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Past management and future challenges with glass fiber composites from wind turbines in Norway

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Past management and future challenges with glass fiber composites from wind turbines in Norway

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Sammendrag: Bladene på dagens vindturbiner er laget av glassfiberforsterket komposittmaterialet. Bladene er laget for å tåle belastning fra vind og vær i opptil 30 år. Etter endt levetid demonteres vindturbinen de ulike materialene gjennvinnes.

Denne rapporten viser at resirkulering og gjenbruk av turbinblader er utfordrende. En gjennomgang av alle nedlagte vindturbiner i Norge viser at i underkant av halvparten av bladene har blitt deponert i deponi og resten har blitt solgt, brukt som deler i andre vindkraftverk eller brent. Rapporten anslår også den totale massen med glassfiberfiberforsterket kompositt i norske vindkraftverk til å være over 70 000 tonn.

Rapporten er utarbeidet av Silje Maya Andreassen, student ved NTNU, på oppdrag fra NVE.

Emneord: Vindturbin, nedlegging, bærekraft

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Abstract

Wind turbines are normally designed with an expected lifespan of 20 to 30 years. When reaching their end-of-life (EOL), they are disassembled, and parts are treated differently depending on what materials they consist of. In contrast to other parts, the wind turbine blades (WTB) and the shell of the nacelle (WTNS) are hard to recycle, as they are made of glass fiber (GF) or carbon fiber (CF) composites. In lack of other options, disposal to landfill has been the most common way of handling waste from WTB and WTNS. In Norway only a handful of turbines have been decommissioned this far. This makes it possible to trace the composite parts post disassembly. In the summer of 2023, the Norwegian Water Resources and Energy Directorate (NVE) commissioned a study into the fate and possible future of decommissioned turbines in Norway. This study has been organized by the section of ”Energy and Licensing” (EK). Silje Maya Andreassen is the student who have been working on the project, and she studies ”Bærekraft-, arbeidsmiljø- og sikkerhetsledelse” (health, environment and safety) at the Norwegian University of Science and Technology (NTNU).

I would like to thank everyone who has contributed to this project, both internally at NVE and externally. A special thanks to my supervisor Thomas Mo Willig.

Contents

1 List of abbreviations

CF Carbon fiber

DAN Calculation method based on the article ”Kortlægning af mængder og behandlingsmuligheder for vindmøllevinger” (Ricard 2023).

EOL End-of-life

GF Glass fiber

NREL Calculation method based on the article ”Wind Turbine Design Cost and Scaling Model” (NREL 2006).

R Blade length

TRL Technological readiness level

WTB Wind turbine blade

WTNS Wind turbine nacelle-shell

2 Summary

Except for the wind turbine blades (WTB) and the wind turbine nacelle-shell (WTNS), most of a wind turbine can be recycled. The WTBs and the WTNS is made to endure the force of nature, thus made from durable glass- or carbon- fiber composites. As few turbines have been decommissioned in Norway, their pathway post decommissioning can be traced. In this report, past-management and future challenges regarding the composite materials have been investigated. Additionally, wind farm operators' thoughts, views and plans for future management of the composite materials are presented. The main findings in this report are summarized below.

- Different waste-management-strategies for wind turbine composites exist, but as all of them have deficiencies none can be labeled as the definitive solution.
- Most of the decommissioned WTBs in Norway have been disposed in landfills. Combined with the WTBs that were incinerated, these two methods have been used on three quarters of the decommissioned WTBs in Norway.
- The amount of already managed GF composites in Norway is just a fraction of what is predicted to come. A large share of this will have to be managed simultaneously.
- In general, the wind farm operators believe that waste-management technology will develop, and they believe that recycling the GF composites will be the most common waste-management-strategy for the next 30 years.

3 Introduction – What are the challenges with decommissioned wind turbines?

Circular economy is a strategy implemented to reduce the anthropogenic pressure[1] on nature and the environment. Circularity contributes to a sustainable future, by prolonging the life of material and minerals already extracted and part of our economical circuit. Importantly, minimizing the resource extraction also includes replacing fossil fuels with renewable energy (WWF 2023).

As a contribution to a sustainable future, more than 1400 wind turbines have been built in Norway over the last thirty years, with more than 60 % installed within the last five years. Although wind power is renewable, the industry has not managed to close the loop of circularity. Most parts of a wind turbine can be recycled, or parts can be reused in new turbines. The major non- recyclable parts are the wind turbine blades (WTB) and the shell of the nacelle (WTNS). These parts are designed to endure the force of nature, as well as being as light as possible, which makes them harder to recycle. Globally the most common disposal method for the blades has so far been disposal to landfills (Paulsen & Enevoldsen 2021). From a circular economy perspective, this is the least sustainable strategy, and can be found at the bottom of the EU-waste hierarchy (European Commission 2023). Disposal to landfills is a contradiction to our perception of renewable energy, as it is not a sustainable disposal strategy, and affects the image of the wind power industry (Paddison 2023).

Few wind turbines have been decommissioned in Norway. We are thus in a position where it is possible to find out what has happened to most of the turbines which have reached their end-of-life (EOL). In addition to presenting the findings, this study includes future perspectives concerning decommissioned wind turbines. Anticipated composite waste from WTB and WTNS in Norway is estimated, and some of the most important stakeholders within the industry have given insight to their thoughts, views and plans for future managing of decommissioned turbines.

[1] Chiefly of pollution or environmental change) originating in human activity".

4 Wind turbines in general

The four main components of a wind turbine are the foundation, tower, rotor (including the hub and three blades) and the nacelle (consisting of the gearbox, shafts, generator, and brakes). When reaching EOL, over 85 % of the materials can be recycled, as the main fraction of the tower are made of steel (Ørsted 2023). Although the turbines have a relatively high recycling percentage, the wind industry have been criticized for their way of handling some of the non-recyclable parts. The material composition of the WTB and WTNS makes them harder to recycle and have mainly been disposed of in landfills. A description of the composite material in the WTB and WTNS are provided in the next subsection (subsection 4.1).

4.1 What are the WTB and the WTNS made of?

The WTB and WTNS are usually made of composite materials. Primarily of glass fiber (GF), and- to some extent - carbon fiber (CF) that are glued together with a resin to form the composite material (Bladena 2021). GF are thin fibers produced out of molten glass (˚Artun 2023) and look like short strains of hair. GF composites are used due to their favorable properties. The material is light, has a high breaking strength, is heat resistant, does not absorb moisture, does not conduct electricity, as well as being resistant to chemicals (Ricard 2023). High durability in demanding weather conditions causes GF composite to be a great material for WTB and the WTNS in the operative part of their life cycle. At the EOL the durability of the composite becomes a problem.

The challenge is to separate the fibers form the resin while keeping the mechanical properties in the fibers. Methods for recycling composites exist, but the different methods are not optimal (Karuppannan Gopalraj & Kärki 2020).

Simens Gamesa, a large original equipment manufacturer, claims their recent technology makes it feasible to produce recyclable blades. They say “The only change to the blade production process is our new resin” (Siemens Gamesa 2023b), and in the recovery process they uses “a mild acidic solution to separate the materials” (Siemens Gamesa 2022a). Based on Simens Gamesa’s claims, materials from turbines developed today can be recycled and reused in the future.

4.2 Ways of handling fiber composites from wind turbines

In the Waste Framework Directive, the five-step “waste hierarchy” establish an order of preference for managing and disposing of waste (European Commission 2023). The hierarchy is displayed in Figure 1. Historically, most WTB and WTNS have been disposed in landfills. Landfills are at the bottom of the hierarchy and should be considered a last resort. Other methods exist, but the quality and practicality of these methods varies. Based on the report ”Kortlægning af mængder og behandlingsmuligheder for vindmøllevinger” (Ricard 2023), this chapter gives a short summary of different methods and the corresponding feasibility for the different methods.

Figure 1: *The "waste hierarchy" provided by the Waste Framework Directive (European Commission 2023).*

4.2.1 Disposal to landfills

In practice, disposal to landfills is conducted by burying the materials no longer used. Globally, this is one of the most common methods of handling old WTB. On the technology readiness level (TRL) scale, the method has the highest score, meaning that the technology is competitive as a functioning system for disposal. The scale goes from 1 to 9, representing the degree of technological feasibility, spanning from "Basic principles observed and reported", to "Actual system *flight proven* through successful mission operations" respectively (NASA 2012).

Disposal to landfills is the cheapest technology on the market, but is considered not sustainable, as no energy or material recovery is achieved. It is space-consuming, and symbolically it is conflicting with "green" energy. In some countries, they have banned disposal to landfills, pushing the sector towards technological innovation (Wind Europe 2021).

