and pulled on board	On drums On an on-board turntable Cut in sections
Directly "Brute forced" (if rock covered)—the cable is pulled free first from the J-tube and then from the rock layer	On drums On an on-board turntable Cut in sections

inspection is required prior to decommissioning planning. The decommissioning concepts for cables are:

- Complete removal of all cables
- Leave all in place
- Partial removal.

The solution depends on the regulatory obligations and/or the economical balance between the cost of recovery and the scrap value. In some cases, it the possible repowering and reuse of cables will determine the best solution. An overview of removal methods for cables is given in Table 22.7.

The best solution for storing the cable is interdependent of transport distance and offload facilities and if direct load-in to scrapyard is relevant. The main vessels used are CLV (Cable Laying Vessel) or CLB (Cable Laying barge). For the jetting operation and attaching the cable to the crane hook a ROV can be applied. Divers are often preferred in shallow waters, or used when the ROV is not applicable.

22.3.6 Met Mast

Wind farms usually have one or more met masts. The design of met masts varies a great deal. Met masts with lattice tower mounted on monopiles are a quite common design. The towers can often be dismantled without crane use. The substructure is more likely to be removed totally—and removing a mono suction bucket substructure totally, by reversing the suction process, has been field proven.

22.4 Vessels and Ports

This section describes the challenges that may arise during the decommissioning process due to inadequate vessel technology or port facilities.

22.4.1 *Vessel Types*

Many vessels are used in the process of decommissioning. The main vessel types are listed in Table 22.8.

Beside the main decommissioning vessels a fleet of support vessel is required. This includes work boats, construction support vessels, diver operation vessel, ROV operation vessels, anchor handling tug and crew boats for transit.

22.4.2 *Vessel Suitability*

The vessels used for the wind farm installation will by nature be capable of decommissioning. However the market for installation vessels is constantly developing

Table 22.8 Main decommissioning vessels

Vessel type	Description
Jack-up barge	Barge or platform equipped with legs and a jacking system allowing the barge to self-elevate when operating. Used for installation of blades, hub, nacelle and tower. The components are transported to the site by a barge.
WTIV	Purpose build jack-up vessel for the installation of blades, hub, nacelle and tower. WTIV is self-elevating similar to a jack-up barge but transport the components on the its own deck.
Heavy lift vessel (HLV)	Designed to lift very large loads and used for installation of topsides and substructures. There are several types and variations of HLV e.g. floating sheerleg cranes, monohull crane vessel, catamaran cranes, semi-submerging vessels lifting with-out the use of cranes.
Semi-submersible crane vessel (SSCV)	Designed with increased stability allowing very large crane capacity. Used for topside installation.
Barge	Capacious flatbottom vessel used for transportation of wind turbines, substructures and OHVS topsides etc.
Cable laying vessel (CLV) and cable laying barge (CLB)	Used for cable recovery by pulling the cable on drums or turntables.

to increasing installation performances—and at the time of decommissioning the original installation vessels could be decommissioned themselves.

The physical character of the structures and the proposed method for removal will result in a number of requirements for the vessels to be used. Parameters to be considered include lift capacity, cargo load capacity, etc. As a key factor in the planning stage the vessels operational limits in regard to environmental loads must be taken into account. Furthermore the logistic planning must take cargo area, transportation/transit speed, length, draft, breadth, and other such factors into account in order to line up port requirements and get realistic cost estimations.

22.4.3 Ports

The receiving port should be able to meet the requirements derived from the load-in and the downsizing activities. Examples of physical requirements for the port include water depth, load capacity, storage facilities, and load-in facilities. The lesser the port restraints, the more vessels are available—leading to increased completion in the tendering process. Other port requirements that should be considered are environmental approvals for emissions, noise, dust, and facilities for the specific hazardous materials. Matching the requirements with vessel performance, port capacity and methodology should be done in an iterative process.

22.5 Removal Sequence and Weather Windows

The removal process must be broken down in a removal sequence to analyse the downtime for the decommissioning operation duration.

