REPORT FROM MEGAVIND
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Technological solutions to reduce the environmental impacts of wind-energy systems

MEGAVIND

Contents

Front page: Courtesy of Thomas W. Johansen/Senatur

Courtesy of DONG Energy

1. Preface

Megavind is Denmark's national partnership for wind energy and acts as a catalyst and initiator of a strengthened strategic agenda for research, development, and demonstration (RD&D). Established in 2006, Megavind aspires to strengthen public–private cooperation in order to accelerate the innovation processes in the areas of wind energy that hold the greatest potential for technological development.

Vision and objective

Megavind's vision is to maintain and enhance Denmark's position as the global wind-energy hub and home of the world's leading companies and research institutes for wind energy. Megavind's objective is to facilitate and accelerate the Danish wind industry's journey towards delivering competitive wind energy on market terms.

Work on the present strategy was carried out by a working group consisting of:

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2. Executive summary and key recommendations

Wind energy will continue to play a significant role in moving Danish and European energy systems in a sustainable direction, with a substantial contribution from renewable energy sources. Despite generally strong public support for wind energy, concerns about and opposition to wind-turbine installations are not infrequent. This contributes to longer project lead-times, often raises costs, and leads to some projects being shelved altogether. Such delays and the uncertainty about return on investment increase the risk for project developers and investors and counteract industry efforts to drive down the cost of energy (LCOE) for wind power[1].

The present strategy deals with the environmental impact of wind-energy systems and points at possible technological innovations, as well as knowledge gaps, related to reducing the impact on the environment. The report addresses the environmental impact of onshore as well as offshore projects, and emphasises aspects where research and technological development may increase understanding and mitigate the environmental impact of wind turbines.

The strategy will contribute to maintaining and expanding Denmark's position as the hub of leading global companies and research institutions in the field of wind energy, and help them be the first to deliver competitive wind-energy solutions to the leading wind-energy markets.

Geographically, the strategy focuses on Denmark and northern Europe; however, because the Danish wind industry operates globally and many environmental aspects are cross-border, international aspects are included where relevant.

The strategy is limited to commercial wind turbines and does not include household turbines.

International and cross-border initiatives

In 2015, Denmark, through the Danish Energy Agency, initiated an Intergovernmental Offshore Wind Forum, which invites authorities from all European countries to take part. Two issues in particular have been discussed: models for tendering offshore wind farms and – relevant to this strategy – knowledge of the environmental impact of offshore wind energy and ways to protect the environment. So far, four meetings, during which state-of-the-art knowledge was shared, have been held in Copenhagen, London, Paris, and Amsterdam.

The offshore working group of Wind Europe (previously the European Wind Energy Association) is another international forum for collaboration. Relevant in this context, the working group has issued a series of Research Notes covering offshore wind energy and the environment.

The main recommendations are listed in the next section in order of importance. More details are provided in the sections that follow.

1 Cost of energy equals costs divided by production. More precisely, LCOE expresses the "levelised" unit cost of 1 MWh over the lifetime of the wind farm by taking the sum of the discounted lifetime costs relative to the sum of discounted energy production.

Megavind recommends initiatives in the following areas

1. Wind-turbine noise

- Develop improved tools for characterising, propagating, and controlling noise from wind turbines, and develop more advanced analytical methods to measure wind-turbine noise
- Carry out additional measurements to verify low-frequency sound reduction in houses, and develop a set of tools in case a house requires additional low-frequency noise reduction, for example, using special insulation materials

2. Visual impact

- Develop an interactive visualisation tool (an app) that allows visualisation of a wind farm from any chosen observation point, such as the neighbour's own house
- Carry out further demonstrations of intelligent aviation-obstruction lights for wind turbines using radar control
- Study the attraction effects on migrating birds at existing offshore wind farms during daylight and night-time

3. Wind-turbine impact on radar systems

- Study radar-system performance with respect to the size of an object (for example a ship or airplane) that can be detected in or behind a wind farm, and evaluate the performance of the radar during heavy rain
- Develop a simulation tool to assess radar-system performance during heavy rain, and validate the tool against measurements

4. Birds

- Carry out studies that improve our understanding of bird population sizes and trends, including their migration systems and population dynamics
- Carry out post-construction studies of bird-displacement effects in terms of rate and distance and possible behavioural adaptations to wind farms over time
- Study the effect of bird displacement on additional mortality and reproduction rates
- Develop improved technological solutions and sensor systems for monitoring bird activity near wind turbines, including identifying species, their direction, and flight speed

5. Marine mammals

- Study the effect on harbour porpoises of piling noise from the construction of monopile foundations, in terms of temporary hearing loss
- Study the North Sea harbour porpoise population for numbers, distribution, and movement patterns, to improve understanding of the harbour porpoise

6. Bats

- Study factors that influence the risk of bats colliding with wind turbines, and assess the effect of possible operational adaptations, such as curtailment
- Study bat attraction to turbine structures, caused by, among other things, increased food availability in the form of insects on the blades
- Study methods and devices to repel bats from wind turbines, such as ultrasound

7. Decommissioning offshore wind farms

- Map and assess existing methods for decommissioning offshore constructions as a basis for planning the decommissioning of offshore wind farms
- Develop efficient methods for decommissioning offshore wind-farm structures with minimal environmental impact for different foundation types, including an assessment of the pros and cons of removing substructures

8. Ice throw and blade failure

- Improve tools for predicting ice formation on wind turbines and other structures
- Develop tools for calculating the throwing distance of ice and all or part of a blade
- Develop a tool for assessing the risk of blade failure
- Develop a standardised methodology and a tool for assessing the risk of ice throw

3. Methods and priorities

In May 2013, Megavind published an updated overall strategy, "The Danish Wind Power Hub." It contained the recommendation for a report on "potential technology-based solutions for reducing environmental and other local impacts of wind turbines". This strategy is a direct response to that recommendation.

The present strategy is based on the outcome of a series of meetings of the Megavind working group during 2015–2016, which included discussions of all environmental issues corresponding to what is normally included in an environmental impact assessment (EIA) for an onshore or offshore wind farm.

The working group has applied the following criteria for prioritising issues and impacts in the present strategy.

- The impact on levelised cost of energy (LCOE)
- Issues that can delay or stop project development
- The potential for a technological solution

Less important issues **not included** in the present strategy are listed in Appendix A.

Throughout its work, the working group has endeavoured to find the right balance between areas to which technological and/or functional solutions and recommendations are most beneficial and areas where filling important knowledge gaps is fundamental to progress and lower costs.