4.2.2 Incineration

Incineration, with or without energy recovery, is also possible, but not recommended. GF is not particularly flammable and large quantities of ashes remain after incineration. Ashes from the WTB are mixed with remains from other incinerated materials, which can often be toxic for the environment. Since the remnants possibly contain toxins, it cannot be used as filling in other products and ends up in landfills. The process is considered commercial, but a TRL score is not available. Incineration is one out of three classifications of thermal recycling. The other two methods are explained in subsubsection 4.2.4.

4.2.3 Cement production

Another method with top score on the TRL scale, is utilizing the WTB in cement production. Granulated composite waste is used as raw material in a process denoted as "co-processing" with cement. In this process, resin is utilized as fuel, as an alternative to natural gas, coal, etc. Due to high temperatures, GF converts into ash, which is further used in cement production and can substitute sand. Thus, both energy and material are recovered from the WTB in cement production.

4.2.4 Recycling

Different recycling methods can recover GF or CF from fiber-reinforced polymer. The different methods can be divided into mechanical-, chemical-, thermal-, and hybrid- recycling. Mechanical recycling is a process where WTB composites are crushed, milled, shredded or grinded into smaller pieces, so it is possible to separate short fibers from polymer resins. The pieces are then reused, either as concrete reinforcement or reused in other applications like dough molding compound, bulk molding compound, polypropylene and more. A more detailed description of the processes, as well as pros and cons are provided in the article "Recycling of wind turbine blades through modern recycling technologies: A road to zero waste" (Khalid et al. 2023).

Chemical recycling "involves the chemical decomposition of polymer matrices to recover both short fibers and other degraded products" (Khalid et al. 2023). Different chemical recycling methods exist, but the most common ones are solvolysis and the use of sub- or super-critical fluids. The remaining can be reused as fuel gas, composite reinforce through recyclates, and fillers (Ricard 2023, Khalid et al. 2023).

Thermal recycling is a recycling process in which heat helps to separate the polymer from the fibers. Two different approaches are shortly explained here. In pyrolysis the blades are heated in a range between 450-1000 °C. The heat converts the polymer resins into vapor or gas, then the polymer separates from the fiber. Reuse applications include pyrolytic oil or gas, organic liquid fuel, or composite reinforced through recovered short fibers. The second method is oxidation in fluidized bed. In this process polymer undergo combustion due to a combination of extreme hot air and oxygen supply. Consequently, polymer and fibers are separated. The fibers can be reused in high-modulus composites, electromagnetic shielded materials, and bulk molding compounds (Khalid et al. 2023).

The combination of thermal, chemical, and mechanical recycling is referred to as hybrid recycling. Hybrid recycling has a low score on the TRL scale and is thus considered a technology in development. Compared with the other recycling techniques, the hybrid version gives promising results in terms of waste management, but more research is needed. Excluding mechanical recycling, the processes have a score of 7 or less on the TRL scale, meaning that they are processes on lab-, or pilot-scale, with a potential for improvement.

4.2.5 Repurposing

Due to the properties of the material, the WTB can be repurposed. Old WTBs can be used as small bridges, bike shelters, rooftops of small shelters, platforms, buoys, sound barriers, and more (Re-Wind 2023). WTBs have also been used as the main components in playgrounds (Guzzo 2019).

4.2.6 Repair, reuse and refurbish

The last option is to reuse, repair, and refurbish the components. Either the wind turbines can be repaired and maintained, extending the life cycle of the components, or they can be refurbished and sold as "used". Vestas, one of the world's leading manufacturers of wind turbines, provides services regarding repair and refurbishment of turbines. They provide this service, as operational circularity is fundamental to their target and goals towards a circular economy (Vestas 2022). WTB can be disassembled, refurbished and sold separately.

4.2.7 Challenges with different methods of handling composite waste

There are some challenges related to handling composite materials. Firstly, methods do exist, but most of them have the potential for improvement of their TRL score. Secondly, the most mature processes, with a high TRL score, are rated poorly in terms of waste management. Therefore, more research is required to achieve a level of recycling that better harmonizes with the concept of circular economy.

Supply and demand are another influencing factor. Small demand, small market values for fiber and raw materials, price competition, and high investment cost have been mentioned as weaknesses and barriers regarding the different processes. Additionally, some of the processes require large- scale facilities, as well as a constant material flow to operate on a commercial scale. Regulations should also be mentioned, as some countries and companies' have banned disposal to landfills, dismissing it as a suitable alternative (Ørsted 2023, Wind Europe 2021). Some companies, such as Vattenfall in Sweden have publicly stated that they will not put WTBs in landfills and want to recycle all blades by 2030 (Vattenfall 2021).

Khalid et al. (2023) states that "Modern recycling technologies have been found as viable and sustainable options for the effective utilization of EOL composite wastes. However, significant efforts are required to address some existing challenges". CETEC[2] (Circular Economy for Thermoset Epoxy Composites) have published that they have a new recycling technology, where both the epoxy and fibers can be recovered and recycled. They believe that the technology will be implemented and commercialized in the near future (Danish Technological Institute 2021). Existing methods of handling composite waste can only be seen as options, as they all have flaws preventing them from being a definitive solution.

[2] Coalition of industry and academia to commercialize solution for full recyclability of wind turbine blades" (Danish Technological Institute 2021).

5 GF composites from wind turbines in Norway

There are currently 65 operational wind farms, with 1392 wind turbines in Norway (NVE 2023*a*). Most of the turbines were commissioned within the last five years, implicating that the Norwegian wind turbine fleet is relatively new. Out of all commissioned turbines in Norway, two thirds were installed between 2017 and 2023 (NVE 2023*b*). Wind power constitutes roughly 10 % of the electricity production and produces approximately 16 TWh a year (NVE 2023*c*).

As with all other constructions, wind turbines have a given lifetime. Normally they have a designed lifetime of 20+ years (Siemens Gamesa 2023*a*, American Clean Power Association 2022). What happens to the turbines after EOL varies, and is discussed in section 3. So far, few turbines have been decommissioned in Norway. As a country, we are thus relatively inexperienced when it comes to handling the GF composite waste from WTB and WTNS. Within the next 20 to 30 years, most of the turbines in the Norwegian fleet will reach the end of their designed life. Consequentially, there will within the same period be a “wave” of GF composites that must be handled. An estimate of the anticipated GF composites from WTB and WTNS is provided in this section.

5.1 Methods utilized to calculate the mass of the GF composites from wind turbines

The mass of the composite parts on the wind turbines are in general kept secret due to competitive advantages within the sector. Considering the number of different turbine models operating in Norway, it would have been both time consuming and challenging to obtain this information. Instead, two approaches, believed to provide good indications, have been used to estimate the mass of WTBs currently in operation.

The first approach is based on equations assembled by the National Renewable Energy Laboratory (NREL). In this equation the mass of the WTB depends on the blade length (R), and is calculated by using Equation 1 (NREL 2006). R is not given, but since the rotor diameter of each turbine is known, R can be derived from Equation 2. Considering that the WTB are attached to the hub, R are less than half of the rotor diameter. Conducting a short analysis of Vestas turbines gave a difference of 2,6 meters between the rotor diameter and R times two. The same ration is in this report assumed to be applicable for all wind turbines.

$$Turbine\ blade\ mass = 0{,}4948 * R^2 \tag{1}$$

$$R = \frac{rotor\ diameter - 2{,}6}{2} \tag{2}$$

In the second approach, referred to as DAN, the mass of the WTB is calculated based on the expected mass of composite materials, per unit installed capacity in MW. Over the years turbines have developed to be more robust and energy efficient, resulting in longer and heavier WTBs (Ricard 2023, Hartman 2022). For instance, no turbines operating in Norway had a rotor diameter greater than 100 meters before 2011. In comparison, less than 15 % of the turbines installed after 2010 has a rotor diameter smaller than 100 meters (NVE 2023*b*). Accordingly, the expected composite material per MW, depends on the year of installation, as well as other factors. Ricard (2023) estimates 12 tons of composite materials per MW, for all turbines installed after 1994. Due to an unexpected increase in the size of new turbines, they state that it could be an underestimation. Nevertheless, the same assumption is used in this report.