The time schedules for offshore operations are based on a weather model or met-ocean data. A common approach to the weather model used for the estimation of operation duration is to combine the planned offshore decommissioning activities (removal sequence)—defined as a combination of duration, required weather windows and weather restrictions specific for selected vessels—with the assumed future weather conditions of wind speed, significant wave heights and peak wave periods. In this manner, the time schedules can include vessel downtime due to weather restrictions.

22.6 Waste and Material Management

The policy for waste treatment is a waste hierarchy, shown in Fig. 22.3.

The EU Waste Framework Directive (EU, 2015) specifies that companies involved in the production of materials, construction, demolition, renovation,

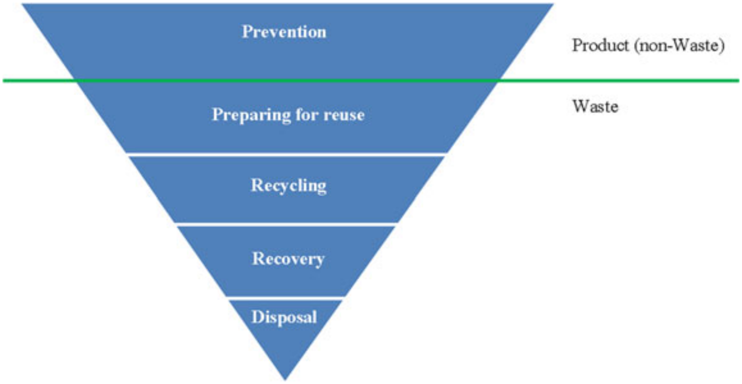

Fig. 22.3 Waste hierarchy

buildings and public works will improve the sorting and recycling of their waste to achieve performance in terms of material recovery of 70 % in 2020. The material received onshore from the wind farm will, as far as possible, be re-used, alternatively recycled or incinerated for energy recovery. If none of these alternatives are possible, for instance, due to content of environmentally hazardous compounds, the material will be deposited at landfills. The trend of circular economy will also influence the offshore wind industry and the design of the modules will by time be easier to dismantle, refurbish and reuse.

22.6.1 Reuse of Components

The nacelle with hub and blades can either be reused completely, or be disassembled in major components and sold as spare parts. The reuse of substructures, towers and sea cables is less attractive. This aftermarket business of selling old turbines is developing as the wind industry is coming to a mature state.

22.6.2 Recycling

The majority of the materials are fit for recycling. All metals, electronics, batteries, gears and motors can be recycled through re-melting. Concrete can be crushed and recycled as secondary construction materials. Oils can be refined and that way upcycled to new oil products. For rubber, plastics and glass fibre, or other composites and epoxy, recycling is possibly, but depending on the quality and compositions of the specific products.

Marine growth on the subsea parts will consist of algae, barnacles and mussels. Due to the anti-fouling agent on the substructure they might be contaminated with the active components of the anti-fouling agent. Due to the organic content in the material, it is possible that the material can be used as other types of sludge.

22.6.3 Incineration

If rubber, plastics and glass fibre, or other composites and epoxy, cannot be recycled it is possible they can be incinerated for energy purposes. For glass fibre it is known that a large amount can cause challenges for the incineration plants filtration system, and that the emission of dioxin can rise.

PVC is a problematic compound, because it can contain phthalates or heavy metals—and if incinerated in a waste incineration plant, the amount of slag produced will increase significantly. This slag is classified as hazardous waste and has to be landfilled. Although a method exists for the recycling of mainly hard PVC, it is not feasible for OWFs. In wind turbines, PVC is sometimes used as cores in the blades and has to be split from the glass fibre, before it can be recycled, which currently is quite difficult. It can therefore be expected that PVC in current blades will be incinerated.

22.6.4 Deposit

Currently, the recycling of composites is quite limited. It is a field of innovation, as presently, these materials are mainly incinerated or landfilled depending on their content. If the marine growth on these materials is highly contaminated by anti-fouling agents the composites will have to be deposited.

Some fractions of hazardous waste must be expected. In some cases, this can be treated (through the use chemicals, for instance); otherwise depositing is the only option.

