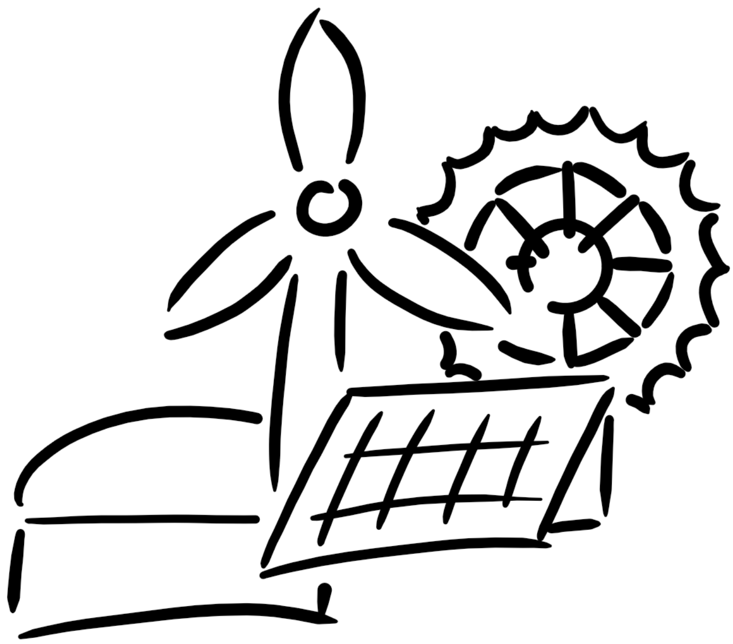
Educational Journal of Renewable Energy Short Reviews



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Münster University of Applied Sciences

Preface

The *Educational Journal of Renewable Energy Short Reviews* (EduJRESR, formally published as 'EGU Journal of Renewable Energy Short Reviews') is a teaching project rather than a regular scientific journal. To publish in this journal, it is a premise to take part in the master course *wind power, hydro power and biomass usage* at the department of Energy, Building Services and Environmental Engineering of the Münster University of Applied Sciences.

Students receive an equivalent of 2.5 credit points (European Credit Transfer and Accumulation System – ECTS) for their engagement in the course and for publishing a short review article of at most 3 000 words in this periodical. The publication process closely mimics the typical publication procedure of a regular journal. The peer-review process, however, is conducted within the group of course-participants.

Although being just an exercise, we think that publishing the outcome of this course in a citable manner is not only promoting the motivation of our students, but may also be a helpful source of introductory information for researchers and practitioners in the field of renewable energies. We encourage students to write their articles in English, but this is not mandatory. The reader will thus find a few articles in German language. To further encourage students practicing English writing, perfect grammar is not part of the assessment.

We especially thank our students for working with LaTeX on Overleaf, although LaTeX is new to some of them. In this way, the editorial workload was reduced to a minimum. We also thank our students for sharing their work under the creative commons attribution licence (CC-BY). We appreciate their contribution to scientific information, being available to every person of the world, almost without barriers. We also thank the corresponding authors and publishers of the cited work, for granting permission to reuse graphics free of charge. All other figures had to be replaced or removed prior to publication.

Peter Vennemann, Christian Klemm, and Benjamin Blankenstein in January 2024

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Environmental impacts of tidal power plants

Current status of the environmental impacts of conventional tidal power plants

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Abstract

Meanwhile, renewable energy sources such as hydropower, solar and wind energy and biomass are increasingly being used to reduce dependence on fossil fuels and thus counteract the ongoing global warming. However, these are also associated with environmental impacts. To that effect, this article takes a closer look at tidal power plants, which are classified as hydroelectric power plants, by conducting a systematic literature review. The results show that the strength and form of the environmental impact depends on the specific location and type of plant. Tidal power plants have an impact on the habitats of marine animals and thus influence their behavior and population. In addition, the operation of tidal power plants changes the sediment distribution, causes a reduction in current velocities and a change in current direction in the surrounding area and leads to a change in wave height. The construction of the power plants is associated with noise, which primarily causes changes in the behavior of some species. Furthermore, the electromagnetic fields generated can also affect marine life. In order to assess the environmental impact of tidal power plants in comparison to other renewable energies, further studies should focus on the environmental impact of the different technologies in relation to the energy yield.

Keywords: tidal power plants, environmental impacts, tidal barrage, tidal stream, hydropower plants, renewable energy

1 Introduction

In recent centuries, fossil fuels such as coal, oil and natural gas have been used to generate electricity in power plants. However, these conventional energy sources emit greenhouse gases such as carbon dioxide when they are used. In order to counteract the ongoing global warming, there is an urgent need to reduce greenhouse gas emissions by reducing the consumption of fossil fuels. Instead, renewable energy sources such as hydropower, solar and wind energy and biomass are increasingly being used to reduce dependence on fossil fuels. Hydropower plants also include so-called tidal power plants, which are examined in more detail in this article. These use the tidal movements of the oceans to generate energy. Tidal power plants are therefore supposedly an emission-free and environmentally friendly source of energy. However, it should not be forgotten that renewable energy sources can also have a negative impact on the environment. The improper use of these can have the opposite effect to the basic idea of environmental protection. For this reason, this article will examine the impact of tidal power plants on the environment. The exact impact may depend on the type of power plant and its location. More detailed information on tidal power extraction methods can be found in Ref. [1, 2], while more information on operating locations can be found in Ref. [3]. Fig. 1 shows the theoretically achievable global energy yields from tidal power and shows which locations are suitable worldwide.

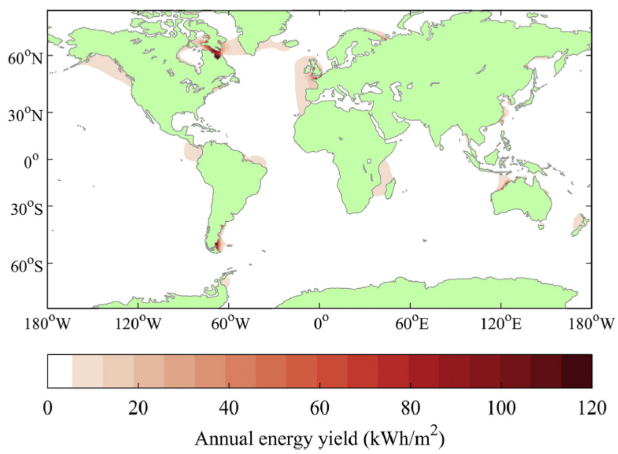

Fig. 1: The global theoretical tidal range energy resource calculated as annual energy yield (kWh/m^2) per model grid cell (1/16° x 1/16°) [4], licensed under a Creative Commons Attribution (CC BY) license.

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2 Methods

A systematic literature search was carried out for the data in this article. The Google Scholar search engine was used to search for relevant literature. Various English and German keywords were used, which are listed below:

- Environmental implications tidal range power plants
- Environmental impacts tidal power plants
- Gezeitenkraftwerk ökologische Auswirkungen
- Gezeitenkraftwerke
- Gezeitenkraftwerke Auswirkungen auf die Umwelt

The German keywords did not lead to any well-founded literature in the search. The main scientific articles on the topic under investigation were written in English. When searching for literature, care was taken to ensure that the sources were not outdated and that they addressed current developments and research into tidal power plants in order to reflect the current situation with regard to environmental impacts.

3 Results

As many tidal power plant technologies are still at the development stage, there are only a few studies on the environmental impact of such technologies [3]. In the following, the currently known environmental impacts of tidal power plants will be discussed in more detail.

3.1 Impacts on habitats and species

3.1.1 Tidal barrage generators

The construction of a tidal barrage at a bay or estuary destroys the pre-existing benthic habitat (the benthos is the entirety of all living organisms found in the bottom zone of a body of water) on the construction site. In addition, the construction and decommissioning work may have an impact on adjacent tidal areas due to the provision of caissons or staging areas. Additionally, the dam affects the habitats upstream and downstream of the facility. When the stored water from the reservoir is released during low tide phases to drive the turbines, the water level in the reservoir decreases until the tide returns. The former lower bank remains flooded. This change leads to a shift in the balance between species in the intertidal zone, with species that specialize on the upper shore potentially being displaced. The retention of water also significantly alters the exposure of mudflats for feeding birds, although the resources on the mudflats may increase in quantity and quality as they are exposed. Therefore, the availability of alternative feeding and resting sites is often crucial [5].

Downstream, the tidal range is often reduced near the dam, while it is increased in other parts of the reservoir. The outflow delays the outgoing tide from about mid-tide so that the tide flows as usual or faster from high tide until the turbines open at mid-tide, after which the outflow velocity decreases or stops. This has a potentially negative impact on birds, although this effect occurs simultaneously with the exposure of the mudflats above the dam. Power generation in dual mode (both ebb and flood tides are used to drive the turbine) reduces the changes in exposure of the intertidal zone and therefore the potential impact on the bird community. The impact on fish that feed on the tides is inverse to that of birds, as the rise in water level gives them more time to forage [5]. However, the step in the dam hinders salmonids, shad and eels from migrating to breed. They may therefore try to pass through the turbines, which increases fish mortality. The structure of the dam also creates an artificial reef on which new species begin to colonize. Despite the massive change in habitat in the bottom zone described above, a net increase in species diversity can still be observed [2].

Furthermore, the disturbance of the river can lead to a change in the turbidity and salinity of the water, which can be harmful to fish, birds and other creatures. The birds living in the estuary depend on salt marshes that grow near the mudflats and form the natural transition between land and sea. Under natural conditions, the tides bring nutrients ashore that support the growth of these salt marshes. The habitat in the intertidal zone consists of two areas. In the high marsh area, black grass (spike grass) grows in the upper area and in the lower area towards the sea, short, smooth cordgrass (salt meadow cordgrass) grows in this section. In the second section, the low marsh area, smooth cordgrass can be found. By influencing the tides as described above, the nutrient supply for these plants is reduced. As a result, the low marsh loses most of its smooth cordgrass, while in the high marsh only a few black grasses remain near the high tide line [2].

The economic viability of a tidal barrage project depends on the volume of the tidal prism (the difference between the highest and lowest water levels), which is why large estuaries and bays are preferred as locations. However, the larger the project, the more likely it is that there are no alternative feeding sites for waders in the vicinity. Fewer feeding areas are associated with increased foraging effort and have a direct impact on population size, as does lower food quality [5]. Environmental pollution from the machines used in the power plants must also be taken into account, as this can have a negative impact on the species, such as the release of hydraulic fluids, lubricants and toxic anti-fouling coatings into the surrounding water [3].

3.1.2 Tidal stream generators

The installation and operation of tidal stream generators also directly affect the benthic habitat at the chosen site by altering water currents, wave structures or substrate composition and sediment dynamics. Small pilot projects on tidal stream power generation have shown that the physical effects are reversible when decommissioned, particularly because strong currents lead to a natural disturbance of the sediments at suitable sites. However, the cumulative effect of multiple turbines must be considered in terms of the impact on the surrounding environment. The deposition of sand can affect seagrass beds by increasing mortality and reducing the growth rate of plant shoots. Conversely, the deposition of organic matter in the wake of tidal stream power plants could promote the growth of benthic invertebrate species that are adapted to this substrate. While the new habitats created by such structures may increase the abundance and diversity of invertebrates, predation by fish attracted to artificial structures may lead to a sharp reduction in the number of benthic organisms [5].

Direct mortality of fish passing through turbines can be high and the disorientation resulting from fish behavior in relation to turbines can affect species viability. However, there is extensive experience with designing sluices, cooling water intakes and turbines to reduce fish injury. These mitigation measures are a critical part of any turbine design and can help to reduce the impact of a tidal stream generator on fish [5]. Studies have observed interactions between fish and turbines, with three distinct behaviors noted. Firstly, some schools of fish feel neither attraction nor repulsion towards the turbine and therefore do not change their course of movement. Secondly, some swarms avoid the turbines by changing direction. Finally, about 5% of the fish passed the turbines directly [2].

The operation of tidal power plants differs significantly from that of tidal barrages. In the latter, a high-speed turbine is installed in a tunnel through which the water flows at high speed and high pressure. As a result, the entrained organisms have little or no chance of passing through the turbine. The system of a tidal stream generator can work without any rotating turbines at all. Some are based on the rocking oscillation of a beam with hydrofoils at both ends. When rotary turbines are used, they are mounted in the open flow field so that the rotational speed is much lower and the organisms have adequate opportunity to avoid direct contact [5]. As a result, the chance of a blade strike can be considered to be low.

No detailed information is available on the collision risk of marine mammals with tidal stream power plants. However, the likelihood of cetaceans failing to detect and avoid a large static structure is considered to be extremely low, especially for species that are echolocating, agile and fast moving. As part of risk mitigation management, the exact placement of a tidal power plant must take into account the species that visit certain areas either through site fidelity or seasonally. Furthermore, the impact of tidal stream generators on seabirds has been reported to be low. With the exception of some deep-diving species such as auks, guillemots and shags, which regularly dive to depths of 45-65 m, the risk of collisions is considered minimal. Given the slow turbine speeds compared to the agility of diving bird species, the risk of mortality is very low. However, diving birds may perceive the moving rotor blades as potential prey and therefore be attracted to their vicinity [5]. Concrete information on the probability of collision is not yet available.

3.2 Impacts on water flow and sediment distribution

3.2.1 Tidal barrage generators

The narrowing of the flow leads to turbulent currents downstream of the dam during outflow and immediately upstream during inflow, which increase mixing. Upstream, the water is static for much of the tidal cycle in the reservoir, leading to stratification and changes in phytoplankton dynamics in summer. Primary productivity is limited and reduced by high turbidity. Energy production can influence turbulent mixing and alter sediment distribution patterns. Currents with a speed of 9 to 15 km/h lead to a continuous intensive mixing process in the water column. At lower speeds, a certain degree of stratification of the water column can be expected. This can lead to increased water clarity due to reduced sedimentation [5].

According to Ref. [2], there are 5 estuaries on the west coast of the United Kingdom (UK) that have the potential for power generation from tidal barrages. Analysis has shown that these dams can increase the tidal amplitude on the east coast of Ireland, resulting in coastal flooding [2]. The impact of tidal barrages on tidal dynamics can also have a massive impact on other coastal areas that are not in the vicinity of the installation site and lead to flooding there.

3.2.2 Tidal stream generators

Tidal stream power plants increase turbulence in the water column, which in turn alters mixing characteristics, sediment transport and possibly wave characteristics. In both the near and far reaches, the extraction of kinetic energy from the tides reduces tidal amplitude, current velocities and water exchange in a region in proportion to the number of units installed, potentially altering hydrography and sediment transport [5]. Studies show that sediment transport depends on grain size. Furthermore, in some cases a tidal stream power plant can also cause a change in current direction [2]. In addition, tidal turbines can change the wave height by using the energy of the underlying current. The impact of structural drag on currents is not expected to be significant [5].

3.3 Noise and vibration

Tidal barrages and tidal stream power plants are all large structures whose construction and decommissioning are associated with significant noise impacts that are potentially harmful to marine life. During construction, noise and vibrations affect different species in different ways. Pile driving, blasting and seismic work, mostly required for installation, are likely to exceed nearby noise level limits for the protection of fish and marine mammals. Although the activities during the construction and decommissioning phases are short-lived, they have the potential to impact cetaceans. At offshore wind farms in Denmark, effects on the behavior and population of harbor porpoises were observed during pile driving. Fewer animals were foraging and there was a short-term reduction in echolocation activity. These effects were documented up to a distance of 15 km from the impact area. As soon as the construction work was completed, these effects were short-lived. Studies suggest that impulsive sounds at high levels have a greater impact on cetaceans than on pinnipeds. The effects on other species are not certain. Direct effects may include damage to sensory or sensitive tissues and indirect effects may include changes in behavior. When evaluating noise impacts, it is important to assess the cumulative impact of the entire system and not just the levels generated by individual elements [5].

It is considered unlikely that the operational noise from any of these facilities is ecologically significant, although very little information is available on the noise levels generated by the operation of tidal barrages and tidal stream power plants. In addition, there are very few specific studies on the response of fish and marine mammals to noise and vibration generated by operations. In the case of tidal stream power plants, operational noise from a small number of units may not exceed the thresholds, while cumulative noise generation from a large number of units may mask communication and echolocation sounds generated by aquatic organisms in the vicinity of the structures. Habituation effects must be taken into account in the behavioral responses of marine mammals to noise [5].

3.4 Electromagnetic fields

The environmental impact of electromagnetic field emissions from cables, switchgear and substations is the same regardless of the power generation facility and therefore the lessons learned from offshore wind developments are also applicable to tidal stream developments. The electricity generated by the existing tidal barrages is carried away via cables on top of the barrage and has no impact on the marine environment. For a typical industry standard cable, it has been shown that the electromagnetic field drops to a background level (approx. 50 μT) within 20 m of the cable. It has also been shown that induced E-fields of up to 91 μV are emitted from cables buried up to 1 m in the sediment [5].

High-voltage DC cables can generate fields of up to 5 μT in up to 60 m around them. Some shark species have been shown to respond to localized magnetic fields of 25-100 μT. There is also evidence that a 3-phase 130 kV cable (not buried) can be perceived by migrating European eels, but does not interrupt their migration [5].

For sea turtles, the effects of magnetic field disturbance range from minimal (i.e. temporary disorientation near a cable or structure) to significant (i.e. altered nesting patterns and corresponding demographic shifts due to large-scale magnetic field changes). In contrast, the survival and reproduction of various benthic organisms are not affected by long-term exposure of static magnetic fields. The evidence for the influence of electromagnetic fields on marine mammals is equivocal [5].

4 Discussion

The previous section presents the currently known environmental impacts of tidal power plants, some of which have already been investigated in more detail. Some of the impacts listed are based on predictions, as there is insufficient information available to the present day. These need to be investigated in more detail in order to obtain evidence. However, the majority of the environmental impacts mentioned have been proven with precise investigations and studies, so that this article provides a well-founded overview of them. The impacts that have not yet been proven are based on the assessment of technical experts and can therefore be classified as probable, as they are based on experience and deductions from other similar areas.

This article refers to the environmental impacts of conventional tidal power plants. These include tidal barrages and tidal stream power plants. Dynamic Tidal Power (DTP) technology offers an alternative to these. This is a newly developed and patented method for generating large amounts of energy from

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the tides, which promises to be cost-efficient and environmentally friendly. While DTP's energy source differs from the well-known concepts of tidal barrages and tidal stream power plants, the technical implementation is based on mature and reliable prefabricated concrete caissons containing turbines. However, DTP does not work with a closed reservoir like a tidal barrage, but catches the tidal energy as it flows through. Using a very long (>10 km) perforated dam built from the shore, Newton's second law is used as an energy source in reverse [6]. This article does not refer to this technology, which means that the environmental impacts listed cannot be transferred to DTP. DTP must be considered and examined individually.

5 Conclusion

Tidal power plants are generally located in coastal areas in bays, estuaries, inlets or straits that are characterized by strong tidal currents. In addition to the great potential for electricity generation, coastal waters also provide important near-shore habitats for many species of marine animals such as seabirds, fish and marine mammals. The construction of tidal power plants in coastal seas causes disturbance to the marine environment. First of all, tidal power plants change the habitats and thus influence the behavior and population of the species living there. In addition, the operation of tidal power plants can lead to a change in sediment distribution, a reduction in current velocities in the surrounding area, a change in current direction and a change in wave height. The construction of the power plants is also associated with noise, which primarily causes changes in the behavior of some species. The impact of operational noise on species is classified as minor. The generated electromagnetic fields can also have an impact on marine life, causing them to become temporarily disoriented in the vicinity of a structure or cable or to adapt their reproductive behavior.

How much and in what form a tidal power plant affects the environment depends on the specific location and the type of plant (tidal barrage or tidal stream power plant). As part of renewable energy, tidal power plants offer significant benefits by avoiding greenhouse gas emissions and providing a predictable and reliable energy supply. However, the impact on marine life and the limited availability of suitable sites pose challenges. Ongoing research and technological advances aim to mitigate these disadvantages and make tidal energy a more sustainable and environmentally friendly energy source. Dynamic Tidal Power (DTP) technology may be able to play a key role in this.

6 Outlook

It is imaginable that tidal power plants, as part of renewable energies, will play a greater role in the global energy supply in the future than they have done to this day. However, this share will be restricted by the limited availability of suitable sites, so that it will probably never be as large as that of wind turbines, for example, as these are better researched and developed and more potential sites are available. When deciding which renewable energies to use in the future, the environmental impact of the various technologies should be taken into account. In order to assess the environmental impact of tidal power plants in comparison to other renewable energies, further research should focus on the environmental impact of the different technologies in relation to the energy yield. The comparison can help to better understand the relative environmental impacts. When comparing the use of tidal power with the use of other renewable energy sources, it is also advisable to consider Dynamic Tidal Power (in contrast to tidal barrage and tidal stream).

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How can artificial intelligence be used to find areas for wind turbines and solve other challenges associated with wind energy?

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Abstract

This article discusses the use of artificial intelligence in the wind energy industry, particularly in addressing challenges and optimizing the expansion of renewable energies in Germany. It highlights the application of artificial intelligence in wind forecasts and yield predictions, bird detection, wind turbine and farm design, condition monitoring, and predictive maintenance. Additionally, it introduces the "WindGISKI" research project, which aims to use artificial intelligence to identify new areas for wind turbines. The project utilizes a neural network to analyze and predict flight routes, potentially reducing bird mortality. The document also emphasizes the potential broader applications of "WindGISKI" in other fields of activity, such as land use planning and city development. Overall, it underscores the significant role of artificial intelligence in addressing challenges in wind energy and outlines the potential for artificial intelligence to drive the expansion of renewable energies while addressing key obstacles.

Keywords: wind turbine, WindGISKI, artificial intelligence

1 Introduction

1.1 Structure

The article begins by explaining the relevance of the topic. This is followed by an explanation of how the results were obtained and the research methodology. This is followed by a description of the four main areas in which artificial intelligence (AI) is already being used successfully in connection with wind turbines. The "WindGISKI" project is then explained. The article ends with a conclusion and outlook.

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1.2 Relevance

The coalition agreement of the current German government stipulates: "To drastically accelerate the expansion of renewable energies". However, this is not proving to be easy. The expansion of onshore wind energy is being halted primarily by complaints from the public. [1]

Currently, around 0.8 % of the land area is designated for wind energy; the German government wants this figure to rise to 2 % by 2032. A solution must therefore be found to develop new potential areas and assess their quality in advance. [2]

Furthermore, the coal phase-out requires secure and stable electricity generation, which is currently not provided by solar and wind energy, as most of the energy generation is lost when there is no wind and clouds in the sky. A lot of research is currently being carried out and studies published in this area. Furthermore, AI is on the rise and has long since arrived in our everyday lives, at the latest with the release of ChatGPT and other chatbots. The use of AI can simplify many things and provide a solution to complicated problems. Problems with wind turbines can also be partially solved or simplified by AI. This article reflects the current state of research and describes the areas in which AI helps to use wind as a sustainable energy source. [3]

2 Methods of literature research

At the beginning, the methods of the literature research are described to make the procedure reproducible. Google Scholar and FH Münster's Findex were used to provide a good overview. The main search queries used were "artificial intelligence wind energy". Without the addition of "wind energy", the spectrum is not differentiated enough. To date, only the participating institutions have published an article on the topic of "GISKI"; even a complex search did not produce any further literature. Furthermore, several AI tools were used to organize this work logically, but also to gain an initial overview of the literature.

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"Perplexity" and "Chat GPT 3.5" were used for this purpose. "Litmaps" was as well used for a visual overview of the literature. The article by Màrquez and Gonzalo was used as the source literature [4]. The articles on "GISKI" are too few for a literature map.

3 AI in the wind energy industry

3.1 Wind forecasts and yield predictions

AI is already being used in many areas of energy generation by wind turbines. Four examples are described below. The first is the calculation of wind speeds and the energy output of wind turbines. Before wind turbines can be integrated into the power grid on a large scale, the uncertainty must be reduced and the continuity of the power supply ensured. To this end, AI has long been used to predict wind speeds. Many studies are currently being published that use AI to provide forecasts for wind speeds. The forecasts are becoming more and more accurate and can look further into the future. It would make no sense to show the latest study here, as this article could no longer be up to date tomorrow. [5]

Nevertheless, an example of artificial intelligence in wind forecasting is given here. Currently, NASA uses the Global Forecast System (GFS) to make predictions with the help of advanced numerical models. However, they are researching machine learning models to make more accurate predictions with larger amounts of data in the future. They are also trying to increase the resolution of the predictions using AI. Given the amount of data generated, numerical algorithms would use too much computing space, which is why they are to be replaced by AI in the future. [6]

3.2 Bird detection

Another example of the use of AI in energy generation with wind turbines is bird detection. Wind turbines are currently a major threat to birds. Studies generally find that onshore and offshore pose a direct and or indirect danger.The Brandenburg State Office for the Environment has published the numbers of reported bird corpses that have died as a result of being hit by wind turbines. A total of 4990 corpses were reported. This figure is of course much lower than the actual number of birds killed by wind turbines because not all birds are found or reported. [7]

NABU estimates the number at over 100,000 per year [8]. To ward off these dangers, images are analyzed by machine learning to detect birds at an early stage. In the 2021 study, for example, Google AutoML Vision was used [9]. This service uses recurrent neural networks to find the best possible neural network. This allows flight routes to be analyzed and predicted, which could reduce bird mortality in the future. [10, 11]

3.3 Wind turbine and farm design

The previous examples were applications for AI in the operation of wind turbines. However, AI is already being used in the development of wind turbines. The design process is characterized by many variables. The complex calculations for the design of wind turbines and entire wind farms are carried out by artificial neutral networks. In the article by Marugán et al. various studies are listed which are used in the calculation of individual variables such as the correction of the lift coefficient for the design of the angle of attack of airfoils. For the design of wind farms, even more variables must be considered. Here, too, artificial neutral grids are often used. [12]

3.4 Condition monitoring for predictive maintenance

AI can help with the condition monitoring of wind turbines in a variety of ways. It enables predictive maintenance, in which sensors continuously record data that is analyzed by AI systems. This allows potential defects to be detected at an early stage and maintenance work to be planned before failures occur. AI-based condition monitoring and predictive maintenance aim to maximize the uptime of wind turbines, prevent costly major damage and extend the service life of individual components through early action. They also enable better monitoring and evaluation of repair measures. AI models can detect anomalies - discrepancies between actual measured and simulated behavior - at an early stage. This enables rapid action and prevents major damage to the main components. [13]

AI can also help to reduce the number of sensors required. For example, AI models can analyze vibration patterns to identify operating speed, eliminating the need for a cumbersome speed reference sensor. [14]

In summary, AI plays a crucial role in the condition monitoring of wind turbines by enabling early detection of faults, optimizing maintenance and ultimately helping to increase turbine efficiency and profitability.

4 Area development through AI

4.1 Research project

As the previous chapter shows, AI is already being used in many areas relating to wind turbines. One of the biggest hurdles in the expansion of renewable energies in Germany is currently the development of

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new areas for wind turbines or wind farms. With the *wind-on-land act*, the German government has decided to expand the amount of land available. By 2032, 2 % of the current 0.8 % of the land area is to be made available. Furthermore, this is to be divided fairly among the federal states and wind conditions as well as nature and species protection are to be considered equally. To this end, the new "WindGISKI" research project was approved by the Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection and supported with two million euros. The eight participating research institutes will develop an AI-based geoinformation system over three years. [2]

4.2 Use of the neural network

The biggest hurdle is to be removed with the help of AI. Currently, many areas are designated as unsuitable because incorrect minimum distances are set. In many places, however, these minimum distances exceed the necessary distances that would prevent a visually intrusive effect and ensure a reasonable level of shadow impact and noise pollution. These small areas are often excluded for wind turbines due to nature and species protection, which is why the areas are not sufficient for the area targets. To avoid these problems, the program starts with an empty map on which, at least theoretically, anywhere would be possible. An artificial neural network is used to solve this problem. [2]

Artificial neural networks solve problems that cannot be defined analytically, based on biological neurons. Simple processing units and weighted connections between them form a neural network, as shown in 1. The neural network is trained with data sets and the connections are reweighted. The network then predicts outputs and can identify fields for potential wind turbines. [15]

The neural network is fed with information on where the construction of wind turbines was possible and where it was prevented by legal action, for example (training). The AI then uses the information to identify areas on the German map. This is divided into 50x50m tiles and each of these tiles is evaluated independently. Where clusters of positively rated tiles are located, potential areas can later be identified (output). [2]

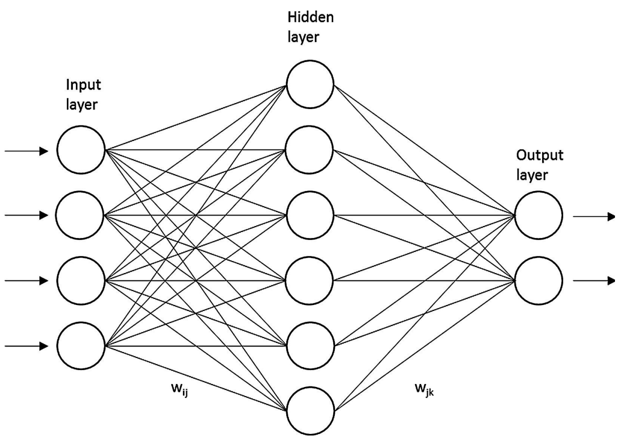

Fig. 1: Structure of an artificial neural network [12]

5 Conclusion and outlook

5.1 What opportunities arise from the use of AI in wind turbines?

Renewable energies are set to replace fossil fuels in Germany. Independence from raw materials and the reduction of air pollution are the main reasons for the energy transition. However, the energy transition in Germany has not yet progressed as far as politicians had planned. There are various obstacles to the expansion of renewable energies. However, the expansion can be driven forward with new technologies. In wind energy, there are many opportunities to use technologies to drive expansion forward. Many problems that repeatedly arise in Germany in connection with wind power are primarily the fluctuation in electricity production, the dangers for birds and the design of the turbines.

AI is being used to find a solution to all these issues. This offers a good opportunity to simplify complicated algorithms and problems and solve them using computers. Progress is constantly being made and new technologies developed. Many studies have been published in this area in recent years and research is continuing. It will be some time before a real solution is found. Nevertheless, it can be said that the solution to these problems lies in AI.

Another problem is currently being researched. The development of land for wind turbines. Currently, 0.8 % of the land area has been designated for wind turbines. Another 1.2 % is to be added by 2032. To achieve this, new methods must be found to develop land. One suitable option could be AI. "WindGISKI" could provide a remedy, as the map of Germany is viewed neutrally and old minimum distances to residential buildings are no longer considered. Only current minimum distances and previous lawsuits against wind turbines are fed into the neural network. However, the project is currently still being researched and is by no means ready for use.

All in all, it can be said that AI offers good opportunities to expand the use of wind energy and prevent its current problems.

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5.2 How can GISKI be used in other fields of activity?

It is quite conceivable that AI will soon be used in almost all areas. The combination of geoinformation systems and AI is another example of this. In the future, all land use plans could be optimized in the same way, making it easier to plan cities. Furthermore, the areas examined could be analyzed for the possibility of solar installations. The field of application is very broad and offers many possibilities. If "WindGISKI" produces a functioning program, it could also be used for all other countries that have a similar problem. The possibilities that this project could provide are huge and could mean a big step for the energy transition in Germany and around the world.