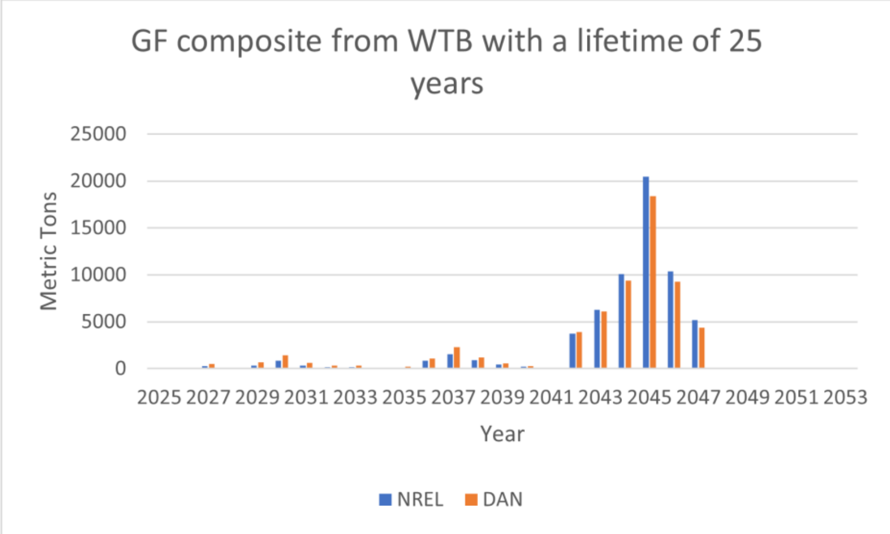
The WTNS consists of the same components as the WTB, thus estimation of their contribution to the stream is included in Figure 3. Again, Ricard (2023) method has been used. In the calculations, the weight of the WTNS is assumed to be 16 % of the total weight of the three WTBs on the associated wind turbine.

Another assumption affecting the estimated stream in Figure 2 and Figure 3, is that the turbines have a lifetime of either 25 or 30 years. This source of error affects the reliability to the results, hence further discussed in subsection 5.3.

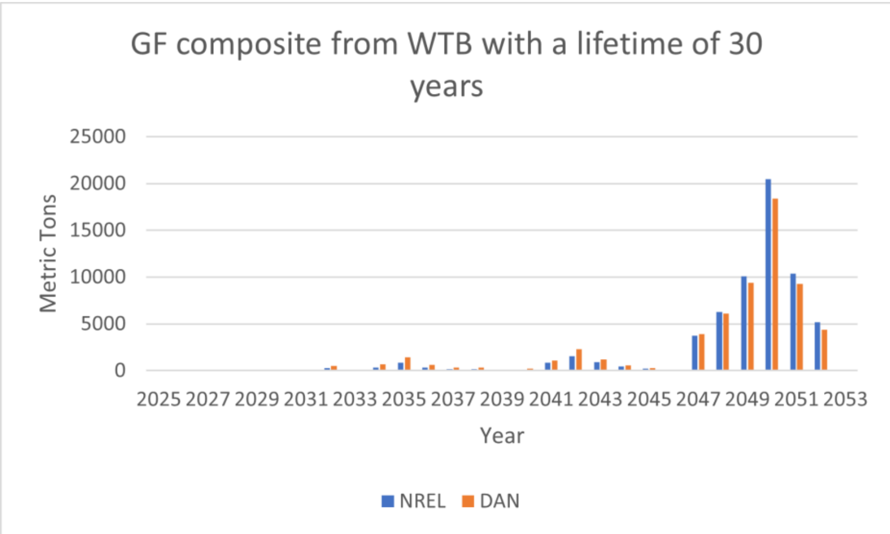
5.2 Anticipated GF composites from wind turbines

As shown in the figures, there is going to be a significant increase in GF composites from the WTBs and WTNSs in the mid-21st century. This is a result of the increased development of wind farms in Norway over the last few years. In 2020 a record number of turbines were assembled, resulting in the peak in Figure 3 passing 20 000 metric tons of composite material in 2045 or 2050 depending on turbine lifespan. The figures do not include already decommissioned turbines, but the total mass of these is in the same order of magnitude as what is expected to be decommissioned in 2030 alone (Figure 2a). The amount of GF composites we have dealt with so far is only a fraction (roughly calculated 1 %) of what is coming within the next 30 years.

As the figures show, different equations give different results. Based on the figures, NREL estimates predict greater mass for bigger turbines with higher installed effect. The increased size of installed turbines in the last years can be interpreted in the figures by observing the differences between the DAN- and NREL-estimates. The reason for this is that the NREL estimates take increased blade length into account, which the DAN estimates do not. This results in the NREL estimates exceeds the DAN estimates after 2042 or 2047 respectively.



(a) Estimated GF composites from WTBs with the assumption that the turbines are in operation for 25 years.

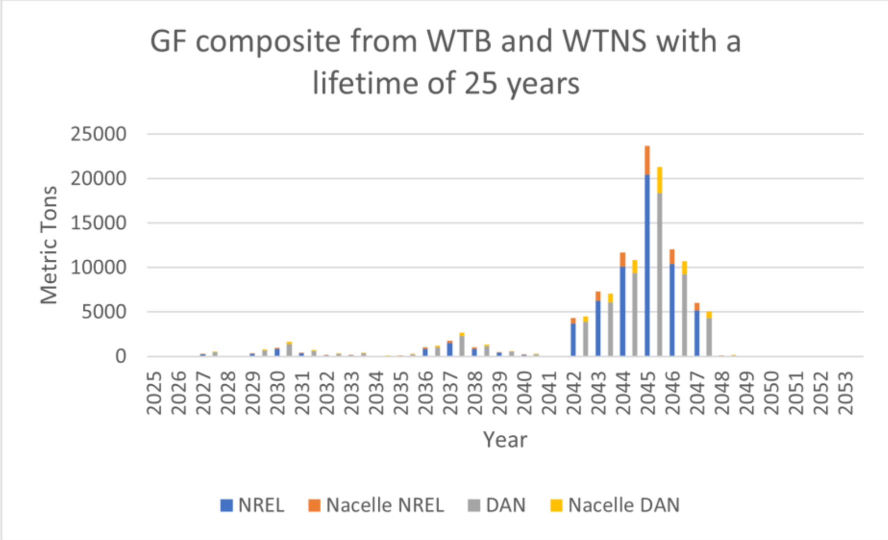


(b) Estimated GF composites from WTBs with the assumption that the turbines are in operation for 30 years.

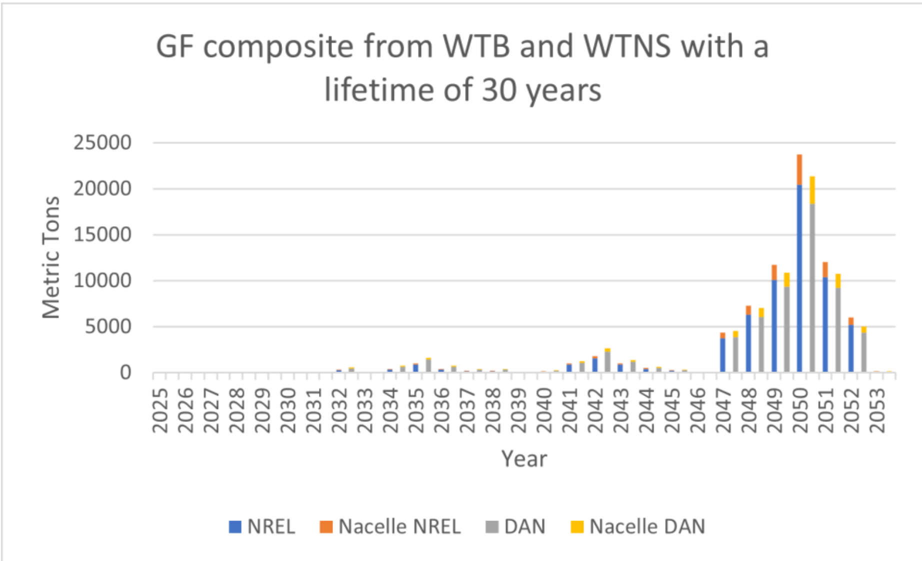
Figure 2: *Estimated GF composites from WTBs. "NREL" is the estimated mass based on an equation assembled by National Renewable Energy Laboratory. "DAN" is the estimated mass based on the same assumptions as provided in Ricard (2023).*

Depending on the turbine type, the precision of the estimations varies. For instance, DAN works best when it comes to the Nordex N80 turbines, while NREL better resembles the mass of the Vestas V90 turbines, see Table 1 in Appendix A. In some cases, both methods underestimate the WTB mass, as can be observed happening with Simens SWT93 turbines.