22.7 Cost Estimation

The cost estimate should include the proposed decommissioning measures described earlier in this chapter (Sect. 22.3). The estimation should have a budget covering:

- Planning and engineering
- Decommissioning design
- Offshore removal and transportation

- Clearance of site
- Onshore dismantling
- Waste and recourse handling
- Assumptions and contingencies

The budget should be accompanied by a time schedule which naturally will appear as the methods are assessed. The schedule should show the different phases of the decommissioning work which naturally would be undertaken in the most suitable part of the year in regards to weather, based on the implementation of sequence and removal windows.

22.8 ODIN-WIND: The Tool

The ODIN-WIND project is a Danish development program under EUDP (energy technological development and demonstration program) supported project NIRAS has, together with its partners, Vattenfall, TWI (Technical Welding Institute), DTU (Technical University of Denmark) and Maersk Broker, created the ODIN-WIND modelling tool.

The ODIN-Wind modelling tool is based on a standard estimation of decommissioning procedures. This includes an input phase where the user is guided through the process of establishing the model. This aids the user in inputting the initial data after which the modelling tool preselects the next steps based on the provided data. Preselection is based on logical choices from what is possible with the previously given input. The user can also update the model to achieve different end results by improving data input, or making different selections. Finally the end result is computed, and results from each iteration can be saved separately for future use. In other words the user can iterate and justify the built model to retrieve the optimised result.

The model is built up in stages and at any time a user can return to previous stages and make changes. However, it is not possible to move on to a later stage unless the previous stage is completed.

The input function part of the modelling tool includes the steps below:

- Log in
- Initial study
- Mapping of Hazardous materials
- Deconstruction
- Receiving ports
- Supplier selection

The end result is presented to the user as a summary of the model with a listing of estimates and relations linked to: the installation details, selected methods, suppliers, geography etc. The end result is presented to the user as relevant information regarding:

- Cost estimation (budget and time schedule)
- Applicable laws, legislation, regulations and standards
- Mapping of Hazardous materials
- Waste and recourse management
- Decommissioning process and methods
- Risk assessments/analysis
- Receiving ports and onshore operations
- Public relations
- HSE

The ODIN-WIND tool is described in more details in the EWEA paper “Preparing for the future—the full process of decommissioning” (Gjødvad 2015).

22.9 Conclusions

As OWFs become increasingly common, there will—inevitably—be a need to decommission obsolete turbines. Decommissioning is a process that has not been explored or researched widely until now, as the need was not so pressing. NIRAS, being at the forefront of technology have anticipated the needs of the industry and developed a comprehensive tool to address the decommissioning process, as described in this chapter.

It is expected that this tool, and indeed the decommissioning process, will be updated and adapted in the future, as wind turbine technology continues to evolve.

Reference

Gjødvad J (2015) Preparing for the future – the full process of decommissioning. Paper presented at the EWEA Offshore 2015 Conference, Copenhagen, 10–12 March 2015

Chapter 23
Wind Turbine Blades: An End of Life Perspective

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Abstract In 2016, the first offshore windfarm constructed in the world—located in Denmark, near Ravnsborg—is turning 25 years old, and will soon be decommissioned. After decommissioning, most of the material of the turbine can be recycled; only the composite materials found in the blades represent a challenge. This part looks at end of life solutions for this material. Wind turbine blade structure and material are described. The ends of life solutions existing and under development are detailed.

23.1 Introduction

Wind turbines are designed to have a lifetime of 20 years (Nijssen and Brøndsted 2013). In this period of time, the turbines can be inspected and some components can be replaced or repaired several times. The blades, for example, can be damaged by hostile weather conditions, impacts or other. However, there can be other reasons for decommissioning a windfarm than the age or the damage state of the turbines. A wind farm can also be repowered with newer and bigger turbines.