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Technologies for structural health monitoring of wind turbine blades

An overview of different techniques

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Abstract

Wind turbine structures take a major role in the modern conversion to renewable energy sources and contribute to the creation of a greener world. In recent years, the development and installation of wind turbines have seen rapid growth. However, with the increasing capacity and size of wind farms worldwide, there are growing concerns about the safety and reliability of these installations. Therefore, structural health monitoring and the detection of damage to wind turbines have gained considerable importance in research. Wind turbine blades are particularly susceptible to various types of damage due to environmental influences. This article provides an overview of signal responses, sensors used and non-destructive testing techniques in the field of damage detection on wind turbine blades. The intention of the article is to give an insight into the possibilities of structural health monitoring and at the same time to point out unsolved problems in this field.

Keywords: structural health monitoring, wind turbine blades, damage detection, measurement, non-destructive testing

1 Introduction

Wind power is becoming increasingly important due to the concept of sustainability in energy generation and the expansion of renewable energies. In the first half of 2023, the number of onshore wind turbines in Germany amounted to around 28,500 [1] and the number of offshore wind turbines to 1,500 [2]. Wind turbines are constantly exposed to environmental influences such as changing wind loads or fluctuations in temperature and humidity [3]. For this reason, they are particularly susceptible to failure. According to [4], around 17 % of damage to wind turbines in Germany between 2016 and 2020 is caused by wind turbine blade (WTB) components. This figure shows, that early detection of this damage category is necessary in order to avoid economic losses and ensure the safe operation of the wind turbines. For this reason, structural health monitoring (SHM) of wind turbines is a current focus of research [5]. This review is intended to provide an overview of possible measures for SHM. The focus will be primarily on non-destructive testing (NDT) methods. This is accompanied by a brief explanation of the possibilities for signal evaluation and the different sensor types used for SHM. The idea is to determine which measures are currently important for research and which methods may already be established. The advantages and disadvantages of the methods must also be considered.

2 Material and methods

To explain the relevance of the topic based on reliable data, contact was made with an insurance company that keeps a damage report on wind turbines. Through e-mail correspondence, the questions relevant to the topic were answered on the basis of the damage report.

A literature review was conducted to identify SHM methods used worldwide. The individual methods were classified, described and the respective advantages or disadvantages were presented. Most of the compiled data was taken from previously published papers and reviews available on Google Scholar.

3 Signal based methods for failure detection

Signal-based damage detection methods comprise two main processes:

1. feature extraction and selection
2. pattern recognition

In the first process, the features are identified and selected to quantify the damaged state of the structure.

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The data is condensed into a small data set that can be better analyzed statistically. This is done, for example, by data normalization to eliminate environmental conditions. [6]

Pattern recognition works with algorithms that can determine the state of damage from the extracted features. These can be divided into three signal processing techniques [6]:

- time-domain methods
- frequency-domain methods
- time-frequency-domain

Measured data from sensors in the **time-domain** contains structural information. It can work with linear and nonlinear functions and does not need any frequency transformation for damage detection [5]. Various approaches and models exist for the evaluation of time domain methods. [6] mentions the use of autoregressive models (AR model), autoregressive models with exogenous inputs (ARX models) and autoregressive moving average vector models (ARMAV models).

The methods of time-domain evaluation can be categorized into two subgroups which are statistical-methods and time-domain modal-based approaches. Statistical methods extract structural changes by statistical parameters such as mean value or standard deviation. Results from practical experience show, that the proposed method performed efficiently when "the data of all measured positions transformed into the normal vibration forms and conditions of the intact blade" [5]. Furthermore, it has been determined that the number of points measured is important for damage detection. Studies on time-domain modal-based approaches show that stable operating conditions must be available for this procedure, as environmental influences directly affect the measured signals. The "bagged tree algorithm", which is used for evaluation, achieved an accuracy of 98 %. [5]

Frequency-domain responses are resulting from the conversion of time-series responses into frequency responses [5]. Fourier analyses, cepstrum analyses, spectral analyses or frequency response techniques are used for signal transformation to extract features in a specific time window [6].

The fast Fourier transform (FFT) is often used for signal analysis. It is not suitable for analyzing non-stationary signals because signals like WTB-vibration are weak. In combination with other methods, such as statistical methods (time-frequency-domain [5]), a better accuracy of the signatures of anomalies and outliers can be achieved. The FFT is used to detect running surface faults in bearings and to detect cracks in gears. [7]

Time and frequency-based approaches are used to analyze non-stationary signals. Current signal processing methods in research include the short-time Fourier transform (STFT), the Wavelet transform or Wigner-Ville distribution (WVD). [5]

4 Sensors for failure detection

This chapter is intended to provide a basic overview of the different sensors that can be used for the SHM of WTBs. According to [5], the following sensors are used for non-destructive testing:

- Strain gauges
- Fiber optic sensors
- Accelerometers
- Acoustic emission (AE) sensors
- Piezoeletric (PZT) sensors
- Scanning laser doppler vibrometer (SLDV) sensors

Strain gauges measure the change in strain of the material. Conventional strain gauges consist of a non-conductive carrier and are attached to the surface to measure the change in resistance. The accuracy depends on the installation and environmental influences such as temperature. [5]

Fiber optic sensors measure strain, temperature and humidity. Interferometers and wavelength-based sensors are used to detect damage to WTBs. They transmit the signals with low losses and do not suffer from electromagnetic interference. Fiber optic sensors are more expensive than conventional strain gauges. [5]

The principle of **accelerometers** is based on measuring the acceleration of a mass after the impact of a force that is suspended from a spring. A classification is made between piezoelectric, piezoresistive and capacitive sensors. For an exact measurement, many sensors are required whose position must be known and which each require an external power supply. However, the sensors are inexpensive and resistant to high temperatures. [5]

Acoustic emission (AE) sensors detect cracks, delamination[1], corrosion and detachment. They are made up of piezoelectric crystals that convert mechanical stress energy from the damaged areas into electrical signals. Because the signals from the sources of damage are detected, the sensors must be positioned close to the damage. However, the sensors do not require external excitation and can operate in a wide frequency range. [5]

[1] Delamination refers to the detachment of layers in advertising materials

The difference between **piezoelectric (PZT) sensors**, accelerometers and AE sensors is that PZT-sensors can act as both sensors and triggers. When it is used as a trigger, the sensors work like the reverse piezoelectric effect, converting voltage into mechanical effects. PZT sensors are very sensitive to structural changes and at the same time inexpensive. However, they should be placed close to the damage. [5]

The velocity sensor **scanning laser doppler vibrometer (SLDV)** is used to measure vibrations. This instrument emits laser beams that are specifically directed at the surface of a structure to analyze the beams reflected from it. The basis of this analysis is the doppler effect, which represents a change between the frequency emitted by the laser source and the frequency reflected by the moving surface. SLDVs can be used for inaccessible areas and work without contact. However, they are expensive. [5]

5 Non-destructive monitoring of WTBs

Non-destructive methods are primarily suitable for SHM of WTBs. Methods that destroy the material, for example through testing, are not considered here. Table 1 summarizes the advantages and disadvantages of the different methods based on the literature reviewed.

5.1 Acoustic emission measurement

Acoustic emission (AE) refers to the emission of elastic (sound) waves with low amplitude and high frequency range within a material. These waves arise from deformation as a result of the release of energy. The process is used during system loading. Elastic waves can also be induced and introduced into the structure and serve as an active SHM method. The waves are converted into electrical signals using piezoceramic sensors. The sensors are mounted close to the surface. Signals with low amplitude must be amplified. However, this also amplifies noise. To eliminate noise, the frequency bandwidth is limited or bandpass filters are used. Data acquisition is then carried out with A/D converters[2] that can operate in a high frequency bandwidth. Analysis parameters that are relevant for the evaluation of AE signals are event counts, rise time, peak amplitude, arrival time, duration, signal energy content and root mean square. [7]

[10] found that the threshold value for processing the sound waves is 45 dB. It was determined that a total of 72 sensors are required to localize damage for a WTB 45 m length. Reducing the threshold value to 40 dB through noise suppression and more complex signal processing could reduce the number of sensors to 32. The accuracy of this method is less than 1 cm [11].

[2] A/D converters are used to amplify signals

5.2 Acoustic measurement

The acoustic-based method analyzes the airborne sound waves to monitor the blade conditions. The acoustic signals are generated and propagated by the structural defects. This is a natural phenomenon. The method analyzes the change in the airborne sound waves during transmission. Cracks, detachments, edge breakouts and holes are examined. The method can be divided into

- passive detection and
- active detection.

In **passive detection**, microphone sensors are installed inside the WTB to record the airborne sound in the cavity. This is illustrated in figure 1. Structural defects change the sound pressure level. Signal processing tools are required to minimize noise. [5]

For **active detection**, loudspeakers are installed inside the WTBs. Microphones are located on the tower of the wind turbines to record the acoustic signals. The damage transmits the sound energy easily through the wall and is detected by the microphones. [5]

The acoustic method is a new, modern procedure. Research in this area focuses primarily on the use of machine learning and the development of wireless systems. [5]

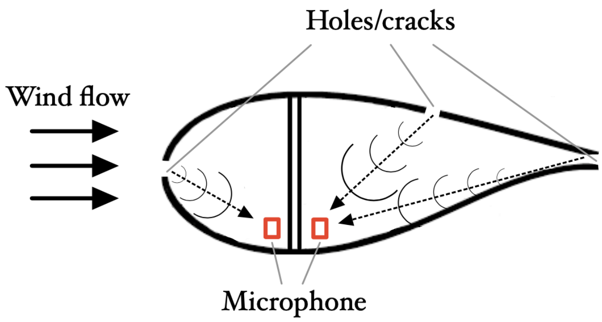

Fig. 1: Schematic illustration of acoustic measurement with passive damage detection (own illustration based on [13])

The method has already been successfully used in a study by [11] to detect cracks and edge breakouts on a 46 m long WTB. In addition to the severity, the location of the damage could also be determined.

5.3 Ultrasonic measurement

The ultrasonic method can be divided into three different types: The pulse-echo, the pitch-catch and the through-transmission [14, 15]. These differ in the positioning of the transmitter and receiver and are shown in figure 2.

Tab. 1: Overview of the methods for structural health monitoring with advantages and disadvantages

NDT technique	Advantages	Disadvantages
Acoustic emission measurement	Monitoring during operation [5, 8]	Multiple sensors are required to increase accuracy [5, 9]
	For large areas [8]	Bad quantitation, difficult interpretation [5, 8]
	Wide frequency range [5]	Noise [5, 8]
	Detect small damages [5, 10]	Unsuitable for offshore WTBs [5]
	Online monitoring [11]	High costs [11]
Acoustic based measurement	Detect damage and severity [5]	Signal processing algorithms required to extract ambient noise [5]
	Requires only a few sensors [5]	Not detectable for damage where the sound energy stays the same [5]
	Monitoring during operation [5]	
	For large areas [5]	
Ultrasonic measurement	High sensitivity and reliability [5]	Signal processing algorithms required to extract ambient noise [5]
	For large areas [5]	Time required for large areas [5]
	Detect the damaged areas [5]	Sensitive to noise [5]
	Online monitoring [11]	Sensors contact surface [5]
	Removal of ice accumulations [12]	High costs [11]
Strain measurement	Monitoring during operation [5, 11]	Many sensors are required for global measurements and to increase accuracy [5]
	High sensitivity [5, 11]	Sensors contact surface [5]
	Mature technique [5, 9]	Positioning of the sensors must be known [5]
	Real-time measurement possible [5]	Temperature influence on the measurement [5]
	Insensitive to electromagnetic interference [5]	
	Online monitoring [11]	
Vibration measurement	Mature technique with high reliability [5]	Many sensors are required to detect damage locations and severity [5]
	Easy installation [5]	Difficult to detect early stages of damage [5]
	Detect damage location and severity [5]	
	Online monitoring [11]	
Thermographic measurement	Non-contact installation [5, 8]	Influenced by temperature fluctuations [5]
	Visual inspection with short time consumption [5, 8]	Difficult to detect early stages of damage [5]
	Drones can be used [5]	Requires a high resolution [5]
	For large areas [5, 8]	High costs [11]
Visual inspection	Low costs [8]	digital cameras required [8]
	Visual inspection with short time consumption [5, 8]	Better results through good image processing software [5]
	Drones can be used	time consuming [8]
	Low costs [11]	
Radioscopy and radiography testing	Non-contact measurement [8]	Instruments for scanning required [8]
	High resolution [8]	X-Ray hazards [8]
Eddy current testing	Non-contact measurement possible [8]	Instruments for scanning required [8]

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Ultrasonic waves are emitted by a transmitter, penetrate the material and are reflected back to a receiver. The condition of the structure can be determined by analyzing the incoming signals. Transmission, attenuation, reflection and resonance all have an impact on the detection of damage to WTBs. [5]

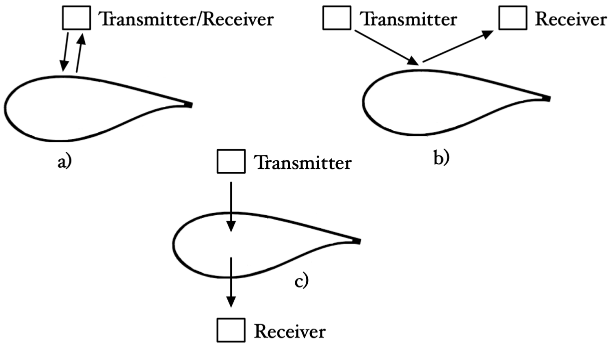

Fig. 2: Three transmitter-receiver settlements used in ultrasonic inspection: a) pulse-echo, b) pitch-catch, c) through-transmission (own illustration based on [16])

A special type of ultrasonic measurement is the measurement using guided waves. In contrast to conventional ultrasonic measurement, the ultrasonic waves expand along the structure and are guided by the structure boundaries. In order to use guided waves for damage detection, the healthy condition of the structure must be known in advance so that it can be used as a reference. [7]

Currently, the procedure is mostly based on the pulse-echo or pitch-catch approach [8]. The difference between conventional ultrasonic measurement and ultrasonic measurement with guided waves is simplified illustrated in figure 3. The precision of ultrasonic measurement is around 1 cm [11].

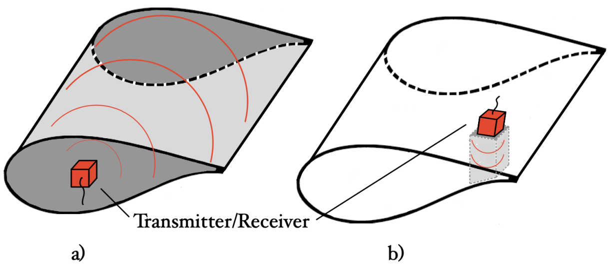

Fig. 3: The difference between a) ultrasonic guided wave measurement and b) conventional ultrasonic measurement

In a study conducted by [12], it was found that the guided ultrasonic waves are also suitable for preventing or removing ice build-up on the WTB by exciting the material particles.

5.4 Strain measurement

For strain measurement, strain sensors are attached to the surface of the WTBs or incorporated into the material to detect compressive and tensile stresses. In order to monitor the local strain continuously, the position of the sensor must be known. Strain gauges or fiber optic sensors are often used. Fiber optic sensors are currently used because they do not require an external energy source. [5]

Strain measurement can be divided into two types [5]:

- direct strain and
- shear strain.

The difference is illustrated in figure 4. The precision of this method is around 1 cm [11].

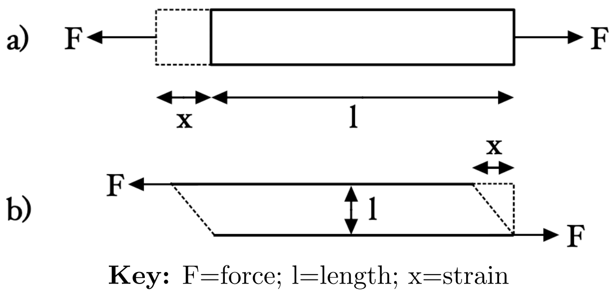

Fig. 4: The difference between a) direct strain and b) shear strain (own illustration based on [17])

5.5 Vibration measurement

Vibrations caused by rotating WTBs are the main cause of wind turbine failure [18]. Vibration analysis can be used to detect damage at an early stage. Damage leads to changes in the material properties of the WTBs. The approach is based on recognizing the change in physical properties through modal characteristics. The parameters which are affected are mass, consistency and damping. [5]

Wind turbines are exposed to wind currents and turbulence, which cause vibrations in the WTBs. Depending on the level of damage, the vibration signals contain different signatures. These are identified using signal processing techniques (time-based, frequency-based, time-frequency-based). [7]

Sensors are used to record the vibration signals. Due to the damping, several vibration sensors are required to identify fault locations. Currently, research is focusing on improving signal processing techniques, for example by integrating them with machine learning tools. [5]

During a 3.5-month test phase on a WTB in operation, [19] detected damage larger than 15 cm using the vibration-based approach.

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5.6 Thermographic measurement

Temperature measurement is used to detect delamination and impact damage. The damage can be detected on the surface as well as in the substrate using this method. [5]

The method for detecting temperature changes is divided into the **passive monitoring method**, in which the ambient temperature is compared with the material temperature and the **active monitoring method**, which is based on the change in the material temperature due to different loads. Passive methods are rarely used in the monitoring of WTBs. The active method is used more often. This requires an external excitation source, such as heat lamps. The transferred energy leads to specific temperature distributions around the damage and thus enables detection. Internal damage such as cracks in the matrix or the pull-out of fibers can also be detected by thermographic measurement. This thermal imaging technology is not suitable for use during operation, because it is heavily dependent on the ambient temperature. [7]

Thermographic measurement can achieve an accuracy of 3-5 mm [11]. [20] have developed a continuous laser thermography method with an algorithm that detects internal delamination on WTBs. The method was successfully verified by an experiment using a WTB with internal damage of 20 mm. Further studies are required for practical use in order to increase the inspection speed.

5.7 Visual inspection

This method is used to detect damage to the surface such as cracks or scratches. Historically, this method is based on the principle of the "naked eye". [7]

Today, image processing systems are used, which include recording devices, computers and image processing algorithms. The method can be used to determine vibration behavior, structural stresses or strains and defects. It is suitable for measuring WTBs because it can capture large areas in a short time. [5]

5.8 Radioscopy and radiography testing

The x-ray imaging technique is based on the non-uniform absorption of x-rays of the damaged area. This method can be used to localize internal damage. An x-ray source and an x-ray detector are required. X-ray sources are often x-ray tubes with a low photon flux. x-ray film is widely used as the x-ray detector. The method is used more for checking the quality of WTBs and not for use during operation. [7]

5.9 Eddy current testing

Eddy current testing is based on the change in the conductivity of the material as a result of damage. Electromagnetic eddy currents are induced in the material. Measuring the high-frequency eddy currents allows conclusions to be drawn about the conductivity. If there is damage, the eddy current density changes and uneven heating occurs, which can be recorded using an infrared camera. The method is also suitable for composite materials. [7]

6 Results

Strain measurement and vibration measurement are two of the methods that have already been established for SHM of WTBs. However, these methods do not only have advantages. For this reason, other methods for SHM have been tested in the past and still offer further potential for research. One reason for researching new techniques is the high demand of sensors for strain measurement or vibration measurement. By using other techniques, the number of required sensors can be reduced without compromising the measurement accuracy and still enabling an area-wide measurement. Methods such as acoustic (emission) measurement or ultrasonic measurement are already widely used. Eddy current testing and radioscopy tend to be the exception. Measures whose data is available online are suitable for SHM. The measurement takes place continuously and during operation.

7 Discussion

With regard to continuous monitoring of the WTBs, SHM measures that can continuously evaluate data in real-time are of particular interest. Measures that cannot be used during operation and therefore do not enable real-time recording should be used as a supplement to increase the accuracy of the monitoring. The research has shown that no method has a unique position in the field of SHM. Rather, it will depend on the boundary conditions as to which method is suitable for the application. However, it can be assumed that strain measurement, acoustic (emission) measurement, ultrasonic measurement and vibration measurement methods in particular will continue to be important in the future, because these methods are already widely used and continue to offer significant scope for research.

The identified techniques provide a good overview of the possibilities for SHM. However, the individual methods can be specifically individualized, for example by using different sensors. The described advantages and disadvantages then apply generally to the method and it must be verified whether advantages and/or disadvantages can be eliminated or

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supplemented by different configurations. It would also be possible to combine different methods to improve the measurements. For example, acoustic emission measurement could be combined with ultrasonic measurement. Ultrasonic measurement can be used to determine the shape and size of the damage. The acoustic emission measurement is then used to localize the damage. In the field, it is necessary to check which process can be used for which material.

8 Outlook

As the study has shown, there will be a need for further research in the field of SHM of WTBs in the future. No method is so mature and fully researched that there is no longer any need for optimization. The following points are particularly relevant:

- Minimizing the number of sensors with the same or better measurement quality
- Reduction of noise to improve measurement quality
- Use of artificial intelligence to detect damage patterns
- General improvement of the sensors and signal processing algorithms

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Drawing up a catalog of criteria for special solutions for fish passages based on the DWA-M 509 leaflet

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Abstract

The preservation of water bodies continuity is fundamental for aquatic communities, particularly for fish populations. Various structures impede watercourse continuity, impacting fish migration and habitat distribution. Conventional fish passages often fall short in diverse scenarios, prompting the development of specialized solutions. This article proposes a criteria catalog for these special fish passage solutions based on DWA leaflet DWA-A 509. It discusses the need for these solutions, presents a selection of specialized options, and outlines criteria from DWA-M 509, construction guidelines, and economic perspectives. It scrutinizes criteria ranging from target fish species to cost considerations. Three examples, including the Runserau fish lift, the bristle ramp fish lock, and the Fishcon sluice, illustrate these specialized solutions, their functionalities, advantages, and drawbacks. Additionally, the article compiles criteria from industry standards and guidelines into a comprehensive evaluation catalog. The criteria, when applied, assist in the selection of suitable fish passage solutions based on specific site conditions and fish species requirements. This holistic approach aims to optimize fishway selection, fostering the ecological sustainability of watercourses. However, this catalog remains dynamic and open to expansion with evolving research and practical application, urging further exploration and validation of these criteria through diverse case studies and technological advancements in the field.

Keywords: Fish passages, Criteria catalog, DWA-M 509, Special solution , Forms of evaluation

1 Introduction

The introduction of the European Water Framework Directive not only gives greater importance to the ecological status of water bodies. It also emphasizes continuity as a fundamental prerequisite for the development of specific aquatic communities. [1] The continuity of water bodies is of great importance for fish. In some cases, fish benefit from the change of location through targeted migration. They can make the best possible use of the resources in their habitat and the population density is optimally distributed between suitable habitats. If watercourses are not passable, this leads to a lower population density and a change in species composition. [2] The continuity of watercourses can be interrupted by a wide variety of structures with different functions and constructions [1]. This is where fish passages can provide a remedy. Conventional fish passages cannot be used in every site-specific situation. In recent years, various special solutions for fish passage have therefore been developed and successfully implemented. [1] In order to provide an overview of the special solutions for fish passage and to be able to classify and use them more specifically, this article deals with a possible list of criteria for special solutions for fish passages based on the DWA-A 509 leaflet.

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2 Material and Methods

In the following chapters, the necessity of special solutions for fish passages is discussed first. A selection of special solutions for fish passages is then presented, along with criteria from the DWA-M 509 leaflet used, criteria from the guidelines for the construction of fish passage and criteria from an economic perspective. The criteria presented are then compiled in a criteria catalog and an evaluation form is drawn up. At the end of the article, the catalog is applied using the example of the two evaluation forms and ends with a conclusion and an outlook on the establishment of a possible criteria catalog for special solutions for fish passages based on the DWA-M 509. The creation and the evaluation of the criteria catalog is limited to the German-speaking countries in this article.

3 Presentation of special options for fish passages

This article presents a selection of special solutions in brief. Three of the special solutions out of the fol-

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lowing list are described below. The special solutions for fish passage are used when standard forms of fish passage are not appropriate or effective. Reasons for inadequate performance of standardized fish passage may include the following :

- height difference [1]
- availability [1]
- estuary/entry situations [3]
- high water velocities [4]
- water level fluctuations [1]
- more ecological design [3]
- costs [4]

Special solutions are used when the standard forms of fish passages are not able to adequately meet the specific conditions of a body of water or the needs of the fish species living there. They form solutions that are tailored to more difficult requirements in order to maximize the efficiency and effectiveness of fish passages. Special solutions for fish passages include the following constructions:

- Multi-structure fish pass [1]
- Fish ladder screw [1]
- Modified denil pass [1]
- Fish lift [1]
- Fish lock [1]
- Double-slot pass [5]
- Combined fish lift system [1]
- Two-chamber fish lift [1]
- Bristle ramp fish lock [6]
- Bristle fish pass [6]
- Super-active baffle pass according to Larinier [6]
- Fish canoe pass [6]

3.1 Runserau fish lift as an example

The way fish lifts work is very similar to that of a passenger elevator. The cage, which contains a water-filled tub, is similarly to an elevator car and is moved from a starting point to an end point. [1]

Fish lifts are characterized by a movable lifting basket in which the fish are transported from the level of the lower water to the level of the upper water. [7] Fish lifts can be divided into three types:

- Vertical elevators (the most common type)[1],
- inclined elevators (such as at Wyaralong Dam and Teviot Brook),[1] and
- Ropeways (such as at the Frieira Dam on the Miño River). [1]

In the example of the fish lift at the Runserau weir, there is an access structure in front of the fish lift in the form of a conventional slotted pass to ensure that it is easy to find. Two entrances, one far from the weir and one close to the weir, which were positioned due to the different discharge situations, take all discharge situations into account. In addition, an attraction flow is flexibly divided between the entrance far from the weir and the entrance near the weir. The slotted passes and the attraction flow guide the fish to the fish lift after the entrance. [1] Fish lifts can be divided into three phases:

1. catching phase [1].,
2. lifting and emptying of the cage [1].and
3. lowering phase, after which the cycle begins again [1]

Figure 1 shows the structure of a fish lift.

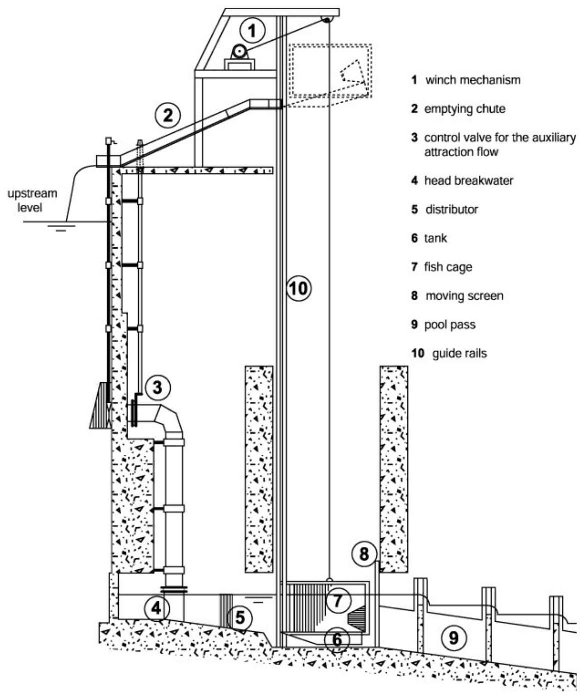

Fig. 1: Illustration of the structure of a fish lift for salmonids as a cross-section [8].

The advantages of the fish lift over conventional fish ladders are Small space requirement, suitable for large height differences and fluctuating headwater levels, can be used at locations where other fish ladders do not work. [3]

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Disadvantages of the fish lift compared to conventional fish ladders are Limited individual locations to date, insufficiently proven functionality, increased maintenance requirements, lack of long-term experience, comparatively higher construction and operating costs, offers no habitat, no possibility for fish descent. [3]

3.2 Bristle ramp fish lock

The bristle fish pass is essentially a channel with a variable wall structure. At the bottom of this channel, which has a rectangular or trapezoidal cross-section, bristle bundles are attached that serve as hydraulic roughness elements. These packages consist of several bundles of elastic individual bristles, typically 5 to 8 bristles per bundle. The operating sequences are divided into several clearly defined phases. At the beginning of the collection phase, the underwater/outlet gate is opened completely, while the knife gate valve of the upper water/intake gate opens partially in order to introduce a pre-determined attraction flow. The water flows under the gate, hits a bristle block and is distributed by percolation via the ramp into the collection chamber. Here it forms an attraction flow for immigration into the sluice chamber. This is followed by the sluicing phase, in which the underwater gate is closed to prevent the fish from leaving the sluice. The water level in the sluice rises to headwater level, while the fish follow the slowly rising current front from the bristle field and are lured up the ramp. This phase is completed as soon as the water level in the sluice box corresponds to the headwater level. [9] The exit phase with siphon operation begins by opening the exit contactor to generate an exit lock flow. Siphons start shortly before full filling and draw off exactly the amount of water required for the exit lure flow. A calmed water outflow already attracts fish back into the entry area (see fig.2). [9] This is followed by the

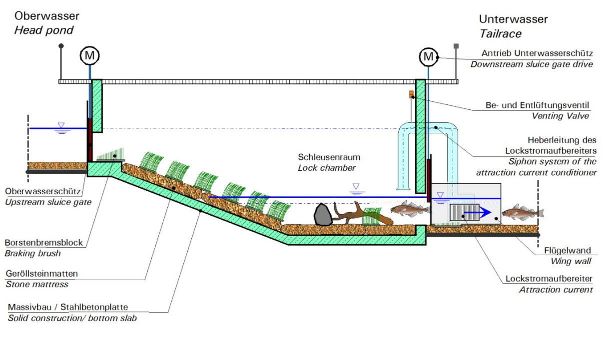

Fig. 2: Components of the Bristle fish lock (longitudinal section) [10].

emptying phase with siphons, during which the upper water gate remains closed while the siphons continue to operate and maintain the lock flow. The water level in the lock drops. At the end of the emptying phase, the underwater gate opens partially to allow water to flow out in a controlled manner and to equalize the water level between the lock chamber and underwater. Immediately afterwards, the upper water gate is pulled into the position for the collection phase to reactivate the lock flow and restart the cycle. [9]

Advantages of the bristle ramp fish sluice compared to conventional fish ladders are: simple construction, low space requirement, shape can be adapted to available space, few fittings and moving parts, fast ascent, low costs. [9]

Disadvantage of the bristle ramp fish lock compared to conventional fish ladders are: one pilot plant has been realized so far. [9]

3.3 Two-chamber fish migration aid using the Fishcon sluice as an example

The two-chamber fish migration aid, also known as the Fishcon sluice, is a further development of conventional fish sluices. It is based on a patented technology that hydraulically connects two lock chambers operated in opposite directions (see fig. 3). This configuration enables a continuous passage of fish from both sides, in contrast to conventional fish locks and elevators, which operate intermittently. This increases the efficiency of the system, which enables both the ascent and descent of fish. [1] The Fishcon

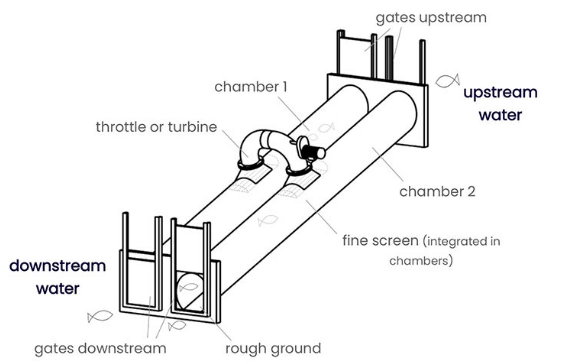

Fig. 3: Structure of the Fishcon fish pass [11].

sluice minimizes turbulence in the chambers by dissipating energy outside the fish migration area and allows the flow velocity to be adjusted for optimum fish migration. It has a continuous bed as standard, which enables the passage of bed-related fish species. The system is resistant to flooding and insensitive to fluctuating water levels. [1] The advantages of two-chamber fish migration aids over conventional fish ladders are: Small space requirement, cost-effective construction. [3] Disadvantages of two-chamber fish migration aids compared to conventional fish ladders are: Limited single sites to date, insufficiently proven

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functionality, requires multiple modules with large height differences, provides no habitat. [3]

4 Criteria for special options for fish passages

In this chapter, the criteria to be met by fish passages are presented so that they can then be summarized in a list of criteria. Criteria from the leaflet DWA-M 509 "Fish passages and fish passable structures - design, dimensioning, quality assurance" and criteria from the guidelines for the construction of fish passages from the Austrian Federal Ministry of Agriculture, Regions and Tourism as well as criteria from an economic perspective are presented.