The recommendations are thus a mixture of technological solutions and analysis and a search for new knowledge. As a result, recommendations for "the good process" and citizen involvement are not included, although Megavind acknowledges the importance of these areas.
For recommendations about citizen involvement, Megavind refers the reader to the research project "Wind2050[2]."

Onshore and offshore wind energy form two separate business areas. Both are needed to fulfil the ambitions of the 2012 Danish Energy Agreement, which states that Denmark should be independent of coal, oil, and gas by 2050, and the European goal of providing at least 27% of the energy consumed in the EU with renewable energy sources by 2030.

Although the working group acknowledge the challenge of prioritising very different issues from the two business areas, it decided to deal with both onshore and offshore wind energy in the same strategy and rank the research priorities, including both onshore and offshore.

The strategy deals with the impact of wind-energy technology on the environment and does not include environmental effects on the wind turbines, such as lost production resulting from ice on the turbine or wave forces on offshore turbines.

The strategy deals with the impact of wind-energy systems on their surroundings; therefore, health and safety issues for employees working on the turbines are not included.

In the following sections, the primary areas of interest will be analysed, along with Megavind's recommendations for research, development, and demonstration. It should be emphasised that the topics appear in order of importance, as ranked by the Megavind partnership.

1. Noise
2. Visual impact
3. Impact on radar
4. Birds
5. Marine mammals
6. Bats
7. Decommissioning offshore wind farms
8. Blade failure and ice throw

Although the topics are ranked in order of importance, this does not apply to the recommendations listed under each topic.

2 www.wind2050.dk

4. Noise

To make recommendations in the area of noise research, it is important to understand both the level of existing noise limits and how noise from wind turbines is assessed, which will be analysed in this chapter.

4.1. What are the noise limits?

Although the noise level from operating wind turbines is not higher than other sources of noise in our society, the issue receives considerable attention in the planning phase of a wind farm. For reference, Table 1 shows the limits for noise from wind turbines in Denmark. The general noise limits (open country and in residential areas) are valid outdoors and less than 15 m from dwellings.

Table 1
Limits in Denmark for wind-turbine noise[3]

Noise limits dB(A) Outdoors, <15 m from dwellings	**Wind speed**	
	6 m/s	**8 m/s**
Houses in the open country	42	44
Residential areas	37	39
Low-frequency noise 10–160 Hz Inside a house	20	20

As points of reference, the sound level of a person whispering 30 cm away is approximately 42 dB and a laptop computer 1 m away is approximately 35 dB. Appendix B gives further examples of sound levels.

In 2012, Denmark became the first country in the world to set limits for low-frequency noise, i.e. noise at frequencies below 160 Hz. The limit is 20 dB calculated inside a house. Low-frequency noise can be caused by moving mechanical parts in the nacelle, aerodynamic interaction between the rotor and the tower[4], or blade interaction with turbulent inflow.

4.2. How noise is assessed

The following describes the principles of assessing noise from a wind turbine. The noise is always calculated and evaluated outside houses where people live. The noise contribution from all nearby wind turbines is taken into account, because the overall noise level is of primary importance[5]. Figure 1 illustrates the three steps in calculating the noise level from a wind turbine outside a neighbouring dwelling. Each step of noise generation, noise propagation, and noise reception is described below. The analysis of each step will lead to recommendations concerning noise.

3 Noise Order No. 1284, 15 December 2011

4 http://share.madebydelta.com/wp-content/publications/akustik/paper_og_rapport/Low_Frequency_Noise_from_Large_Wind_Turbines_-_Summary_and_Conclusions_on_Measurements_and_Methods.pdf

5 Noise from Wind Turbines, Recommendation No. 1, the Danish Environmental Protection Agency, 2012

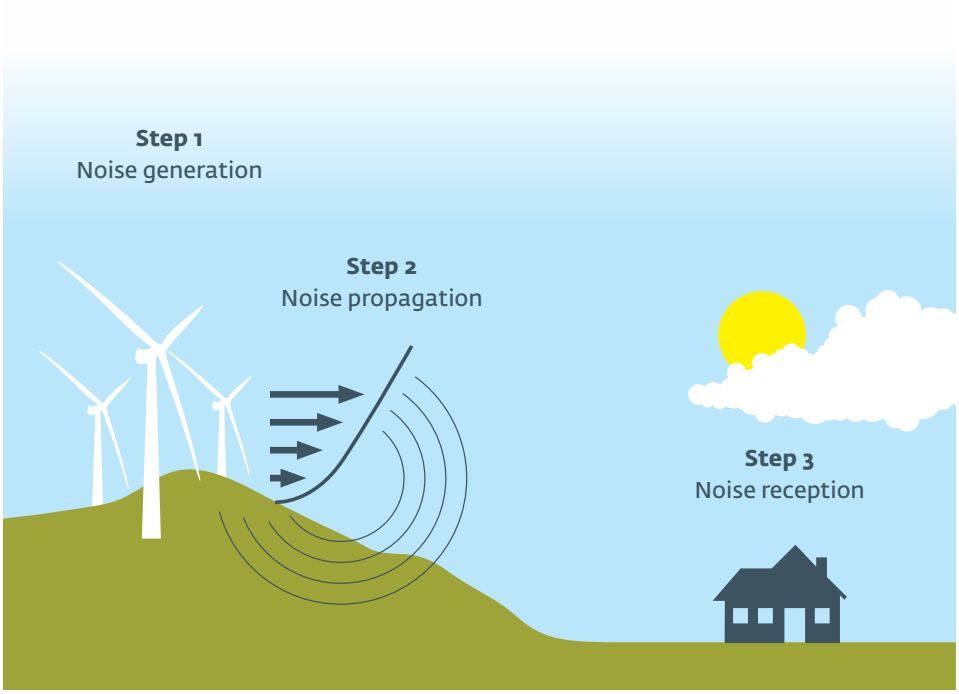


Figure 1
The three steps in the prediction of noise from a wind turbine.

4.2.1. Noise generation

Noise from a wind turbine can be separated into mechanical noise and aerodynamic noise.

Mechanical noise

Mechanical noise is generated by components in the nacelle, especially the gearbox and generator. Mechanical noise can contain pure tones in contrast to broadband noise, which consists of many frequencies from the blades. Pure tones above a certain threshold can be distinctly heard, which is potentially annoying. Mechanical noise can be reduced in many ways, for example by proper gearbox design and maintenance, and good acoustic insulation of the nacelle. For modern, well-maintained wind turbines, mechanical noise is normally low and does not influence the siting process. Therefore, Megavind does not recommend specific initiatives in relation to mechanical noise. Some wind-turbine designs include an external fan coil or heat exchanger to expel internal waste heat into the environment. A heat exchanger with a fan for forced cooling is an additional potential source of noise, however technological solutions exists in this area.