A wind turbine is basically composed of a rotor, a nacelle, a tower and a foundation. Figure 23.1 shows the weight of each part for an onshore Vestas V82 turbine (Schmidt 2006). The foundation made of concrete and steel represent nearly 80 % of the structure total weight. At the end of life of the turbine, the foundation can be left in situ or destroyed and the site restored. The environmental risk associated with leaving the foundation in situ can in some cases, be considered as relatively low compared to the environmental impact generated with excavation, breaking, processing, and transporting activities needed to remove it (Welstead et al. 2013). The tower is the next largest component in terms of weight and is mainly made of steel. Metals such as steel, aluminum and copper represent 94 % of the turbine weight excluding the foundation and are generally considered as materials that can be recycled (Schleisner 2000). The 6 % remaining corresponds to plastic, rubber,

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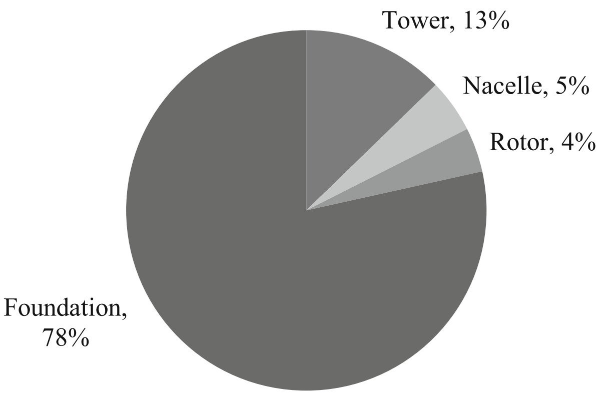

Fig. 23.1 Diagram representing the weight of the part and the corresponding percentage in a Vestas V82 onshore turbine (Schmidt 2006)

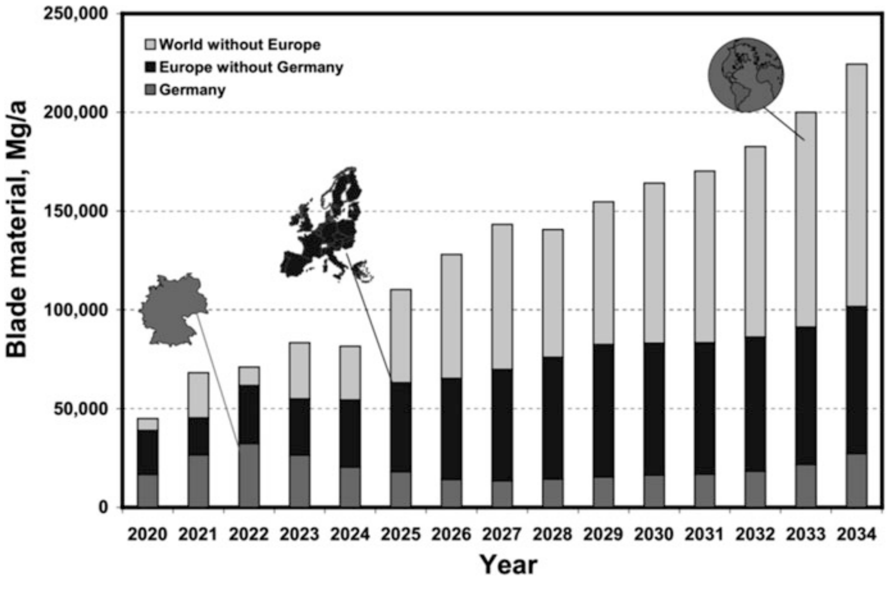

Fig. 23.2 Expected amount of end of life blade material in Germany, in Europe and worldwide from 2020 to 2034 (Albers et al. 2009)

fibre reinforced polymer composites and other. These materials are mostly found in the rotor blades and do not have established recycling solutions.

The amount of wind turbine blade material expected to reach end of life in the coming years is shown in Fig. 23.2. It is estimated to reach 50,000 tons per year in Europe, in 2022.

In Europe, the legislation on the disposal of composite waste is mainly regulated by the waste framework and the landfill directive (Halliwell 2006). The implementations of these directives in the European countries have, for examples, led to higher tax on landfill or a prohibition to landfill in Germany. Recycling solutions for composite waste are therefore needed and research project investigating this issue are ongoing in Europe. In Denmark, the innovation consortium named GenVind (2012–2016), is looking at possible recycling solutions for wind turbine blade and other products made of glass fibre reinforced polymer composite. The project's many partners, from both industry and universities are working to develop suitable technologies and future industrial applications. This section will detail some of the outcomes of the project and other existing solution for end of life rotor blade.