4.1 Criteria from the DWA-M 509 leaflet

The information sheet lists eight general requirement criteria for fish passage.

- target species and target stages [2]
- operating time [2]
- migration corridor [2]
- detectability [2]
- passability [2]
- design of the exit [2]
- maintenance and operation [2]

In principle, a fish passages should allow all fish species, from low-performing to high-performing species, to migrate. The various fish species differ in terms of their behavior, growth and performance. The different species therefore have different requirements of the fish passage. In the early developmental stages of young fish, meeting certain requirements is problematic as their performance is still limited. For example, flow velocity can be a selective factor for certain fish species. [2] Fish passability should be guaranteed all year round, as fish migration occurs all year round. As this can hardly be achieved technically due to absolute high and low water levels, there is a practical compromise of 30 days on which it is acceptable to exceed the limit. The fish passage must be in continuous operation around the clock, as fish migrate both during the day and at night and sometimes take several days to ascend. [2] The migration corridor is a space that provides ideal conditions for all fish to orient themselves and swim upstream against the current. These ideal conditions are created by sufficient dimensions of the corridor and a directed current with little turbulence. The migration corridor is continuous and extends from the underwater area of an obstacle to the fish passage or structural work that can be passed by fish and extends into the upstream area. [2] The following points should be taken into account to ensure that fish passages are easy to find:

- Large-scale arrangement of fish ladders and fish passable structures in the watercourse [2]
- Character of the guiding current [2]
- Local positioning of the entrance (outlet) of a fish ladder or the migration corridor via a fish-passable structure [2]
- Design of the entrance [2]

The fish passages or a fish passable structure is considered passable if all fish species and developmental stages according to the fish species and fish stages that have found the entrance and are also able to pass the entire structure during high and low water. For smaller and less efficient species and individuals, the hydraulic conditions are particularly decisive, while the passability for larger specimens depends primarily on the size of the migration corridor. [2] Overcoming a fish passages is a considerable challenge and results in the fish swimming upstream being exhausted by the time they reach the headwater. The area should therefore be free of strong turbulence and high flow velocities. [2] The principle states that functionality is only guaranteed if it is regularly maintained. Proper maintenance includes weekly checks of the system and the occasional removal of floating debris and other faults. In addition, the lift should be taken out of service at least once a year to identify and rectify debris, potential damage to the bottom protection and problems in the areas below the water surface. [2]

4.2 Criteria from the guidelines for the construction of fish passage

The following general criteria are listed in the guidelines for the construction of fish passages:

- Ensuring findability [7]
- Ensuring passability [7]
- Sufficient service life throughout the year [7]
- Ensuring operational safety [7]
- Appropriate accident prevention [7]
- Size-determining fish species [7]

Criteria such as ensuring detectability, ensuring passability, passability of the facility, functional acidity, operational safety and the general criteria for fish species were explained in the chapter above. To prevent potential disturbance, measures must be taken to protect the facility in the event of flooding, driftwood or other forms of destruction. It is important to establish an appropriate procedure for any necessary fishing operations. In the event of a damming or low water levels, an emergency supply should be guaranteed. In the event of a failure of the regular water supply, defined minimum quantities of water must be statically available. [7]

4.3 Determined criteria for the selection of special solutions for fish passage

If there are specific conditions at a site that cannot be met by conventional fish passage, a special solution must be found. Factors such as the height to be overcome, space requirements, complex estuary and entry situations, high water velocities, water level fluctuations and financial resources are the criteria according to which special solutions for fish passage can be selected. By simultaneously considering the general requirements for conventional fish passage and the combination of site-specific requirements for special fish passage solutions, a list of criteria for the selection of special fish passage solutions can be drawn up.

5 Summary of the criteria in a criteria catalog

The requirements listed in chapter three are summarized in this chapter and formatted in an evaluation catalog for use in selecting a suitable special solution. A selection of criteria was chosen based on the general criteria listed and the criteria for the construction of special solutions for fish passages. As the general criteria must also be observed when constructing special solutions, these play a less important role in the catalog. There are general criteria and decisive ones for the choice of special solutions. For example, the target fish species is a strong criterion when choosing a special solution. In the case of passability, it is assumed that these criteria are prerequisites and do not need to be evaluated separately in a catalog for special solutions. The same applies to the operating time, which is defined in accordance with DWA-M 509, the migration corridor, findability and the design of the exit. At this point, it should be noted that criteria such as passability, maintenance and operation should be assessed in a different way. For example, the criterion of the number of structures already built by the special solutions plays a role here. The number of realized locations of special solutions and their evaluation can be used to draw conclusions about passability, maintenance and operation. As the disadvantage of the special solutions is the limited number of individual locations, the existing locations of the special solutions are included as a criterion. In addition, the decisive factors for the need for a special solution (see section 3.3) are also taken into account. In summary, the following criteria form a possible catalog for the selection of special solutions for fish ladders:

- Target fish species
- Height difference
- Space availability
- Costs
- Realized locations
- Maintenance and service life

5.1 Presentation of the criteria catalog

The figure 4 shows a possible representation of the criteria mentioned in sections 4.3 and 5. Further criteria can be added in the columns if necessary. The respective special solutions for fish migration can be evaluated in the rows.

	Criteria						
special solution	Target fish species	Height difference	Space availability	Costs	Realized locations	Maintenance	Service life
Fischlift							
Bristle ramp fish lock							
Two-chamber fish migration aid							

Fig. 4: Presentation of the criteria in a catalog

5.2 Evaluation of the criteria catalog

The evaluation of the criteria catalog can be filled out site-specifically for a special case in order to be able to select a choice of special solutions for the fish ladder or generally in order to compare the special solutions with each other (see fig. 5). For a site-specific evaluation, the evaluation catalog can be used as follows:

- ++: fully applies
- +: applies
- O: neutral
- -: does not apply
- –: does not apply at all

After the site-specific assessment, the special solution with the most positive results can be selected with ease.

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	Criteria						
special solution	Target fish species	Height difference	Space availability	Costs	Realized locations	Maintenance	Service life
Fischlift	+	++	++	--	++	--	-
Bristle ramp fish lock	+	--	-	+	o	-	+
Two-chamber fish migration aid	++	--	--	+	o	++	++

Fig. 5: Exemplary evaluation form of the catalog for a special case

	Criteria						
special solution	Target fish species	Height difference	Space availability	Costs	Realized locations	Maintenance	Service life
Fischlift	Depending on the built-in catch chamber	10 m	low	Depending on circumstances: between 100.000 € and 30 Mio. €	Many and well-documente d locations	Comparatively higher	Rather lower in comparison due to many fittings and moving parts
Bristle ramp fish lock	Also for weak swimmers	/	Small and customizable	Comparatively low	Pilot plant on the Aare	Low due to few fittings and moving parts	High due to few fittings and moving parts
Two-chamber fish migration aid	sole migrants, weakly swimming fish species	1,5 – 6 m	Very small due to compact design	Cost-saving investment	Very many locations	Resistant	High due to few fittings and moving parts

Fig. 6: Exemplary evaluation form of the catalog for various special solutions

In a comparison of the special solutions for fish migration without site-specific conditions, which can be included in the criteria, the evaluation may be as the follwing figure 6.

For example, two types of application and forms of evaluation of the established criteria catalog could look like this.

6 Conclusion and outlook

The investigation of special solutions for fish ladders has shown that the importance of the continuity of water bodies for aquatic ecology is crucial. Standardized fish ladders reach their limits when it comes to adapting to site-specific conditions. The development of special solutions has proven to be an effective alternative to meet these requirements. A set of criteria that takes into account both general and site-specific requirements can optimize the selection and implementation of tailor-made fishways and thus promote the ecological sustainability of watercourses. It should also be noted that the established list of criteria is only one possibility for evaluation and can be supplemented by further criteria. Furthermore, a list of criteria for general consideration should always be updated, as new findings will emerge in the future. It was also not possible to provide a meaningful answer to every criterion in the evaluation examples, as some information was missing. The work on a catalog of criteria for special solutions for fish ladders represents an important step in supporting the field of aquatic ecology. Future research could focus on validating and expanding this catalog by applying it to different sites and new technologies. It would also be interesting to conduct case studies to verify the practical application of these special solutions and evaluate their effectiveness in different environments. This could help to identify best practices and enable the development of even more effective special solutions for fish migration.

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Water wheels for energy recovery in the outlet of wastewater treatment plants

Using the example of the water wheel at the Warendorf central wastewater treatment plant

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1 Abstract

The annual wastewater flow that is treated by public wastewater treatment plants in Germany amounts to approx. $10 * 10^9 \frac{m^3}{a}$ and forms an "artificial" hydropower potential that can be used for energy generation or recovery. In the context of this paper, energy recovery in the outlet of wastewater treatment plants is examined using the specific example of the water wheel at the Warendorf central wastewater treatment plant. The "artificial" hydropower potential can be roughly estimated at up to 20 to 105 $\frac{GWh}{a}$, whereby this is largely dependent on the hydraulic gradient. The strong variance results, among other things, from the findings of the water wheel operation in Warendorf. The decisive aspect here is the differential factor, which describes the deviation between the theoretical and actual energy yield of the water wheel. The factor includes maintenance work, downtimes and insufficient inflows, which are associated with a loss of output. In the case study, the annual energy recovery amounts to approx. 2 % of the annual electricity consumption of the wastewater treatment plant and can be estimated to 23,500 kWh (2022). In the context of the economic analysis, it can be seen that despite the "low" yield, economic operation is possible if the system is viewed as a long-term investment - payback period of the example is approx. 14,5 years. The 27-year operation (1996 - 2023) of the water wheel at the Warendorf central wastewater treatment plant confirms this and important findings on successful practical operation can be shown in the context of this paper.

Keywords: energy recovery, wastewater treatment plant, water wheel, potential, real example

2 Introduction

Over 96 % of the total German population is connected to the public sewer system, which feeds the collected wastewater into around 10.000 public wastewater treatment plants. The wastewater flow amounts to a total of approx. $10 * 10^9 \frac{m^3}{a}$, which is purified by the public wastewater treatment plants and then fed back into the water cycle [1].

This wastewater flow forms an "artificial" hydropower potential that can be used to generate or recover energy. This can take place, for example, within the sewer network, in drop structures or in the outlet of wastewater treatment plants [2, 3]. In the context of this paper, energy recovery in the outlet of wastewater treatment plants is considered using the specific example of the water wheel of the Warendorf central wastewater treatment plant, although it should be mentioned that other hydropower machines are available for potential utilization, such as hydropower screws or various turbines.

3 Methods and approach

This paper is based on an on-site visit of the waterwheel of the Warendorf central wastewater treatment plant (population value: 80.000), which was built in 1996. Through the operation of this waterwheel until today (2023), important practical knowledge could be collected regarding energy recovery through water wheels. These are supplemented by the results of online research and the associated literature, which is primarily based on the keywords. On the one hand, it is thus possible to estimate the total hydropower potential of wastewater treatment plant outlets in Germany and, on the other hand, advantages and disadvantages as well as practical experience can be shown with regard to utilization by means of top-shaft water wheels.

4 Hydropower potential of the wastewater treatment plant outlets

The theoretical hydropower potential in the outlet of a wastewater treatment plant results from the design discharge and the hydraulic gradient between the

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receiving water and the outlet [3]. It can be calculated using the following formula [4]:

$$P_{el} = \rho * g * h * Q * \eta \tag{1}$$

- $P_{el} = electrical\ power\ in\ W$
- $\rho = density\ of\ the\ medium\ in\ \frac{kg}{m^3}$
- $g = gravitational\ acceleration\ in\ \frac{m}{s^2}$
- $h = drop\ height\ or\ wheel\ diameter\ in\ m$
- $Q = volume\ flow\ of\ the\ medium\ in\ \frac{m^3}{s}$
- $\eta = overall\ efficiency\ of\ the\ hydropower\ machine\ in\ \%$

Under the following assumptions, the theoretical total hydropower potential of Germany's wastewater treatment plant outlets can be estimated as shown in Figure 1 (potential according to drop height without differential factor [differential factor: Deviation between theoretical [Theoretical yield$_{8760\frac{h}{a}}$] and actual energy yield [Real yield (2022)], based on the water wheel at the Warendorf central wastewater treatment plant shown in Table 1]):

- $\rho = 1000\ \frac{kg}{m^3}$
- $g = 9,81\ \frac{m}{s^2}$
- $Q = 317,1\ \frac{m^3}{s}$
- $\eta = 0,7$ [3]

If the findings from the operation of the water wheel at the Warendorf central wastewater treatment plant are taken into account, it can be seen that the potential can vary significantly due to the differential factor of approx. 4.95 (potential according to drop height with differential factor).

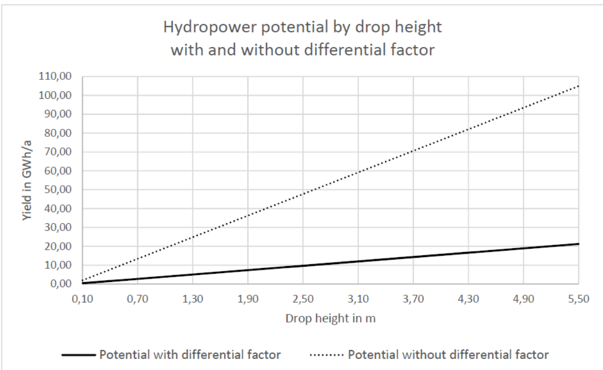

Fig. 1: Estimation of the total hydropower potential of wastewater treatment plant outlets in Germany

A more precise estimate of the total hydropower potential of wastewater treatment plant discharges in Germany is difficult, as this would require a closer examination of the individual plants with regard to their discharge volumes and hydraulic gradients.

5 Water wheel of the Warendorf central wastewater treatment plant

Due to the hydraulic gradient of > 5 m between the outlet and the receiving water, the waterwheel of the Warendorf central wastewater treatment plant was designed as a top-shaft cell construction - see Figure 2. The treated wastewater is fed (partly shown in Figure 2) via a foil-lined wooden channel and is equipped with an overflow so that the design flow rate of 400 l/s is not exceeded, for example in the event of heavy rainfall. A shut-off valve is also installed so that the flow to the water wheel can be shut off in the event of an emergency. The water wheel itself consists of a hot-dip galvanized steel shaft as well as spokes and reinforcing struts on which the stainless steel paddles/cells are mounted. The shaft rests on two bearings and ends in a coupling. In the event of a frictional connection, the speed is adjusted by a planetary gearbox, which enables the significantly higher nominal speed of the asynchronous generator. The design parameters and other key figures are shown in Table 1 [5]. The differential factor describes the deviation between the theoretical and actual energy yield of the water wheel. The factor includes insufficient inflows, maintenance work and downtimes, which are associated with a loss of output.

Fig. 2: Water wheel in the outlet of the Warendorf central wastewater treatment plant (2023)

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Tab. 1: Design parameters and key figures of the water wheel at the Warendorf wastewater treatment plant

Parameter	Unit	Value
Type of construction	-	top-shaft
Year of construction	yyyy	1996
Drop height	m	5,5
Water wheel diameter	m	4,83
Width of water wheel	m	1,5
Wheel speed	rpm	6,5
Max. absorption capacity	l/s	400
Theoretical output (manufacturer specification)	kW	13,6
Actual output	kW	12,6
Theoretical yield$_{8760\frac{h}{a}}$	$\frac{kWh}{a}$	116.219
Real yield (2022)	$\frac{kWh}{a}$	23.500
Differential factor yield	-	4,95
Electricity requirement (2022)	kWh	1.270.000
Real energy recovery	%	2
Total energy recovery	$kWh_{1996-2023}$	634.500

6 Advantages and disadvantages of a water wheel for energy recovery and findings from practical operation in Warendorf

Due to the 27 years of existence and operation of the waterwheel at the Warendorf wastewater treatment plant, important findings could be gained, which are listed below in combination with advantages and disadvantages.

(+) Due to the continuous operation of the sewage treatment plant and the hydraulic gradient between the outlet and the receiving water, there is always (waste-)water potentially usable for energy recovery ([5], findings from internal study from 1990).

(+) The system design is simple and tends to require little maintenance. Regular maintenance includes two gear oil changes per year as well as regreasing the shaft bearings [5].

(-) Due to the established technology, water wheels are generally robust and durable systems [2, 6]. When designing or constructing the system, the resulting torque or mechanical forces and loads should not be underestimated. In the case of the Warendorf waterwheel, it was necessary to replace the coupling and redesign the spokes several times [5]:
- Version 1: Classic construction with a set of wooden spokes leading to insufficient stability
- Version 2: Double spoke set made of hot-dip galvanized steel getting cracks at the weld seams after approx. 10 years of operation
- Version 3: Double set of spokes made of hot-dip galvanized steel and reinforcing struts and plates

(+) The effluent water from a wastewater treatment plant does not contain any impurities [3] or fish populations, so that neither a screen nor a fish ladder is required, which reduces the construction costs.

(-) The difference between theoretical and actual yield can be significant - see differential factor yield at Table 1.

(+) The Warendorf waterwheel was realized near the Ems-cycle-path and represents, among other things, visible public relations work [5] - "Fascination waterwheel".

7 Discussion and conclusion

It is already clear from the estimation of the hydropower potential of Germany's wastewater treatment plant outlets (Figure 1) that an individual consideration of the wastewater treatment plant with regard to discharge volume, hydraulic gradient and general location is always necessary. In general, however, the collection of this data is simple, so that a rough estimate of the potential is easy. Further planning is then possible, particularly in the context of the constant (waste-)water flow.

Table 1 shows that there can be a factor difference of up to 4,95 between the theoretical and actual yield. Furthermore, the energy recovery of 2 % of the annual electricity consumption can be assessed as low, but economically viable operation is possible, which is shown in Table 2 below. No statements were made by the Warendorf wastewater treatment plant with regard to investment, maintenance and operating costs. The values assumed in this regard in order to make an estimate are indicated by sources. The industrial

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electricity price for 2023 was assumed to be constant, although it is subject to annual fluctuations.

Tab. 2: Economic assessment (estimation) of energy recovery by the waterwheel at the Warendorf wastewater treatment plant

Parameter	Unit	Value
Operating time	a	27
Real yield (2022)	$\frac{kWh}{a}$	23.500
Industrial electricity price (2022) [7]	$\frac{Euro}{kWh}$	0,2251
Gross savings through energy recovery	$\frac{Euro}{a}$	5.290
Maintenance and operating costs [4]	$\frac{Euro}{a}$	1.500
Net savings through energy recovery	$\frac{Euro}{a}$	3.790
Investment costs (estimate [4])	$Euro$	55.000
Amortization time (excl. new construction spokes)	a	14,51
Net savings until 2023	$Euro$	102.330
Previous "profit" (2023)	$Euro$	47.325

Table 2 shows that the economically viable operation of a water wheel for energy recovery is possible, but that it is a long-term investment. With reference to the Federal Network Agency's electricity price analysis [7], however, the potential savings increase annually due to the constantly rising price trend. Apart from the repeated redesign and repair of the spokes, the 27 years of operation of the waterwheel at the Warendorf central wastewater treatment plant to date is a positive confirmation of the technology. Nevertheless, other technologies for energy recovery should also be considered in the course of planning, which include for example: Hydropower screws, Pelton turbines, through-flow turbines and submersible pump turbines [3].

8 Outlook

Due to the constantly growing global demand for energy [8] and the advancing energy transition, the topic of energy recovery will become even more relevant. Utilizing the "artificial" hydropower potential of wastewater treatment plant outlets is a possibility, regardless of the technology used. Building on this paper, a closer look at the differential factor and a detailed comparison of the available technologies would be useful.

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Comparison of small wind turbines for urban areas, a market analysis

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Abstract

This document presents a comparative analysis of horizontal and vertical small wind turbines for urban areas in three power classes up to 10 kW in different categories. The main objective was to conduct a market analysis to assess the marketability of these wind energy systems. The aim was to make it easier for potential customers to make a decision. However, due to the limited availability of data, the project encountered considerable difficulties. As a result, the study became a comparative assessment, which led to results that may not be readily transferable to urban environments, slightly missing the original objective of the study. The results underline the difficulties associated with conducting a comprehensive market analysis in this sector and highlight the need for an independent series of tests under specific conditions. The paper concludes with a plea for future research efforts to adapt data collection methods to urban conditions in order to improve the relevance and applicability of such studies in practice.

1 Introduction

The need to supply urban regions with sustainable energy has led to a growing interest in small wind turbines as a promising solution [1]. In the wake of this energy transition, the market for small wind energy is facing a remarkable challenge that needs to be addressed. However, the number of technologies, performance characteristics and economic aspects is confusing and has led to a complex landscape that needs to be untangled. This market analysis looks at the current confusion in the market for small wind turbines in urban areas. It looks at different models and manufacturers to help urban planners, energy experts and investors select the optimal solution for their specific requirements. In an environment where innovation is the norm, it is of great importance to keep an overview of the best available technologies. The aim of this analysis is to shed light on the current confusion in the market in order to help guide the urban energy transition.

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2 Methodology

To prepare the paper, suitable sources were initially researched using the "Google Scholar" platform. However, high-quality sources were difficult to find, as both topicality and citation frequency and ratings had to be taken into account. Furthermore, search terms such as "market analysis of small wind turbines" in the context of urban areas did not lead to any useful results. There are many good sources on the topic of urban wind energy, but the market is very volatile, making it difficult to find up-to-date sources for a market analysis. After a suitable paper was found, the search was extended with the AI tool "researchRabbit". However, the sources found were not sufficient to create our own market analysis. For this reason, sources of lower quality and therefore less trustworthy were used. Some of these sources have not been verified by third parties.

With regard to the market analysis, it should be noted that various public market analyses were used for an initial overview. It was found that many of these analyses had qualitative shortcomings and only a little good information could be obtained from them [2–4]. When checking the facts, you often end up on the manufacturers' websites, which contain the information mentioned. It is noticeable that the manufacturer websites often provide more information than the compared analyses and further information can be provided on request.

Due to the size of the market for small wind turbines, only a small selection of available turbines are compared. The selection is based on a list of the most relevant companies in this sector. The list was compiled by "Market Research Future" in 2022 [5]:

- Kingspan Group Plc. (Ireland)
- Bergey Wind Power Co. Inc. (U.S.)
- S.L. (Spain)
- Guangzhou HY Energy Technology Co. Ltd (China)
- Shanghai Ghrepower Green Energy Co. Ltd (China)

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- Aelos Wind Energy Ltd (U.K.)

A distinction is made between the horizontal and vertical axis. The key difference between these models is the position of the axis of rotation - horizontal or vertical - which distinguishes between horizontal and vertical axis wind turbines. The advantages and disadvantages of both variants will be worked out. A direct performance comparison is not possible due to the principle of operation. The following performance classes are also differentiated:

- less than 2 kW
- 2 kW up to 5 kW
- 5 kW up to and including 10 kW

The following criteria are to be examined for the various systems:

- Investment
- Security
- Maintenance
- Power
- Noise emissions

The data collection comes from various sources and therefore a direct comparison cannot be guaranteed.

3 State of the art

The vast array of small wind turbine models available in today's market poses a significant challenge for prospective buyers seeking an overview. Horizontal wind turbines currently dominate the market and have established themselves as the technical standard in both the small turbine and megawatt range. There are no quality labels for the German market that are comparable to those in the USA or Japan. However, the IEC 61400-2 standard does exist, which prescribes comprehensive tests for wind turbines[6]. The international standard IEC 61400 is designed for large wind turbines. The following standards are relevant for small wind turbines:

- IEC 61400-2: Design requirements for small wind turbines
- IEC 61400-12-1: Measurement of the performance of a wind turbine
- IEC 61400-11: Sound measurement method
- ISO 9001

The certificate remains valid for a period of 5 years. If a change is made to the system, the certificate must be a new test must be carried out. Systems with IEC 61400-2 certification fully comply with the safety standards set out in the standard.

Alongside China, America is one of the largest markets for small wind turbines. In 2009, the American standard for small wind turbines was developed and published for certification by the American Wind Energy Association (AWEA) in cooperation with the American National Standards Institute (ANSI), manufacturers, technical experts, public authorities and consumers. Like most national standards, it is based on the IEC 61400 series of standards and focuses on ensuring the performance, quality and operational safety of turbines. The most important technical data, such as rated power at 11 m/s, noise emissions at 5 m/s and energy yield for a defined location, are presented in the form of a label and made available to consumers.

The systems in England are tested and approved by the Microgeneration Certification Scheme (MCS). This standard was developed jointly by consumer and public interest groups, manufacturers and interest groups. It applies to small wind turbines with an output of up to 50 kW (micro and small wind certification) and a swept rotor area of up to 200 m^2. The tower and foundation are not tested. The implementing institutes are nationally recognized and accredited certification bodies of the United Kingdom Accreditation Service (UKAS). MCS006 (Micro and Small Wind Certification) refers to the "Renewable UK Small Wind Turbine Standard", or RUK for short, which was published in January 2014 and replaces the BWEA Small Wind Turbine Performance and Safety Standard. Similar to the US standard, quality (endurance test), performance and noise emissions are tested.

The operation of a small wind turbine in densely populated areas, in the immediate vicinity of buildings close to or on top of buildings requires additional requirements or changes to the assessment of aspects already taken into account. These additional requirements are not included in any recognized standard [7].

Small wind turbines are of particular interest in urban areas due to their use as a decentralized energy source in the immediate vicinity of consumers. The availability of this technology in urban environments is influenced by various factors such as building structures, local wind conditions and regulatory frameworks.

Real-world experience in urban environments provides valuable insights into the effectiveness of small wind turbines. Case studies and examples of successful implementations show not only positive results, but also challenges faced by users in cities. The evaluation of practical experience enables a realistic assessment of the performance and potential impact of small wind turbines in urban areas. Unfortunately, not all small wind turbines available on the market are tested under urban conditions. Therefore, the turbines have to be compared based on the available data.

4 Use of wind power in urban areas

Wind conditions in the countryside and in the city differ due to various factors. In the city, the so-called "Urban Wind Island Effect" (UWI) occurs, where the average wind speed can be surprisingly higher than in the countryside, even though the city is rougher. This effect occurs in the afternoon and is caused by differences in the growth of the atmospheric boundary layer, surface roughness and ageostrophic wind between urban and rural areas [8]. But in generally the increased roughness of the city leads to a reduction in wind speed compared to open land [9]. The turbulence caused by buildings in urban areas increases the turbulence and thus deepens the boundary layer. This impairs the use of wind turbines [8]. Over urban areas or uneven terrain, the wind gradient effect can lead to a reduction in wind speed of 40 to 50 percent [10]. The change in wind speed over height in different environments is shown in Figure 1. Despite the difficult conditions, the use of wind energy in the city is possible. The following points must be observed for efficient use:

1. Location
2. Turbine
3. Approval process
4. Maintenance

The site of a potential wind turbine should have sufficient wind potential and be characterized by low turbulence and low interference from other structural elements and activities. The frequency of wind speeds above the starting speed of the turbine used should be as high as possible. No clear figures are available, as the economic efficiency also depends on the varying investment size. To avoid possible bad investments, it is advisable to carry out a one-year measurement at the site before the actual installation. Predictions of wind conditions in urban areas are often associated with a high degree of inaccuracy [11]. The choice of turbine has a significant influence on points 3 and 4. When making the decision, attention should be paid to noise emissions and maintenance intensity. Noise emissions and shadow impact in particular influence the approval. In areas with a high population density, these factors are much more likely to disturb local residents than in rural areas.

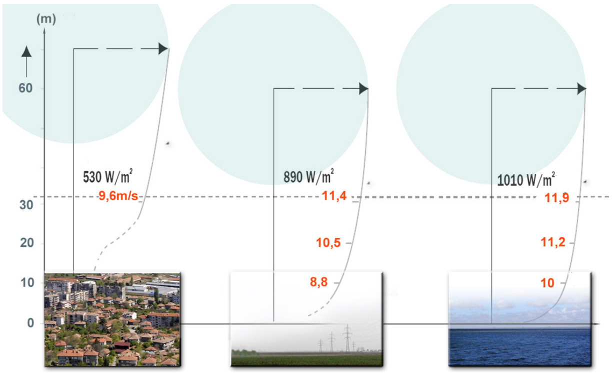

Fig. 1: Wind potential in different environments [12]

5 Results

To improve clarity, the company names and models in Table 1 have been numbered. The numbers are used in Tables 2, 3, 4 and 5.

There is only one company on the list that deals with the sale of small vertical axis wind turbines. The horizontal axis dominates the market, but the number of vertical axis small wind turbines for urban areas is increasing [13]. Table 2 compares the small wind turbines with a vertical axis.

All vertical small wind turbines are CE certified and have been tested in accordance with ISO 9001. They can be installed in urban areas and can also be installed on the roofs of buildings with suitable statics. The cheapest turbine is number 13 with a specific price of 2.51 €/W. The most expensive system is number 10 at 6.61 €/W, more than twice as much. The cut in speed, guarantee period and noise emissions are identical for all systems. The survival speed is 50 m/s for the three smaller systems and 52.5 m/s for the two larger ones.

Table 3 compares the small wind turbines with a horizontal axis. The table is sorted in descending order of turbine output.

The system with index number 2 belongs to the medium performance class and has the highest price of all the systems. It's specific price is 9.14 €/W. In contrast, the system with the index number 15 belongs to the lowest performance class and has the lowest specific price of 1.30 €/W.