The mass of the WTNS has been difficult to find, as the mass of the nacelle is often given including the components inside. If those values had been used, the mass from the WTNS would have been overestimated, thus Ricard (2023) method is utilized. Compared with the mass of the WTBs, the mass-contribution from the WTNS is small, but not neglectable. In the year in which the peak occurs, approximately 3000 metric tons stems from the WTNS alone. The total mass of composites within those years are estimated to be more than 70 000 metric tons.



(a) Estimated GF composites from WTBs and WTNS with the assumption that the turbines are in operation for 25 years.



(b) Estimated GF composites from WTBs and WTNS with the assumption that the turbines are in operation for 30 years.

Figure 3: *Estimated GF composites from WTBs and WTNS. NREL and DAN is calculated as in Figure 2. "Nacelle NREL" and "Nacelle DAN" is calculated using the same method as in Ricard (2023), based on the mass of NREL and DAN respectively.*

5.3 Sources of error

An evident source of error is the assumption that all turbines are operating in the exact same amount of time. In reality that is not the case, as many factors influence the lifespan. Most important is the environmental conditions determining the level of loading. Especially the rotating parts are prone to fatigue when exposed to extreme climate, thus harsh conditions have the potential to decrease the lifespan significantly. Turbines can also be damaged if they are struck by lightning or are sited in turbulent areas. In Norway turbines have been decommissioned due to all above mentioned factors, both separate and in combination.

Extended lifespan can be obtained thought monitoring and maintenance, given that it is economically beneficial and technically feasible. Depending on the state of the turbine, Siemens Gamesa (2022*b*) claims that they can prolong the lifetime of a turbine by up to 10 years. The "life extension" service includes theoretical analysis of the turbine, component upgrades, site specific maintenance program and more.

In Denmark turbines have been prematurely decommissioned despite being operationally capable. The premature scrapping was caused by a sharp subsidy drop (happening in 2003), proving that politics also influences the turbine lifespan. Mauritzen (2014) states that ”The most common reason for scrapping a wind turbine in Denmark is to make room for a newer turbine. The decision to scrap a wind turbine is then highly dependent on an opportunity cost that comes from the interaction of scarce land resources, technological change and changes in subsidy policy”.

Considering all factors affecting the lifespan, it is nearly impossible to know for how long the individual turbines will operate, as the lifespan can either be prolonged or shortened. Consequently, the graph in Figure 2 and Figure 3 can be improperly distributed, or the peak can potentially occur in another year. Despite being inaccurate, the figures shows that we must be prepared to handle significant amounts of composites from the turbines in the future, and that a lot of it needs to be handled simultaneously.

The calculation methods are also a source of error. Firstly, the equations are assumed to be applicable for all models, which is not the case. Demonstrated in Table 1 (Appendix A), the accuracy of the calculations compared with the actual mass of the WTB varies. Secondly the assumptions the equations are based on can be misleading. It is possible that DAN is underestimating the mass of newer turbines. Accordingly, it could be that DAN should have been more similar to NREL (in Figure 2 and Figure 3). As for the lifespan of the turbines, the mass calculations are not accurate, but still useful as they can be used to indicate the expected quantities of composite waste from the turbines.

6 What have happened to the decommissioned turbines in Norway?

In the late 20th century, the first commercial wind power plants started operating in Norway (NVE 2023a). Since then, some turbines from Lindesnes, Mehuken 1, Vikna, Valsneset, Hundhammerfjellet, Havøygavlen and Frøya wind farm have been decommissioned. In addition, turbines at Sandøy are decommissioned the summer of 2023.

Unlike Denmark (a pioneer within the industry), in Norway only a handful of the turbines have been decommissioned, making it possible to investigate what have happened to them after their operating time (Tranberg et al. 2022). In the attempt of tracing old turbines, wind farm operators, renovation companies and others have been contacted.

6.1 Lindesnes

Lindesnes wind farm, also called Fjeldskår consisted of five Wind World W4800 turbines. They were commissioned in 1998, and in operation until 2018. Towards the end of the lifespan the turbines had high operational costs because of component failure, combined with the struggle to obtain spare parts (Norsk miljø energi AS 2017). Therefore, the turbines were replaced. The GF components, the WTBs and WTNS were sent to Knudremyr, a landfill site close to Lillesand. In total 40,5 metric tons of sliced GF composite waste was delivered to Knudremyr. Other parts of the turbines, such as the towers were sent to Hellik Tegen As (Hokksund) for metal recycling. In general, they slice the metal in smaller parts and sell it based on quality.

6.2 Mehuken 1

Mehuken 1 consisted of five Vestas V52 turbines commissioned in 2001. Due to high operational costs and need for maintenance they were replaced by Mehuken 3, consisting of three more energy efficient turbines (Kvalheim Kraft DA 2013). In 2013 all turbines from Mehuken 1 were sold to Windbrokers, today replaced with Windworst–company. Windbrokers was a company trading pre-owned wind turbines. They sold three of the turbines to Italy, and two were sold to Poland, all with the intention to continue operating. Since Windbrokers is no longer a company, and all turbines were sold separately to individual customers, it is hard to trace their current location. Henk Van Den Bosch, founder of Windbrokers (Windvorst 2023), says “As far as I know those turbines are all still in operation”.

6.3 Havøygavlen

After 19 years in operation, 15 Nordex N80 turbines approached the designed lifespan at Havøygavlen (Finnmark kraft 2018). In 2021 they were taken down as Havøygavlen was going to be re-powered.[3] Due to many years in demanding weather condition the blades were worn out and could not be resold or reused. They were cut in half and sent to Østbø AS where they were shredded and incinerated with energy recovery (Finnmark Kraft 2022).

AF Decom oversaw the disassembly of the turbines excluding the fundaments. In their final report it is stated that 467,3 metric tons of residual waste was sent to Østebø AS and Rask AS (AF Decom 2021). As GF composites form WTBs and WTNS were the dominant fraction of the residual waste, most of it were therefore sent to Østbø AS (Norconsult 2020). The estimated weight of each WTB was 9,2 ton (Norconsult 2020). For the rest of the turbines, 175 tons were reused including some generators, pitch-systems, some electronics, some gearboxes, etc. None of the towers were reused, but they were recycled.

[3] Replacing old turbines by more powerful and efficient models” (Wind Europe 2022).

6.4 Hundhammerfjellet

In a period between 2011 and 2019, 16 turbines were decommissioned at Hundhammerfjellet. The length of the lifespan varied as some only operated for 2 years, while others operated for 19 years (NVE 2023b). During operational time an additional two sets of WTBs were damaged, hence in total 54 WTBs were decommissioned. The WTBs and WTNS were cut into pieces, and approximately 70 % of it were disposed in landfills, while the remaining 30 % were incinerated with energy recovery. More than 180 metric tons of ”residual waste (glass fiber)” needed to be managed from the disassembly of 7 of the wind turbines (Containerservice Ottersøy AS 2019). Franzefoss Lia, is a landfill site who received some of the decommissioned WTB.

6.5 Vikna

Vikna is the first operative wind farm in Norway, it started operating in 1991. Since then, 5 Vestas turbines have been decommissioned. As for Hundhammerfjellet some WTBs were damaged, hence in total 18 WTBs have been disposed in landfills.

6.6 Valsneset

At Valsneset three test-turbines have been decommissioned. Two of the turbines were relatively small, a Vestas V27 and a NEG Micon 900kW, and they were disassembled by an unknown Danish company. Both were supposedly utilized as spare parts machines. The last turbine, a 3 MW demo turbine from Blaaster (with a rotor diameter of 101 meters), were decommissioned in 2019. As it was a prototype the residual value in the components were limited, thus it was taken down by overturing it.[4] The remaining were sorted, metal and other parts were recycled, and the blades were disposed in landfills.

6.7 Sandøy

Sandøy wind farm started operating at Harøya in 1999. Operational problems entail operational costs; thus, they plan to re-power their turbines. Currently the WTBs and WTNS of 5 Vestas NEG Mincon turbines are being disassembled. The parts will be sent to Denmark, there it will be refurbished, sold, and recommissioned at another site. If the blades turn out to be impossible to refurbish, in accordance with Vestas circular economy targets, they will be recycled (Vestas 2022). The WTBs and WTNS will be replaced by 5 refurbished Vestas V52 turbines, while the old towers and foundations will remain (Norconsult 2021).