This chapter is organized as follows: the wind turbine blades structure and materials are first presented. Then, the recycling solutions for wind turbine blades are presented, starting with the one implemented on an industrial scale followed by the solutions used occasionally and ending with the solutions on a research stage.

23.2 Wind Turbine Blades: Structure and Materials

Two parts can be distinguished in a blade, the root section and the aerodynamic section. The root section is the part of the blade connected to the turbine (Fig. 23.3a). It is tubular with a circular shape, as shown in Fig. 23.3b. The composite material used for this section is a thick unidirectional glass fiber laminate. Metallic T-bolt also named IKEA bolts or treaded bushings are inserted for mounting the blade to the hub. The root section shown in Fig. 23.3 is from a 25.8 m blade. It has a diameter of 1675 mm and a composite thickness of 80 mm.

In the full blade length, the cross section can be designed as shown in Fig. 23.4a, with a girder box on which two aerodynamic shells are bonded, one on the suction or downwind side and one on the pressure or upwind side. The two sides are adhesively bonded to the box and at the leading and the trailing edge. In other designs the girderbox is integrated as beams in the aerodynamic profile and the two shells

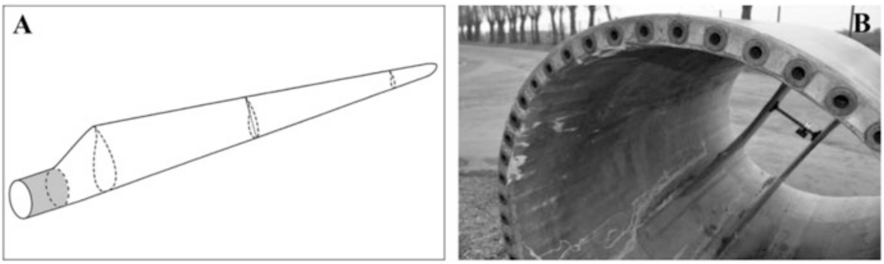

Fig. 23.3 The root section of a wind turbine blade, (**a**) Location of the root section, (**b**) Closer view of the metallic bolt

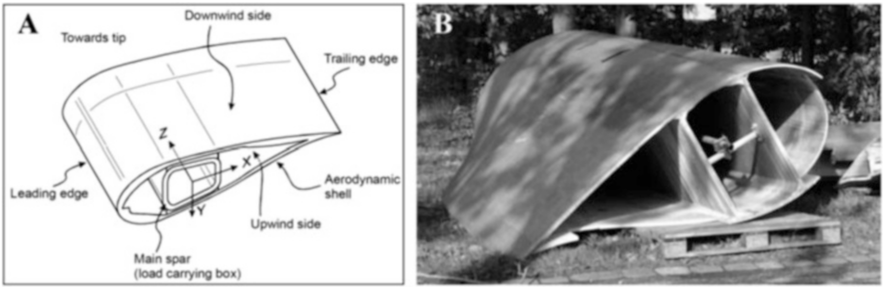

Fig. 23.4 Cross section of a blade, (**a**) Design with a load carrying box (Sørensen et al. 2004), (**b**) Design with two shear webs LM25.8

will be supported in by one or more structural shear webs (Fig. 23.4b). All these structural components are assembled using adhesive bonds.

Regarding the materials, the load carrying beam, the trailing edge and the leading edge are mostly made of unidirectional glass fibre reinforced thermoset matrix. The glass fibres used are E-glass fibres, which are inexpensive and combine high strength from 1500 to 2500 MPa and stiffness, 72 to 76 GPa. As the trend goes towards longer blades, the weight and the stiffness of the blade become an issue. Therefore, reinforcement with a high modulus glass or a hybrid combination made of glass and carbon fibres are introduced in the composites to keep the weight down. The thermoset resins used can be epoxy, polyester or vinylester resins. The shells and the shear webs are made of sandwich structure composites, built as biaxial or multiaxial glass fiber laminates with balsa wood or polyvinyl chloride foam as core material. Surfaces are protected using gel coats, polyurethanes and thermoplastic foils or special paints are used on leading edges (Brøndsted et al. 2005).