The survival speed ranges from 45 m/s to 70 m/s. The most expensive system is at 70 m/s and the cheapest at 45 m/s. This shows a clear correlation between price and strength. Particularly in urban areas, strong turbulence and gusts of wind can occur, which cause a short-term and strong increase in wind speed. A wind turbine with insufficient strength therefore represents an increased risk in urban areas. The most expensive turbines come from the Kingspan Group and have the ability to bend their blades backwards elastically if the wind is too strong. This allows the rotor to continue

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Tab. 1: Company and model of the small wind turbines analysed

company	model	nr.
Kingspan Group Plc. (Ireland)	KW6	1
Kingspan Group Plc. (Ireland)	KW3	2
Bergey Wind Power Co. Inc. (U.S.)	BWC Excel 10	3
S.L. Borney (Spain)	wind 13	4
S.L. Borney (Spain)	wind 25.2	5
S.L. Borney (Spain)	wind 25.3	6
Guangzhou HY Energy Technology Co. Ltd (China)	HY 400 L	7
Guangzhou HY Energy Technology Co. Ltd (China)	HY 600	8
Guangzhou HY Energy Technology Co. Ltd (China)	HY 1000	9
Aeolos Wind Turbine	Aelos-V 300W	10
Aeolos Wind Turbine	Aelos-V 600W	11
Aeolos Wind Turbine	Aelos-V 1000W	12
Aeolos Wind Turbine	Aelos-V 3000W	13
Aeolos Wind Turbine	Aelos-V 5000W	14
Aeolos Wind Turbine	Aelos-H 500W	15
Aeolos Wind Turbine	Aelos-H 1000W	16
Aeolos Wind Turbine	Aelos-H 2000W	17
Aeolos Wind Turbine	Aelos-H 3000W	18
Aeolos Wind Turbine	Aelos-H 5000W	19

Tab. 2: Comparison of small wind turbines with vertical axis

nr.	price [€]	power [kW]	rotor diameter [m]	cut in speed[m/s]	survival speed[m/s]	warranty [a]	Noise emissions[dB(A)]
10	1982,16	0.3	1.2	1.5	50	5	45
11	2971.72	0.6	1.6	1.5	50	5	45
12	4032.71	1	2	1.5	50	5	45
13	7516.18	3	2.8	1.5	52.5	5	45
14	14109.14	5	4.5	1.5	52.5	5	45

Tab. 3: Comparison of small wind turbines with horizontal axis

nr.	price [€]	power [kW]	rotor diameter [m]	cut in speed[m/s]	survival speed[m/s]	warranty [a]	Noise emissions[dB(A)]
3	60320.65	10	7	2.5	60	5	42.9
1	33621.04	6.1	5.6	3.5	70	5	40
6	8275.00	5	4.05	3	60	3	-
19	-	5	6.4	3	45	5	45
5	5675.00	3	4.05	3	60	3	-
18	-	3	4.8	2.5	45	5	40
2	22859.77	2.5	3.8	3.5	70	5	-
17	2766.35	2	3.2	2.5	45	5	30
4	4100.00	1	2.65	3	60	3	-
9	-	1	1.96	2.5	50	-	33
16	1657.66	1	3.2	2.5	45	5	30
8	1187.74	0.6	1.75	2.5	50	-	38
15	649.15	0.5	2.7	2.5	45	5	25
7	887.46	0.4	1.5	2.5	50	-	25

turning with a reduced area of attack and increases the survivability of the turbine. The less expensive variants use a simple brake for the rotor, which means that the area exposed to the wind remains the same and the mast supporting the rotor is not relieved. Although this variant has the advantage of being considerably cheaper, it loses survivability.

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The warranty period is 3 to 5 years and some providers offer their own service centers to support the product even after the sale. For maintenance, systems 1 and 2 require an inspection every 2 years, system 4 every 6 months, 7, 8 and 9 also every 6 months, but here the blades and possibly the battery must also be replaced every 5 years. This maintenance work means considerable additional costs. No maintenance information could be obtained for the remaining systems.

There is a correlation between system size and noise emissions, with larger systems emitting more noise. However, this correlation cannot be confirmed in the upper performance class. Notably, there are significant differences in price, which could indicate that cheaper models have lower quality sound insulation.

The systems can be divided into three categories: Systems with a starting speed of 2.5 m/s, systems with a starting speed of 3 m/s and the vertical systems with a starting speed of 1.5 m/s. At first glance, this does not appear to be a major difference. The incidence of wind speeds above this threshold in urban areas is quite low compared to rural areas. This difference can therefore have a major impact on the annual amount of energy produced [14].

Not all small wind turbines are suitable for roof mounting. In particular, systems from a size of 5 kW can only rarely be installed on roofs in urban areas for structural reasons. These systems are often installed on offshore platforms to ensure reliable self-sufficiency [15–17]. In the medium power range, there are only a few systems installed in urban areas [18]. Here too, the systems are often too large to be accepted in these areas. The smallest output class, on the other hand, is very often used in urban areas. Aeolos systems are a good example of this. Hundreds of Aeolos 300W and 500W wind turbines have been installed in China, Japan, Romania, Brazil and Spain for hybrid wind-solar street lighting [19]. Smaller systems have the advantage that they are often quieter and do not generate large static loads, which increases acceptance in the surrounding area.

6 Discussion

The results have shown that there are sometimes considerable differences between the individual systems. One of the most significant differences is the price. The price range of the systems is very wide. This is partly due to the differences in quality, but also to the production process. The most expensive systems are only produced in small quantities, which means that the specific price of a system is significantly higher than for mass-produced systems. However, it is unclear why the higher quality products have not made it into mass production. One assumption is that the difference in quality was not communicated well enough to the consumer and therefore a large

Tab. 4: Certificates of individual small wind turbines

nr.	certificate
1	IEC61400-2
2	IEC61400-2
3	AWEA
4	IEC61400-2
5	-
6	-
7	ISO9001, CE
8	ISO9001, CE
9	ISO9001, CE
10	ISO9001, CE
11	ISO9001, CE
12	ISO9001, CE
13	ISO9001, CE
14	ISO9001, CE
15	ISO9001, CE
16	ISO9001, CE
17	ISO9001, CE
18	ISO9001, CE
19	ISO9001, CE

Tab. 5: Sources of prices and data

nr.	source of the price	general source
1	[20]	[15]
2	[21]	[16]
3	[22]	[17]
4	[23]	[18]
5	[23]	[18]
6	[23]	[18]
7	[24]	[25]
8	[26]	[25]
9	-	[25]
10	[27]	[28]
11	[29]	[28]
12	[30]	[28]
13	[31]	[28]
14	[32]	[28]
15	[33]	[28]
16	[34]	[28]
17	[35]	[28]
18	-	[28]
19	-	[28]

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number of pilot projects did not materialize. Only when a company can forecast a certain level of product sales with sufficient certainty will it go into mass production.

With regard to the installation potential in urban areas, it can be stated that vertical small wind turbines perform significantly better than some horizontal ones. However, an exact statement about the respective yield for urban areas cannot be derived from the data collected. All publicly available data was generated under standard conditions and is therefore difficult to transfer to urban areas. In order to secure a market advantage for urban areas, interested companies should adapt the environmental conditions to urban areas when collecting data. It has been shown that the wind potential in this area deviates significantly from the standard conditions [36].

The purpose of this document is to offer a basic outline of various small wind turbines to aid potential customers in decision-making. Nevertheless, customer requirements vary widely, hence it is essential to specify the desired performance class and the resultant yield first. For better comparability, it would be sensible to examine systems with the same output as much as possible, although acquiring the data presents a challenge. The limited number of systems within the three performance classes in this study prevents any overarching claims about generally available systems. The study shows, though, that a larger comparison is worthwhile, because even with this small sample, large differences in the individual categories could be identified. It would be prudent to increase the number of categories for further analysis. The comparison of yield under certain conditions would have been a suitable criterion to consider, although it could not be included here due to a lack of data. Some corporations conduct such tests, but the framework and parameters of these assessments differ. It would be more appropriate to administer a standardized test conducted by a neutral entity.

7 Conclusion

The market analysis reveals distinctions among the individual systems within their respective performance classes. It was not possible to identify the best system for a given power class, as all systems have their advantages and disadvantages. Nevertheless, a prospective purchaser can select a system for themselves if they specify particular weightings in each category. However, it is worth noting that this sample is only representative and therefore, it is possible that there are significantly more suitable systems available in individual cases. The actual suitability and comparability of the systems for urban areas could not be accurately analyzed. The effectiveness of some systems for urban areas can only be inferred from their real-life applications. No tests were conducted in this particular environment for any of the systems, thus making it challenging to interpret the comparison. The values given under standard conditions are the only reference available. Additionally, the collection of data was either carried out or commissioned by the companies themselves, thereby raising doubts about its authenticity. Consequently, the paper's goal could not be fully achieved. In order to achieve the aim of the paper, an investigation is recommended according to the following criteria:

- Selection of a performance class with minor deviations
- Construction of/ finding a test field representing the urban area
- Acquisition of the systems to be tested
- Testing the systems as an independent person
- Evaluation of the results

Significantly better comparability can be achieved through independent tests under defined conditions. However, this approach is associated with enormous costs for the purchase of the equipment and for the construction and operation of the tests. In addition, the market is subject to constant change, so that the results of this complex procedure can lose their significance after a short time. For these reasons, the implementation of such a test is considered unlikely. The question therefore remains as to how one can currently obtain a good overview of the market for small wind turbines for urban areas. As a customer, you are still faced with a large selection of turbines and are dependent on comparisons with little data or data that is unsuitable for the planned environment. When implementing larger projects, it is advisable to consult an energy consultant who may be able to provide information from various pilot projects. However, even this information will only relate to a small proportion of the systems available on the market.

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Fish mortality at hydropower plants

Protection Measures and Solutions

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Abstract

The construction and operation of hydropower plants for energy generation is a major issue in sustainable energy production. Nevertheless, hydropower plants have a negative impact on fish populations. It is crucial to understand the causes and consequences of fish mortality in hydropower plants in order to find sustainable solutions that reconcile the need for energy with the conservation of aquatic ecosystems. This article examines the fish protection measures that can be implemented to reduce fish mortality and maintain ecological balance. Based on the main literature reviewed, this article mainly refers to Germany in terms of studies carried out and hydropower plants.

Keywords: Fish mortality, Turbine-related injuries, Fish migration aids, Fish-friendly turbines, Mortality rates

1 Introduction

The number of hydropower plants is increasing rapidly worldwide. In Europe alone, 21,000 plants are already in operation, while a further 8,500 planned plants are waiting to be realized [1]. The impact of hydropower plants on fish populations is an increasingly important issue. The mortality of fish in such plants is a complex and controversial issue. The construction and operation of hydropower plants can have a significant impact on the aquatic environment by altering natural habitats and affecting fish populations. The Water Resources Act emphasizes the importance of protecting fish through appropriate measures at hydropower plants. Such begs the question: *What measures can be taken for reducing fish mortality at hydropower plants?* This article first delineates the risks posed to fish in hydropower plants. It then explores various potential solutions aimed at mitigating these risks and preserving fish populations in such settings.

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2 Legal area

The implementation of fish protection measures at hydropower plants is highly relevant, as this is required by the Water Resources Act. According to Section 35 (1) of this Act, the use of hydropower may only be permitted if suitable measures are also taken to protect fish [2]. If no measures are implemented in this regard, the hydropower plant may not be put into operation. This regulation does not apply exclusively to specific fish species or water body types. According to this, plant operators must prove that the operation of the hydropower plant has no negative impact on the fish population or that sufficient measures are implemented to protect and maintain the population [3]. In order to achieve the objectives of the EC Water Framework Directive in many watercourse systems in Germany, measures are needed to improve fish passability both upstream and downstream. The installation of fish ladders at weirs and other barriers to fish migration as well as the integration of fish protection and downstream fish migration systems at hydropower plants, are of particular importance to achieve this goal. It is therefore urgently necessary to review the current state of knowledge on the effectiveness of fish protection and downstream fish migration systems. This requires methodological approaches to ensure a comparison of the efficiency of different concepts and to develop recommendations for preferred solutions [4].

3 Risks and Implications of Hydropower Plant Encounters for Migratory Fish

When fish migrate downstream, there is a possibility that they will be caught and pulled along by the turbines in hydropower plants and thus pass the obstacle. This could expose them to conditions that increase the risk of injury and mortality. These risks vary depending on fish species, developmental stage, size, turbine type and operating conditions. The main injury mechanisms occurring are due to contact with the turbine blade and the pressure drop in the turbine. Other mechanisms include shear forces and turbulence. Given the comparatively high costs of

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fish protection measures and the associated technical or operational risks, a clear basis for decision-making on appropriate fish protection regulations is essential [5]. High killing risks arise when certain species have to travel long distances due to their behavior and reproductive cycle. Species that are forced to migrate are generally more likely to come into contact with hydropower plants. As hydropower plants are positioned as transverse structures in the main watercourse, the downstream movement inevitably requires passage through these structures. As a result, species such as the eel (Anguilla anguilla) and the anadromous sea trout (Salmo trutta) are particularly at risk. In the case of anadromous fish species that migrate repeatedly, the migrating juveniles in particular are at risk. These juveniles are often not protected from passing the turbines by screens. Potamodromous species such as the nase (Chondrostoma nasus) sometimes traverse extensive distances within a water system and are therefore also at risk of passing existing hydropower sites during their migration. Compared to typical river fish species, lake species are generally less likely to encounter hydropower plants. Although the probability of encounter for lake species was classified as very low, it cannot be completely ruled out that certain lake species may encounter hydropower plants, particularly in the vicinity of lake outlets or storage power plants [3].

3.1 Injuries caused by turbines

As fish mortality is mainly caused by turbines, the rest of the article refers to turbine-related fish mortality. A study showed fish experiments at one of the world's first construction sites for a shaft hydropower plant (SHPP) on the Loisach near Großweil in southern Bavaria to investigate the mortality of fish at this plant. The fish were released in front of the hydropower plant and then caught again. The hydropower plant has a head of 2.5 meters, a power plant discharge of 22 cubic meters per second and an output of 420 Kilowatt-hours (kWh). The power plant also has two identical, double-regulated, horizontally arranged Kaplan bulb turbines, each with four blades [6]. The study focused on how the fish population reacted to the specific operating conditions and structural features of this plant. The potential for fish mortality and injury following turbine passage of the SHPP was investigated. The fish species used for the study included:

- European eel (Anguilla anguilla L.)
- Common nase (Chondrostoma nasus L.)
- Brown trout (Salmo trutta L.)
- Perch (Perca fluviatilis L.)
- Barbel (Barbus barbus L.)
- Roach (Rutilus rutilus L.)
- Grayling (Thymallus thymallus L.) and
- Danube salmon (Hucho hucho L.)

For each of these fish species, the widest available size range was used, which was within a range of 3 to 67 centimetres [7]. The recaptured test fish showed various injuries after passing through the turbines. The most common were fin tears and scale loss, which were found in 83% and 66% of the recaptured fish respectively. More serious injuries such as amputations and bruises to the head and body occurred less frequently and were only found in 2.7% and 3.7% of the recaptured treated fish respectively after turbine passage [7]. A comprehensive assessment of fish injuries requires the capture of fish below hydropower plants. Both recapture and subsequent handling can cause stress to the fish, resulting in significant injuries such as fin tears, scale loss or skin lesions [8].

3.2 Turbine-related fish mortality

The mortality rates of the various test fish species in relation to the SHPP study varied significantly. There were clear differences in the specific mortality rates of the individual fish species. Mortality after passage through the turbines was significantly increased for all test fish species. Particularly high turbine-related mortality rates were found in roach, with 20% at high turbine loads and 44% at low turbine loads [7]. Furthermore, fish tests at different locations with three different turbine types - the Kaplan turbine, the screw turbine and the Very-Low-Head turbine (VLH turbine) yielded different results in terms of fish mortality rates. In general, maximum mortality rates of less than 83% can be determined for conventional Kaplan turbines and less than 64% for novel turbines. The lowest average mortality rates, with mean values between 2% and 6%, were recorded for the VLH turbines [9] as slow-turning turbines such as very-low-head turbines and water wheels are less harmful than most conventional turbine types [1]. This was followed by the screw turbines with 3% to 6% and the conventional Kaplan turbine with 5% to 8%. At locations with the highest maximum and average mortality rates were both Kaplan and one of the VLH sites recorded. Here, most of the severely injured fish died immediately after passing through the turbines. Accordingly, the pattern of fish injuries and mortality is strongly dependent on various factors, such as the life stage of the fish [1], the type of turbine, the location and the specific characteristics of the fish. The circumferential speed of the runner has a more significant influence on fish injuries than other turbine parameters. In the case of Kaplan turbines, blade runout is the decisive factor for the risk of mortality. The same applies to VLH turbines, whereby their passage mainly leads to collision-related injuries that are

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either internally visible or of lesser severity, such as internal vertebral fractures or deformations as well as bone fractures. Furthermore, the number of turbine blades, the drop height and the total length of the fish have a significant influence on certain types of injury. Loss of scales, internal fractures, pigmentation and fin amputations, for example, increase with the number of turbine blades. This tendency is particularly evident in VLH turbines with eight blades, which have a comparatively low impeller speed, however, leading to an increased probability of low-intensity collisions. In addition, the rate of body part amputations increases with increasing drop height. A comprehensive overview of the presence or absence of fish damage, as well as fixed effects such as turbine or hydropower plant and fish characteristics, but also random effects such as location and fish species, can be seen in Figure 5 by Mueller et. al [9]. Furthermore, vertebral fractures also increase with increasing total length of the fish and the circumferential speed of the impellers. This emphasizes that the European eel, as the longest fish in this study, has the highest mortality rate in the Kaplan turbines [9]. From this it can be concluded that the risk of mortality generally increases with the size of the fish, with larger fish tending to have the highest risk of mortality [1].

4 Possible Solutions for Reducing Fish Mortality at Hydropower Plants

In the context of this paper, two specific approaches are now briefly presented that aim to reduce or avoid fish mortality at hydropower plants.

These are:

- Fish-friendly turbine design
- Fish migration aids

4.1 Fish-friendly turbine design

The best solution are turbines that reduce fish mortality due to technical and operational configurations and at the same time successfully prevent the animals from entering the turbines in the first place [1]. Fish-friendly turbines such as the Minimum-Gap-Runner are characterized by a small number of turbine blades. They have a large diameter, a comparatively low rotational speed, low head and generate only minimal negative pressure. These characteristics make it possible to significantly reduce mortality to below 3%. Similarly turbines currently under development, such as the Alden turbine, also reduce the mortality of fish, which in tests caused mortalities of 0% to 2% in 20 centimeter long individuals of various fish species [10]. The goal in developing a fish-friendly turbine is to maintain high efficiency while minimizing low-pressure zones. This is achieved by having a low number of blades and minimizing gaps to avoid fish entrapment. The reduction of the gaps has a positive effect on the scouring of the blade profiles, both on the pressure and suction side of the turbine. This measure has a positive effect in two ways. Firstly, the risk of cavitation is reduced at this point. Cavitation leads to abrupt pressure drops followed by rapid pressure increases, which would be potentially harmful to fish. Secondly, minimizing the gap positively contributes to reducing zones of high turbulence that could otherwise affect the fish laterally [5].

4.2 Fish migration aids

4.2.1 Slotted pass

The main principle behind the construction of a slotted pass is to divide the entire height difference of the dam between the upstream and downstream water into numerous smaller water level differences. This is achieved by the arrangement of basins whose dividing walls are well permeable for the passage of fish through narrow slits [11]. With the slot pass, which is also known as the "vertical slot pass", one or two open slots run vertically across the entire transverse wall, which leads to improved passability. The number of slots installed depends on the size of the watercourse and the available discharge capacity [12]. The fish migrating upstream must orient itself to the current in order to recognize the outgoing current, which emanates from both the fish ladder and the attracting current. The attracting current is generated, for example, by sheet piles or guide piles consisting of armourstones or wooden pile foundations. These guide the fish into the entrance of the fish facility. Once the fish has found the entrance to the system, there is a high probability that it will be able to swim through it successfully. It is important that the maximum current speed is maintained [13].

4.2.2 Fish lift

Fish lifts are characterized by a movable lifting basket or container that enables the fish to be transported from the level of the underwater to the level of the upper water [14]. In this system, a luring current guides the upward-migrating fish into a cage. In order to overcome the height difference with the fish lift, the cage acts as a transport container for the fish and is pulled upwards with the help of a winch. The fish are then transported to the upper water. As soon as the difference in height has been overcome, the transport container opens and the fish are guided down a chute into the upper water. However, the descent of the fish requires additional equipment [15]. Another variant of the fish lift is the fish lift sluice. This has a structure consisting of floats, fixed connecting pieces

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and perforated plates. This arrangement enables the transport system to float up and down without additional external energy. This means that even large differences in height can be overcome without taking up too much space. During the transport phase of the fish over the height, it is not possible for them to enter the lifting basket or the container from below. Access to the fish lift can be via a slotted pass [14].

4.2.3 Fish ladder snail

The fish ladder screw conveyor is used to transport the fish effortlessly and without injury to the headwaters [16]. This type of fish migration aid differs between the monotube auger and the twin-tube auger. The monotube screw conveyor is a simple screw conveyor that is driven by an electric motor. The systems realized to date have diameters between 1,000 and 1,400 mm. The double-tube screw consists of two concentric, counter-rotating screws. The outer screw is used to move the inner fish ladder screw and also serves to generate energy. The diameter of the fish ladder screws manufactured to date is 1.2 m, while the diameter of the outer tube screw varies between 1.8 m and 2.4 m. With fish ladders, the water is generally transported upstream. For the fish that migrate upstream against the current, an internal guiding current is generated in the lower part of the fish ladder screw. This directs the fish into the screw conveyor so that they can be transported further from there [14]. The guiding current encourages fish and other aquatic creatures to swim into the slowly rotating fish ladder on their own [16].

4.2.4 Fish ladder

There are various types of near-natural fish ladders. These include riverbed ramps and slides, bypass channels and streams. Bottom ramps and glides are integrated directly into the course of the river and do not require any special adjustments to the adjacent bank area. This involves placing boulders about 1 meter in size on the bed substrate to create natural currents. Care is taken to create different current strengths to allow different species of fish to swim upstream. The bypass channel is an artificially created, stream-like river course. This form of fish ladder is very popular as it creates additional habitats and spawning grounds. Fish swimming upstream are guided to the bypass channel by an attracting current, which they can then pass through [12].

Table 1 summarizes the advantages and disadvantages of the fish migration aids described in Chapter four, based on the literature reviewed.

Tab. 1: Overview of the advantages and disadvantages of fish migration aids

Fish migration aids	**Advantages**	**Disadvantages**
Slotted pass	Suitable for upstream and downstream hikes [17], Suitable for confined spaces [12]	High quantities of water required [17]
Fish lift	Space-saving and height-independent [14]	Not suitable for a downhill hike [14]
Fish ladder snail	No susceptible risk of injury [16], Low energy consumption [16], Uniform conveying [16], No scaring effect on fish [16], Introducing the motive water at the inlet [14]	Additional energy required [14]
Fish ladder	Optics adapted to nature [12]	Costs depend on the size of the river [12]

5 Conclusion

In summary, the application of fish protection measures is essential. Studies have shown that the mortality rate of fish at hydropower plants is high and that these affect the fish population. Accordingly, this article describes two separate main measures to meet the requirements of the Water Resources Act and to address the question: *What measures can be taken for reducing fish mortality at hydropower plants?* This includes a fish-friendly turbine design, which aims to reduce fish mortality by reducing gaps, cavitation and turbulence [5] as well as various possible fish migration aids to overcome barriers. The paper argues for ongoing research, comprehensive strategies and a balanced approach to ensure both fish protection objectives at hydropower plants and the protection of the aquatic environment. However, it is up to the hydropower plant operator to decide which of these measures will be implemented.

6 Outlook

In order to continue to ensure fish protection at hydropower plants in the future, further investigations are required. The following approaches could be proposed as potential improvements:

- Further investigation of effectiveness and continuous improvement of new turbine designs
- Application of monitoring and control systems to reduce the interaction between fish and turbines
- Development of new fish protection measures to further reduce fish mortality

There is only a low risk of killing fish if there is adequate fish protection. Therefore, the aim of hydropower plants should be to improve the ecologically and energetically balanced solution.

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Impact of robotics on the operation and maintenance of offshore wind turbines

A review

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Abstract

This article analyses the impact of robotics on the operation and maintenance (O&M) of offshore wind turbines (OWTs), with a particular emphasis on the challenges and benefits. As the world's reliance on renewable energy, particularly offshore wind, increases to reduce climate change, the growing number of OWTs requires effective O&M. Challenges consist of logistics, accessibility and high costs. The paper presents the application of climbing robots, unmanned aerial vehicles and underwater robots to overcome these challenges.

The combination of multiple robotic platforms, such as autonomous surface vehicles and autonomous underwater vehicles, represents a collaborative approach to O&M. Obstacles include the need for accurate navigation, building trust between humans and robots, and research into artificial intelligence.

In conclusion, the integration of robotics in O&M presents considerable advantages, increasing efficiency, safety and cost-effectiveness. Further progress and research into artificial intelligence are crucial in achieving complete automation, which will transform the O&M of OWTs.

Keywords: offshore wind turbine, operation and maintenance, robotics, climbing robots, underwater robots, unmanned aerial vehicles, multi-robot platform, LCOE

1 Introduction

Renewable energies are being expanded worldwide to reduce CO_2 emissions and to counteract climate change. Offshore wind in particular has a significant impact on meeting these targets. One reason for this is that, in addition to the limited area available for the development of wind energy on land [1], a comparable system at sea requires less area [2]. Furthermore, installation sites located further from the coast offer an opportunity to harness stronger winds, allowing for higher and more consistent energy production. This also helps to mitigate conflicts of interest, such as social acceptance [3]. Meanwhile, the increasing number of turbines is having an unavoidable impact on the O&M of offshore wind parks. As a result, there has been an increase in the use of robots in the O&M of OWTs. The incorporation of robots presents both challenges and opportunities.

This article evaluates the effects of robotics on the O&M of OWTs. It focuses on the challenges and benefits of using robotic systems for the maintenance of OWTs. The paper also highlights the emerging trends in this field and presents practical application examples.

2 Methods

This chapter offers an overview of the methodology implemented in the creation of this review article. The objective is to present readers with a clear understanding of the methodological approach and to guarantee the transparency and reproducibility of the analyses performed.

Initially, the systematic literature search was carried out through the *Google Scholar* search engine, employing a range of keywords, including those listed previously. Next, a literature map was developed with assistance from the AI tool *Research Rabbit*. The method enabled a re-evaluation of sources and facilitated the discovery of new, pertinent literature. In addition, the writing assistant *Deepl Write* was used to improve text quality during writing.

The application of literature research and evaluation in conjunction with AI tools enabled a comprehensive approach to creating this review article. The use of supporting tools ensured the quality of sources and the development of a well-founded overview of the research field.

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3 Operation & Maintenance of offshore wind turbine

3.1 Current state

The O&M of OWTs is more and more dependent on logistics and transport due to the increasing distance from the mainland. Crew transfer vessels (B), as shown in figure 2, are the current means of transport. For maintenance work further offshore, service operation vessels are used as floating hubs. They provide accommodation for offshore technicians and store spare parts for OWTs. A service operation vessel can accommodate up to 88 technicians at sea for 4 weeks. Helicopters (D) can be used to supplement ships. They reduce transit time and improve access, but come at a higher cost [3, 4].

All vehicles carry divers (C) and rope-access technicians, who typically carry out inspection and repair work on the OWT. The technicians face difficult environmental conditions that may compromise safety. Furthermore, adverse weather conditions that hinder accessing the OWT elevate their downtime. This, together with logistics and transportation costs, is a significant contributor to O&M costs [5].

3.2 Importance of effective Operation & Maintenance

Early detection or prediction of damage is essential to reduce costs. This can prevent further damage that would necessitate replacement of system components. Failure to identify faults in a timely manner can result in extensive maintenance work and consequently increase the downtime of the OWT. This leads to a decrease in electricity generation and consequently an increase in the levelized cost of electricity (LCOE) (refer to figures 4 and 5 in [6]). In particular, due to the increasing output of recently installed turbines.

Therefore, the primary objective for every wind farm operator is to minimize their maintenance expenses while maximizing operational hours [7]. With an average annual failure rate of 8.3 per OWT and a growing number of turbines, these developments highlight the difficulties associated with the O&M of OWTs [1, 8].

3.3 Current Challenges

As previously stated, OWTs have an advantage over onshore turbines in terms of available area. However, onshore turbines have a decisive advantage in terms of LCOE, as shown in figure 1. These costs depend on several factors, such as the environmental conditions at sea, accessibility and O&M costs.

To meet these challenges, it is necessary to develop efficient and cost-effective O&M strategies, as described by Ren et al. [9] to ensure continuous operation of the OWT. This requires balancing factors such as capacity, timing, route planning or risk, among others, to ultimately achieve the maximum component life, maximum wind turbine operating hours, minimum repair and maintenance costs for the operator, and minimum downtime. Weather and environmental conditions due to wind and sea also influence this planning [9]. In the following chapters, the challenges of the O&M of OWTs are discussed and implemented in more detail.

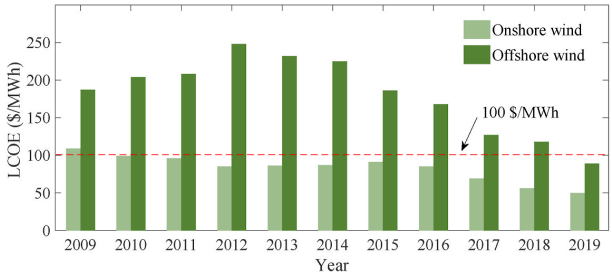

Fig. 1: Comparison of LCOE for onshore and OWTs between 2009 and 2019 [9]

3.3.1 Environmental conditions & Accessibility

One of the biggest challenges in operating and maintaining OWTs is the harsh environment at sea. This places a constant strain on the equipment, transport vehicles and technicians. For example, wave action and salt water affect the corrosion of the turbines. In addition, the high wind speeds are beneficial for higher power generation, but they also put continuous stress on the rotor blades. Both result in shorter lifetimes and an increasing number of inspections of turbine components and infrastructure. Carroll et al. [8] show that there is a strong correlation between increasing wind speed and increasing failure rate (see figure 10 in [8]). This alone leads to a 33% higher failure rate due to wind speed compared to onshore wind turbines.

Due to the prevailing environmental conditions, OWTs face a number of challenges. The high wind speeds and wave movement hinder the accessibility of these turbines by helicopters or transport vessels, necessitating the use of more expensive ships equipped with motion-compensating gangways. Furthermore, the transportation of equipment, components, and personnel has become increasingly challenging. When technicians are sent from shore to perform maintenance, the increasing distance of installed OWTs from shore results in longer repair times and smaller weather windows available for maintenance. Consequently, work must be rescheduled, thus increasing downtime and subsequently the LCOE [1, 9].