6.8 Frøya

Frøya is included in this rapport because some WTB have been damaged. One of the turbines has been decommissioned, in addition a blade has been replaced due to damages. Damaged WTB were sent to Meldal landfill, while the rest of the components have either been sent to Denmark or recycled. A WTB was also damaged while being on hardstand, what happened to it is unknown, but it may have been used in recycling-experiments.[5]

[4] ”Tip (something) over so that it is on its side or upside down”.

[5] A paved or hard-surface area.

6.9 Overview of dissembled WTBs

Figure 4 is an overview of what have happened to WTBs in Norway so far, including the plans for WTBs at Sandøy as it is an ongoing process. Disposal in landfills has been the most frequent way of handling the WTBs. Approximately half of the WTBs ending up in landfills comes from Hundhammerfjellet, implying that the distribution in Figure 4 highly depends on how the WTBs have been handled at the wind farms operating most turbines. Secondly, WTBs have been incinerated with energy recovery. Havøygavlen and Hundhammerfjellet is the only wind farms in Norway where incineration have been utilized, confirming that large wind farms highly influence the distribution in Figure 4.

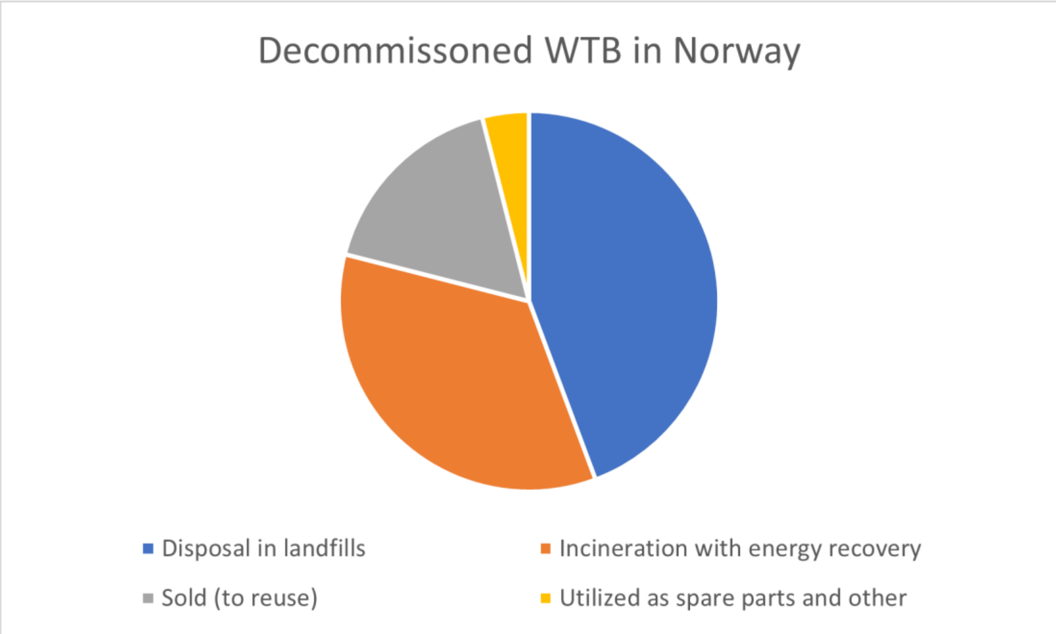


Figure 4: *A illustration of what have happened to WTBs in Norway. The illustration includes the ongoing re-powering at Sandøy where WTBs are going to be sold.*

In conversation with companies operating landfill sites, the overall message was that the composite waste from WTBs were unpractical to handle due to its volume. Cutting WTBs into smaller parts makes them disposable, but it is a costly process as expensive cutting equipment is required.

At Meldal landfill in Trøndelag they are currently trying to find equipment suitable for disassembling, as well as searching for other recycling solutions. Although John Horg, project manager at Meldal, states that there are challenges regarding the logistics as well as challenges regarding sliced parts, he said that they are able to receive WTBs. He states that early involvement in the decommission process, combined with an open dialogue with wind farm owners is prerequisite to find the best solution. Based on information from Denmark and Germany, the price per metric tons will be in a range from 6000 to 10000 NOK, thus Horg states that an open dialog "will be logistically wise, and economically beneficial for the wind farm owners". Figure 5 is a picture taken at Meldal landfill, were they received a WTB from Frøya.

Figure 5: *WTB received by Meldal. The picture is used on permission from John Horg.*

Not all landfill sites will accept future WTBs. Lia landfill in Trøndelag, specializes in contaminated masses, have earlier received some of the WTBs. Their operational practice makes it challenging and expensive to manage WTBs composites, thus they do not accept it anymore.

7 Future plans

To uncover the industry thoughts, views and plans for future managing of decommissioned turbines, a questionnaire was sent to ten of the biggest wind farm operators in Norway. The questionnaire is found in Appendix B, consisting of six multiple choice questions. For most questions they had the option to answer openly either to clarify, elaborate or add on to their answers. The response rate was 60 % as six out of ten were able to reply.

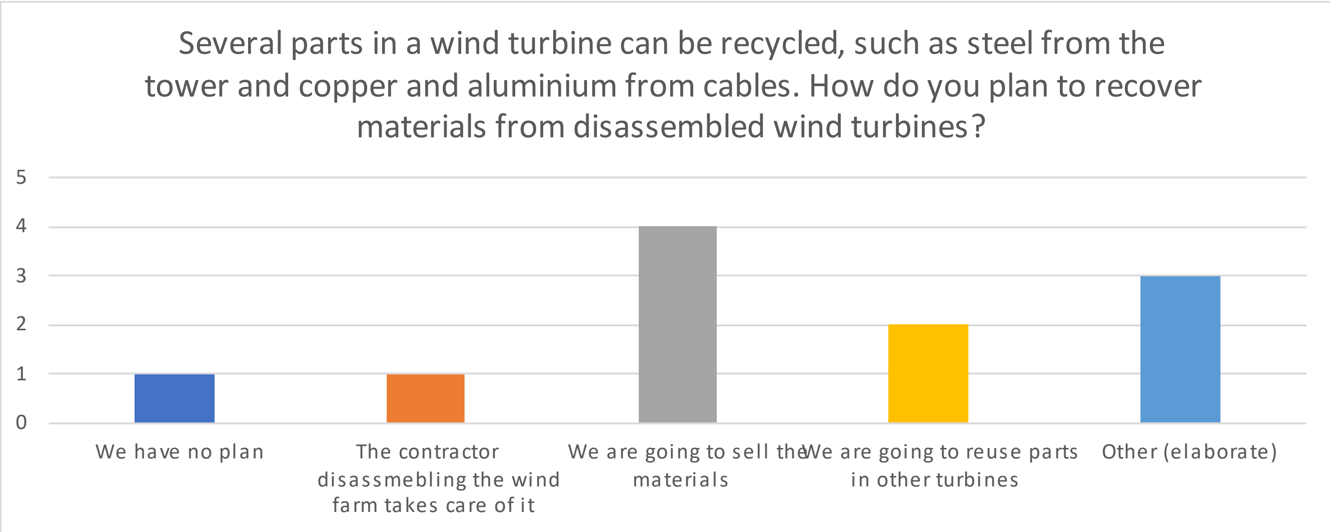


Figure 6: *Answers from question 1 in Appendix B.*

As described in section 3 recycling the GF composite parts on the turbine are challenging, in contrast to other parts of the turbine which can easily be recycled, such as the tower. When asked how they are planning to recycle the material from turbines in general, most of them said that they are planning to sell or reuse parts, as demonstrated in Figure 6. For those who do not have a plan, all options will be considered depending on the future state of the materials. They commented that 10 to 25 years remains of the designed life, which is why they still do not have a plan.

Everyone answered that one of the most important aspects of material recycling is the contribution to circular economy. Reputation and income from sales were also important. As shown in Appendix B, Figure 10 question 2, all participants recognize recycling as beneficial as no one answered d) “Recycling is not beneficial”. Overall, they gave an expression of wanting to, and planning to manage waste on a high level in the waste management hierarchy. Reducing the climate footprint was also mentioned as a beneficial part of recycling.