As a part of the GenVind project, the residual strength of the composite material from a wind turbine blade after being tested in fatigue was investigated. The aim was to get an idea of the quality of real end of life composite laminate from blades. The results of these measurements demonstrate that the material is keeping its high strength and stiffness. A measurement of the porosity of the materials shows high fiber volume fraction and low porosity content. The microstructural investigation does not reveal any traces of fatigue damages due to the blade testing (Fig. 23.5).

A common size of turbine in 1990 had a power of 600 kW and blades length of 18 m. In year 2015, one of the biggest turbines produced was a 7 MW turbine with about 85 m long blade. The design of blade has also improved throughout the years. To ensure the lifetime of 20 years, the first blades produced were based on conservative design, using more material compared to the blade produced nowadays. Thanks to more optimized design, the blades produced nowadays are lighter (Mølholt Jensen and Branner 2013). This means that, after 20 years, the first blades produced might still be able to last a number of years more.

To summarize, blades are a complex structure made of different parts and materials, which will have different structure depending on the manufacturer and the year

Fig. 23.5 Microstructure of a unidirectional composite from the load carrying beam

of production. When decommissioned, blades will be found in different condition depending on their design and the reason for decommissioning. Altogether, this will make recycling of blade challenging. The following part looks at solutions for end of life wind turbine blades at an industrial scale.

23.3 Industrial Scale Solutions

23.3.1 Refurbishment

The first and simplest end of life solutions for wind turbine blades is to be reused after being decommissioned. This way, their service life is extended. As previously explained, after the design lifetime of 20 years, the wind turbine blades may still have high residual capacity. A study conducted in Germany by Sayer et al. (2009) support this statement. Sayer et al. (2009) investigated the effect of service life on wind turbine blades based on the comparison of the performance of the blades after 20 years of use. The study reported no significant damages by visual inspection and no significant lost in stiffness of the blade. Therefore, reusing wind turbine and wind turbine blades is technically possible. In Europe and in Northern America, a number of companies such as Green-Ener-Tech, Repowering Solutions, Enerpower, Windturbines i.e. and Blue Planet Wind have built business on selling refurbished wind turbine. The advantages are among other an access to a wide range of proven small and medium size turbines, a short lead time and a low cost of about half the price per MW (Tucker 2009).

Standardized refurbishment procedures may include visual inspection, ultrasonic inspection, and natural frequency measurements of the blades. The blades can also be repaired, repainted, weighed and balanced (Beauson et al. 2013). Refurbishment seems technically affordable for blades with a rather small size. The companies mentioned previously handle wind turbine in the range of 10 kW to 1 MW. For blades longer than 50 m, which are commonly produced nowadays, the viability of that solution might be challenged, due to transport difficulties.

23.3.2 Incineration

Blade material can be incinerated for energy recovery. This solution is currently used in Denmark. It has however several drawbacks. Structural composite material, such as the one used in wind turbine blade contain up to 70 wt% of glass fiber. Energy recovery will be difficult, as glass fibers are not combustible and will hinder the incineration (Duflou et al. 2012). It has also been reported that the presence of glass fibre in the flue gas could disturb the gas cleaning system (Schmidt 2006). Finally, the large amounts of fly ashes, which will come from the combustion of large structure such as blade, will remain at the end of the combustion process. This residue also needs to be disposed of or used (Papadakis et al. 2010).

23.3.3 Mechanical Grinding

Mechanical grinding of composites consists in reducing composite waste down to pieces of a few centimeters or less. The resulting mixture, also called shredded composite, is then used in new applications. A number of companies dedicated to collect and process the composite waste brought mechanical grinding to an industrial scale. However, they all terminated, such as Phoenix Fibreglass Inc. in Canada, which was active from year 1990 to 1996 or ERCOM GmbH in Germany from 1990 to 2004.

More recently and until 2014, the company Zagons in Germany collected and grinded wind turbine blade material to be used in cement production. The procedure implemented by Zagons started by cutting the blades onsite to pieces of 10–12 m. At the factory place, these sections were further reduced to pieces of about 1 m in length. These smaller sections were then transformed to shredded composite material by a series of crushing and shredding steps. The resulting material had a size of 5 cm and was mixed with other wet waste materials. Finally, this mixture was sent to the cement production factory Holcim, which used it as a substitute for fuel, to reduce coal-ash, and as a raw material to replace virgin washed sand (Job 2013). Since 2012, using composite waste in the production of cement is considered as a viable recycling solution by the European Union (European Commission Directorate General Environment 2012; European Composites Industry Association 2013). Unfortunately, Zagons was the only industrial scale factory able to process end of life wind turbine blade for cement production worldwide.