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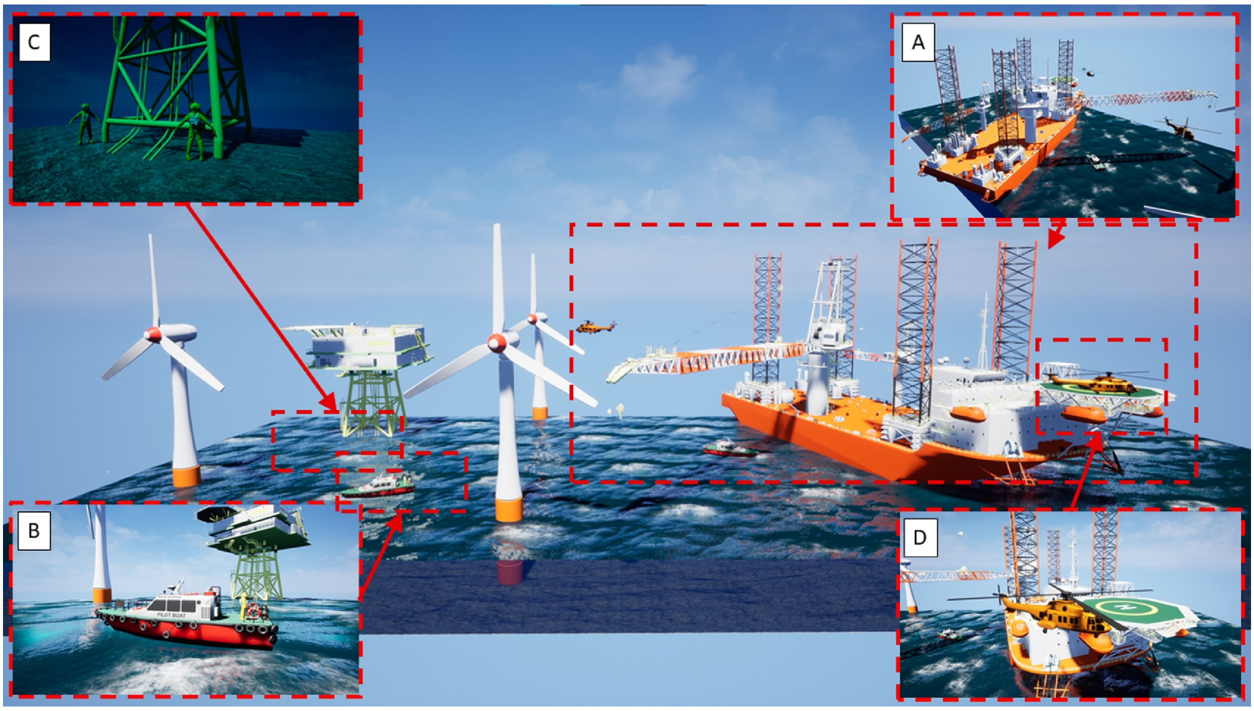

Fig. 2: Current assets and the supporting infrastructure within the lifecycle of an OWF array [4]

3.3.2 Operation & Maintenance costs

OWTs exhibit a higher failure rate under high wind speeds. This results in increased repair and maintenance costs. Although wind farm operators strive to mitigate this issue by selecting turbines with low failure rates and minimal maintenance needs [8], the expenses involved in the O&M of an OWT account for 30 to 35% of the total life cycle costs. For onshore wind turbines, these costs are lower, ranging from 25 to 30% of the life cycle costs [3]. In terms of total investment costs, the difference is considerably greater with OWTs accounting for 23% of the investment cost, compared to 5% for onshore turbines.

The offshore sector incurs average maintenance costs that are two to three times higher than those on the mainland. Mitchell et al. [4] argue that this is mainly due to shipping and logistics, which account for 60% of operating costs. They also note that accessibility, and therefore the transport of technicians to OWTs, accounts for 80% of O&M costs. As OWT installations increase, repair and maintenance work expands, and more transport and personnel capacity is required further driving up these costs [9].

As a result, OWTs have a noteworthy drawback in terms of O&M costs as compared to onshore turbines. This highlights the importance of implementing effective strategies. As a solution, robots can be employed to overcome this challenge, rather than relying on maritime technicians.

4 Robotics

Current trends in the industry indicate the continued development of new robotic technologies for OWT maintenance. This trend is underlined by the findings of Mitchell et al. [4], which show a sharp increase in the number of patents. The various technological and robotic advancements consequently offer differing advantages.

For structures above water, this work focuses on the two technologies, unmanned aerial vehicles (UAVs) and climbing robots, using the example of rotor blades. This is due to their high failure rates in OWT, as previously mentioned. Figure 3 in [8] illustrates that the failure rate of OWT blades per component ranks fifth. In terms of system component failures, the rotor blades rank second and third in average repair time and material costs respectively, at approximately 290 hours and 90,000€ (see Figures 13 and 14 in [8]). Regarding the average number of technicians required to repair a component, rotor blades top the list with over 20 technicians (see Figure 15 in [8]).

The failure of the blades is caused by the environmental conditions and forces. The rotor sheets are exposed to large loads due to strong winds, rain, snow, and ice, which in turn affects the aerodynamics [2]. In addition, the blades are mainly made of fibre-reinforced composite materials, which are relatively new materials for use in such environments. Although composite materials display no external damage when subjected to forces, they can still be damaged internally. These damages can lead to greater consequential damage over time. Regular checks are therefore essential [10].

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4.1 Climbing robots

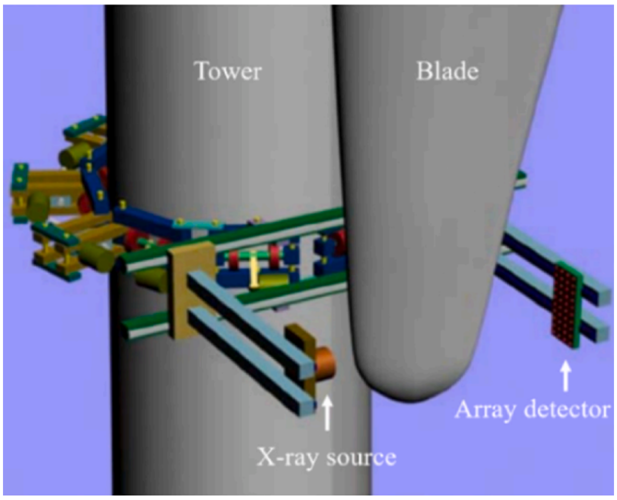

Fig. 3: Schematic illustration of a climbing robot for inspection of a OWT blade [2]

Nevertheless, carrying out the inspections poses a significant risk to the cable access technicians and is prohibited at wind speeds of 20m/s and above [9]. To overcome this, climbing robots can be used to inspect the rotor blades, allowing inspections to be carried out in harsh conditions. A modular climbing robot capable of spanning the entire tower is shown in figure 3. By doing so, a better distribution of forces and a higher payload can be achieved. Furthermore, the ring's diameter can be adapted to the tower using feathers while climbing. For rotor scanning, an arm equipped with measuring instruments can be installed on one side of the robot. Using two motors mounted on the modules, Sattar et al. [10] built a prototype that allows the robot to move horizontally, vertically and spirally on the tower of the OWT.

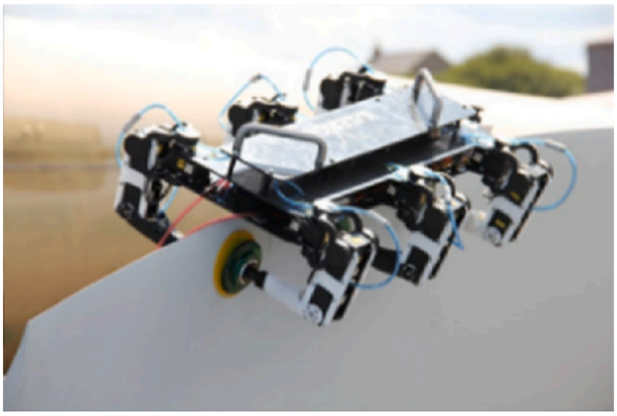

Fig. 4: friction-based climbing robot [2]

In addition to the increase in safety, the use of climbing robots makes it possible to work directly on the blade. Unlike UAVs, which need to keep a safe distance from OWTs, robots provide a more stable scanning platform, leading to more accurate data and precise results in identifying damages. In relation to O&M costs, a climbing robot, as shown in figure 4, has the potential to lower them by approximately 30% [2].

4.2 Unmanned aerial vehicles

UAVs can inspect various components of the OWTs with greater efficiency. Thus, the disadvantage of UAVs having to maintain a safe distance from OWTs is offset by their flexibility as an advantage. However, adverse weather conditions like wind or rain may pose operational challenges. In addition, lower payloads and inefficient flight times are caused by limited battery capacity. In summary, while UAVs have a lower payload and need to maintain a safety distance, they offer greater efficiency and flexibility [2].

Table 1 indicates that the inspection costs can be reduced by approximately 90% when an inspection with drones is compared to an inspection by technicians at the same OWT. This is due to the considerably reduced inspection time. An OWT inspection takes a technician 7 hours, but a UAV within the visual line of sight (VLOS) can reduce this time to 15-30 minutes. With full automation and no human intervention, the UAV can complete the inspection in just over 6 minutes. To do this, path points are created around an OWT, as shown in Figure 7 in [6] or Figure 3 in [2]. These are then flown off from the UAV. As noted by Poleo et al. [6], there is currently no definitive information or study on the lifetime of these systems in offshore operating conditions. It is believed that drones have a lifetime of 4,000 flight hours.

Overall, the faster inspection time can lead to significant cost reduction while enhancing safety by eliminating the need for height work [6]. If the UAV is not operational, another one can maintain the system by overlapping usage areas [4].

4.3 Underwater robots

For structures below the water surface, underwater robots are presented in this section. Their applications include the creation of 3D models and the performance of inspections and maintenance for foundations or mooring systems. The robots are able to hold their position in water currents of up to 1.5m/s or follow road points like UAVs [2].

Mooring lines for connecting the floating foundations of OWT to the seabed require regular maintenance. However, a detailed inspection of the mooring lines only takes place every five years on the surface [3]. If any damage to an mooring line is detected, and a replacement is required, the costs can vary from £0.6 million to £1.2 million [4]. As the number of turbines connected by multiple mooring lines continues to increase, maintenance demands will also rise

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Tab. 1: Comparison of Directly incurred (DI) cost of inspecting 139 individual wind turbines once a year: OPEX and revenue lost for technicians and UAVs based VLOS case according to Poleo et al. [6]

Item	Technicians		UAVs	
	DI Cost per time unit	Time-units required	DI Cost per time unit	Time-units required
Workforce (Technicians)	£18/h	139*3*7 [a]	£18/h	18*2*7 [f]
Workforce (boat)	£18/h	139*7 [b]	£18/h	18*7 [g]
Transport (boat)	£600/day	139 [c]	£600/day	18
Consumables	£1500/year	4 [d]	£5.35/h	18*7 [g]
Onshore Admin	£20/day	139 [c]	-	-
Revenue lost (worst case)	£237/h	139*7 [e]	£237/h	139*0.5 [h]
Training	-	-	£1500/year	1
Insurance	-	-	£1500/year	1
Civil Aviation Regulation Fees	-	-	£750/year	1
Total	Up to £392 k per year		Up to £39 k per year	

On 8th December 2023, the exchange rate between the British pound and the Euro was 1£ = 1.17€.
[a] Based on 3 technicians, inspecting 139 turbines and assuming each turbine takes 7 h to inspect.
[b] Based on utilising 7 h a day for 139 days.
[c] 1 day per turbine.
[d] 1 per person involved (3 wind turbine technicians and 1 boat operator).
[e] Based on shutting down the turbine.
[f] Based on 2 UAV operators being able to survey a 139 turbine farm in 18 days (8 turbines per day).
[g] 18 days for 7 h each.
[h] Assumes turbine needs to be shut down for 30 min for inspection.

correspondingly. Hence, there is a necessity for autonomous systems in this field of maintenance that can conduct maintenance activities more safely, deeper, less expensively and more efficiently than divers.

An example of an underwater robot that can perform underwater inspections, maintenance and repairs is the *Eelume*, shown in figure 5. Its flexible body is equipped with batteries, lights, sonar, cameras, sensors and positioning systems, and it can remain underwater permanently either autonomously or under the control of an operator [1]. Integration into the wind farm can be achieved by using underwater garages, which function as both storage and charging points for the robots. Maintaining the robots presents a challenge due to the environmental conditions. Moreover, these conditions might affect the photos or videos captured by the robots [2].

Fig. 5: The Eelume underwater robot was developed by NTNU and Equinor [1]

4.4 Multi-robot platform

An important emphasis in the integration of robots is the development of collaborative robots that form a complete system and can autonomously perform inspection, maintenance and repair tasks on OWTs. Research conducted by Khalid et al. [3] describes how an autonomous surface vehicles (ASVs) is capable of transporting and launching an autonomous underwater vehicle (AUV) as a part of an extensive system. During the inspection, the AUV can stream the recorded video to the ASV. The two devices can also communicate with each other via data exchange, thereby enabling recovery. A comparable system is shown in figure 6.

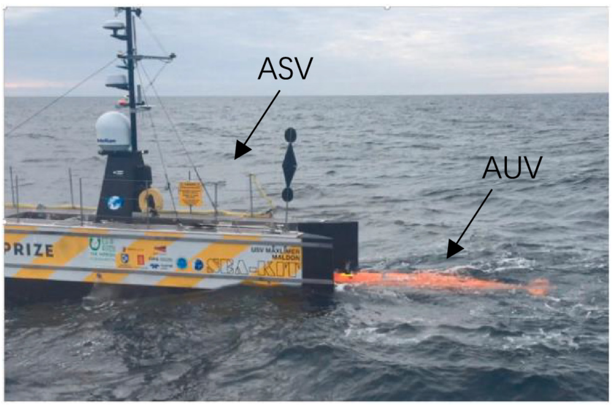

Fig. 6: Sea-kit Maxlimer ASVs recovering the HUGIN AUV [3]

Bernardini et al. [5] describe a similar system in which the ASVs brings a unit of UAVs and climbing robots, as shown in figure 4, to the OWTs. Both robot types then inspect the turbines, where the UAVs can be used as both inspection and transport units for the climbing robots, see figure 3 in [5]. To do so, the challenge is to land safely on the rotor blade without causing damage, and to recover the climbing robot safely.

5 Future challenges in the implementation of robotics

Besides the challenges in the interaction of multiple robots, trust between human and machine is probably the biggest challenge. When autonomous robots operate in the sea and act beyond the VLOS, there can be problems with the understandability of the robot's behaviour. This problem may be exacerbated by further or full automation of OWT O&M, as human operators increasingly rely on robotic data for decision making [5].

Another challenge, for example, is the introduction of more precise navigation systems that will enable UAVs to get closer to OWTs and thus carry out more accurate and safer inspections. Additionally, there is an effort ongoing to optimise the payload and battery capacity of UAVs to extend their operational time beyond the current 30-minute limit [2].

6 Conclusion

The development and implementation of robots to assist in the O&M of OWTs is increasing. This is due to the ability to enhance efficiency, productivity and safety when compared to the current maintenance process. The comparison of technicians and UAVs has indicated that the costs of inspection alone can be reduced by up to 90%. Since O&M costs account for approximately one-third of the total life-cycle costs of an OWT, significant savings can be achieved.

Furthermore, the significant reduction in inspection time per turbine from 7 hours to up to 6 minutes means that the number of inspections can be increased. Moreover, the robots have been designed with enhanced weather resistance, which can help to minimise turbine downtime and ultimately lower the LCOE. Overall, it is becoming apparent that the incorporation of robots in the O&M of OWT offers numerous benefits.

7 Outlook

However, much further development and practical effort is needed to fully automate O&M. It is worth exploring the potential application of artificial intelligence, which was not analyzed in this article. The increasing number of OWTs also requires more robots, which collect a large amount of data. The analysis of these data could be more accurate and faster with the use of artificial intelligence.

All of the factors described above will lead to robots and artificial intelligence replacing the current workforce. One possible initial step is the remote control of robots by human operators within the VLOS. Subsequently, remote control can be extended beyond the VLOS. Both steps build trust in the technology. This shift in workplace dynamics has the potential to significantly restructure roles and responsibilities, necessitating that employees acquire additional skills for efficient collaboration with the robots. Consequently, the ways in which OWTs are managed will change significantly in the future.

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Effects of Noise Emissions from Offshore Wind Turbines on the Marine Environment

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Abstract

The pursuit of Offshore Wind Energy (OWE), integral to the German government's ambitious renewable energy goals raises concerns about the environmental impact of noise emissions on marine life. This paper delves into the theoretical background of Offshore Wind Turbine (OWT) noise, exploring its various phases from the survey to decommission. It examines the types and causes of noise emissions, their effects on marine wildlife and potential mitigation measures. Highlighting the regulatory framework in Germany, the paper emphasises the need for nuanced approaches to balance renewable energy objectives with marine ecosystem preservation.

Keywords: Offshore Wind Turbines, Noise Emissions, Marine Wildlife, Environmental Regulations, Mitigation Measures

1 Introduction

The German government has taken significant steps in promoting OWE as a crucial component of the global energy transition. Enacted through the OWE Act, the government aims to achieve a minimum installed capacity of 30 gigawatts by 2030, almost twice as much as the current capacity and 70 gigawatts by 2045 [1]. The pursuit of OWE presents a viable path for sustainable power, but it raises environmental concerns, particularly regarding noise from Offshore Wind Farm (OWF) activities. Such begs the question: *What impact do noise emissions from Offshore Wind Turbines have on marine wildlife?* This paper explores the theoretical background of OWT noise and its impact on marine wildlife. It examines various phases from survey to decommission and delve into types and causes of noise emissions, their effects on wildlife and potential mitigation measures. Achieving a harmonious coexistence between renewable energy objectives and marine ecosystem preservation demands a nuanced understanding and proactive solutions.

2 Theoretical Background

2.1 Significance of the Topic

OWF activities, along with other sources of underwater noise, can harm marine wildlife by affecting their physiology and behaviour. The impact depends on factors like intensity, frequency, distance and duration of the noise, as well as the animals' hearing ability, distribution and habitat use [2]. Marine species heavily rely on sound as their primary sense for communication, navigation and survival [3]. Human-generated noise often overlaps with natural ocean sounds, posing a challenge for marine wildlife (cf. Fig. 1) [3].

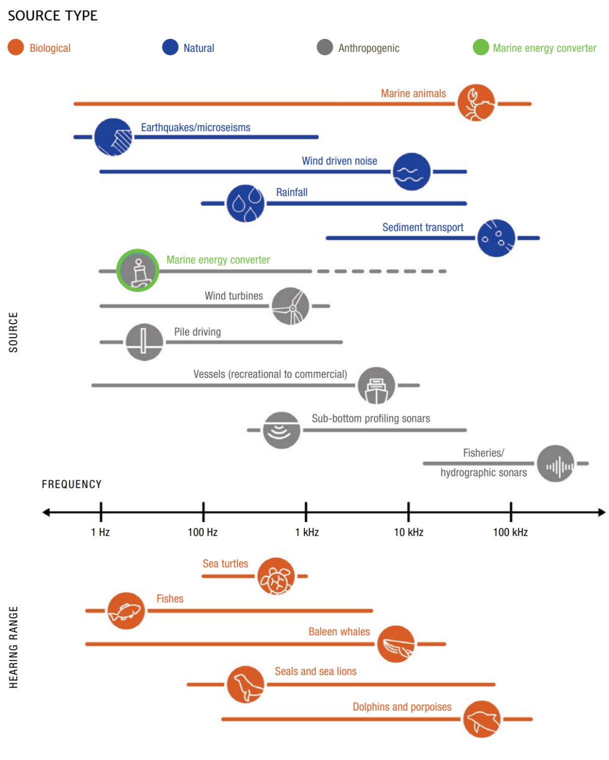

Fig. 1: An overview of biological, natural physical and anthropogenic noises in marine environments and the hearing ranges of marine animals [4], adapted from [3]

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2.2 Acoustic Background

Sound travels at 1,500 m/s in the sea, five times faster than in the air [5]. Acoustic signals consist of sound pressure and particle movement [5]. Sound pressure, measured in Pascals (Pa) or micro Pascals (μPa), is a scalar quantity [5]. A distinction must be made between different parameters. The Sound Pressure Level (SPL) (in dB re 1 μPa) measures the sound pressure at a specific point and time [6]. The Sound Exposure Level (SEL) (in dB re 1 $\mu\mathrm{Pa}^{2} \cdot \mathrm{s}$) represents the cumulative exposure to sound over a specified period [6]. Additionally, the Peak Sound Pressure Level (LPeak) (in dB re 1 μPa) indicates the maximum sound pressure reached during an event, irrespective of its duration [6].

2.3 Environmental Regulations of Noise Emissions from Offshore Wind Turbines

The noise protection standard for impact sound in Federal Maritime and Hydrographic Agency (BSH) approval documents, determined since 2008, is specified as a dual criterion. Within a 750 m radius from the pile-driving location, the following thresholds must not be surpassed [2, 7]:

- Sound Exposure Level (SEL)[1] of 160 dB re 1 $\mu\mathrm{Pa}^2\mathrm{s}$
- Peak level (LPeak)[2] of 190 dB re 1 μPa

Since 2011 it has been compulsory to implement noise abatement systems to meet the specified noise mitigation values in the German Exclusive Economic Zone of the North and Baltic Seas, because without proper measures, the measured values at a distance of 750 m from the source would be up to 183 dB re 1 $\mu\mathrm{Pa}^{2} \cdot \mathrm{s}$ (SEL) and 205 dB re 1 μPa (LPeak). [6]

The third OWE Ordinance, in addition to previously stated requirements, mandates specific measures in section seven to mitigate noise emissions during the foundation, installation and operation of OWTs. The ordinance requires noiseless work methods during facility foundation and installation. This involves following the state of the art and considering the prevailing circumstances. Additionally, the ordinance emphasises the imperative for deterrent measures against marine animals. Furthermore, it obligates project proponents to choose construction methods that are operationally soundproof according to contemporary standards, explicitly prohibiting detonations. Also, each foundation type, like Monopiles or Jackets, has a designated maximum ramming duration (Monopiles: 180 min, Jackets: 140 min). Section eight emphasises compliance with the 'Concept for the Protection of Harbour Porpoises from Sound Exposures during the Construction of Offshore Wind Farms in the German North Sea' (2013). This requires project proponents to coordinate piling activities with concurrent OWF developments in the North Sea's exclusive economic zone. All of these requirements serve to ensure compliance with the prohibition of killing and injuring species and the prohibition of disturbance under the German Federal Nature Conservation Act (Section 44(1)(1) and (2)). [7]

In the United States and the United Kingdom, similar guidelines are followed, drawing from technical recommendations provided by the National Oceanic and Atmospheric Administration [8] and Southall et al. (2019) [9]. These guidelines incorporate frequency-weighted parameters tailored to different species [6].

[1] Sound Exposure Level in dB re 1 $\mu\mathrm{Pa}^2$ s; dB = Decibel; re = in reference to; 1 μPa = 1 Micro Pascal; 1 $\mu\mathrm{Pa}^2$ s = 1 Micro Pascal squared * second; the reference level for water is 1 μPa.

[2] Peak Sound Pressure Level in dB re 1 μPa; dB = Decibel; re = in reference to; 1 μPa = 1 Micro Pascal; 1 $\mu\mathrm{Pa}^2$ s = 1 Micro Pascal squared * second; the reference level for water is 1 μPa.

3 Noise Emissions of Offshore Wind Turbines

In the case of OWTs and their noise emissions, various phases of the wind turbine project need to be considered. This includes site surveys, the construction phase, the operational phase and the decommissioning phase (cf. Fig. 2). [10]

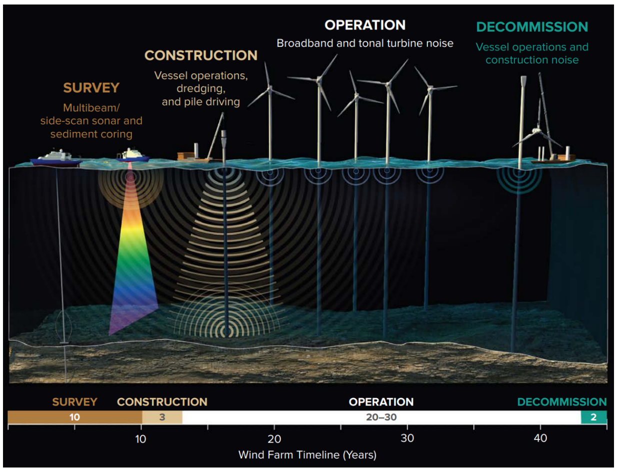

Fig. 2: Acoustic life of an Offshore Wind Farm area, including during site surveys, construction, operation and decommissioning [5]

3.1 Survey Phase

3.1.1 Types and Causes of Noise Emissions

The survey phase involves geophysical profiling with multibeam and side-scan sonar, mapping the seabed.

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Special sensors, cameras, sampling and seismic systems can be used to characterise the benthos (depth, morphology, sediment, geology and biology). Examples for seismic systems are echosounders and sparkers. Echosounders have depth limitations (< 2–20 m) and a 240-250 dB re 1 μPa source level, offering a 2-22 kHz frequency range and 5-15 cm vertical resolution. For deeper grounds (100 m to 1 km), sparkers with 222 dB re 1 μPa source level are used (40 Hz to 1.5 kHz, 20 cm to 10 m vertical resolution). It should be noted that seismic airguns are rarely used in the survey phase of OWTs, which is why they are not discussed any further. [5]

3.1.2 Effects on the Marine Wildlife

While active acoustic benthic surveys are common, the impact of echosounders and related technologies on marine wildlife remains insufficiently explored. Sonar systems, operating at frequencies often undetectable by aquatic organisms, have limited effects [11, 12]. Extensive research on mid-frequency active (MFA) sonar in the 1-7 kHz range has been conducted, yet echosounders and chirp sonars lack comprehensive studies [5]. Clupeids exhibit sensitivity to mid-frequency sonar, but MFA sonar experiments on adult herring reveal no significant behavioural responses [13]. Limited MFA sonar studies suggest marginal effects on fish hearing, with no observed impacts on rainbow trout and minimal, inconsistent shifts in auditory thresholds for channel catfish [12]. One study acknowledges potential hearing loss induced by low-frequency sonar at high SPLs (193 dB re 1 μPa) [11]. Its impacts on invertebrates remain unexplored [14]. Ship noise (130-200 dB re 1 μPa [15]) during site surveys, despite its intermittent nature, can mask communication signals of haddock, cod and other taxa, inducing physiological stress, impairing foraging and predator responses in fish and invertebrates [16]. The intermittent nature of vessel noise is a key factor in elevating stress-related responses [17]. While harmful effects on marine mammals are unlikely, their exposure to noise levels above the background could induce behavioural changes in sensitive species (cf. Fig. 3) [15, 18].

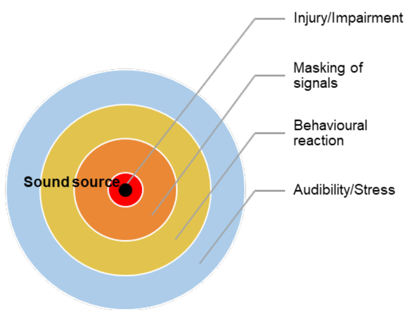

Fig. 3: The different effects of noise on marine mammals, adapted from [19, 20]

3.2 Construction Phase

3.2.1 Types and Causes of Noise Emissions

OWTs can be categorised based on foundation types (cf. Fig. 4), which is crucial for determining installation methods [21].

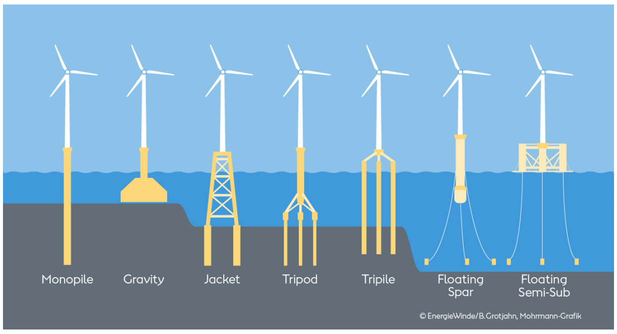

Fig. 4: Different types of foundations of Offshore Wind Turbines [22]

The selection of foundation types, such as Monopiles and Tripod systems, depends on site conditions. Monopile foundations, characterised by a single steel tube, emerge as the most frequently employed and cost-effective solution for OWTs (cf. Fig. 5). For larger turbines positioned farther offshore, there is a growing preference for Jacket and Tripod systems. [5]

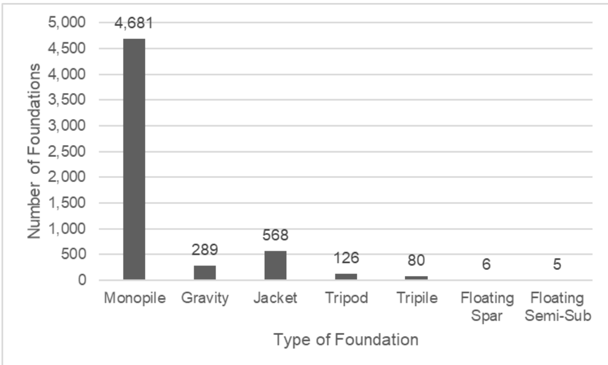

Fig. 5: All foundations installed with and without grid connection by the end of 2020 in Europe, adapted from [23]

The construction phase of OWFs typically spans one to three years and raises ecological concerns, primarily due to the substantial noise generated during the installation of foundations using impact or vibrational hammers [5, 24]. During the foundation installation LPeaks result at 220 dB re 1 μPa at 10 m and 200 dB re 1 μPa at 300 m from (0.75 m and 5 m diameter) piles [25]. The primary energy is concentrated below 500 Hz, extending beyond 1 kHz [5]. This aligns with the auditory bandwidth of marine species, potentially impacting underwater ecosystems (cf. Fig. 6) [5].

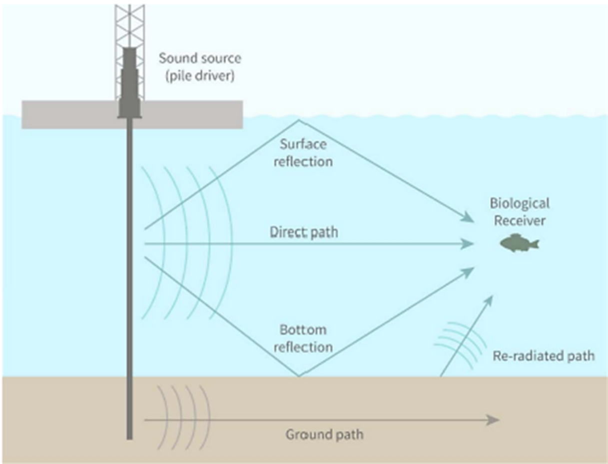

Fig. 6: Sound propagation paths associated with pile-driving [26], adapted from [27]

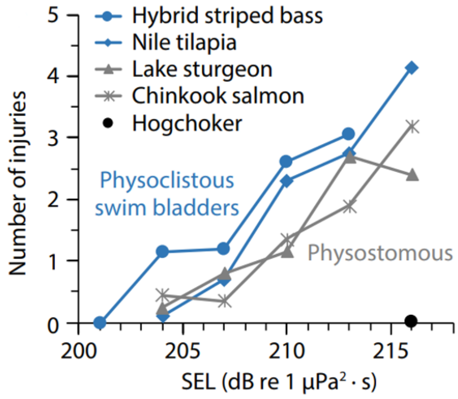

Fig. 7: Barotrauma effects on marine species exposed to pile-driving noise [5], adapted from [29, 30]

Additionally, a pile-driving operation can take 157 min required 7,000 blows of the hammer. Predicting effects is challenging due to the dynamic nature of acoustic pulses during propagation. LPeaks at 205 dB re 1 μPa at 100 m, yet signals remain detectable up to 70 km. Close to the source (1 km), the initial waveform peak lasts 10 ms, but at 40 km, durations extend to 200 ms, indicating a less impulsive nature of signals at greater distances. This complexity is amplified by additional noise sources like vessel movements, trenching, dredging, drilling and scour protection laying within 1 km of the turbine site. [28]

3.2.2 Effects on the Marine Wildlife

Numerous studies have investigated construction noise, notably pile-driving, in aquatic ecosystems. Results, spanning various methods and species, reveal a spectrum of effects from severe physical injury to minimal impact. For instance, hybrid striped bass experienced multiple injury types when exposed to simulated pile-driving signals, with injury numbers and severity increasing with fish size (cf. Fig. 7) [29]. In Lake sturgeon and Nile tilapia, injuries occurred at lower SELs (204 dB re 1 μPa$^2 \cdot$ s), intensifying at higher levels (216 dB re 1 μPa$^2 \cdot$ s) [30]. Comparative studies highlight greater vulnerability in fish with physoclistous swim bladders (closed structures not connected with digestive tract) compared to physostomous swim bladders (open structures connected with digestive tract) [29, 30]. European seabass displayed physiological and behavioural effects, including disrupted schooling structures and increased swimming speeds at 154 dB re 1 μPa$^2 \cdot$ s [31]. Also, they demonstrate heightened swimming speeds and depths, decreased inter-fish distances, increased startle responses and a tendency to move away from the sound source at exposure levels ranging from 200 Hz to 1 kHz and a mean SPL of 180–192 dB re 1 μPa [32]. Certain fish species, like sheepshead and flatfish, minimally respond to noise from activities such as pile-driving [33, 34]. Limited research on invertebrates highlights potential negative effects on species like hermit crabs and blue mussels due to simulated pile-driving and sediment vibrations [35, 36].