Aerodynamic noise

The second and most important type of wind-turbine noise is generated by the movement of the blades through the air (aerodynamic noise). The noise is generated principally at the trailing edge and near the tip of the blade and is amplified by atmospheric turbulence (eddies or chaotic flow). For turbines operating in clusters or wind farms, the complex inflow from upstream turbines can likewise increase the noise generated. Furthermore, the emitted noise scales up strongly with the velocity at which the blades are moving relative to the airflow.

Besides turbulence in the inflow air, the vertical wind-speed profile (shear) is also an important influence on the noise generated, because wind speed increases with height above the ground. Today's large turbines have rotors with large vertical spans (100–150 m), with a wide variation of wind speeds from the lowest to the highest points. When the rotor blade moves from bottom to top and experiences this cyclic change of wind speed, the aerodynamic noise changes

cyclically. The shear profile depends on terrain and meteorological conditions. It is believed to be a major source of noise amplitude modulation, which in some situations of shorter duration can be heard as a cyclic variation and modulation of the aerodynamic broadband noise from the turbine.

It is possible to reduce aerodynamic noise either by suppressing or reducing the intensity of the noise sources (by applying noise-optimised airfoils, reducing the rotor speed, and pitching blades) or by altering the interaction mechanism that produces noise (by applying serrations or brushes to the blade's trailing edge). Many turbines are equipped with a noise-reduction operation mode, where both wind-turbine power output and aerodynamic noise generation are reduced.

To improve the models of aerodynamic noise generation for wind turbines in particular, it is important to be able to characterise the generated noise accurately, including the amplitude (intensity). More work is therefore needed in this area.

The noise levels mentioned in Section 4.1 involve the accumulated effect of all wind turbines, both new and existing, in an area. In some cases, it may be more beneficial and cost-effective to reduce the noise emission from existing turbines, which requires tools to reduce both mechanical and aerodynamic noise from existing (old) wind turbines.

4.2.2. Noise propagation

Overall, noise intensity decreases proportionally to the square of the distance from the source. Viscous effects of the atmosphere and reflections from the ground provide damping (noise reduction), which is most effective at high frequencies. Therefore, low-frequency noise travels significantly farther from the source. The impact of the mechanisms of amplification and/or attenuation of the propagating noise depends on the configuration of the terrain, wind direction, and atmospheric stability conditions. The interaction of these effects results in complex patterns. For example, temperature stratification (layers in the atmosphere with different temperatures) and wind shear can cause the noise path to be bent upwards or downwards, respectively, creating locally silent or high-noise-level zones at considerable distances from the turbine (Figure 1, Step 2).

The models used to calculate noise at the receptor (often a house) already include many of the issues mentioned above; however, the models can be improved, for example with respect to the variation of the noise with time (noise amplitude modulation).

4.2.3. Measurement of noise

The noise contribution from a wind turbine at a receptor, such as a house, is often at the same level or lower than the background noise generated by the wind in the vegetation (trees) around houses, traffic, and so on. Consequently, measuring wind-turbine noise is very difficult outside the house (for general noise) and even more difficult inside the house (where the low-frequency limits in Table 1 apply). Instead, measurements are taken close to the turbine in a downwind direction (Figure 1), and the overall noise level at the receiver is calculated by the noise-propagation model used in the country in question. For low-frequency noise, the damping by the house is taken into consideration by applying a sound-insulation value corresponding to a modern Danish house.

The values applied to the damping of low-frequency noise by a house, however, are based on relatively few measurements. It is recommended that the basis for these calculations be extended by taking additional measurements to increase confidence in the sound-insulation values used to make the calculations. If measurements reveal generally lower sound-insulation values than have been assumed, the values must be improved. One way is to increase the house's sound insulation at lower frequencies, for example by installing noise-damping panels inside the house. Megavind recommends developing a toolbox that includes a set of standardised modifications to a house with known effects. These will facilitate the work as well as expedite budgeting.

4.2.4. Noise perception

An important aspect of wind-turbine noise is how it is felt/perceived by humans. This has two aspects. First, each person is physiologically different and will not hear the sound with the same intensity. Second is the annoyance felt as a result of the noise. Individual psychological factors play an important role in how noise is perceived and assessed by humans. Research reveals that the environment and the view (are wind turbines visible?) also influence how noise is perceived and whether it is annoying or not. This means that, although a neighbour living close to a wind farm and feeling a certain noise level may not be annoyed, another neighbour living farther away from the same wind farm may perceive the (objectively lower) noise level as annoying. As mentioned in Section 4.2, in addition to noise perception, meteorological conditions also have an impact.

To illustrate wind-turbine noise, a kit has been developed that allows individuals wearing a special headset to experience an audio demonstration of wind-turbine noise under different conditions. Experience shows, however, that perceived turbine noise depends on a number of factors (such as, can the person see a wind turbine?), not all of which are easily controlled. Therefore, Megavind recommends that the noise-illustration kit be validated by evaluating under which conditions it might provide additional information to the public, especially neighbours of a wind farm.

The potential impact of wind-turbine noise on human health has been investigated in a separate study[6] and is not included in this strategy.

Megavind's recommendations concerning noise

The following recommendations are based on the analysis above, taking into account both the level of existing noise limits and how noise is assessed.

- Develop improved tools for noise characterisation, propagation, and control, including noise amplitude modulation
- Develop a toolbox for new as well old houses, to increase damping of low-frequency noise
- Develop a toolbox for noise reduction of existing turbines
- Develop improved methods for analysing wind-turbine noise measurements, by improving knowledge of noise variability
- Verify low-frequency sound-reduction values for houses through additional measurements
- Evaluate a kit for illustrating noise levels, to be used at public meetings

6 http://vindinfo.dk/sundhedsundersoegelse.aspx

5. Visual impact

This chapter contains recommendations concerning visual disturbance and landscaping, and aviation obstruction lights.

5.1. Visual disturbance and landscaping

As with noise, visual impact is very important in siting wind turbines. A wind farm requires more area for the same output than a coal-fired power plant (without the coalmine facilities), because of the wind resource's lower energy density. More importantly, a wind farm's placement makes it very visible in the landscape, because it must be exposed to the wind.

Evaluation of visual impact is a multidisciplinary and subjective issue that draws on aspects of sociology, psychology, and geography, as well as engineering. It is clear that aesthetic values play a central role in shaping attitudes and perceptions, as do the experiences associated with the landscape where the person in question lives.

Today, visual impact is judged by means of visualisations based on photos taken from positions where many people will see the wind farm, overlaid with images of the wind turbines in the correct location and relative size.