The main challenge of this recycling solution is to find applications for the shredded composite material. Apart from the cement production, reinforcement of concrete and polymer composite have also been investigated. However, published results on concrete reinforced with shredded composite underline the need for a consistent quality of shredded composite to observe improved properties of concrete (Asokan et al. 2009). Reinforcement of polymer composite with shredded composite does not provide better results. Shredded composite is a dry material

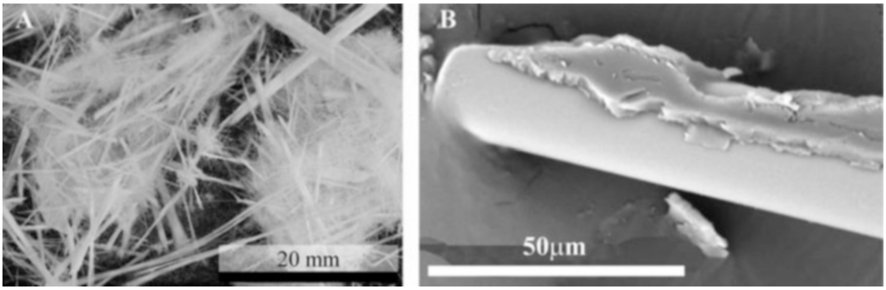

Fig. 23.6 Shredded composite, (**a**) Shredded composite from unidirectional glass fiber composite, (**b**) A glass fiber from shredded composite covered with old matrix material (Toncelli 2014)

which needs a lot of resin to be impregnated properly (Fig. 23.6a). A study conducted under the GenVind project investigated the quality and the performance of composite manufactured with shredded composite. The conclusion is that the shredded composite shows no adherence to the new polymer matrix, because the fibres present in the shredded composite are covered with old matrix material (Fig. 23.6b). The resulting composite tensile strength is very low (Toncelli 2014).

Shredded composite can also be used in sound insulation panel, by using glue to agglomerate it. This is currently under development by a Danish company named Miljøskærm (Friis Farsøe 2013). Mass production is not available yet.

Grinding wind turbine blade material has one considerable drawback; it does not take advantage of the initial structural properties of the composite and reduces considerably the value of the material. The next solutions presented look at reusing the structure and the properties of these composites. These solutions benefits from the capacity of the material, but are difficult to implement on an industrial scale. These solutions are named occasional solutions.

23.4 Occasional Solutions

23.4.1 Large Sections

Large sections of wind turbine blades can be reused for architectural or other structural purposes. This solution offers the possibility to use the good quality and the structural capacity of the blade material. It also extends the life of the material with little re-processing. On the other hand, the number of possible applications is limited by the complexity of the structure of the blade and a mass production is close to impossible. To industrialize such solution a reliable source of material with given dimension is needed, and this is difficult with end of life wind turbine blade. Examples of occasional applications have been proposed by the SuperUse studio in the Netherlands. These are a playground for children (Fig. 23.7a) or benches on a

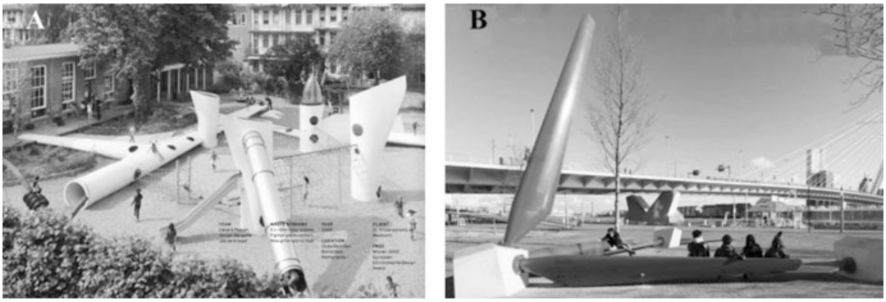

Fig. 23.7 Examples of applications for large sections of wind turbine blades by the SuperUse studio, (**a**) Wikado playground in Rotterdam, (**b**) Benches at Willemsplein in Rotterdam

Fig. 23.8 Furniture made out of end of life wind turbine blades by Wigh Design, (**a**) Table and longboard, (**b**) Prototype of furniture

public place (Fig. 23.7b). Within the GenVind project, a bridge is under planning by the same Dutch architectural studio. The bridge will use two blades from Siemens Wind Power and will be located in Aalborg in Denmark.