Marine mammals face potential hearing loss, for cetaceans at 5 m and pinnipeds at 20 m and temporary at 10 m respectively 40 m within the pile-driving operation [28]. If noise levels at 100 m are below safe limits (166 dB re 1 μPa$^2 \cdot$ s), there is no indicating damage beyond this distance for these types [28]. Harbour porpoises may experience behavioural disturbances up to 70 km, with strong avoidance reactions up to 20 km [28]. Pinnipeds are affected within a 14 km zone [28]. Bottlenose dolphins and minke whales may show disturbances at 50 and 40 km, respectively [28]. Acoustic deterrent devices and gentle approaches can cause a significant directional movement away from the sound source before pile-driving [37].

3.3 Operation Phase

3.3.1 Types and Causes of Noise Emissions

The underwater sound generated during the operation of an OWE system mainly comes from rotating machine parts like rotor blades, gearbox and generator (cf. Fig. 8) [38]. These components cause vibrations in the nacelle and tower structure, propagating beneath the waterline and emitting underwater sound [38]. The SPLs can range from 111 to 123 dB re 1 μPa (< 1 kHz) at 100 m, contingent on wind and rotation speed [39]. These sounds, inclusive of those from ships and transformers, can extend over several kilometers [5]. Turbine size influences the noise and different foundation types may have varied acoustic impacts [5]. With a lifespan of 20-30 years [5], the emissions persist at least for a long time and pose challenges for marine animals. Current noise mitigation methods may be unsuitable due to prolonged operational times and relatively low noise levels [5].

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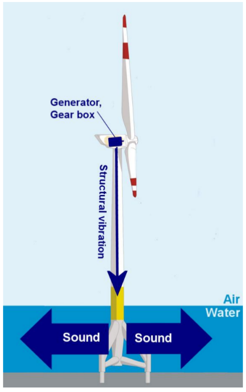

Fig. 8: Schematic representation of the entry of machine noise into the water [38]

3.3.2 Effects on the Marine Wildlife

Operational noise from OWFs has varying effects on fish. While direct physical injury is unlikely due to moderate noise levels, long-duration exposure may induce temporary threshold shifts, affecting fish communication, foraging and predator detection [5]. Studies in Sweden indicate a negative correlation between fish abundance and local noise levels, with reduced catches at higher noise levels [40]. Behavioural responses differ; some fish show increased catchability near turbines when not operating, while others, like tagged cod in a Belgian OWF, exhibit no change [41]. Studies dismiss the possibility of killing or injuring marine mammals due to temporary or permanent threshold shifts (TTS and PTS) [9]. Other studies affirm these findings with minimal impacts like reacting to avoidance or disruptive effects [42]. Also new gearless OWTs generate lower-frequency tones with reduced amplitudes compared to geared OWTs [38]. This decreases for instance the likelihood of detection by porpoises (cf. Fig. 9) [38]. OWTs may have a more notable impact in regions with minimal background noise and limited ship activity [39].

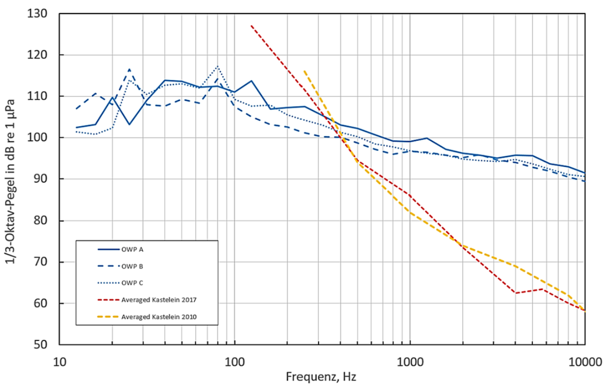

Fig. 9: Harbour porpoise hearing thresholds vs. operational noise at 100 m from three turbines (OWP = OWT) [38], created from [43, 44]

3.4 Decommission Phase

3.4.1 Types and Causes of Noise Emissions

Decommissioning involves the removal of turbines, foundations, cables and other structures, which can have a significant impact. One of the few studies found that the SPL, when cutting a steel pylon during OWF decommissioning, can be high (198.7-199.8 dB re 1 μPa) at a 10-50 m distance. The predominant portion of this sound energy fell within the frequency range of 250 Hz to 1 kHz. [45]

3.4.2 Effects on the Marine Wildlife

Research on the impact of OWF decommissioning on marine wildlife is limited as decommissioning is still in its early stages. The effects on marine wildlife are difficult to predict, but there is the potential for disturbance such as masking, displacement, physiological stress and other factors, particularly in habitats around OWF piles or foundations while decommissioning. [5]

4 Measures to Minimise Noise Emissions

Recognising the significance of environmental sounds and minimising human-made noise impacts is crucial for the economy, national security and maintaining a balance with the ocean's essential role [3].

In general, noise mitigation involves two main categories: primary measures (Noise Mitigation Systems) aim to reduce impulsive noise during foundation structure installation through source strength reduction or alternative, low-noise methods. Secondary measures (Noise Abatement Systems) focus on minimising impulsive pile-driving noise in water. Experience from 21 offshore wind projects shows that three effective secondary noise abatement systems are in use: Noise Mitigation Screen (IHC-NMS), Hydro Sound Damper (HSD) and Big Bubble Curtain (BBC and Double BBC), which have successfully reduced noise levels by approximately 17 dB re 1 μPa in water depth 25-40 m. The combination of near-pile and far-pile protection systems enables a reduction of $\geq$ 20 dB re 1 μPa up to a depth of 40 m. Technical requirements and site-specific adaptations are important. The spectral sound reduction varies depending on the system and frequency range. A sound-optimised pile-driving process can achieve additional reductions. [6]

Koschinski and Lüdemann (2011, 2013, 2020) overview sound protection and alternative foundations, highlighting innovations like AdBm and Blue-Piling for reduced noise and environmental impact. Suction Bucket, Floating Foundation and ongoing research on Vibro-Piling are discussed. [46–48]

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5 Knowledge Gaps and Research Needs

- Survey Technologies: Impacts of current-use seismic sources on marine wildlife
- Alternative Foundations: Research technologies to reduce noise and environmental impact
- Long-term Noise Effects: Study continuous operational noise on marine wildlife
- Operational Noise Effects: On early developmental stages in various species
- Decommissioning Impact: Evaluate OWF decommissioning, particularly noise
- Decommissioning Practices: Evaluate adherence to environmental regulations

6 Conclusion

In conclusion, while the German government's push for OWE signifies a positive step in the global transition to sustainable power, the question arises: *What impact do noise emissions from Offshore Wind Turbines have on marine wildlife?* This paper has illuminated environmental concerns related to noise emissions from OWTs. The examination of various project phases reveals complex issues impacting marine wildlife, necessitating robust environmental regulations. Existing German standards are discussed, emphasising the importance of nuanced approaches and mitigation efforts such as bubble curtains. Despite progress, challenges persist, particularly in understanding the decommission phase impacts on marine mammals, fish and invertebrates. The paper calls for ongoing research, comprehensive strategies and a balanced approach to ensure the coexistence of renewable energy goals and marine ecosystem preservation. Future advancements and collaborative efforts will be crucial for refining mitigation measures and addressing knowledge gaps in this evolving sector.

7 Outlook

As the OWE sector continues to expand globally, proactive research and collaborative efforts are crucial to refine noise mitigation measures and address knowledge gaps. Ongoing technological advancements will play a pivotal role in minimising the impact of noise emissions on marine ecosystems. A balanced approach that harmonises renewable energy development with environmental conservation is essential. The call for continued research underscores the commitment to achieving sustainable coexistence between offshore wind energy objectives and the preservation of marine wildlife.

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State of the art: Corrosion protection for offshore wind turbines

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Abstract

This review paper provides an initial overview of the state of the art of common corrosion protection methods for offshore wind turbines. The functions of the individual corrosion protection methods and their interaction are explained. In addition, the specific corrosion protection of different zones and components of an offshore wind turbine will be discussed. Finally, some information is given on current and possible future developments in this subject area.

Keywords: corrosion protection, offshore wind turbines

1 Introduction

In recent decades, the use of offshore wind turbines to generate electricity has significantly increased as they present a sustainable and environmentally friendly energy source. A major expansion of renewable energy is required in all sectors to meet the German government's ambitious target of making German electricity generation 80 % climate-neutral by 2030 and completely climate-neutral by 2045. In the first half of 2023, renewable energy sources only provided around 52 % of the electricity consumed in Germany [1]. Offshore wind can therefore represent an important component for climate-neutral electricity generation in the coming years. Offshore installations are exposed to extreme environmental conditions such as salt water, wind and waves, which leads to an increased risk of corrosion. Corrosion can not only significantly shorten the service life of the turbines, but also lead to significant economic losses. As a rule, these structures are designed to last more than 25 years. It is therefore of great importance to develop and apply effective corrosion protection measures to ensure the long-term performance and reliability of these systems.

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2 Corrosion mechanisms at sea

The environmental conditions at sea demand much greater resistance and durability from wind turbines. The turbines are exposed to various, sometimes extreme stresses at sea:

- Extreme weather conditions
- Mechanical stresses
- Biological stresses

Extreme weather conditions at sea are characterised by wind, waves, extreme temperatures, UV exposure and especially increased exposure to salty seawater [2, 3]. Compared to drinking water, seawater can be characterised as corrosive due to its salt content. Corrosion effects increase with rising salt content [4].

Offshore wind turbines are exposed to additional mechanical stresses due to currents and waves, floating objects, the landing of boats and the installation of the structure [2, 5].

Furthermore, marine growth, e.g. by mussels, barnacles or algae, can have an additional influence on the chemical conditions of the metal surface of the structure and negatively affect the corrosion behaviour [2, 5].

When considering corrosion-promoting stresses at sea, it is therefore a complex combination of different influencing factors. Careful analysis of all factors and their interaction is necessary to ensure sustainable utilisation of the systems over a long life cycle. Due to their high susceptibility to corrosion, offshore structures are categorised in the most critical category CX "extreme corrosiveness" [6].

Corrosion and fatigue are the main causes of the primary loss of strength of steel in offshore wind turbines [3]. Corrosion can reduce the thickness of steel components and thus increase the risk of fatigue cracking and buckling. Information on corrosion appearances and failures on offshore wind turbines is generally rare, as systematic analyses were or are often not part of the maintenance and repair activities and information on damage is kept secret for intellectual property reasons [5].

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Plagemann and Momber [5] provide an overview of the causes of corrosion in the first years of operation of a plant:

- Mechanical damage (30 %)
- Wrong design (30 %)
- Insufficient coating (24 %)
- Welding (11 %)
- Environment (5 %)

The causes of corrosion can often be traced back to defects or damage to the protective coatings during the installation of the plant or the manufacture of the components [2, 3, 5]. Flange connections, in particular, can be critical structural parts due to corrosion in gaps (crevice corrosion) resulting from moisture and inadequate coating adhesion during installation [2, 7]. For corrosion protection reasons, welded connections are generally preferable to flanged connections.

Wind turbines at sea are usually categorised into different zones, which are exposed to different conditions, show varying degrees of corrosion and therefore require different corrosion protection. Figure 1, based on [5], provides an overview.

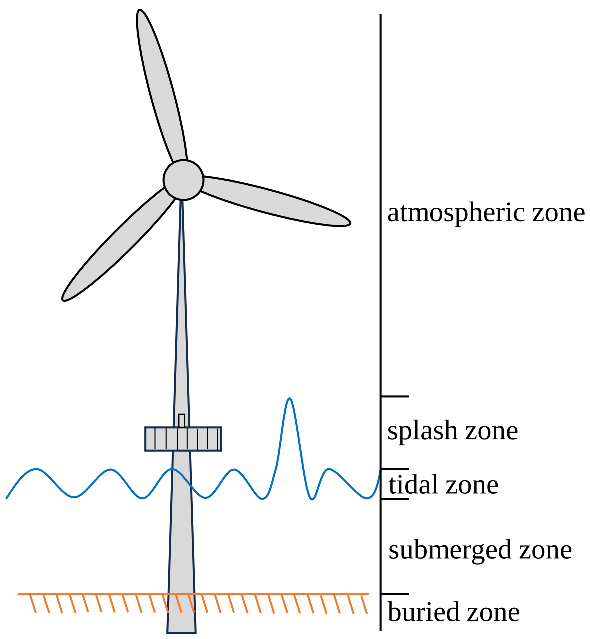

Fig. 1: Stresszones offshore wind turbines

Different corrosion rates are assumed for each zone. According to DIN EN ISO 12944 [6], the maximum corrosion rate for heavily loaded components is 0.7 mm/a, whereas Momber et al. [2, 3] report maximum corrosion rates of up to 2.5 mm/a under extreme conditions. Components located in the tidal and splash zones experience the highest levels of stress because they are subject to alternating wet/dry cycles and the surface is often permanently covered with a thin film of moisture through which oxygen can easily diffuse to the metal surface, allowing corrosion to progress most rapidly. The rate of corrosion is reduced underwater (submerged zone) because oxygen can hardly reach the metal surface. The impact of marine growth has not been clearly investigated in the literature, although it is known that microbiologically induced corrosion (MIC) can lead to serious and rapid corrosion failures [2, 3, 5]. In addition, the corrosion rate is lower when in the atmospheric zone, where salt has a reduced influence, and infrequent wet/dry cycles occur.

3 Corrosion protection

Corrosion protection at sea is not a fundamentally new issue that has come up with the construction of wind turbines at sea. The majority of measures to protect against maritime corrosion originate from shipping, harbours, and oil and gas extraction at sea [2–4]. Nevertheless, offshore wind turbines differ from oil and gas extraction in that they mostly remain unmanned structures with very limited access. On oil and gas platforms, corrosion protection systems are usually subject to permanent inspections, which is often not the case with offshore wind energy. Therefore, reliable corrosion protection is all the more important to guarantee a long, reliable service life. To achieve this, several guidelines and standards provide reliable guidance, such as [8–12].

It is generally split into active and passive corrosion protection. However, it is important to note that corrosion allowance, a corrosion-friendly design, as well as maintenance and inspection also have important roles to play.

3.1 Passive corrosion protection

Passive corrosion protection describes the application of a barrier layer to prevent the material from coming into contact with the corrosive environment. This creates an artificial barrier on the material surface and represents the most used form of corrosion protection on offshore structures [3].

The most important criteria when choosing a coating system are [3]:

- Type of building
- Importance of the structure
- Environmental condition
- Required durability
- Performance

- Costs
- Surface preparation
- Application

Several layers of coating with different properties can be applied to structures. The compatibility and adhesion between individual layers is of great importance. These layers can be metallic, non-metallic or a combination of both [2, 3]. Metallic layers protect the structure through galvanic protection and by acting as a barrier layer. As a rule, non-ferrous metals such as

- Aluminium
- Zinc
- Alloys of both metals

can be used because they are more corrosion-resistant than ferrous metals. Non-metallic coatings are mainly organic based. Developments are focused on [2, 3]:

- Antifouling coatings
- Composite materials
- Nanocoatings
- Self-healing coatings
- Sol-gel coatings

As mentioned by Price and Figueira [3], there are only a limited number of studies and field reports on self-healing and sol-gel coatings, as these coating systems are not yet established on the market and are still in the development and optimisation phase. Organic protective coatings are commonly used in combination with metallic coatings [3, 5]. It is also important to note that the use of only metallic coatings is not allowed [10]. The most corrosion-resistant protective coating is currently considered to be the duplex system, as reported in [2, 3, 5]. This includes applying a metal coating (ZnAl15 base layer that is thermally sprayed) along with an intermediate layer made of particles-reinforced epoxy resin and a top layer made of polyurethane.

This coating system is used on all metallic components of the offshore structure, including the submerged zone. It is important to note that repairs cannot be made in these underwater areas after installation. To effectively prevent corrosion, active corrosion protection must be used in addition.

The long-term impact of coating systems in terms of emissions and impact on the marine environment is still unclear [4].

3.2 Active corrosion protection

Active corrosion protection aims to minimise the rate of corrosion if the protective barrier has been damaged, and corrosive substances have come into contact with the metal surface. This protection is electrochemical in method.

The aim is to supply electrons that prevent the metal from dissolving through an electrochemical reaction. This is done by providing the metal surface with a protective electrochemical potential. To achieve this, an electric direct current (DC) is passed through the corrosive medium into the object to be protected. The direct current causes cathodic polarisation, which shifts the metal potential to more negative values and simultaneously reduces the corrosion rate [4, 5, 13, 14]. Effective corrosion protection occurs when the current density on the surface is strong enough to decrease the potential to an acceptable level, resulting in an acceptable corrosion rate for the structure [14].

This type of corrosion protection is known as "cathodic corrosion protection" and is mainly applied to the components of an offshore structure that come into contact with water, making it a key factor in the stability of the system [11]. There are two widely-used techniques to implement cathodic corrosion protection. These include employing either galvanic anodes (GACP) or inert anodes (ICCP), also known as impressed current system. These two options provide a protective current for the polarization of the metal surface, either through the galvanic reaction of a metal that is less noble than the metal structure (GACP) or through an active current (ICCP) [4]. It is regardless for the protective effect of the structure which method is used to supply the protective current, be it from a galvanic anode or a DC power source [13].

Even a hybrid system consisting of GACP and ICCP can be used. This is especially useful during the installation phase of the offshore plant, when the structure will be without power for an extended period of time. During this phase, the galvanic anode serves as the primary cathodic corrosion protection; once the power supply is connected, the galvanic anode can support the impressed current system [10].

3.2.1 Galvanic Anodes Cathodic Protection (GACP)

Galvanic anodes represent the most basic form of cathodic corrosion protection. Their function is to dissolve a metal with a lower electrochemical potential than steel (colloquially known as a less noble metal). The typically used materials for technical applications are zinc, magnesium or aluminium as the anode material [5]. Aluminium anodes are mainly used for offshore wind turbines due to their protective effect and light weight [4, 5]. Aluminium has a high electrochemical capacity in seawater (2000 Ah/kg)

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compared to zinc (780 Ah/kg) or magnesium [4]. Galvanic anodes vary in the amount of required anode material per year from a few kilograms (e.g. monopile structures) to several tonnes (e.g. jacket structures) [4]. The quantity of anodes material required depends on:

- Type of foundation (different surface)
- Desired service life
- Seawater conditions
- Combination with other corrosion protection methods

Galvanic anodes are generally not provided with a monitoring system, even though this would be beneficial for early detection of increased wear. Only about 10 % of offshore structures with GACP are equipped with remote monitoring [11].

Due to the high rate of anode wear, this method of corrosion protection is considered to be the most emission generating. Annual emissions from a system range from kilograms to tonnes [4].

3.2.2 Impressed Current Cathodic Protection (ICCP)

Unlike galvanic anodes, where protection is achieved by the difference in electrochemical potential of the materials, impressed current systems provide direct current (DC) from an external power source to the steel surface of the structure [4]. Inert anodes are used which typically consist of [4]:

- Titanium
- Iridium
- Iridium/ruthenium MOX coatings
- Magnetite
- Platinum with titanium, niobium and tantalum coatings

These do not need to be replaced and have low annual emissions in the range of milligrams to grams [4, 5].

Unlike GACP systems, impressed current systems must be equipped with measurement, monitoring and control systems to monitor and control key system parameters. The output current of the protective device can be controlled by [14]:

- Constant output voltage: Current is controlled by the resistance of the circuit, external influences lead to changes in the values of the current fed in.
- Potential control: The system potential is measured at one point and signalled to the protection device. The DC current fed is then controlled according to the set target value of the system potential.
- Current control: The protective current device supplies a predefined current.

The correct device settings must be permanently secured [10, 11]. The height of the required protective current depends on:

- Type of surrounding medium
- Type of protected object
- Type of surface
- Combination with other corrosion protection methods

Bette and Büchler [13] specify a required protective current density of approximately 120 to 160 mA/m² for the North Sea.

3.3 Corrosion allowance

Corrosion allowance implies the use of thicker steel than required for the construction of the system to withstand corrosion effects in a marine environment. Its use is only considered as a backup solution when conventional protection systems do not work or when damage to coatings needs to be covered. In addition, a corrosion allowance covers the period until a cathodic protection system is installed.

The thickness of the corrosion allowance is estimated based on the expected corrosion rate of the structure and is between 0.2 and 1.2 cm [4].

The emission potential of this corrosion protection method is classified as low [4].

3.4 Corrosion protection of individual zones

The offshore wind turbine zones are subject to different loads and conditions and must be individually protected against corrosion. Table 1 relates the corrosion protection methods to different zones of the wind turbine.

3.5 Maintenance and inspection

Maintenance, inspection and repair work in an offshore environment is associated with difficult conditions. In order to inspect the system, personnel have had to climb the system in most cases. The same applies to

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Tab. 1: Corrosion protection from different turbine zones

Zone	Corrosion protection method	Reference
Submerged zone	Combination of coating systems with cathodic protection and corrosion allowance for corrosion losses. Mainly protected thru cathodic protection. Coating systems cannot be repaired here.	[3–5]
Tidal & splash zone	Area affected by oscillations, subject to wet and dry cycles, highest corrosive loads. Corrosion protection primarily through coating systems, additional use of cathodic protection and corrosion allowance for critical components.	[3]
Atmospheric zone	Low corrosive load. Corrosion protection mainly through coating systems and corrosion allowances. Critical components made of resistant material, e.g. stainless steel.	[3]
Indoor area/ gondola	Sensitive electrical and mechanical components indoors must be protected from high humidity. Aerosol and air separators are used for this purpose. Mild overpressure inside prevents penetration of salty aerosols. Coating of coatable components. Critical components made of resistant material, e.g. stainless steel.	[3, 5]

maintenance and repair work, especially on the outside of the turbine. This is not only time consuming, but can also be dangerous.

The coating systems should be inspected every 4200 hours, which represents an enormous amount of work with approximately two inspections per year [8].

Repairing the coating system on site is difficult. Salt and moisture residues and difficult surface preparation make application difficult and expensive. The cost of on-site coating can be up to 1000 €/m², a huge increase compared to factory coating costs of 15-20 €/m² [3].

The latest developments in this field have resulted in a repair paint that is better able to handle the conditions it is exposed to and can therefore guarantee a good protective performance despite poor surface preparation (moisture, salt) [5]. In addition, inspections of protective systems are increasingly being carried out using drones or quadrocopters [5]. These are unmanned flying objects equipped with camera systems with image stabilisation systems and laser scaling systems. The flying objects and digital image analysis ensure that only identified repair areas need to be inspected and repaired by hand. Furthermore, the use of the quadrocopter is more flexible, as it can also be used in higher wind situations, compared to manual inspection, for example.

The additional integration of camera and sensor monitoring systems and the connection to existing plant monitoring systems (e.g. SCADA) could significantly reduce on-site inspection work in the future.

4 Conclusion and outlook

The protection against corrosion for offshore wind turbines is of utmost importance and should not be underestimated. The harsh conditions at sea can result in increased corrosion rates and significant wear and tear on the structures of an offshore turbine.

The adoption of known standards, regulations and procedures from the oil and gas industry for the extraction of fossil fuels provides a good basis for providing reliable corrosion protection for offshore structures. For the protection of steel structures in the marine environment, active and passive corrosion protection methods are generally suitable, as long as the protection devices are not damaged or worn.

Intensive inspection and maintenance are necessary for offshore wind turbines to detect and repair damage in a timely manner, as these turbines are not typically monitored continuously. Currently, personnel must climb the turbines to conduct these tasks manually, resulting in significant time, potential shutdowns, and costs.

However, there is a trend towards increased digital monitoring and a reduced use of manpower for specific fault analysis and repair only. Furthermore, the development of dependable and uncomplicated repair processes is of significant importance. These developments need to be followed and driven forward.

Only by combining active and passive corrosion protection, with a reliable digital monitoring system and sophisticated repair procedures, can the demands to ensure the strength of each turbine over a lifetime of more than 25 years be met while the number of offshore wind turbines rises and their distance from the coast increases.

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Dismantling of wind turbines

An overview of methods

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Abstract

This paper outlines the three main areas relevant to dismantling: the rotor blades, hub and nacelle, the tower and the foundation. The paper discusses the dismantling procedures, including the removal of the top structure, the tower and the foundation, and evaluates various methods of dismantling the tower, such as modular dismantling, collapse blasting, folding blasting, wrecking ball demolition and hydraulic ram demolition. The assessment of these methods in practice and the potential challenges and considerations for future dismantling, particularly as wind turbine heights increase, are also addressed.

Keywords: dismantling, disassembly, deconstruction, demolition, blasting, onshore, wind turbine, repowering

1 Introduction

Germany currently has around 28,500 onshore wind turbines in operation [1]. Since the expansion in 2000, there has been an increasing number of questions about their continued operation and eventual dismantling. On the one hand, dismantling is necessary because the technical service life of the turbines is limited. On the other hand, the subsidy period for wind turbines under the Renewable Energy Sources Act (EEG) ends after twenty years [2]. Given the trade-off between revenues from alternative marketing channels and the costs of continued operation, it is generally the operator's decision whether and when to decommission a wind turbine. Based on the date of installation, decommissioning is expected to peak in the years up to 2030 [3]. The development of wind energy is a key pillar of the energy transition, which is intended to enable the phasing out of fossil fuels and nuclear power. According to the current coalition agreement of the German government for 2021-2025, two per cent of the country's land area is to be designated for onshore wind energy [4]. The detailed formulation of the area target is to be set out in the Building Code § 249 [5]. The importance of the necessary expansion of wind energy is also reflected in current geopolitical changes, such as the war in Ukraine. The current German government has set itself the goal of doubling the amount of electricity generated from renewable sources by 2030 [4]. Wind energy has an important role to play. The "Wind-an-Land Gesetz" aims to significantly accelerate the expansion of wind energy in Germany by requiring the federal states to designate 2 % of the federal territory for wind energy by the end of 2032 [6]. By 2027, 1.4 % of the country's land area should be available, with priority given to repowering measures at the same location [6]. Many wind turbines therefore need to be dismantled. There are several methods of dismantling wind turbines. This paper will list and compare these methods.

2 Methodology

The methodology for this essay on the "Dismantling of Wind Turbines" involved a targeted literature search using keywords such as

- "Demontage von Windkraftanlagen" (dismantling of wind turbines),
- "Rückbau von Windenergieanlagen" (decommissioning of wind energy plants),
- "Onshore-Windenergie Rückbau" (onshore wind energy decommissioning),
- "Repowering",
- "Sprengen" (blasting) and
- "Rückbauverfahren" (dismantling methods).

The search was conducted in both German and English to ensure comprehensive coverage of available literature. Due to the limited literature on the topic, publications from the Umweltbundesamt (UBA) and DIN SPEC 4866 were primarily used as key sources. These selections were made to provide a well-rounded overview of legal frameworks, standards, and methodologies in the field of wind turbine decommissioning. An interview was also conducted. The literature

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search was conducted systematically in GoogleScholar, ResearchGate and FINDEX, considering search results in both German and English. The selected sources were carefully analyzed to ensure they represented current standards and developments in the field of wind turbine decommissioning. A literature map was developed with assistance from the AI tool Research Rabbit. The analyzed information from the identified sources was integrated into the essay to offer a comprehensive insight into the methods, legal regulations, and current practices.

3 Legal framework for wind turbine dismantling in Germany

The legal framework plays a central role in the context of wind turbine dismantling, as it defines the guidelines, standards and regulations that shape this process. This chapter presents the main legal aspects that influence the dismantling of onshore wind turbines in Germany. These legal standards have a direct impact on the methods, approval procedures and environmental requirements associated with the dismantling of wind turbines. Only public law regulations are considered. The operator of the wind turbine is responsible for the dismantling, or the client who commissioned the dismantling bears the overall responsibility. The areas of responsibility are divided into planning, monitoring and disposal responsibility. If the responsible person does not have his own expertise, suitable specialists must be engaged. Financial provisions in the amount of the expected costs of complete dismantling are required under Section 35 of the German Building Code (BauGB) for the licensing of the plant, so that the public authorities do not have to bear the costs in the event of insolvency[5]. The obligation relates to the dismantling, which includes the building itself, but may also include ancillary facilities, pipes, paths and yards. The soil sealing caused by the installation must also be removed. In particular, wind turbines with a hub height of more than 50 metres require an immission control permit in accordance with § 4 of the Federal Immission Control Act (BImSchG)[7]. This Act requires the site to be restored to its original condition after the plant has been shut down. The protection of soil is of secondary importance in this area and only applies when the specialised laws do not cover the impacts on the soil. In individual cases, additional claims may arise under private law. Annex A of DIN SPEC 4866-2020-10 provides an overview of the applicable laws for the dismantling of wind turbines[8]. From a legal perspective, dismantling and the disposal of the waste generated during dismantling fall under different regulatory regimes. Therefore, the existing regulations for disposal are not presented. Other relevant laws, guidelines and regulations apply during the dismantling process, such as the German Occupational Health and Safety Act (ArbSchG), TA Lärm, AVV Baulärm, as well as the German Waste Management Act (KrWG), nature conservation laws and water legislation.

4 Methods of dismantling windturbines

A modern wind turbine is made up of a large number of components, which can be broadly divided into mineral and metallic components, as well as various types of plastic[9]. The weight of a typical wind turbine can be broken down as follows: Concrete tower systems consist of approximately 80-90 % concrete (tower and foundation), steel tower systems consist of approximately 20-25 % concrete based on the foundation. Even if a steel tower is not used, a large amount of iron is used in the concrete tower. The hub, to which the rotor blades are attached, and the nacelle, which houses the drive train with the rotor shaft, generator and possibly the gearbox, are also mainly made of iron. The rotor blades themselves are usually made of composite materials such as glass fibre reinforced plastics (GRP) and carbon fibre reinforced plastics (CFRP). Small amounts of non-ferrous metals such as copper and aluminium, cable materials such as polyvinyl chloride (PVC) and operating fluids are also used [10].

4.1 Building structure of a wind turbine

A wind turbine can be divided into three assemblies or areas relevant to dismantling: The first consists of the rotor blades, hub and nacelle. In addition to their height, their weight, attachment points and weight distribution are important. The second area is the tower, where information on design, structure, weight with mass proportions of construction materials, radii and segment geometry and their attachment points are important. The third area is the civil engineering with the foundation. Relevant information here is the type of foundation, weight including steel and concrete content, depth and, where applicable, the number and length of piers. Ancillary systems such as cabinets, cabling and other infrastructure are not taken into account [9].