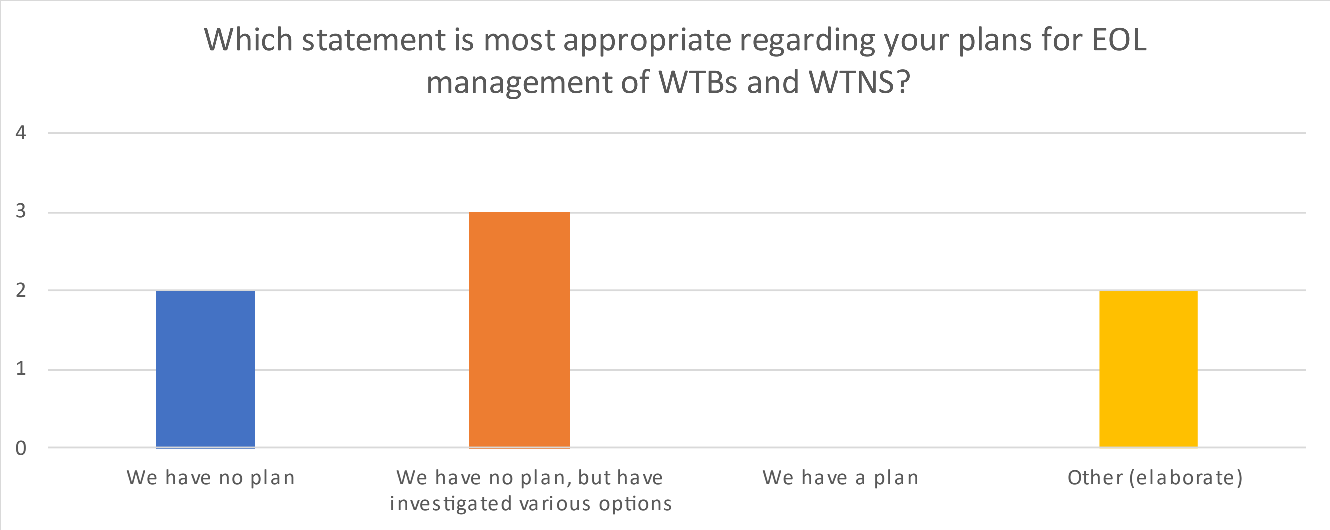


Figure 7: *Answers from question 3 in Appendix B.*

Regarding the WTBs and WTNS it appears that the companies are aware of the complexity of handling the waste but believe that the technology will develop. Throughout the survey the time-to-EOL assumingly affects the answers. Since new technology can enter the market, and that the condition of the turbines when reaching EOL are unknown, specific waste management plans are incomplete or absence. Displayed in Figure 7 no one have a specific plan for managing the WTBs and WTNS. In general, they give the impression of wanting to find the best solution available when the turbines reach EOL, thus options have been explored but not chosen. Some have not yet investigated the alternatives as they still have a lot of time to do so, as well as awaiting new technologies.

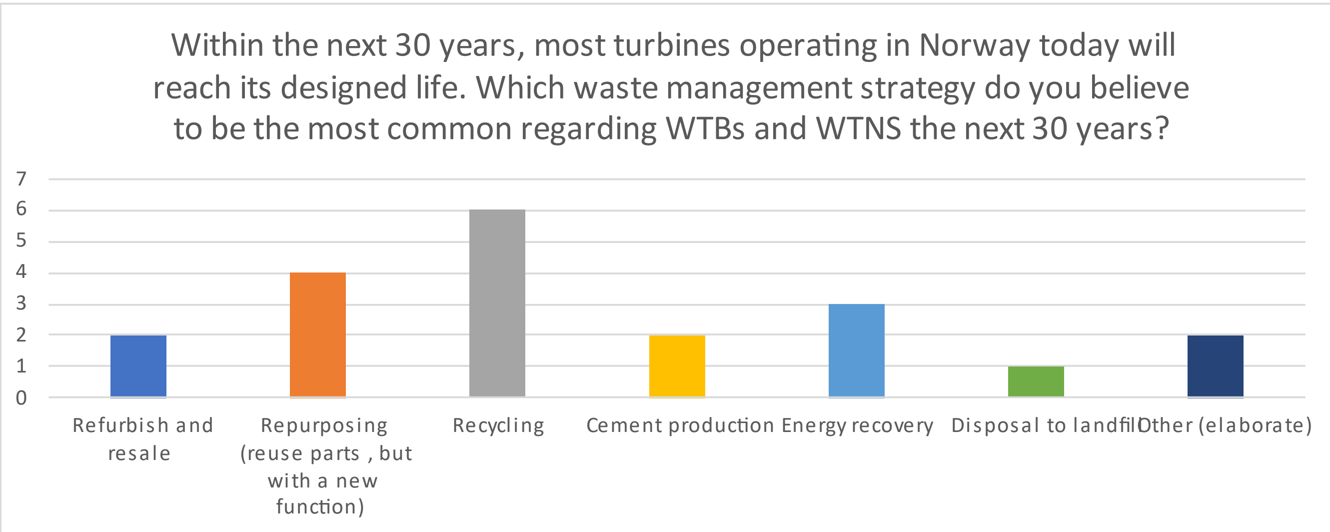


Figure 8: *Answers from question 4 in Appendix B.*

Figure 8 shows that within the next 30 years the respondents believe that the most utilized management method will transition to be material recycling. Considering the historical management of the GF composites the result are somewhat surprising. As demonstrated in Figure 4 no decommissioned WTBs in Norway is affirmed to be recycled, nevertheless recycling is believed to be predominant the next decades.

Another aspect in Figure 8 is the fact that the answers are ”mismatching” existing technology. ”Disposal to landfill” and ”Cement production” are ”flight-proven” management systems, nevertheless only two companies gave those options a vote. Importantly, one of those companies gave all options a vote as they commented ”We believe all methods will be relevant, but the turbine components must be assessed”. Although CETEC are planning to reveal a promising recycling solution within next years (Danish Technological Institute 2021), the recycling technology, scoring high regarding waste management, are imperfect as it have the potential to improve. Exaggerated, they believe ”flight-proven” technology expires, while newer technologies will develop and become most common.

Many factors may have influenced the answers. In general, the questionnaire is relatively simple, thus the answers give no insight considering how they emphasize the economical perspectives. If a prize were added to the different methods, would the distribution have been identical? As stated in subsection 5.3, politics regulates the economy which have the potential to influence decisions. Secondly, some might consider ”disposal to landfill” to be a none optional future solution as Norway can adopt landfill-ban regulations from other European countries. Regardless, question 4, Figure 8 confirms a general optimistic attitude towards recycling-technology. It is in correspondence with question 5 in Appendix B, where they answered that they, in a range from medium- to a large- extent, think technological development makes it feasible to recycle the WTBs and WTNS.

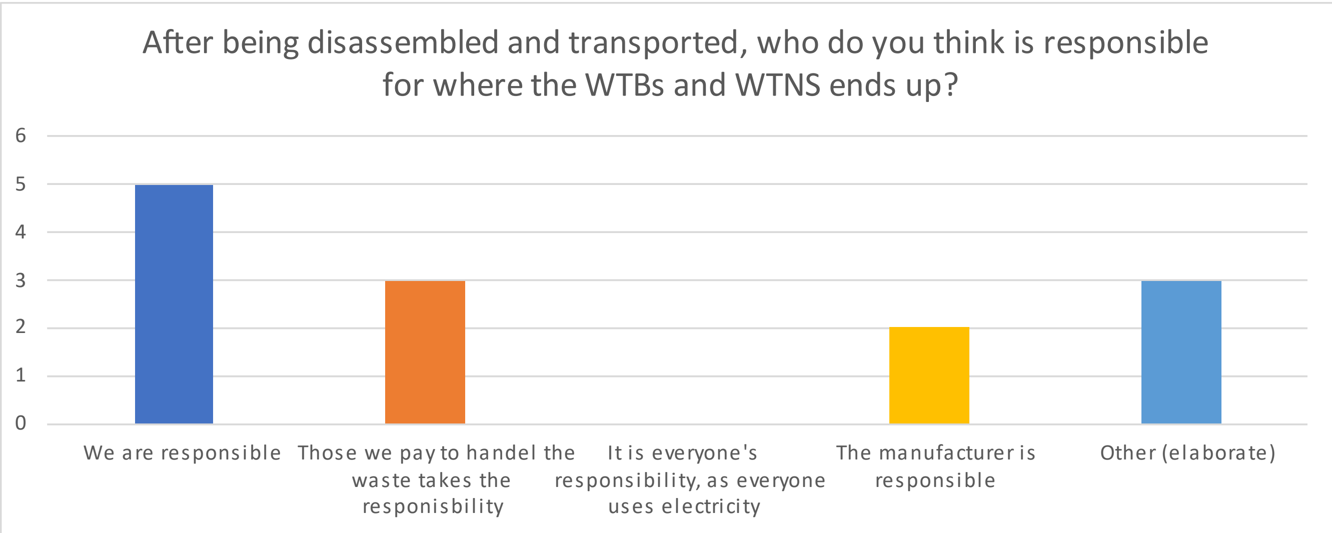


Figure 9: *Answers from question 6 in Appendix B.*

As Figure 9 demonstrates, most companies agreed upon being responsible regarding the waste management. Simultaneously they considered other stakeholders to share the responsibility. Mentioned was the producer’s accountability regarding the content in the products, ”they should be obligated to attempt to find alternative solutions”. The supplier is also considered responsible depending on the length of their service agreement, and waste management firms are responsible of handling received waste in accordance with laws and regulations, ”similar to waste from other constructions”. Apparently, they assign the responsibility to the main stakeholders within the sector including themselves, thus none of the companies consider the consumers (all people using electricity) to be responsible for where the WTBs and WTNS end up.