23.4.2 Construction Element

Construction elements such as beams, plates and curved elements can also be cut out of the blades. This requires heavier reprocessing and the geometries of these elements are also restricted by the blade structure. However, the production of such standard element could diversify the possible applications. The use of such material in furniture has been investigated by Lars Wigh in the GenVind project, as shown in Fig. 23.8. Similar to the use of large section of wind turbine blade, industrialization of this recycling solution would also require having a reliable source of wind turbine blade material with known dimensions.

23.5 Solutions on a Research Stage

The last recycling solutions presented in this chapter are the ones requiring the heaviest re-processing and still mostly exist on a research stage; these solutions do not exist, or have not been trialed, on a commercial scale yet. Research on composite recycling technique has been ongoing for more than 20 years (Job 2013; Pickering 2006). The techniques are usually divided into two categories: the thermal and the chemical recycling processes. The thermal recycling techniques are for example pyrolysis or fluidized bed and allow recovering of the fibers mainly. Pyrolysis is the decomposition of organic molecules to smaller ones in an inert atmosphere with processing temperature ranging from 300 to 700 °C depending on the heating system used and the presence of a catalyst (Allred and Busselle 2000; Åkesson et al. 2012). Pyrolysis was once used on a commercial scale by ReFiber, a Danish company recycling wind turbine blade into glass fiber insulation material. The company stopped its activities in 2007. The fluidised bed is a thermal oxidative process with a processing temperature around 450 °C. The main disadvantage of these thermal recycling techniques is the reduction by a factor two or more of the glass fiber tensile strength (Kennerley et al. 1998; Thomasson et al. 2014).

Regarding the chemical recycling techniques, the most advanced and promising one is probably supercritical fluids, which uses both heat and chemicals. Supercritical fluids are fluids at temperature and pressure just above the critical point, where the fluid presents itself in one single supercritical phase, having combined characteristics: liquid like density, dissolving power, diffusivity and gas like viscosity (Oliveux et al. 2012). With this technique both the resin and the fibers can be recovered. This technique also investigated under the GenVind project has shown that glass fibers can be recovered with most of their initial tensile strength (unpublished work).

These recycling techniques are meant to enable the reuse of recycled glass fibres in new polymer composite. However, the decreased tensile strength of the fibers, the degraded surface properties (loss of the silane coupling agent) and the cost of these fibers, more expensive than pristine fibers, make it difficult.

23.6 Conclusion

Wind turbine blades are a complex structure made of different composite materials. They are built according to different design and are produced at different length. In addition, windfarms will be decommissioned at different time and for different reasons. End of life wind turbine blades material is therefore a discontinuous and inhomogeneous source of material. Altogether, this makes end of life wind turbine blade a material challenging to recycle. This section reviewed recycling solutions which are used or could be potentially be used nowadays.

The potential of these recycling solutions can be compared on: the amount of reprocessing involved, the value of the material produced and the number of possible applications. Ideally, a recycling solution would involve little reprocessing to produce a cheap valuable material, which can be used in many applications.

Considering the amount of reprocessing needed in the different solutions presented, refurbishment is certainly the one requiring the less, compared to a process like mechanical grinding or supercritical fluids. When comparing the value of the material produced, here again, refurbishment, by renewing blades which will produce electricity for a couple of more years is probably of higher value than expensive recovered glass fiber with low mechanical properties. However, when considering the number of possible applications which can be made out of the material produced, the solutions involving heavy reprocessing might be more interesting. All in all, this shows that the recycling solutions presented in this section all have advantages and drawback, which could be attenuated by combining them.

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