4.2 Dismantling procedure

Regardless of the method of dismantling, the basic procedure will be similar as the preparatory measures will be the same. Before the actual dismantling begins, instructions are given with the site kick-off meeting, ensuring that no voltage is present and that the power supply is disconnected, securing the site and setting up the site. In preparation for dismantling, lubricants and other hazardous substances are removed from open and closed systems. Following the preparatory

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measures, the three assemblies are dismantled in the reverse order to the assembly of the wind turbine [8].

4.2.1 Dismantling of the upper structure

The first components to be removed are the rotor blades, hub and nacelle. There are two options for the removal of the rotor blades and the hub. In the case of single blade disassembly, the rotor blades are separated from the hub one by one and lowered by crane. The hub is removed separately. This is necessary due to the weight and height at which the cranes have to operate, compared to star disassembly where the hub is lifted together with the rotor blades. The wind turbine manufacturer usually specifies the option of single blade or star disassembly. Due to the size of the turbines, single blade disassembly will be the preferred method in the future. Special cranes, such as mobile cranes or crawler cranes, are used because of their height and weight, and there are very few of these in Germany and neighbouring European countries. The nacelle can then be lifted off, leaving behind the tower, which forms the second assembly. The controlled dismantling of this assembly can only be carried out using special cranes. [9] If it is not possible to dismantle the first assembly in this way, due to an accident or limited stability, the only remaining option is to demolish the tower including the building structures, which results in a large amount of flying debris, mixing of building materials and increased exposure to dust. This does not meet environmental requirements and is not state of the art for systems that do not meet these specific conditions [11].

4.2.2 Dismantling of the tower

Five different methods are available for dismantling the wind turbine tower:

1. Modular dismantling
2. Collapse blasting
3. Folding blasting
4. Wrecking ball demolition with crawler cranes
5. Crumble with hydraulic rams

Modular dismantling Modular dismantling is possible for tower structures that were also built using modular construction methods. This includes tubular steel and lattice towers, as well as concrete towers built using segmental construction. The individual modules are hooked into a special crane, which is also used for dismantling the buildings, separated from the tower by industrial climbers, lifted, swung away and lowered. The size of the modules to be dismantled is based on the size previously determined for construction, so weight and size are not a problem. [12] However, the large number of modules or lattice tower sections results in a large number of crane lifts, which is time consuming. The components can be crushed on site or, after removal, at the dismantling company's premises. The advantages of this method are the low emission dismantling of the tower and the small space required for dismantling, which is limited to the crane site with the handling area. On the other hand, the process is very time-consuming, especially with regard to the use of the special crane, which increases the cost of dismantling. Hybrid towers are a special case. These tower structures consist of a prestressed concrete tower made of precast concrete elements and a steel tower connected to the concrete tower by a transition piece. They are dismantled in the same way as pure steel and concrete towers. If the tower is not of modular construction or cannot be dismantled because the modules are glued together, the tower can be cut into transportable modules using sawing technology. However, there are significant additional costs associated with the use of sawing technology. Modular dismantling offers the possibility of secondary use of the system. However, the market for reuse of systems is small compared to the number of systems to be dismantled [13].

Fig. 1: Execution of a tower demolition using the folding blast method. Using a second explosive charge at 1/3 of the total height, the upper part of the tower collapsed in the opposite direction to the lower part. This method is more space-saving than a conventional tower collapse blasting. © Reisch Sprengtechnik GmbH

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Collapse blasting Collapse blasting usually involves sawing a wedge into the base of the tower, leaving small supports so that the targeted blast will cause the tower to fall. Alternatively, this wedge can be blown up, which is more expensive but increases safety when working on damaged wind turbines. After blasting, the tower falls over lengthwise. The advantage of this method is that it is much faster than dismantling the modules or using mechanical methods. This method also eliminates the need for costly special cranes. This option is economically advantageous for both damaged and very tall wind turbines. In exceptional cases, this method can also be used to demolish wind turbines, including the nacelle, hub and rotor blades. The main disadvantage of blasting is the vibration caused by the impact of the tower and the flying debris from the blast and impact, which also creates a considerable amount of dust. A vibration expert report may be required. [11]

Folding blasting Folding blasting is the process of weakening the tower by sawing out another wedge at a second level, causing it to collapse. This results in a significantly reduced impact on the surrounding area, as a smaller drop bed is required and low impact speeds are achieved, resulting in less flying debris and dust. The advantages therefore lie in the environmental aspects, while the disadvantage is the increased cost of sawing the second wedge and loading the second blast layer. [11]

Collapse by wrecking ball with crawler crane Causing the collapse of a component by deliberately weakening the structure using a wrecking ball as a mechanical method has long been the state of the art. This method has rarely been used to demolish tower structures because the height of the structure does not allow the crane operator to work at a safe distance from the tower. This makes it impractical for tower demolition. [14]

Crumble with hydraulic rams Crumbling the tower with hydraulic rams is a development of the Wörmann Group. The new process is based on a traverse that is inserted into the tower from above using a crane, and then the tower is pushed apart from the inside using hydraulic rams. The advantages of this method are said to be the cost reduction compared to blasting, the avoidance of earthworks and vibrations, and the time advantage compared to modular dismantling. The main disadvantages are the cost of the special crane needed to lift the truss, the lack of proof of stability due to cracks, a high debris shadow due to small spalling, and the low maturity of the truss as there are increasing problems with the iron mesh of the reinforced concrete. [15]

4.2.3 Dismantling of the foundation

Foundation demolition is the final step after the tower has been removed from its foundation. Once the existing topsoil has been removed and the foundation exposed, it can be crushed by conventional demolition using hydraulic chisels on mobile excavators or, alternatively, by detonation blasting. The reinforced concrete is then scooped out and the foundation components removed. It should be noted that the higher the structure, the stronger the foundation. Accordingly, shallow foundations of more than 800 m^3 of reinforced concrete are possible, speeding up the demolition of these heavily reinforced foundations with loosening blasting. The main advantage is the cost saving, as the costs of drilling the blast holes and the blasting process are quickly recouped. The emissions from the hydraulic chisels are also not significantly lower than those from loose blasting. [11]

5 Assessment

The methods are first evaluated on the basis of a survey of the application in practice. Of all the companies surveyed by the Umweltbundesamt, mechanical demolition, such as modular dismantling, was the most frequently used demolition method. The second and third most common methods were blasting to loosen the foundations and folding blasting. In the civil engineering sector, all companies mainly demolished shallow foundations. As with the tower demolition method, all respondents indicated that mechanical demolition was the most commonly used method of demolition prior to blasting, including the demolition of foundations. [16] Although mechanical dismantling was the most common method, blasting is the second most common method of tower dismantling. This is because especially small towers were dismantled and blasting does not block cranes, which will be in high demand in the coming years. The addition of 115 GW of onshore wind turbines under the EEG will tie up a lot of crane capacity [2]. The resulting annual addition of 9 GW is already a major task, which will increase the prices of special cranes due to the supply and demand effect.

6 Conclusion

It should be borne in mind that relatively few turbines have been dismantled to date and that the number of small turbines with low hub heights, which are increasingly in the 90 metre hub height range, has also decreased. Therefore, the experience from the survey does not yet take into account the turbines that will be dismantled in the coming years. In addition, the hub height of wind turbines is currently 175 metres, and taller towers are already being planned, which

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Tab. 1: Overview of the different methods of dismantling the tower

Assessment categories	**Modular dismantling**	**Collapse blasting**	**Folding blasting**	**Wrecking ball demolition**	**Crumble with hydraulic rams**
Required time	-	+	+	-	-
Machine utilisation	-	+	+	-	-
Material usage	+	-	-	+	+
Required space	+	-	+	-	+
Debris area	+	-		-	-
Safety during dismantling	+	+	+	-	
Environmental impact	+	-	+		
Authorisation effort				-	
Total costs	-	+	+	-	-

Key: + = relative advantage; - = relative disadvantage; blank = neutral advantage

will make dismantling even more difficult [16]. The situation is further exacerbated by the availability and cost of the cranes needed to erect and dismantle wind turbines. As a result of the increased costs, there will be no alternative to folding blast technology where environmental factors allow. However, a rethink will be necessary in five years' time, as more attention has been paid to dismantling in recent years and the modular construction method has also been designed for dismantling. In particular, the technological changes in machine technology will require a review, as these are developing significantly.

7 Outlook

The new technology for dismantling will initially involve robots or, increasingly, remote-controlled excavators and vehicles, as the use of personnel is costly and risks can be minimised. Automated work in high-risk areas using three-dimensional models and the drilling of blast holes will be the first to enter the market. Developments in crane technology will change applications and costs through faster set-up times and higher lifting capacities. It is not yet possible to predict how the increased use of drones will affect demolition activities in the future. Blasting technology will also continue to evolve. Examples include recently developed emulsion explosives, which are faster, cheaper and safer to use, and ignition technology with electronically programmable detonators.

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Technical challenges and trends in upscaling wind turbines

A review

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Abstract

The upscaling of wind turbines has been increasing in recent years and will continue to play a significant role in the future, as it allows for the reduction of electricity generation costs. Various challenges arise when it comes to upscaling. This article summarizes the technical challenges associated with upscaling wind turbines and presenting their problem-solving approaches and research trends based on other reviews. It was found that the most frequently cited challenges are related to individual components, such as rotor blades, drive train, generator, tower, and noise impact.

For rotor blades, the challenges are increased flexibility, more aeroelastic vibrations, increased wear, interferences with radar and transportation difficulties. Proposed solutions include the use of carbon-fiber blades, prebending, novel paints, and for transportation, segmented rotor blades and on-site manufacturing. In the gearbox, torque increases, leading to higher weight and susceptibility to errors. As a result, the trend is moving towards gearless systems with permanent magnet synchronous generators. Transportation is the major issue with towers, which can be resolved with on-site manufacturing. In terms of noise emission, reducing aerodynamic noise plays the most significant role.

Keywords: upscaling wind turbines, large wind turbines, trends and challenges wind turbines, wind turbine enlargement

1 Introduction

The goal of European climate and energy policy by 2030 is an increased proportion of renewable energy to 45%. To achieve this goal, among others the expansion of wind power in Europe is continuously progressing. In addition to more wind parks, the capacity of individual turbines is increasing which can be achieved by upscaling the turbines. It is still an ongoing trend for both onshore and offshore wind turbines because a higher-power wind turbine system leads to a lower levelized cost of energy (LCOE) [1]. Current developments range from 6 to 8 MW for onshore wind turbines [2]. Offshore wind turbines aim for capacities of 10 to 15 MW [2]. The largest onshore turbines reach heights of 200 m with a rotor diameter of 150 m, while the largest offshore turbines reach heights of 250 m with a diameter of 200 m [3]. The enlargement of wind turbines presents a range of challenges. This paper summarizes the challenges, problem-solving approaches and trends associated with the upscaling of wind turbines.

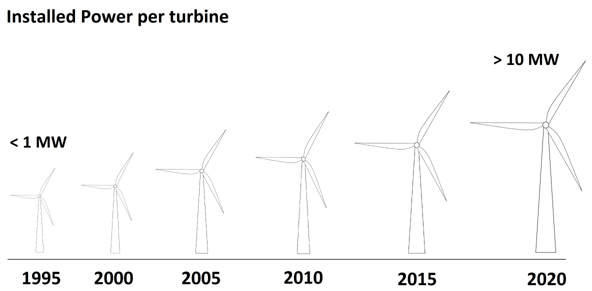

Fig. 1: Size evolution of wind turbines [Source: Author]

2 Methods

This paper is written as a systematic review, as the challenges associated with upscaling are multifaceted and manifest in multiple domains. The research for the cited articles was conducted using Google Scholar with the assistance of ChatGPT. Specifically, ChatGPT generated search terms that were then put into Google Scholar. Literature maps were created using Researchrabbit, but they proved unhelpful, as they included articles unrelated to the topic and many sources were outdated. Initially, more general articles on wind power were read to identify articles related to upscaling and extract relevant articles. Subsequently, information on the challenges, solving approaches and trends associated with upscaling gathered from the relevant articles were compiled.

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3 Challenges and Trends

3.1 Rotor blades

When enlarging the rotor, a challenge arises in that the flexibility of the rotor blades increases. This results in a reduction in the distance between rotor blades and the tower under heavy loads. Methods to increase this distance include pre-bending the blades, which leads to difficulties in manufacturing and transportation as the blade size increases. Another option is the use of carbon fiber instead of commonly used glass fiber, which has a higher specific stiffness, but carbon fiber is more expensive than glass fiber [3].

Additionally, there is an increased occurrence of harmonic and aeroelastic vibrations with blade enlargement. One approach to address this is improved damping, which can be passive (structural and aerodynamic) or active through the turbine controller [3].

Another problem is the wear (fouling) caused by insect impacts and icing. Increasing erosion due to abrasive particles is also a concern. These problems increase especially in regions with higher wind speeds, and lead to poorer aerodynamic performance. Novel paints with nano-composites can provide a solution [4].

Moreover there are concerns regarding the interference with radar. For this, the employment of anti-reflection or stealth rotor blades has been explored, but requires further research [4, 5].

Fig. 2: Segmented rotor blade of an Enercon E115 with mechanical joints [6]

A further challenge related to enlarged rotor blades is their transportation. Transportation can occur by road, rail, water, or air. On the road, there are limits regarding width, height, and weight. On rail, trains must travel at slower speeds. Shipping requires the use of expensive fixtures to prevent twisting of the ship. In the air, helicopters are considered risky, so research is being conducted on blimp-like air lifting devices [7]. There are suggestions to improve transportation methods, such as rotatable rotor blades on truck to pass bridges [8], or floating sealed rotor blades via waterways [9]. The production in small on-site factories with prepared material kits from the main factory is also suggested [10].

Furthermore, there is the possibility of segmented rotor blades. This leads to smaller lengths, heights, widths, and weights and therefore easier transportation. To attach the segmented blades, there are options for adhesive joints or mechanical joints [7]. Fig. 2 shows a segmented blade with a mechanical joint.

3.2 Gearbox

The drive trains can be distinguished into systems with and without gearboxes. With the increase in rotor diameter and consequently its weight, higher torques occur in the drive train. This increases the susceptibility to errors in the bearings and, if present, in the gearbox, thereby raising the requirements. The most powerful gearboxes for wind turbines can support up to 15 MW, with torque densities of 200 Nm/kg and gear ratios of up to 200 [2].

The trend for larger wind turbines is increasingly moving towards systems without gearboxes due to size, efficiency and availability [11]. There are several advantages of direct-drive systems. While the error rate is highest in blades/pitch, electric, and control systems, errors in the gearbox, bearings, and hydraulic system have the most significant impact on downtime, especially in hard-to-reach offshore environments [4, 11]. The global efficiency increases due to reduced friction losses. Furthermore less oil needs to be changed. The reduction in moving parts enhances reliability, thereby reducing maintenance costs. Additionally, the elimination of the gearbox leads to a decrease in noise emissions and vibrations [11]. Advantages of indirect-drive systems are reliability, simplicity and low cost, but the advantages of direct-drive systems outweigh the disadvantages for large systems [11].

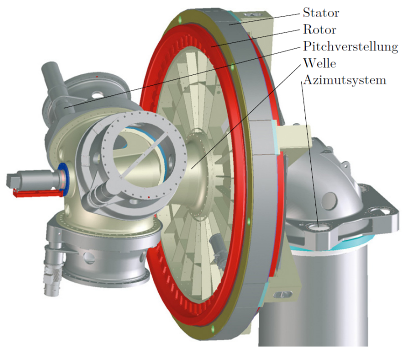

Fig. 3: Direct-drive turbine [6]

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3.3 Generator

For larger wind turbines without gearboxes (low-speed direct-drive systems), electrically excited synchronous generators (EESG) and permanent magnet synchronous generators (PMSG) have gained popularity among manufacturers [11]. The trend is moving towards PMSG because EESG involves higher maintenance requirements for brushes and more heat losses due to current in the excitation windings, leading to increased complexity in the cooling system. In contrast, PMSG eliminates the excitation current and the need for brush maintenance. The electrical properties, such as copper losses, are improved, and the overall weight is reduced. In PMSG, the energy yield and efficiency increase overall [11]. A disadvantage of PMSG is that they require expensive rare-earth elements like neodymium, praseodymium, and dysprosium. To reduce the demand for rare-earth elements, new technologies are under development, including high-temperature superconducting generators, which could become commercially viable in the next decade [3]. These promise higher efficiency and lower weight compared to conventional generators [11]. The power converters in systems exceeding 10 MW are duplicated to prevent excessive current loading per converter [2].

3.4 Tower

The most commonly used types of towers are steel towers and hybrid towers made of both steel and concrete. With increasing tower height, either the tower base must become wider or the wall thickness must be increased while keeping the diameter constant due to the statics. It is cost-effective to keep the wall thickness constant to minimize material costs. However, since prefabricated tower segments made of steel or concrete are limited in diameter for transportation reasons, reinforcing the wall thickness remains the option for prefabricated tower segments [12, 13]. In addition to prefabricated steel or concrete tower segments, there is the opportunity of large diameter steel towers, which are additionally segmented lengthways to reduce diameter during transportation with an on-site assembly after transportation [12].

On-site manufacturing to avoid transportation is another option. For this purpose, the tower must be at least partially made of concrete to be cast on-site [4]. There is also a proposal to cast the entire tower on-site (Full-Concrete Field-Cast Towers). Advantages of this technology include a reduction in primary material costs and independence from steel prices. A disadvantage is the higher labor costs on-site. Another mentioned alternative is lattice towers, which facilitate transportation, but the labor costs are also high due to the relatively challenging construction process [13].

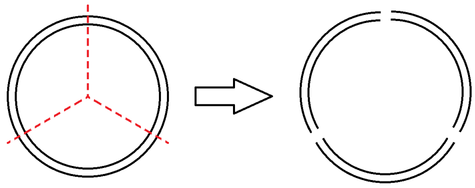

Fig. 4: Lengthways segmented tower segment (front view) [Source: Author]

3.5 Noise emissions

Noise emissions from wind turbines require an increased distance from settlements and/or residential houses. With larger turbines, the noise emissions are amplified. The noise emitted by a wind turbine can be categorized into mechanical and aerodynamic noise. Mechanical noise is generated by moving components such as the gearbox, electrical generator, and bearings. Mechanical noise can be reduced through design measures and acoustic insulation. Aerodynamic noise results from the airflow over and around the turbine blades. It increases with the blade tip speed. This is why the aerodynamical noises are dominant in larger systems, while the mechanical noises dominate in smaller ones [4, 11]. Individuals may experience headaches and other health issues due to aerodynamical noises [14]. They can be mitigated through blade design improvements such as trailing edge serrations [15, 16]. Additionally, reduction is possible through lower angles of attack, higher stall angles, and automatic blade pitching [4]. It is also feasible to place obstacles in the propagation path to alleviate aerodynamic noises [14].

Fig. 5: Trailing edge serrations for mitigating noise emissions [6]

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Tab. 1: Summarized Challenges and their problem-solving approaches and trends [Source: Author]

Component	**Challenges**	**Problem-solving approaches & Trends**
Rotor blades	Flexibility	Pre-bending Carbonfiber blades
	Vibrations	Active and passive damping
	Erosion & Fouling	Novel paints
	Radar interference	Stealth blades Anti-reflection blades
	Transportation	Segmented blades On-site manufacturing Concepts like floating sealed blades or blimp-like air lifting devices
Gearbox	Higher requirements	More powerful gears Trend: direct-drive (gearless) systems
Generator	Less maintenance, more reliability & heat losses	Permanent Magnet Synchronous Generators (PMSG)
	PMSG: reducing rare-earth elements & weight	Superconducting generators
	High current in Power Converter	Duplicated Power Converters
Tower	Transportation	Pre-fabricated: Thicker walls due to width-limit or lengthways segmented segments On-site manufacturing: Partial concrete or Full-Concrete Field-Cast Towers Lattice towers
Noise emissions	Mechanical noises	Direct-drive systems Acoustical insulation
	Aerodynamical noises	Blade design improvements Lower angles of attack Higher stall angles Automatic blade pitching Obstacles in propagation path

4 Summary

In this review, the technical challenges and trends in upscaling wind turbines which are mentioned in other reviews have been compiled. Onshore turbines are currently being upscaled to 6-8 MW, and offshore turbines to 10-15 MW, as this can lead to a reduction in the cost of electricity generation. The main focus areas in this article are rotor blades, gearbox, generator, tower and noise emissions. Tab. 1 lists the challenges and their problem-solving approaches and trends for each of these components.

In the case of rotor blades, one issue is an increase in flexibility, which can be addressed by employing pre-bending or rotor blades made of carbon fiber with a higher specific stiffness than glass fiber. Increased vibrations can be reduced through active or passive damping. Additionally, fouling due to insect impacts, icing and erosion is a concern. Countermeasures may include novel paints. For interference with radar, anti-reflection and stealth blades are under research. Another important aspect is the transportation of rotor blades, which becomes more challenging with upscaling. In addition to segmented rotor blades, which are assembled during installation, there are proposals like floating sealed blades or blimp-like air lifting devices. On-site manufacturing, eliminating

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the need for transportation, is also suggested.

With upscaling, higher demands arise for the gearbox. As the gearbox is one of the components which is responsible for the longest downtime, the trend is clearly moving towards direct-drive systems without a gearbox. For the generator, there is a shift towards permanent magnet synchronous generators, as heat losses and maintenance can be minimized by eliminating brushes and exciting current. However, the use of expensive rare-earth elements is necessary in this case. Superconducting generators are under research and could become market-ready in the next decade. Regarding the power converter, a dual design is necessary due to high current.

For the tower, the most crucial aspect is transportation. As the facilities become larger, either the diameter or the wall thickness must increase for prefabricated tower segments. Due to road restrictions, the options here are to reinforce the wall thickness or to segment the segments additionally lengthways. On-site manufacturing can also provide a solution. For this purpose, the towers must be at least partially made of concrete. There is also the proposal of the Full-Concrete Field Cast Towers, which consists entirely of concrete. Another option are lattice towers.

Concerning noise emissions, either the distances to homes and settlements must be increased, or the noises must be reduced, as excessive noise levels can lead to health issues. In wind turbines, there are mechanical noises caused by moving parts, and more importantly for larger turbines, aerodynamic noises caused by the flow of air over and past the blades. Aerodynamic noises can be reduced through constructive blade design, lower angles of attack, higher stall angles, and automatic blade pitching. Placing obstacles in the propagation path is also an option.

5 Conclusion and Outlook

This review deals with the challenges and trends in upscaling wind turbines. The relevance of this topic is high because manufacturers are increasingly moving towards upscaling wind turbines due to levelized costs of energy. The most frequently mentioned challenges and trends were summarized from current literature. It can be said that upscaling extends to all areas of a wind turbine from a technical point of view. In some cases, there are already solutions for the mentioned challenges, which then have to be dimensioned according to size, such as reducing noise, while in other cases new technologies such as superconducting generators or stealth blades are being developed or tested. There are also problems that only arise with an increase in size, such as transportation, where one solution is on-site manufacturing, for example. This paper can be used to gain an initial overview of the technical problems associated with upscaling wind turbines. It should be noted that the challenges and trends illustrated here do not reflect the full spectrum, and that there are certainly other technical challenges as well as challenges relating to the environment, the legal situation and the economic aspects of upscaling wind turbines. This could be points for future work in order to obtain a more interdisciplinary overview of the topic.

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Relevance of Bird Strikes on Wind Turbines in Germany: A Review

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Abstract

As Germany aims to increase its utilization of wind power, the potential threat to bird populations due to this expansion is a controversial issue. This paper aims to collect data on the magnitude of bird strikes on wind turbines, review existing protective measures and explore innovative solutions. After a thorough examination of the literature, it was concluded that although the impact on bird populations is significant, it may be overemphasized in popular debates. This statement is not final as further research is necessary to assess the impact of bird strikes and explore new solutions. Comprehensive studies on this specific topic in Germany are limited, which makes a thorough evaluation challenging. While there are measures in place to protect species that may be negatively impacted, it is possible that these measures will not be adequate for all of them. While several innovative methods are under examination, progress in testing and implementation is slow. Lastly, an information problem was identified. Since the topic is highly politicized and polarizing, it is crucial to provide the public with accessible and reliable information on the discussed themes. This is currently not the case due to a lack of data and missing information campaigns.

Keywords: bird strike, wind power, red kite

1 Introduction

With the goal of reducing carbon emissions by 55 percent from 1990 levels by 2030, phase out coal usage for electricity generation and adopt renewable energy, Germany is witnessing a steady increase in the adoption of wind turbines, both onshore and offshore. In the first half of 2023, over 28,000 onshore wind turbines with a total capacity of approximately 59,000 MW are operational in the country [1]. In 2022, wind accounted for 22 % of Germany's gross electricity generation, surpassing lignite at 20 % to become the leading source of electricity [2]. In line with the EEG 2023 (renewable energy law), which aims to increase onshore wind power capacity to 160 GW by 2040, identifying suitable areas for wind power generation is a key priority for expansion. The German population generally views the expansion of renewable energy favorably, with only approximately 9 % of survey participants opposing it [3]. However, the creation of new wind farms is often met with skepticism from both residents as well as environmentalists. One concern regularly raised is the impact of bird strikes on local and migratory birds. In this review paper,the relevance of bird strikes on wind turbines in Germany will be examined. The solutions that are currently in use as well as the ongoing development in this area will be analyzed.

2 Methodology

This paper represents a literary analysis aimed at compiling the existing information regarding the inquiries posed in the introduction. To simplify the process, several AI tools with different levels of usefulness were used for research and writing. Perplexity AI and Chat-GPT were used to refine the central questions and to build a general understanding of the topic. ResearchRabbit was utilized to construct a literary map from the initial literature obtained via Perplexity. Finally, the text was written with the assistance of a translation service and an AI writing assistant from DeepL.

3 Relevance of Bird Strikes in Germany

In 2019, an industry study revealed that protecting flying species like birds and bats was a significant point of contention in 48 % of lawsuits against wind turbines, followed by formal and procedural errors at 32 percent [4]. This highlights the importance of bird strikes in shaping German public opinion on wind turbines. However, determining the legitimacy of these concerns is a challenging endeavor. Data for this issue is primarily collected by counting randomly discovered bird carcasses, as experimental setups raise ethical and logistical concerns. Wind turbines are typically

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situated in somewhat remote areas to prevent disrupting local populations and there is only a short period to locate birds killed by wind turbines before they are either consumed by scavengers or shifted. Furthermore, not all bird carcasses found are documented and recorded. Only a rough estimate of bird fatalities can be determined, with NABU approximating about 100,000 bird deaths yearly. Figure 1 illustrates that this number pales in comparison to the approximately 20 to 100 million deaths caused by domestic cats, 70 million deaths caused by traffic and 100 to 115 million deaths caused by collision with glass panes [5]. Legal and illegal hunting along with power lines account for an additional 2.7 to 4 million deaths combined. A 2009 study suggests that wind turbines cause ap-

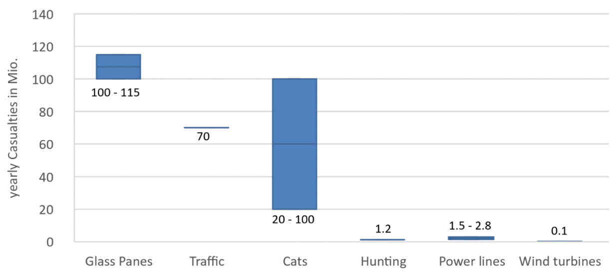

Fig. 1: Causes of bird deaths in Germany based on NABU [5]

proximately 0.3 deaths per GWh generated, whereas fossil fuels cause about 5.2 deaths per GWh generated, mainly as a result of habitat destruction and pollution [6]. Although this study focuses more on the United States, it still provides a compelling picture. However, these results may not apply directly to Germany's situation. Nevertheless, wind turbines do not appear to pose a significant problem in terms of raw numbers. More complexity arises when examining the impact on various species. Research indicates that birds of prey are particularly prone to colliding with wind turbines. The most comprehensive study concerning this issue to date is the PROGRESS study. It focused on northern Germany and determined that there might be a negative impact on the populations of buzzards and red kites [7]. However, criticisms challenge the findings' validity as data was not collected when these species were absent, thus potentially overestimating the perceived threat of wind turbines [7]. The project "LIFE EUROKITE" is currently examining the impact of wind turbine collisions on this species to determine the relevance of potential casualties. The purpose of this pan-European initiative is to collect and analyze telemetric data to ascertain the patterns of habitat use by birds of prey and the perils that threaten their populations [8]. While there are no final results available at present, with the earliest expected at the end of 2023, EUROKITE identifies illegal and accidental poisoning as the primary threats to the kite population [9]. This might further relativize the impact of wind turbines. While wind turbines are not likely the greatest threat to any bird species, they may indeed have a significant, avoidable impact on some. The following chapter describes some well-known means of preventing bird collisions and the current state of research regarding alternative methods.

4 Current Measures

Since the prevention of bird strikes on wind turbines is beneficial to both nature conservation and the operation of onshore wind farms, several methods have been developed and fully or partially implemented. For the operation of onshore wind farms in Germany, these measures are legally anchored in § 45 of the Federal Nature Conservation Act (Bundesnaturschutzgesetz, BNatSchG); some measures are listed in Appendix 2. These measures are listed below.

4.1 Siting

The process of determining the location of wind turbines is called "siting" and consists of two parts - macrositing and micrositing. Macrositing usually involves the decision on a general area in which a wind farm is gonna be built based on several factors. Micrositing is the process of determining a precise location for each wind turbine to optimize spatial use, power generation, cost and other relevant factors. It is common practice to consider the protection of birds in the siting process by maintaining a reasonable distance between wind farms and migratory routes as well as nesting sites. Annex 1 of the BNatSchG specifies near, central and extended areas that have to be checked for the protection of 15 species of nesting birds. While this method of micro-siting is supposedly effective for all of the species listed in the legislature, according to NABU most nesting birds tend to use areas in immediate reach of wind turbines anyways and are mostly not negatively impacted by wind parks.

4.2 Anti-Collision System

The purpose of anti-collision systems is to detect specific avian species through the use of cameras and/or radar technology. If a member of the target species is detected falling below the minimum distance, the wind turbine's rotation will slow down and the system will enter idle mode to avoid a collision. So far there is only one anti-collision system that has been thoroughly tested. The system in question is called "IdentiFlight" and is so far only recommended for the protection of red kites. The results of a three-year study at six german locations showed, that on average 92 % of red kite activity in the relevant area was detected, slowing down the turbines in time at a rate of 77-91 % [10], exceeding the requirements posed by the Competence Center for Nature Conservation

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and Energy Transition (KNE). Following these results, the KNE issued a press release in 2021 stating that IdentiFlight is ready for implementation [11].

4.3 Shutdown during Agricultural Management Events

Another viable solution involves temporarily halting the operation of wind turbines during agricultural events in the immediate vicinity of the turbine (mowing shutdown). This measure has been proven effective for certain species, such as red and black kites, among others. The effectiveness, however, depends on the precise timing and surrounding circumstances. These circumstances include windspeed, which influences the flight patterns of red kites, as well as factors such as time of year, use of other measures and duration of usage. An observation is that the risk of collision seems to normalize after about two days [12]. Research indicates that certain species are drawn to the sound of heavy machinery for a brief period [13], thus accounting for the observed impact of this action.