8 Discussion

The GF composite components are difficult to recycle as no commercial recycling strategy and/or methods are perfected. Up to this date, most of the decommissioned WTBs in the Norwegian fleet have been disposed in landfills.

Estimations from section 5, shows that a total of 70 000 metric tons of GF composites from WTBs and WTNS in Norway needs to be handled. Although uncertainties regarding the estimations exist, they show that a lot of the GF needs to be managed simultaneously, especially towards th e middle of the century. Considering that current technology has a potential to improve, either on the TRL scale or in terms of waste management, the degree in which the technology develops highly influences the future of the composites and the associated challenges.

None of the wind farm operators who responded to our inquiry have a waste management plan for EOL of GF composites, however options are being explored. A desire to find the best waste- management-solution available, and time-to-EOL, has proven to be the main reasons why no one has planned future management in detail. They believe that the most common waste strategy will be recycling, secondly re-purposing. They believe newer technology will be predominant, rather than existing commercial (known-to-work) technology. Seemingly it can be argued that at present, there is a gap between existing- and desired- waste-management-strategies.

Due to its volume and durability, WTBs can be problematic for disposal in landfills. While it is economical feasible for wind farm operators to dispose GF composites in Norwegian landfills, it can be costly for the landfill-companies. John Horg stated that compared to other GF composites, the disposal price for WTBs needs to be higher, as more is required to handle them adequately. Not all landfill sites will accept WTBs anymore, as it previously has been challenging. For the ones who do, being involved in early planning of the decommissioning is considered important, as it is logistically wise and economically beneficial. In general, landfill sites hope for alternative solutions, and re-purposing parts in constructions is mentioned as an option.

Siemens and CETEC have stated that they have found recycling solutions. Siemens targets the blades, making them recyclable (RecycleBlade), and CETEC has developed a recycling process making the epoxy-resin circular, which enables recycling old WTBs. Both strategies are in the beginning of commercialization. However, since the technology is new they are not yet qualified to reach the top of the TRL scale, as time is needed to verify that the system is “”flight proven” through successful mission operations”. The strategies might be revolutionary recycling solutions, or they can increase the number of sub-optimal options, only time will tell. It is not certain that there will be one definitive solution, or if several options may have to be combined.

As the bulk of GF composites from wind turbines are yet to come, future waste-management- strategies are more important than past strategies. Previous experiences show that cooperation between the main stakeholders is essential to create circularity, as the entire life cycle of the turbines affect the EOL-management.

References

AF Decom (2021), Sluttrapport: 8278 - afd havøygavelen vindpark. Unpublished final report with information about waste management.

American Clean Power Association (2022), 'Wind turbine disposal and recycling strategies'. Accessed: 2023-07-28.
URL: https://cleanpower.org/wp-content/uploads/2022/08/ACP_FactSheet_WindTurbineDisposal_220830.pdf

Bladena (2021), 'The blade handbook'. Accessed: 2023-08-02.
URL: https://www.bladena.com/uploads/8/7/3/7/87379536/blade_handbook_2021_v20.pdf

Containerservice Ottersøy AS (2019), 073 avfallsrapport. Unpublished final report about the waste from the disassembly of seven wind turbines.

Danish Technological Institute (2021), 'About cetec'. Accessed: 2023-07-26.
URL: https://www.project-cetec.dk/uk/about/

European Commission (2023), 'Waste framework directive'. Accessed: 2023-06-29.
URL: https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en

Finnmark kraft (2018), 'Konsesjonsøknad for havøygavelen vindkraftverk - reetablering'. Accessed: 2023-07-12.
URL: https://webfileservice.nve.no/API/PublishedFiles/Download/201804779/2365039

Finnmark Kraft (2022), Nye havøygavelen vindkraftverk - sluttrapport for riveplan. Unpublished final report about the decommissioning process.

Guzzo, D. (2019), 'Blade made'. Accessed: 2023-07-19.
URL: https://re-use.eu/blade-made/

Hartman, L. (2022), 'Wind turbines, the bigger, the better'. Accessed: 2023-07-14.
URL: https://www.energy.gov/eere/articles/wind-turbines-bigger-better

Karuppannan Gopalraj, S. & Kärki T. (2020), 'A review on the recycling of waste carbon fiber/glass fiber-reinforced composites: fiber recovery, properties and life-cycle analysis', SN Applied Sciences.
URL: https://doi.org/10.1007/s42452-020-2195-4

Khalid, M. Y., Arif, Z. U., Hossain, M. & Umer, R. (2023), 'Recycling of wind turbine blades through modern recycling technologies: A road to zero waste', Renewable Energy Focus 44, 373– 389.
URL: https://www.sciencedirect.com/science/article/pii/S1755008423000121

Kvalheim Kraft DA (2013), 'Konsesjonsøknad'. Accessed: 2023-07-11.
URL: https://webfileservice.nve.no/API/PublishedFiles/Download/200702243/722821

Mauritzen, J. (2014), 'Scrapping a Wind Turbine: Policy Changes, Scrapping Incentives and Why Wind Turbines in Good Locations Get Scrapped First', The Energy Journal.

NASA (2012), ‘Technology readiness level’. Accessed: 2023-07-26.
URL: https://www.nasa.gov/directorates/somd/space-communications-navigation-program/technology-readiness-levels/

Norconsult (2020), ‘Havøygavlen vindraftverk riveplan’. Accessed: 2023-07-12.
URL: https://webfileservice.nve.no/API/PublishedFiles/Download/e98b1a36-4748-466d-a818-e88de6ce3085/201913827/3382797

Norconsult (2021), ‘Nye sandøy vindkraftverk’. Accessed: 2023-07-24.
URL: https://webfileservice.nve.no/API/PublishedFiles/Download/36adebb5-68a3-4117-b9bb-f9e9c7a0380f/202108001/3424925

Norsk miljø energi AS (2017), ‘Konsesjonssøknad’. Accessed: 2023-07-12.
URL: https://webfileservice.nve.no/API/PublishedFiles/Download/201709647/2245702

NREL (2006), ‘Wind turbine design cost and scaling model’. Accessed: 2023-07-14.
URL: https://www.nrel.gov/docs/fy07osti/40566.pdf

NVE (2023a), ‘Data for utbygde vindkraftverk i norge’. Accessed: 2023-07-11.
URL: https://www.nve.no/energi/energisystem/vindkraft/data-for-utbygde-vindkraftverk-i-norge/

NVE (2023b), Høyde vindturbiner. Unpublished excel sheet. NVE (2023c), ‘Kraftproduskjon’. Accessed: 2023-07-25.
URL: https://www.nve.no/energi/energisystem/kraftproduksjon/

Paddison, L. (2023), ‘Wind energy has a massive waste problem. new technologies may be a step closer to solving it’. Accessed: 2023-08-02.
URL: https://edition.cnn.com/2023/05/28/world/wind-turbine-recycling-climate-intl/index.html

Paulsen, E. B. & Enevoldsen, P. (2021), ‘A multidisciplinary review of recycling methods for end - of-life wind turbine blades’, Energies 14(14).
URL: https://www.mdpi.com/1996-1073/14/14/4247

Re-Wind (2023), ‘Repurposing wind blades’. Accessed: 2023-07-19.
URL: https://www.re-wind.info/

Ricard, L. M. (2023), Kortlægning af mængder og behandlingsmuligheder for vindmøllevinger, Miljøstyrelsen.

Siemens Gamesa (2022a), ‘Commanding circularity: Siemens gamesa announces recyclableblade for onshore wind power projects’. Accessed: 2023-06-28.
URL: https://www.siemensgamesa.com/newsroom/2022/09/092222-siemens-gamesa-press-release-onshore-recyclable-blade

Siemens Gamesa (2022b), ‘Prolong the lifetime of your wind turbines’. Accessed: 2023-07-18.
URL: https://www.siemensgamesa.com/-/media/siemensgamesa/downloads/en/products-and-services/services/life-extension/siemens-gamesa-wind-service-life-extension-flyer-en.pdf

Siemens Gamesa (2023a), ‘Pros and cons of wind energy. uniting environment and technology’. Accessed: 2023-07-25.