Figure 2
The impact of two different sized wind turbines, illustrated by a visualisation of three 1.75 MW (93 m) turbines (top) and three 3.6 MW (150 m) turbines (bottom) from a Danish project in the Gisselbæk Danish Energy Authority (2010).

Typically, the visual impact is judged at three different distances: a short distance where the wind turbines are larger than any other feature in the landscape; a medium distance where the wind turbines are similar in size to other features of the landscape; and a long distance where the wind turbines are generally smaller than other features of the landscape. Different types and numbers of turbines are compared at these distances. An example of the impact of size is shown in Figure 2. The top photo shows wind turbines appearing to be of similar size as the landscape features. In the lower photo, seen from the same distance, the larger turbines appear larger than the landscape features and therefore more dominant.

On land, the visual impact on the landscape will be limited by landscape features, such as hills, mountains, trees, and houses, which restrict the observer's view. Offshore and nearshore wind farms will be visible for long distances, and the farms' visibility from the coast – which many associate with recreation – is a challenge.

Because of its subjective nature and the difficulty of establishing thresholds, the visual impact of a wind farm is by far the most difficult aspect of planning and development to mitigate. Denmark requires[7] that the layout pattern of an onshore wind farm should be easily recognised, for example, groups of 3–4 turbines should be sited in straight lines, and larger groups should be sited in straight lines or arcs, or follow specific features of the landscape, such as a dike. Regulations also require that a group of turbines or a wind farm have the same type, colour, hub height, rotor diameter, and rotational speed. These requirements for a homogeneous appearance minimise the visual impact on the landscape.

The EIA report includes a number of visualisations from points where many people will view the wind farm. To supplement the "official" visualisations in the EIA report, Megavind recommends that the feasibility of developing an interactive visualisation tool be investigated, which can be used, for example, at public meetings. Using maps of the wind farm and related data, the tools should be able to create rough visualisations from any position at or farther from the wind farm.

7 Recommendation for planning wind turbines, The Danish Nature Agency, 2015. https://erhvervsstyrelsen.dk/sites/default/files/vejledning_06012015_web.pdf

5.2. Aviation obstruction lights

Usually, the visual impact of a wind farm is greatly reduced at night. This may not be the case, however, if legislation requires aviation-warning lights on the turbines. Obstruction lights are required day and night on all structures taller than 150 m. If lights are required, simple measures can be taken to reduce their visual impact. These include synchronising their intermittent light, placing shielding around the lights so that they can be seen only from heights greater than the turbines (that is, from an aircraft), and reducing light intensity during periods of good visibility. For wind turbines with a total height greater than 150 m, white flashing lights are used, and the lights' intensity is controlled in two steps: a medium-intensity daytime light of 20.000 candela, and a night-time intensity of 2000 candela. Furthermore, two low-intensity red lights are required on the nacelle.

In areas near wind farms with limited air traffic, it is possible to control the obstruction lights using a radar installation to detect approaching aircraft. The obstruction lights are shut off most of the time and only lit when an aircraft is approaching (intelligent or on-demand aviation obstruction lights). Figure 3 shows the principle behind Denmark's first demonstration installation at the Danish National Test Center at Østerild. Because commercial aircraft fly at high altitudes, the radar control is relevant only to local traffic consisting of small aircraft flying at relatively low altitudes using visual navigation.

Several systems are being developed. Some are based on a single-turbine approach, where each wind turbine has its own radar. Other systems are designed to control an entire wind farm or even several wind farms placed in different sectors, as seen from the radar. These systems are still under development and Megavind recommends further demonstrations of intelligent aviation obstruction lights for wind turbines.

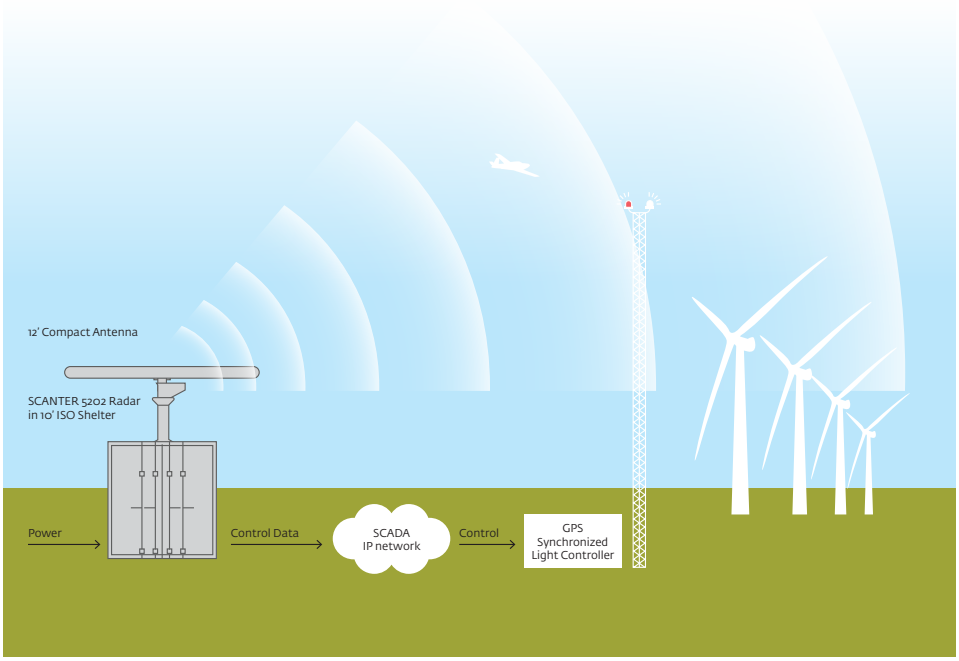


Figure 3
System for radar control of obstruction lights at the Danish National Test Center at Østerild. Used with permission of Terma.

For nearshore wind farms, obstruction lights can be seen over long distances, because the sea has no hills or trees, and a reduction in the time the lights are lit will be perceived as being beneficial.

Another less expensive technological solution is to install transponders in all aircraft, similar to those used by commercial aircraft[8]. Only aircraft with a transponder will be "seen," and the aviation lights will be turned on. The dilemma is that the commercial aircraft that have these transponders do not come near wind farms, whereas small, private pleasure aircraft might or might not have a transponder that is well maintained and in operational condition. This will require that transponders be made mandatory in all aircraft. Transponders have been considered in other Scandinavian countries (Norway and Sweden), but were not selected as the preferred solution for the reasons mentioned above. Therefore, Megavind does not recommend a transponder solution.