4.4 Creation of Attractive Alternative Feeding Habitats

Alternative feeding habitats are intended to redirect bird activity from the wind turbine's location in the long run by establishing habitats that mimic natural environments, such as wetlands. Implementing this measure can present challenges due to the requirement for long-term agreements between parties and the availability of functional spaces in the surrounding area. This is commonly considered an adjunctive measure rather than a primary solution, it should only be utilized in conjunction with more efficacious strategies.

4.5 Reducing the Attractiveness of Habitats in the Mast Base Area

It is argued that the installation of wind turbines can unintentionally result in the development of abundant hunting grounds for birds of prey. Small mammals, which make up a large part of these birds, are easily spotted on fallow lands, pathways and pitches around the turbine. Additionally, structures such as fences serve as perching sites for birds of prey [14]. Measures to decrease the appeal of these territories involve refraining from creating fallow land and utilizing vertical structures like fences and high seats [15]. The United States Fish and Wildlife Service (USFWS) recommends eliminating carrion, specifically to reduce the attractiveness to golden eagles [16]. Other measures entail abstaining from nutrient input through fertilization [17] and eliminating manure heaps, which have been observed to lure red kites [13].

4.6 Phenology-Related Shutdown

The last measure recommended in the current edition of the EEG involves a phenology-related shutdown of wind turbines. This entails shutdowns during daytime for extended periods of four to six weeks during times of increased activity around nesting sites, such as during mating times. While this technique appears to be effective for all impacted species, it incurs significant energy losses due to the prolonged shutdown. Consequently, it is only recommended as a last resort when no other measures are possible.

5 Research

Expanding on the measures in place to prevent bird strikes, ongoing research is dedicated to finding new methods to combat this issue and enhance current practices. This section will explore some of these approaches.

5.1 Siting

As described in chapter 4.1, bird protection is already considered in the siting process. This process is continually reviewed to include more details to achieve this goal. An example of this is the identification and avoidance of areas with updrafts, which are known to attract soaring birds of prey [18]. An open access tool based on a geographic information system (GIS) and thermal imagery has been developed at the Norwegian Institute for Nature Research (NINA) as a cost-effective tool that could be used for this purpose [19].

5.2 Anti-Collision Systems

Anti-collision systems are already being used to protect red kites, as mentioned in chapter 4.2. In addition, current research aims to extend this technology to other species. Researchers at Identiflight tested the existing system's efficiency for safeguarding sea eagles, which lack adequate protection measures [20]. Reaching similar results as in safeguarding kites, it is expected that this system can be implemented in the future.

5.3 Deterrence through Acoustic Signals

One way to keep certain species of birds away from wind turbines may be the Use of long range acoustic devices (LRAD). A study conducted in Cadiz, Spain demonstrated the effectiveness of this technique for various species, including the griffon vulture [21]. Different species have varied reactions to specific noises and mimicking naturally occurring sounds proves to

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be more effective while avoiding acclimatization in comparison to artificial noises [22].

5.4 Ultraviolet Lighting

In a pilot study, researchers at NINA found that ultraviolet lights can diminish bird flight activity. During UV light exposure with a 365 nm wavelength, 27 % less activity was recorded compared to control nights [23]. The measure is still in its early stages of research and has not been widely implemented.

5.5 Painted Structures

There are promising studies investigating the low-tech solution of improving turbine visibility by painting them black. The impact varies based on the portion of the turbines that is coated.

5.5.1 Tower

In a recent study, it was found that the lower 10 meters of ten wind turbines were painted. Following the implementation of this measure, a decrease of 48 % was observed in the discovery of ptarmigan willow carcasses, without any adverse impact on the surrounding, unpainted towers [24]. While this measure seems promising, it may not effectively achieve the goal of protecting raptors. The potential impact on willow ptarmigans could be significant, given their propensity for colliding with the bases of towers.

5.5.2 Blade

In another experiment conducted by researchers at NINA, a single turbine blade was painted black. Subsequently, the effects of this alteration were analyzed. The results show that "there was an average of 71.9 % reduction in the annual fatality rate after painting at the painted turbines relative to the control turbines" [25]. While this is a significant accomplishment, the researchers observe a significant variability between years, indicating the necessity for more research. Nevertheless, implementing this measure appears to be a highly cost-effective solution, particularly when painting the blades before their installation on the tower.

6 Discussion

As demonstrated in this paper, the significance of bird strikes is a debatable topic for numerous reasons. Although certain species seem to be affected negatively to a significant extent, quantifying this impact is difficult. The crux of the matter revolves around data collection issues. To date, the PROGRESS study, published in 2016, remains the most extensive research on this matter in Germany. A central finding of the study was that current collision prediction models are inadequate, an issue that has yet to be resolved. The findings of the EUROKITE project are anticipated to provide insight into the effects of certain significant species, although not all have been thoroughly examined. The buzzard, which may be adversely impacted as per the PROGRESS study, is not the focus of this project. Given the context, further research is necessary to investigate the impact of bird strikes on these species. Without accurate determination of the impact of wind turbines on certain species, it is impossible to quantify the urgency with which this issue should be addressed. Not knowing the precise extent of the impact is not a justification for disregarding its existence entirely, nor is the notion that there are greater risks to the population of the species at hand. Some Conservationist groups contend that the expansion of wind energy is crucial to achieving the goal of renewable energy and combating climate change, which poses a greater threat to diversity overall [26]. This expansion should be undertaken cautiously while implementing measures to mitigate their impact on endangered species. In this paper, various measures currently in use, as well as those under development, are presented. The evidence suggests that there is a significant amount of untapped potential. While some measures are currently in use, it remains unclear to what extent they are utilized and their level of effectiveness. For the experimental measures, there seems to be a lack of testing and implementation in Germany. In particular, some of the measures being researched at NINA seem promising, but there are no sources of testing in Germany, even though some of the proposed methods are relatively low-tech, such as the painting of rotor blades. Testing and implementation of these or other measures is crucial to ensure that the planned massive increase in wind power over the next few decades does not lead to unexpected adverse effects, most likely necessitating more costly and less effective retrofitting of protection measures. Finally, it is necessary to disseminate information regarding the utilization of these measures. There is a lack of accessible and comprehensive data available to individuals who are not extensively involved in this matter to fully comprehend the ramifications of bird strikes and the actions being implemented. One website that has served this purpose to some extent is "www.wind-ist-kraft.de," an informational campaign and website operated by the German Nature Conservation Ring (DNR) with support from the German Federal Ministry for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection (BMUV). However, the Internet Archive indicates that this website has been unavailable since at least March 14, 2017.

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7 Conclusion

Overall, further research is needed to examine both the impact of wind turbines on bird populations and the development of new measures to prevent bird strikes. Although other factors can have a greater impact on bird species, such as collisions with powerlines and poisoning, it is crucial to mitigate preventable negative impacts and promote acceptance of wind power expansion among the population. There is also a lack of easily accessible information regarding this research and the effectiveness of measures. Half-baked disinformation campaigns are a potential threat in the absence of information campaigns.

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Guidelines for Onshore Repowering in Germany

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Abstract

Wind energy plays a major role among renewable energies. Its expansion is therefore important in order to achieve the climate targets. Repowering is an important element in the expansion of wind energy. On the one hand, it offers a solution for many wind turbines in Germany that are no longer subsidised due to their age. On the other hand, modern turbines are significantly more powerful and enable more efficient land utilisation. This article provides an overview of the most important aspects of onshore repowering.

There is a lot to consider when repowering wind turbines. The legal situation for repowering aims to be improved through simplified authorisation procedures. Even though efforts are being made by the government, there is still room for improvement. The repowering potential is also dependent on the various distance regulations to residential buildings in the federal states. These regulations might also be improved in the future. Another aspect is the remuneration, which is now closer to market developments due to the market premium model. It is also subject to greater competition as a result of the tendering process. At the same time, interest rates and turbine prices have risen, which creates economic challenges for the operators of future wind farms. Last but not least, repowering also depends on public acceptance. This is also to be regulated by law in the future.

Keywords: Onshore repowering, simplified authorisation procedure, distance regulations, market premium model, tendering, inflation, public participation,

1 Introduction

To achieve the set climate protection targets, it is important to accelerate the expansion of renewable energies [1]. Wind energy plays a key role in this with a share of 25 % of the renewable energy supply in 2022 [2].

Wind turbines in Germany receive remuneration for 20 years [§25 EEG 2023]. As can be seen in Figure 1, many wind turbines are in the final years of subsidisation or have already been phased out. Operators of such plants must weigh up whether they want to continue operating the plants without remuneration (if technically possible). Old turbines also often cause the highest maintenance costs in the final years of operation, which is why repowering can be a better alternative.

Repowering means replacing outdated, low-performance and low-yield wind turbines with modern ones. The construction of new turbines has many advantages. Modern turbines are now being erected with outputs of 4-7 MW and achieve higher yields. Good wind farm sites can therefore be utilised more efficiently. In addition, the appropriate infrastructure is already in place from the old plants. [4–6]

This paper aims to provide an overview of the relevant aspects that currently need to be considered regarding the repowering of onshore wind turbines in Germany.

2 Legal regulations

Wind turbines with a total height of over 50 metres are approved under the Federal Immission Control Act (BImSchG) [§2 4. Federal Immission Control Ordinance (BImSchV)]. The requirements for the authorisation of repowering projects are described in the BImSchG and the Federal Nature Conservation Act (BNatSchG).

2.1 Federal Immission Control Act / BImSchG

The BImSchG regulates the requirements for repowering in §16b. This is a modification of the authorisation of installations with significant changes (§16 BImSchG). It was introduced in 2021 to transpose the requirements of the Renewable Energy Directive of the European Union (EU) into German law [7]. Repowering should therefore be carried out in a simplified procedure [Art. 16 Section 6 Directive (EU) 2018/2001].

The paragraph 16b BImSchG contains the following aspects:

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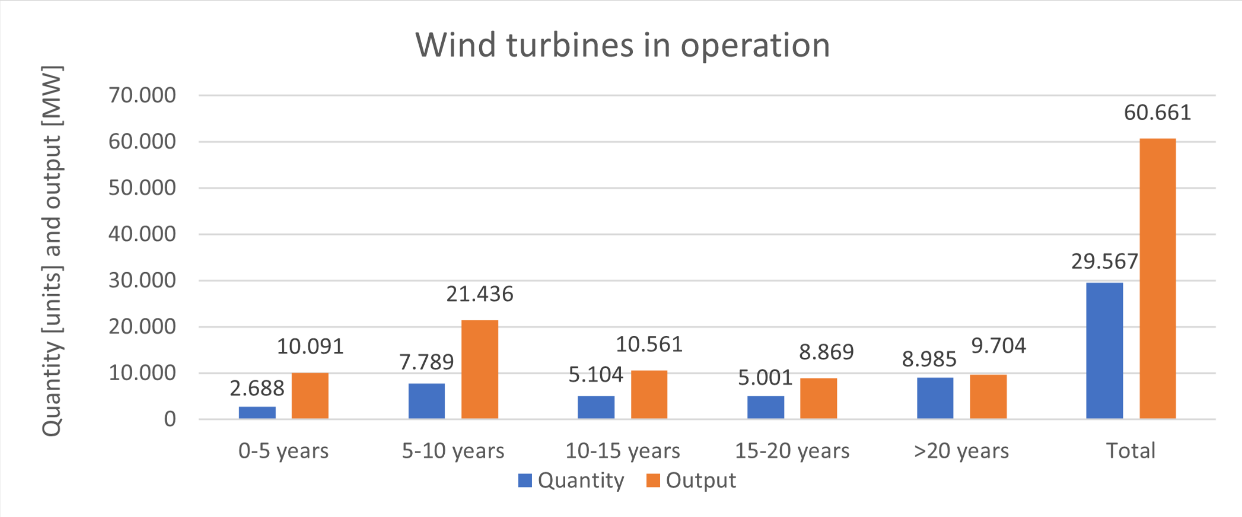

Fig. 1: Age structure of wind turbines in Germany (status 08.12.2023). Own illustration based on [3].

- Only check requirements according to BImSchG if negative effects are expected (due to repowering or change of turbine type)
- Examination of other public law concerns in all aspects (e.g. construction planning, labour protection, nature conservation, etc.)
- No limitation of the repowering measure in terms of size, increase in output, number of turbines
- Construction within 24 months of dismantling the old turbine
- Maximum distance between old and new turbine two times the total height
- Authorisation despite non-compliance with some immission limits if the total immission contribution is lower
- No need for a public hearing
- Simplified procedure for up to 19 wind turbines
- Simple assessment of stability and effects of noise and turbulence in the event of a change in power output

According to §16b, repowering includes the complete or partial replacement of wind turbines, operating systems or operating equipment. Only requirements that change the current conditions, taking into account the old systems, need to be checked. There will be a so-called delta test for this purpose. If the repowering leads to an improvement or unchanged impact on the wind farm sites, no assessment is required. [8]

A draft bill is currently being discussed in the Bundestag that contains the following improvements to §16b [1, 9]:

- Construction within **48 months** of dismantling the old turbine
- Maximum distance between old and new turbine **five times (5H)** the total height
- Use of §16b also for turbines that have been authorised under other specific laws
- Authorisation despite non-compliance with some immission limit values if the total immission contribution is lower **in absolute terms** (e.g. 0.1 dB is sufficient[10, 11])

Although the wind industry welcomes the planned changes in general, there are still suggestions for improvement. According to the BImSchG, a modification authorisation can only be obtained by an identical operator. There is no corresponding special regulation for repowering, although in reality the operator often changes in this case. [10–12]

Another suggestion for improvement is the seamless transition between old and new wind turbines. In fact, it makes sense to continue operating the old turbine until the new one has been completed to ensure a high level of efficiency. A corresponding clarification is missing so far. [10, 11]

The regulations on changing the type of wind turbine were also criticised. It is no longer possible to change the type of turbine via a simple modification authorisation [10]. This type of authorisation is regulated in §15 BImSchG and only requires notification to the responsible authority [§15 BImSchG]. It also remains unclear whether the change in turbine type also takes relocations into account. This often occurs in the practice and is not mentioned in the law. [8]

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2.2 Federal Nature Conservation Act / BNatSchG

In addition to §16b, there are also regulations on repowering in the Federal Nature Conservation Act (BNatSchG). Similar to the delta test, the effects of old turbines are also taken into account in protecting wildlife. For example, protective measures already taken, breeding sites and characteristics of the old turbines are analysed. Compensatory measures already taken are also assessed and deducted from the new measures to be taken. In the BNatSchG, the 5H regulation and the time limit of 48 months in deviation from §16b already apply. [§45c BNatSchG]

3 Political aspects

As a result of repowering, wind turbines are not only significantly more powerful but also significantly taller. According to a study by Lacal-Arántegui et al. [13], repowered wind turbines have on average twice the hub height and three times the rotor diameter . This results in a significantly greater total height compared to the old turbines. For a high energy yield, wind turbines must keep a certain distance from each other [14]. A general rule of thumb is based on the rotor diameter and specifies a distance of 10 rotor diameters in the wind direction and 5 rotor diameters in the crosswind direction to keep field losses below 10% [14]. New wind turbines therefore require significantly more space than the old ones. This can lead to conflicts with politically determined distance regulations regarding residential buildings [4].

There are currently different distance regulations in Germany depending on the federal state. In Bavaria, for example, wind turbines may not be built closer to residential buildings than ten times their total height (10H). In other federal states, on the other hand, a distance rule of up to 1000 metres applies. Saxony-Anhalt, Saarland and, more recently, North Rhine-Westphalia have not set any blanket distance regulations. [15, 16]

Grau et al. [17] demonstrate the relevance of distance regulations in a study on the repowering potential in Germany. In the study, the potential of various scenarios was determined, which differ according to the size of the new wind turbines and the strictness of the distance regulations. The potential in the various scenarios was identified with distances of 500 metres (scenario 1-5), 1000 metres (scenario 5-10) and 10H (scenario 10-15). Figure 2 shows an example of three scenarios with different potentials for repowering turbines with a capacity of 4 MW (230 m total height) and various distance regulations. Table 1 expresses the potential of the scenarios for the year 2040 in numbers. It is clear to see that the repowering potential is affected, particularly with the 10H regulation as in Bavaria.

The possibilities for repowering therefore depend on the political regulations of the respective federal state. This situation may improve in the future. To accelerate the expansion of wind power in general, the Wind Energy Area Requirement Act (WindBG) came into force on 1 Feb. 2023. Therefore, all federal states must designate an area of around 2 % for wind turbines by the end of 2032 [§3 WindBG]. Previously, only 0.8 % of the area was designated across the country and only 0.5 % was available. The individual distance rules of the federal states will then only apply if the requirement of the new law is met. [18]

Tab. 1: Repowering scenarios and potential wind energy generation (WEG) in 2040. Modified by the author. Based on [17].

Scenario	Distance (m)	WEG (TWh/yr)
S5	500	85,37
S10	1000	70,91
S15	10H / 2300	26,54

4 Economical aspects

The economic situation today is not the same as when the old wind turbines were built. This is not only due to a different remuneration model for the electricity generated but also to the changes in recent years regarding the financing of wind power projects and the costs of wind turbines.

4.1 Remuneration for electricity generated from wind turbines

The remuneration for electricity generated from wind turbines has been in existence since the Renewable Energy Sources Act (EEG) came into force in the year 2000 [§9 EEG 2000, §25 EEG 2023]. Under the old system (until EEG 2012), the electricity was sold to the grid operators and remunerated independently of the market. This reduced the investment risk and increased planning security for project planners, which led to an ever-increasing expansion of wind energy. [6]

The EEG 2017 fundamentally changed the remuneration model. Accordingly, the remuneration is now determined via a tendering procedure. The tender is limited in volume and also specifies the highest possible remuneration [§28, §36b EEG 2023]. Future wind farm operators can take part in the tendering process after receiving the authorisation under BImSchG and submit a bid for the desired remuneration [§36 EEG 2023]. The limited volume ensures competition as the highest bids are excluded due to the limited volume [Section 32 EEG 2023]. If, for example, the volume

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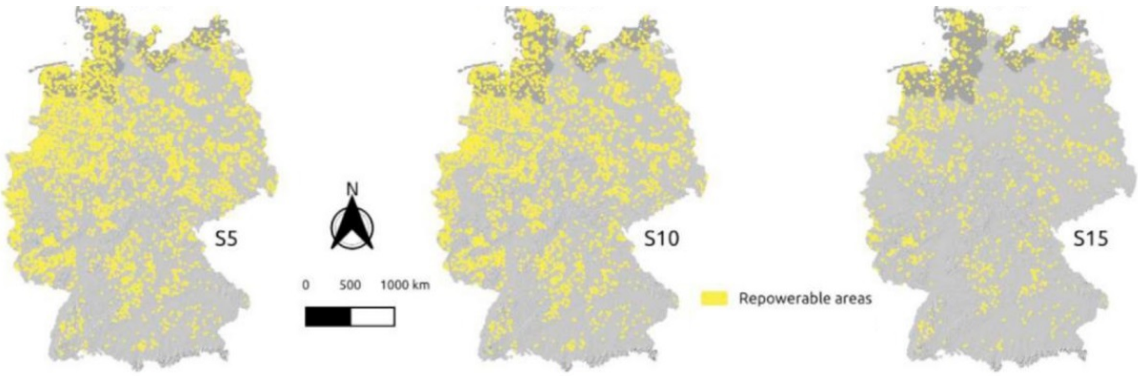

Fig. 2: Repowerable areas with various distance regulations and a wind turbine capacity of 4 MW. Modified by the author. Based on [17].

is not utilised, the Bundesnetzagentur (Federal Network Agency) can subsequently adjust the volume to maintain competition [§28 EEG 2023]. If the highest possible remuneration is no longer appropriate, this value can also be adjusted by up to 25% [§85a EEG 2023].

The remuneration value determined in the tender is adjusted using a location factor. If the wind forecast is better than a defined reference location, the remuneration value is adjusted downwards. If the wind farm site is estimated to be worse, the remuneration is set higher. The actual performance is analysed every 5 years and subsequently adjusted. This may result in subsequent refunds or payments. [§36h EEG 2023]

The EEG 2012 also introduced the market premium model. It became mandatory for systems with an output of more than 100 kW with the EEG 2017 [§19 EEG 2017]. Under this model, the electricity must be sold directly to third parties or via the stock markets. The remuneration (set in the tender since EEG 2017) is offset against the earnings from direct marketing. [§33 EEG 2012, §23a EEG 2017] The actual remuneration therefore only covers the difference between the sales earnings and the remuneration value [6]. If the proceeds from sales are equal to or higher than the remuneration value, the remuneration is reduced to zero.

From EEG 2014, there is also a rule that no more remuneration is paid if the spot market price on the stock market is negative for a certain period in succession [§24 EEG 2014]. According to the latest regulations, the number of hours is reduced annually to 1 hour in 2027. Currently, no remuneration is paid for negative price periods of four hours or more. [§51 EEG 2023]

The tenders and the market premium model ensure more competition and market orientation for renewable energies. Due to the fixed remuneration value, this system nevertheless offers guarantees to ensure a certain degree of planning security for investors [6].

4.2 Financing and costs

The planned expansion of wind power was not achieved in 2022 and will not be achieved in 2023 either. Table 2 shows an overview of the tenders. It shows the initially planned tender volume, the offered volume and the volume that was finally awarded.

Tab. 2: Results of the tender process. Own illustration based on [19–26].

Date	Quantity (MW)			Price
	planned	offered	awarded	(ct/kWh)
01.02.22	1333	1328	1332	5,88
01.05.22	1333	1320	931	5,88
01.09.22	1333	1320	773	5,88
01.12.22	1190	603	189	5,88
01.02.23	3210	3210	1441	7,35
01.05.23	3210	2866	1535	7,35
01.08.23	3210	1667	1433	7,35
01.11.23	3210	2088	unknown	7,35

It can be seen that the volume offered was not achieved in all tenders after February 2022 despite frequent reductions. The last tender date in 2022 in particular was significantly below the volume offered. This problematic development can be explained by various mechanisms. In addition to the effects of the COVID-19 pandemic, the war in Ukraine in particular has recently led to major price increases and inflation of up to 8.8 % (November 2022) [27, 28]. To reduce the high inflation, the ECB has started to raise the interest rate on the main refinancing operations since July 2022 [28, 29]. If this interest rate is raised, credit interest rates will also rise [28, 30]. The financing conditions for investments in renewable energies have therefore deteriorated. For example, loans from the KfW-bank for renewable energies were available for an interest rate of 1.8 % in 2021 [31]. The interest rate is now 5.04 % [32] (assumptions: as in [31]: 20-year term, 3 redemption-free start-up years, 20-year fixed interest rate, risk class B).

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Due to the price increases and higher financing costs, the electricity production costs in the wind industry have risen. An expert report by Deutsche Windguard [31] analysed the cost trend in great detail (status: 29.11.2022). Table 3 shows the result of a comparison of two similar wind turbines from the report. Due to the changed financing conditions, a higher equity ratio and a higher return on equity were assumed. It can be seen that all cost units show an increase. However, the financing costs in particular stand out clearly. Despite the improved technology of the newer turbine, the LCOE increased by 43 %.

The operators of future wind farms are therefore faced with the challenge of achieving good profitability under the maximum prices prescribed in the tender and at the same time significantly higher electricity production costs. Based on the report by Deutsche Windguard, the Federal Network Agency raised the maximum tender price for 2023 to 7.35 ct/kWh to improve the situation for wind power expansion [31, 33]. As can be seen in table 2, there was a higher expansion this year compared to 2022. However, the planned tender volume was undercut again despite being reduced. The increase in the maximum price seems to be not sufficient yet. The results of the last tender on 11/01/2023 are not yet known.

5 Social aspects

If a wind power project is to be realised, it is also important to consider the social aspects. The acceptance of the public plays a central role in the selection of wind turbine sites and is therefore a key criterion for enabling the expansion of renewable energies [34, 35]. According to a survey conducted by Fachagentur Windenergie an Land e.V. [36] in 2022, over 80% of the German population consider the use of wind energy to be rather important or very important (figure 3). Figure 4 also shows the survey results regarding wind turbines in the immediate residential area. A distinction is made here as to whether wind turbines have already been erected in the residential area or not. Acceptance is high in both parties. It can also be seen that citizens with wind turbines in their surroundings show an even higher level of acceptance, which is beneficial for repowering projects.

Even if acceptance is generally very high, there is always a part of the local population that is against wind turbines. Windemer [34] conducted a survey in which citizens living near wind farms were interviewed. The survey showed that even years after the wind turbines were erected, there were no major changes in attitudes towards wind power. In repowering projects, negative attitudes in particular can therefore lead to new protests . To maintain a high level of acceptance and increase it further for future expansion, it is important to consider what the affected citizens wish for. According to Windemer [34], a study by Huebner

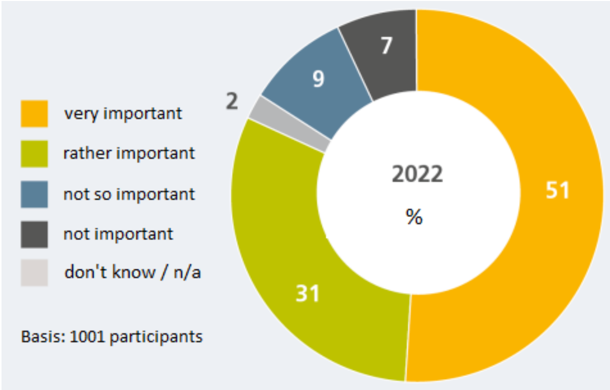

Fig. 3: Acceptance of wind energy onshore. Modified by the author. Based on [36].

and Pohl [37], as well as the survey by Fachangentur Windenergie an Land e.V. [36], the following factors can increase acceptance:

- Transparency and information over the entire operating period (not just the planning phase)
- Participation of citizens and local authorities in the planning process
- Taking issues and complaints seriously
- Financial participation opportunities for citizens and municipalities
- Enable discounted electricity contracts

In the version of the EEG valid from 1 January 2023, local authorities are to be paid 0.2 ct/kWh to increase the acceptance of wind energy expansion. However, this is only a voluntary measure. [§6 EEG 2023] To give citizens an appropriate financial share in the future, a draft bill is currently under discussion in the state parliament of North Rhine-Westphalia [35]. The proposed Citizens' Energy Act (BueEnG) provides for the mandatory participation of citizens living in municipalities where wind turbines are built [§7, §8, §9 BueEnG]. Nevertheless, as the studies show, citizens should not only be financially involved in wind farm projects.

The study by Huebner and Pohl [37] also shows that citizens are more likely to be disturbed by changes to the visual landscape, whereby a greater distance does not lead to greater acceptance. Repowering projects could therefore be advantageous, as the greater output of the turbines means that not as many are needed as in the old wind farms. The new wind turbines technically require more space to achieve a high level of efficiency [13]. However, the noise pollution from new turbines is lower [38]. As the influence of distance on citizens appears to be minimal, it is possible that the space criterion does not affect acceptance significantly.

Tab. 3: Comparison of the cost components of wind turbines. Modified by the author. Based on [31].

Start of operation	**2021**	**2025**	**Change**
Site quality	100 %	100 %	
Turbine output	4317 kW	4573 kW	+6 %
Hub height	140 m	146 m	+4 %
Rotor diameter	138 m	140 m	+1 %
Annual energy yield	14666 MWh/a	15287 MWh/a	+4 %
Equity share	14 %	18 %	+25 %
Debt capital share	86 %	82 %	-5 %
Return on equity	8 %	10 %	+25 %
Debt capital interest rate	1,8 %	4,81 %	+167 %
Main investment costs	958 €/kW	1159 €/kW	+21 %
Ancillary investment costs	488 €/kW	637 €/kW	+31 %
Operating costs - first decade - fixed, annual	28 €/kW	33 €/kW	+19 %
Operating costs - first decade -variable	0,6 ct/kWh	0,7 ct/kWh	+18 %
Operating costs - second decade - fixed, annual	35 €/kW	43 €/kW	+22 %
Operating costs - second decade - variable	0,8 ct/kWh	0,9 ct/kWh	+22 %
Power generation costs	**4,8 ct/kWh**	**6,8 ct/kWh**	**+43 %**

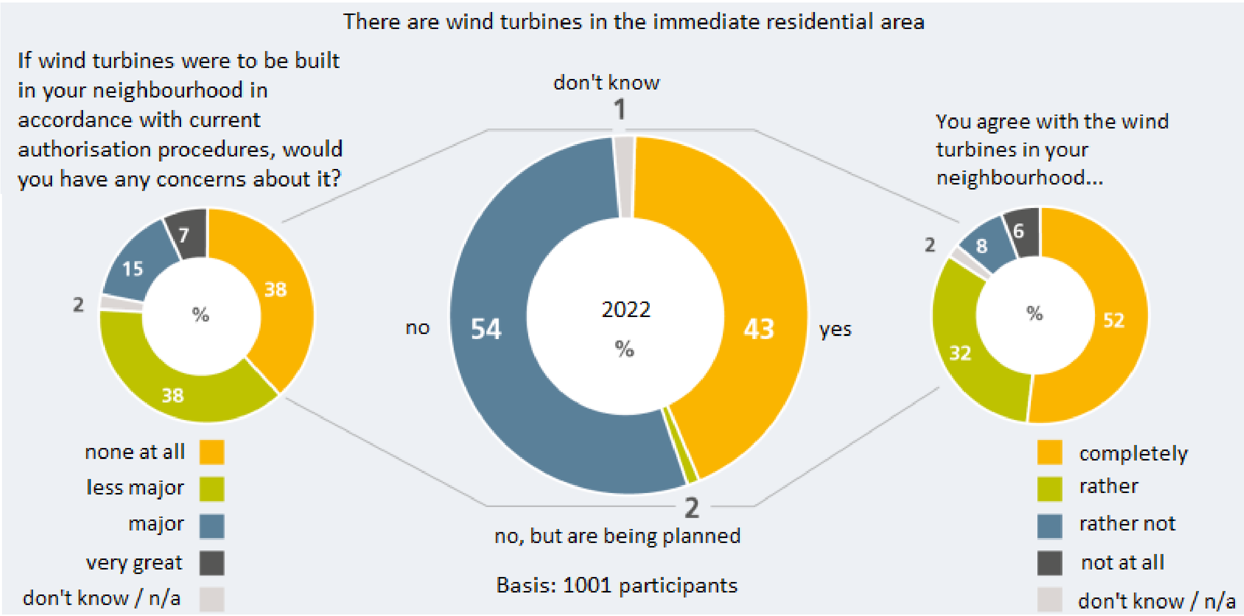

Fig. 4: Opinions on wind turbines near residential buildings. Modified by the author. Based on [36].

6 Conclusion

To summarise, many important aspects should be considered in a repowering project. The wind industry is highly dynamic and conditions can change quickly. There are various reasons for this. One of the main reasons centres on the actions taken to achieve the climate targets. The expansion of wind energy needs to be accelerated, which affects all of the mentioned aspects in different ways. At the same time, new wind energy projects shall be orientated closer to the market to increase competitiveness. Last but not least, the crises of recent years are also causing turbulence and major changes.

Due to the changing conditions, it is difficult to give generalised and quantitative statements. In a repowering project, the aspects explained should be taken into account to draw individual conclusions.

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