URL: https://www.siemensgamesa.com/explore/journal/uniting-environment-and-technology

Siemens Gamesa (2023b), 'RecyclableBlade'. Accessed: 2023-06-28.
URL: https://www.siemensgamesa.com/en-int/explore/journal/recyclable-blade

The Wind Power (2023), 'The wind power'. Accessed: 2023-07-14.
URL: https://www.thewindpower.net/turbine_en_22_siemens_swt-2.3-93.php

Tranberg, B., Tranberg, K. & Michalco, D. (2022), 'Statistics on wind turbines in denmark'. Accessed: 2023-07-28.
URL: https://turbines.dk/statistics/

Vattenfall (2021), 'Vattenfall commits to landfill ban and to recycle all wind turbine blades by 2030'. Accessed: 2023-08-07.
URL: https://group.vattenfall.com/press-and-media/pressreleases/2021/vattenfall-commits-to-landfill-ban-and-to-recycle-all-wind-turbine-blades-by-2030

Vestas (2022), 'Scaling-up sustainably with strategic partners'. Accessed: 2023-07-24.
URL: https://www.vestas.com/en/sustainability/reports-and-ratings

Wind Europe (2021), 'Wind industry calls for europe-wide ban on ladfilling turbine blades'. Accessed: 2023-07-28.
URL: https://windeurope.org/newsroom/press-releases/wind-industry-calls-for-europe-wide-ban-on-landfilling-turbine-blades/

Wind Europe (2022), 'Repowered wind farms show huge potential of replacing old turbines.'. Accessed: 2023-07-27.
URL: https://windeurope.org/newsroom/news/repowered-wind-farms-show-huge-potential-of-replacing-old-turbines/

Windvorst (2023), 'Windvorst'. Accessed: 2023-07-11.
URL: https://www.windvorst.com/

WWF (2023), 'En sirkulær øknomi setter naturen i sentrum'. Accessed: 2023-06-28.
URL: https://www.wwf.no/dyr-og-natur/en-sirkulaer-okonomi-setter-naturen-i-sentrum?utm_source=1400&gclid=EAIaIQobChMIuaHx877j_wIVk9LVCh2XwwjQEAAYAyAAEgL-TvD_BwE

Årtun, T. (2023), 'Glassfiber'. Accessed: 2023-07-25.
URL: https://snl.no/glassfiber

Ørsted (2023), 'Can wind turbines be recycled?'. Accessed: 2023-07-19.
URL: https://orsted.com/en/insights/the-fact-file/can-wind-turbines-be-recycled

A Wind Turbine Models

Table 1: A comparison between the mass of turbine blades and the calculated mass.

Wind Turbine Model - Mass			
Wind Turbine Model	Weight [Metric Tons]	NREL [Metric Tons]	DAN [Metric Tons]
Nordex N80/2500	9,2*	5	10
Vestas V90/3000	6,8**	7	12
Siemens SWT93/2300	20***	7,6	9,2

The actual and calculated weight of different turbine model blades is given in Table 1. (*) The weight is based on standard-values (Norconsult 2020).

(**) The weight is found in Ricard (2023).

(***) The weight includes the hub, thus each blade weighs less than 20 metric tons (The Wind Power 2023).

B Questionnaire

Designlevetiden til vindturbiner er mellom 20 og 30 år. Etter endt levetid må turbinene demonteres og materialene håndteres. Noen av materialene er enklere å resirkulere, noen er vanskeligere.

1. Flere deler i en vindturbin kan resirkuleres, slik som stål i tårn og kobber og aluminium fra kabler. Hvordan planlegger dere å gjenvinne materialer fra demonterte vindturbiner? (Flere svar mulige)
   (a) Vi har ingen plan
   (b) Entreprenøren som legger ned vindkraftverket tar seg av det
   (c) Vi skal selge materialene
   (d) Vi skal gjenbruke delene i andre turbiner
   (e) Andre planer (utdyp)

2. Hva ser dere på som viktige fordeler ved gjenvinning av materialer? (Flere svar mulige).
   (a) Inntekter fra salg av materialer
   (b) Bedre omdømme
   (c) Bidrar til en sirkulær økonomi
   (d) Det er ingen fordeler med gjenvinning
   (e) Annet (utdyp)

3. Hvilken påstand passer best om deres plan for håndtering av blader og turbinhus etter endt levetid?
   (a) Vi har ingen plan
   (b) Vi har ingen konkret plan, men har sett på ulike alternativer

(c) Vi har en plan

(d) Annet (utdyp)

4. Innen 30 år vil de fleste vindturbiner som er i drift i Norge ha nådd designlevetiden sin. Hvilken avfallshåndteringsmetode for blader og turbinhus tror dere kommer til å bli mest brukt de neste 30 årene? (Flere svar mulige)

   (a) Overhaling av gamle deler og videresalg til andre vindkraftverk

   (b) Gjenbruk av deler, men med en ny funksjon (støyskjermer, små broer, etc.)

   (c) Materialgjenvinning

   (d) Sementproduksjon

   (e) Energigjenvinning

   (f) Deponering

   (g) Annet (utdyp)

5. I dag er det vanskelig å resirkulere blader og turbinhus. I hvilken grad tror dere den teknologiske utviklingen de neste 30 årene gjør det mulig å resirkulere blader og turbinhus produsert før 2023?

   (a) Svært liten grad

   (b) Liten grad

   (c) Middels grad

   (d) Trolig

   (e) Stor grad

6. Hvem mener dere har ansvaret for hvor bladene og turbinhus ender opp etter de er demontert og fraktet vekk fra planområdet? (Flere svar mulig.)

   (a) Vi har selv ansvaret

   (b) De vi betaler for å håndtere avfallet overtar ansvaret

   (c) Alle bruker elektrisitet, så det er alle sitt ansvar

   (d) Produsenten har ansvaret

   (e) Andre (utdyp)

   Figure 10 is an overview of the answers from the questionnarie.

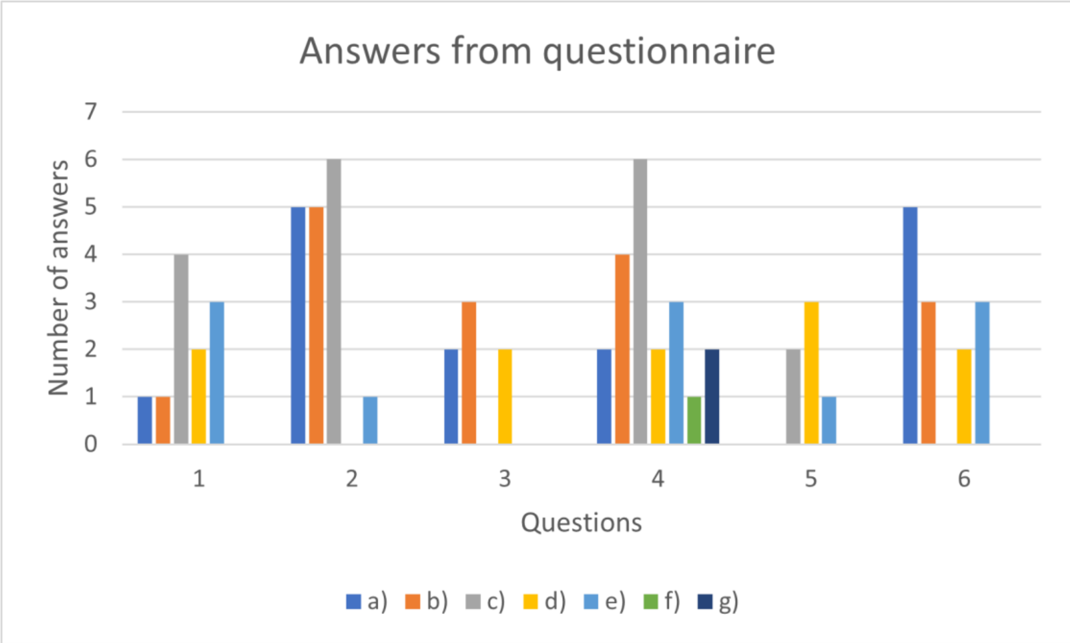


Figure 10: *Results from the questionnaire.*

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