Studies indicate that, in some cases, offshore wind farms can attract migrating birds. It is believed that the obstruction lights attract the birds. The attraction of migrating birds by aviation lights may increase the risk of collision with wind turbines. The level of attraction seems to depend on the lights' colour (green seems less attractive to migrating birds), intensity, and light operation (flashing vs. permanent light). More knowledge of these phenomena is required. In any case, it is clear that solutions that allow on-demand operation of aviation lights will significantly reduce bird collisions.

Megavind's recommendations concerning visual impact

- Develop an interactive visualisation tool that allows observers to choose the point of observation and view a visualisation of the proposed wind farm from the point of view of their own house. This might be in the form of an app for mobile platforms to be used, for example, at public meetings
- Demonstrate intelligent obstruction-light systems for onshore and nearshore wind farms
- Study the attraction effects from lights on migrating birds to existing offshore wind farms during daylight and night-time.

8 http://www.trafikstyrelsen.dk/DA/Databases/~/media/Dokumenter/05%20Luftfart/01%20Publikationer%20luftfart/Aeronautical%20marking%20and%20lighting%20of%20wind%20turbines.ashx

6. Wind-turbine impact on radar

At airports and military installations, long-range radar installations are used to monitor air traffic; similarly, military surveillance radar is used to monitor the airspace around a military installation. These radar systems are capable of detecting an aircraft's position and speed some 80–400 km away. A large wind farm consisting of several wind turbines placed close by might affect the radar, causing areas where the radar cannot detect flying objects and/or creating false signals. The default solution so far has been to locate wind farms farther from airports or military installations. To avoid this, several mitigation measures have been promoted by different radar manufactures, each with different capabilities. These have been offered either as an update or replacement of the primary radar or as the addition of a second gap-fill radar to supplement existing radar.

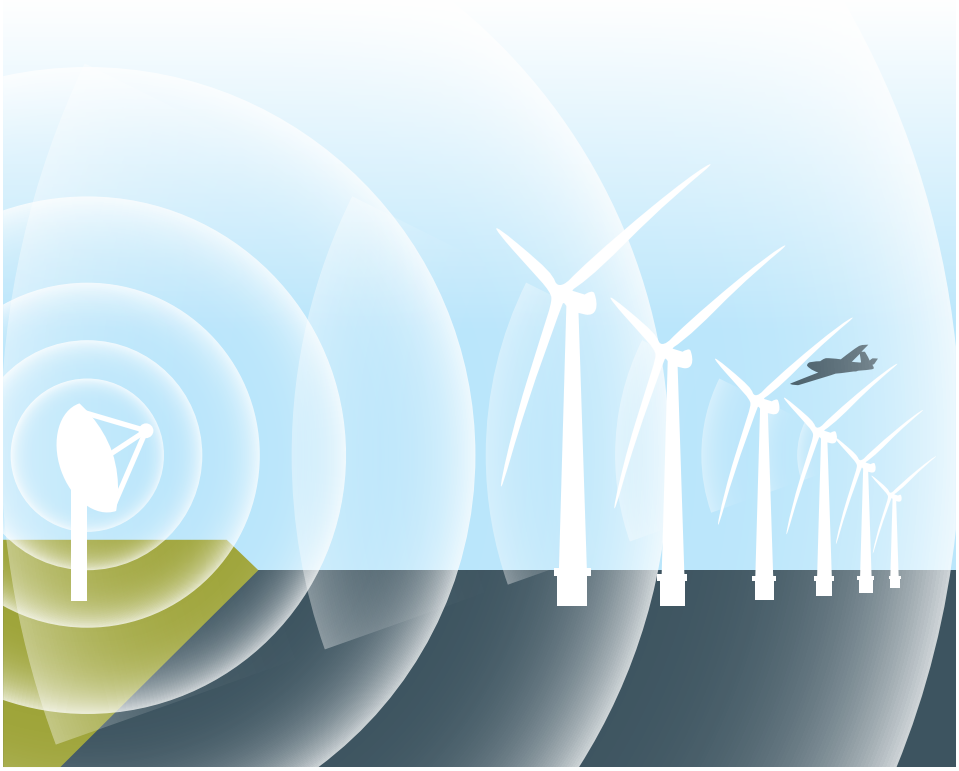


Figure 3
The effect of wind turbines on radar systems

Another possible solution is to modify the wind turbines, not the radar installation, by giving the wind turbines a "stealth" appearance, using military technology to reduce the turbines' visibility to the radar. This has been implemented at one of France's largest onshore wind farms, the 96 MW Ensemble Eolien Catalan located in southern France. In many cases, however, it is more cost-effective to upgrade the radar systems to better distinguish wind turbines from other moving objects than modifying all of the wind turbines.

One general problem with radar detection of objects flying near or behind a wind farm is to quantify the "radar cross section" of the object for different wind turbines in the different frequency bands. This is required to develop a suitable method to evaluate the ability of individual radar types to distinguish flying objects from wind-farm turbines.

Another general problem is determining radar performance during rain. Typically, different, constant rain situations are evaluated when specifying the precipitation capabilities of a radar, which are not the same as the real weather conditions under which radar operates. Therefore, better models or simulation tools are required, capable of representing the distribution of precipitation, both in range and altitude, based on live data collected from meteorological institutes or other recognised sources.

Megavind's recommendations concerning wind turbine impact on radar systems

- Study radar-system performance with respect to the size of an object (for example a ship or an airplane) that can be detected in or behind a wind farm, and evaluate the radar's performance during heavy rain
- Develop a simulation tool to assess radar-system performance during heavy rain (including a realistic precipitation scenario), and validate the tool against measurements.

Test installation of SCANTER 4002 radar, CPH Airport

7. Birds

Birds are an important concern, both offshore and onshore, because they often affect the position and number of wind turbines to be erected. The impact on bird communities and individuals can be divided in two categories: displacement from the wind-farm area and the risk of collision with wind turbines. These two distinct effects may involve breeding birds or migrating and resting birds in a wind-farm area. Potential effects on bird displacement have led to the cancellation of planned offshore wind-farm construction, such as the UK Docking Shoal wind farm. Recently in Denmark, a site at Sejerø Bay was removed from nearshore tendering because of impacts on sea ducks. Generally, bird collisions with wind farms are not the most significant impact on birds. Collisions with traffic and power lines can have more significant effects. For several birds of prey and other larger bird species, however, collisions with wind turbines can be the most significant impact and a threat to population stability. Known examples include impacts on red kite populations in Brandenburg, Germany, and impacts on the white-tailed eagle in the Norwegian municipality of Smøla.

Despite a substantial effort in recent decades to improve the scientific basis for analysing bird-population status and the effects of collision and displacement, important knowledge gaps still exist, leading to an excessive reliance on the precautionary principle when evaluating the effects of wind-farm projects on birds, in this case, leading to very conservative assessments resulting from lack of data.

A significant challenge is that different bird species respond differently to wind farms. There is no one-size-fits-all answer. Knowledge building should thus concentrate on conflicts with species of key concern. In addition, developments in recent decades in turbine size, inter-array spacing, and noise mitigation possibly cause birds to perceive a modern wind farm with large turbines differently from an older wind farm with smaller turbines and very different spacing. Consequently, knowledge of bird behaviour must be understood as being partially dynamic, changing with the overall development of turbine and wind-farm size.

Photo John Larsen, DOF

7.1. Displacement of birds from wind farms

We are interested in building offshore and nearshore wind farms in shallow waters to minimise the investment. In some cases, these areas can be important feeding grounds for certain water birds. This may lead to bird displacement, which is considered the most important bird-related issue concerning offshore and nearshore wind farms in northern Europe. In this context, displacement means that the effect of human activity and the physical presence of a wind farm in an area may lead the birds to leave the area. The displaced birds will then move to other areas, where bird density and competition for food resources may increase, which can ultimately lead to decreased survival or reproduction of the affected individuals. For onshore wind farms, bird displacement is not normally an important issue.

Today, bird displacement from offshore and onshore projects is well documented in only a few studies and for a few species. But as the number of wind farms increases and their operational years expand, better documentation will be available with variations in location, type of habitat, and possible species adaptation to wind farms. This will help qualify the evaluation and decrease dependence on the precautionary principle.

The effect on mortality and reproductive success, caused by a higher concentration of displaced birds, is based on unproven assumptions. It is important to note that this factor has a great influence on the result of the assessment. For example, in Danish nearshore wind-farm projects, the assessment of the lethal effects of displacement on the common scoter was based on a reference study[9] of variations of oystercatcher (Danish: strandskade) winter mortality related to the density of birds on mudflats in England. Obviously, species-specific knowledge of density-dependent mortality will lead to more precise evaluations of the effects of displacement.

When assessing the impact of potential displacement-induced increases in mortality on the overall population level, potential biological removal (PBR) is often used. This simple method is applied in the absence of precise knowledge of population size and other human effects on the population. The more accurate the knowledge of these factors, the more precise and robust the evaluation of the effect of a wind farm will be, allowing the application of models that are more developed and realistic. Limited knowledge of these factors increases the assessed population impact, because of reliance on the precautionary principle.

The following questions point to important knowledge gaps

- What percentage of resting birds at a species-specific level will be displaced from the wind-farm area, and what are displacement distances at a species-specific level in the surrounding area?
- What are the consequences of displacement on the survival of the affected individuals?
- What is the status of the affected populations (size and trend), how are populations defined, and what are the human pressures on the population in general?

9 Durell, et al. (2001; 2000); Goss-Custard and Durell (1984).

7.2. Collision risk

Collision risk can be viewed as either a local risk related to breeding bird species and resting birds, or a regional-scale risk related to migrating birds. Local birds are subject to collision risk on a daily basis, whereas migrating birds are subject to collision risk on an annual basis. For onshore development, it is evident that several species of medium- and large-sized birds of prey, in particular, collide relatively frequently with turbines (buzzards, kites, eagles, and vultures). It has also been demonstrated that many other species collide with onshore turbines. In general, the number of collisions with individual onshore turbines is small (0–43 birds per turbine per year)[10]. Knowledge of collision risk is species or group specific, and methods are based on a number of assumptions required to model the collision risk. Important assumptions include flight height and speed and avoidance behaviour to rotor blades on different scales. The important knowledge gaps relate to the validation of assessed collision rates/probabilities. To collect data on collisions and avoided collisions, human observation and technological solutions can be applied. However, the sensors available to detect birds cannot deliver the type of reliable data needed to increase knowledge and, based on that, develop technological solutions to minimise or avoid collisions. Moreover, understanding of behavioural responses leading to collisions (or avoidance) is important in developing effective mitigation methods.

Megavind's recommendations on bird collision and displacement

- Conduct general studies leading to a basic understanding of population sizes and trends, migration systems, and population dynamics
- Study post-construction, species-specific displacement effects repeatedly for rate and distance and possible behavioural adaptation to wind-farm disturbance over time
- Study the effects of bird displacement on additional mortality and reproduction rates
- Develop technological solutions and sensor systems – improved in cost, mobility, and accuracy – for monitoring birds near wind turbines, including identifying species and determining flight direction, altitude, and speed. Better technological solutions will provide improved validated data on collision/avoidance rates as well as support the development of mitigation methods, that is, solutions to detect and avoid collision

Recommended offshore focus species: common scoter, velvet scoter, common eider, red-throated diver, and long-tailed duck.

Recommended onshore focus species (Denmark): red kite, Bewick's swan, pink-footed goose.

10 Everaert (2014). Collision risk and micro-avoidance rates of birds with wind turbines in Flanders. Bird Study, DOI: 10.1080/00063657.2014.894492

8. Marine mammals

Today, most offshore wind farms are installed on large, steel monopile foundations that are impact-driven into the seabed, leading to high noise emissions into the water column during the construction. In the North Sea and Baltic Sea, where a significant percentage of the world's offshore wind-energy development is taking place, two mammals are primarily relevant: harbour porpoises (a small whale) and seals. Studies reveal that the harbour porpoise is the more sensitive of the two and, for this reason, the following analysis is based on this species, assuming that seals are also covered by the analysis.

The harbour porpoise uses echolocation for communication and detection of prey, and can be affected by the underwater noise from piling activities. For this reason, the interaction of harbour porpoises and pile-driving is an important issue in the approval and construction of offshore wind farms in the EU. This section considers this issue.

Limits on the impact of piling activities are being implemented in all European countries to protect harbour porpoises and other marine mammals against the harmful effects of underwater noise. These are based on assessments of thresholds for affecting populations and damaging hearing of individual mammals. The national implementation, however, is quite different.

The regulation may – as in Germany and, more recently, in Denmark and the Netherlands – be implemented and expressed as a requirement to:
(1) Repel the animals from the construction site area;
(2) Limit noise emissions to a certain dB-threshold value;
(3) Mitigate noise during piling, if the threshold cannot be met. Because pile driving for offshore wind-farm projects causes noise emissions that typically exceed current threshold values in the range 12–20 dB, the application of noise-mitigation systems is necessary.

Results from wind farm projects installed in German waters in recent years have demonstrated that the German noise threshold (currently the strictest) can be met through the application of various technological mitigation tools. The cost of the necessary noise mitigation is, however, substantial, and experience from a range of German projects demonstrates that the current cost of noise mitigation alone accounts for 1,5–3% of the total project investment or EUR 15–35 million per project[11]. This is expected to increase in the future, because larger turbines require larger foundations, which in turn require greater piling energy, resulting in increased noise emission.

At the same time, the available biological knowledge and scientific background behind the current regulations and requirements for underwater noise mitigation across the EU are weak. Actual knowledge of the significance of piling noise effects on marine mammals is extremely limited. Current threshold limits for underwater noise related to injury are all based on one study[12], where temporary hearing loss was studied in a captive porpoise exposed to single air gun pulses. More recent work, based on captive porpoises exposed to playback of piling noise, indicates much higher onset levels[13]. From research on temporary hearing loss, permanent hearing loss can be estimated without harming the animals.

Such limited, basic knowledge causes great uncertainty about current noise thresholds and the application of a high level of precaution.

12 Lucke, et al. (2009)

13 Kastelein, et al. (2015)

In a regulatory context, the significance of the disturbance caused by wind-farm construction noise is related to the consequences for the affected population. Evidence is growing, based on the distance and duration of disturbance during piling, and it is well established that porpoises will return to the site soon after construction is completed. Understanding the consequences of this temporary disturbance on the survival and reproduction of the affected individuals, and ultimately the viability of the population, is a significant challenge.

Within the joint industry-funded DEPONS project (Disturbance Effects on the Harbour Porpoise Population in the North Sea), the Danish Centre for Environment and Energy (DCE) at Aarhus University is currently developing an individual-based model to address this question about the porpoise population in the North Sea[14]. Research and monitoring that could help further strengthen the development and application of this model would be valuable and could include, among other things, tagging and improved monitoring of porpoises in the North Sea to enhance understanding of their movement and distribution patterns, population size, and development.

Megavind's recommendations concerning marine mammals

- Study the effect on harbour porpoises of piling noise in terms of temporary hearing loss
- Conduct studies to improve understanding of the harbour porpoise population in areas where many wind farms are installed, such as the North Sea, in terms of numbers, distribution, and movement patterns.


Courtesy of Fjord & Bælt, Florian Graner

14 DEPONS webpage at DCE Aarhus University; http://depons.au.dk/

Courtesy of NatureEyes/Kim Aaen

9. Bats

The interaction of bats with wind turbines is a relatively new issue in Denmark and little is known about it, although many studies have been carried out, especially in Germany and North America, of onshore wind farms. For this reason, the topic has been included in the present strategy. Bats are seldom considered an important issue for offshore wind farms.

Most bat species are active only at relatively low wind speeds, typically at wind speeds lower than 5 m/s, although occasionally vigorous activity has been observed at wind speeds as high as 6–7 m/s.

North American studies have revealed reductions in bat fatalities when the blades are pitched at wind speeds lower than those used by normally operating turbines. Systems to control a "bat-friendly" turbine operation are under development in Germany and the US. These systems advise the turbine to shut down during periods of substantial bat activity, assuming that substantial bat activity equals high collision rates. This may or may not be the case. However, a better understanding of when collisions take place would probably improve and increase the application of such systems to optimise curtailment, so minimising power-production loss.

An alternative to shutting down turbines, which leads to a loss of production, is to frighten the bats that have been attracted. One method being investigated is the use of ultrasonic transmitters to repel the bats from the rotor-swept area and thereby reduce bat fatalities, but further testing of the technology is needed.

Recent studies indicate that the surfaces of the turbines (the tower and nacelle in particular), which are heated during the day and emit heat at night, may attract nocturnal insects and consequently lead to bats concentrating in the area to feed on the insects. It must be determined whether this phenomenon poses a significant danger or not. If so, relevant mitigation methods must be developed.

Megavind's recommendations concerning bats

- Study factors that influence collision risks and possible operational adaptations, such as curtailment
- Study methods and devices for repelling bats, such as ultrasound
- Study factors causing bat attraction to turbine structures, caused by, among other things, increased food availability in the form of insects on the blades

10. Decommissioning

In general, wind farms produce a small amount of waste during their lifetime, most notably, used lubrication oil from gearboxes and hydraulic oil from pitch systems. Solid waste consists mostly of packaging for spare parts (wood and cardboard). These sources of waste are well known, and the Danish recycling system is well equipped to handle them.

The decommissioning of wind farms is an issue that has emerged recently. Onshore, in several repowering schemes, small (kW), outdated wind turbines have been dismantled to allow larger (MW), modern turbines to be erected. In most cases, the procedure has not generated a large amount of waste, because the wind turbines were purchased by specialised companies that refurbished and resold them, often to eastern European or developing countries. The first offshore wind farms have just started to be decommissioned. This topic is treated in the following section.

10.1. Decommissioning offshore wind farms

Decommissioning offshore wind farms still lies mostly in the future. The first decommissioning of an offshore wind farm, Yttre Stengrund, occurred at the beginning of 2016, after only 13 years of operation. It consisted of five 2-MW turbines and was located in the Swedish waters of the Baltic Sea. The turbines were part of a small series of only 50 wind turbines, and getting spare parts was increasingly difficult.

Figure 4
Decommissioning the Yttre Stengrund wind farm in February 2016.

With an agreed operational lifetime of 25 years, the oldest Danish offshore wind farms will enter the decommissioning phase in the next decade. The world's oldest offshore wind farm, Vindeby, will be decommissioned in 2016.

The current decommissioning requirements set by the EU are mainly theoretical and lack practical application to verify their functionality. With some variation among countries, requirements typically include removing cables and foundations and cutting off the foundation below the surface of the seabed, restoring the seabed to its former condition, and removing the scour protection, if necessary. It is likely that requirements will be imposed mandating the use of the best available technology and environmental practice in removing the plant.

In a recent report on regulatory practice in offshore wind[15], the offshore wind industry emphasised that, as decommissioning practice and technologies develop, requirements must be continuously improved through collaboration between the industry and authorities. Further, the report proposes that decommissioning requirements for individual wind-farm components should be assessed on a site-specific level, based on safety, economic, and environmental considerations. Generic requirements should be avoided. The site-specific assessment should consider the necessity of cable removal, foundation removal (to a reasonable level below the surface of the seabed and depending on the foundation type), scour protection removal, and all structures above the seabed.

For owners of wind farms, confidence about the regulatory framework for decommissioning and the development of a proof of concept for decommissioning technologies is vital for minimising uncertainty and therefore reducing the cost of energy.

Planning for the removal of the Vindeby plant is in progress. It is anticipated that all structures and components will be removed completely. The foundations are gravity-based concrete structures, and their removal will probably be the reverse process of the installation. Because no precedent or state-of-the-art exist, bidders in the tender process will propose methods of decommissioning.

It will be possible to extend the lifetime of some wind farms with limited investment. Aspects of this decision will be further elaborated in a separate Megavind strategy on the extension of lifetime.

In line with proposals advanced by Wind Europe (previously the European and the impending need for applied and balanced requirements to allow safe and environmentally optimal decommissioning at the lowest cost, Megavind recommends the following.

Megavind's recommendations concerning decommissioning offshore wind farms

- Map and assess existing methods for decommissioning offshore constructions
- Develop efficient methods for decommissioning offshore wind-farm structures with minimal environmental impact for different foundation types
- Assess the pros and cons of removing substructures after their end of life, including the benefits to marine life of removing such components as scour protection and parts of the foundation on the seabed
- Study and assess recycling and reuse of composite (glass/carbon fibre) parts

15 Regulatory Practices in Offshore Wind: A Report from the Offshore Wind Industry, November 2015, EWEA

11. Ice throw and blade failure

Ice throw

In cold climates or at high altitudes, ice can form on a wind turbine's rotor blades and nacelle. The amount of ice accretion depends on meteorological conditions and the wind turbine's operational mode. The icing of wind-turbine components certainly affects turbine performance, but ice shedding affects the safety of both the general public and maintenance crews (employee safety is outside the scope of this strategy). Ice shedding is a sudden detachment of ice pieces of different weights and shapes from the tower, nacelle, and rotor-blade surfaces. It can occur during standstill, idling, or normal operation. Rotor-blade ice can be detached by natural conditions, such as increasing ambient temperatures, or through the operation of a de-icing system.

Figure 5
A wind turbine with ice in Northern Sweden.

In parts of the world such as Sweden, Canada, Russia, China, and alpine regions, winter ice accretion is significant, and the risk of ice throw is high. Therefore, access to wind farms is often controlled during winter for service crews as well as for the public. Other environmental impacts of icing include increased noise emission when the wind-turbine rotor is iced and iced obstruction lights, potentially leading to dangerous situations for aircraft. For wind turbines located in or near areas with public access, a risk assessment is often made in connection with the environmental impact assessment (EIA).

In order to carry out a risk assessment, information is needed about how much and what type of ice is formed and under what conditions it is detached from the turbine. A tool must be developed to calculate throwing distances under various conditions.

Ice throw is a leading topic for the IEA Wind Task19 Wind Energy in Cold Climates and is included in its work programme for the period 2016–2018. Members of the working group represent Austria, Belgium, Canada, China, Denmark, Finland, Germany, Norway, Sweden, Switzerland, and the UK.

In Denmark, the winter climate is relatively mild and the risk of ice throw is low.

Blade failure

In the early days of wind energy when the technology was young, wind-turbine blades sometimes failed, and all or part of the blade might be thrown from the turbine. Often, this occurred in connection with a faulty turbine-control system. With today's modern wind turbines, this is a rare occurrence. Publically available information about failure rates for older wind turbines indicates that the failure rate is on the order of 10^{-4}–10^{-3} per year[16]. This includes failures where all or part of the blade is thrown (up to 500 m) from the turbine. No information is available about new wind-turbine blades. The latest international standards for structural design requirements[17] demand that the target annual failure probability for wind turbines is equal to 5×10^{-4}. By comparison, buildings in Denmark are designed to an annual failure probability equal to 10^{-5}.

Owing to the risk of ice throw and blade failure, as well as the risk to drivers of being distracted, the recommended *minimum* distance from major roads in Denmark is equal to the total height of the wind turbine[18]. Local conditions might initiate a concrete risk assessment in connection with the EIA process, leading to a recommendation of increasing the distance from 1.0 to a maximum of 1.7 times the total height of the turbine.

Most often, wind turbines are placed at remote sites where human traffic is scarce and there are no other buildings. In that case, a blade failure where all or part of the blade is detached from the turbine does not create a risk that needs special consideration. In some cases, however, a specific risk assessment must be performed as part of the EIA. This is the case if a wind turbine is placed close to areas with public access, for example, a bicycle path, a pedestrian area, spectator areas, ski slopes, residential buildings, and industrial installations with hazardous materials. Such a risk assessment should consider relevant scenarios and include estimates of the probability of blade failure in combination with estimates of likely throwing distances of the blade part(s). The risk assessment should consider both individual risk and societal risk as described in the report "Miljøstyrelsen 2008"[19]. However, these general requirements should be adapted to wind turbines.

To carry out a risk assessment and take advantage of the (anticipated) lower blade-failure rates for new wind turbines (compared with older wind turbines), it is important to examine relevant blade-failure rates during the EIA process. If an older, existing wind turbine must be included in the risk assessment, blade-failure rates for older wind turbines will be required. The individual risk is often represented by contour lines showing probabilities equal to 10^{-5} and 10^{-6} per year.

It is important that the risk assessment includes an estimate of the distance from the wind turbine that parts detached from the turbine can be thrown. For this, computational tools must be developed that can model both the aerodynamics and the randomness associated with the throwing process. When combined with failure-rate statistics and risk-acceptance criteria, the risk around a wind turbine can be properly quantified. No such tool exists today.

Megavind's recommendations concerning ice throw and blade failure

- Improve tools for predicting ice formation on wind turbines and other structures
- Develop tools for calculating the throwing distance of ice and all or part of a blade
- Develop a tool for assessing the risk of blade failure
- Develop a standardised methodology and a tool for assessing the risk of ice throw

16 Braam and Rademakers (2004). Guidelines on the environmental risk of wind turbines in the Netherlands. ECN Report, ECN-RX--04-013.

17 CD IEC 61400-1 ed. 4 (2015)

18 Trafik og bygningsministeriet 2011. http://www.trm.dk/da/publikationer/2011/vindmoellers-afstand-til-overordnede-veje-og-jernbaner .

19 Miljøstyrelsen 2008. Acceptkriterier i Danmark og EU, Arbejdsrapport fra Miljøstyrelsen Nr. 8.

Photo Thomas W. Johansen/Senatur

Appendix A: Other issues of lower importance

This appendix describes blade coating and shadow flicker which are issues of low importance, and therefore not included in the strategy.

Blade coating

An example of an area where a technological solution for an externality has been found is the coating of wind turbine blades. Initially the surface finish of wind turbine blades was blank similar to pleasure boats. It was quickly discovered that the blank surface could be a source of light reflections from the sun. Modern wind turbine blades have a mat surface and the reflections are no longer an issue.

Shadow flicker

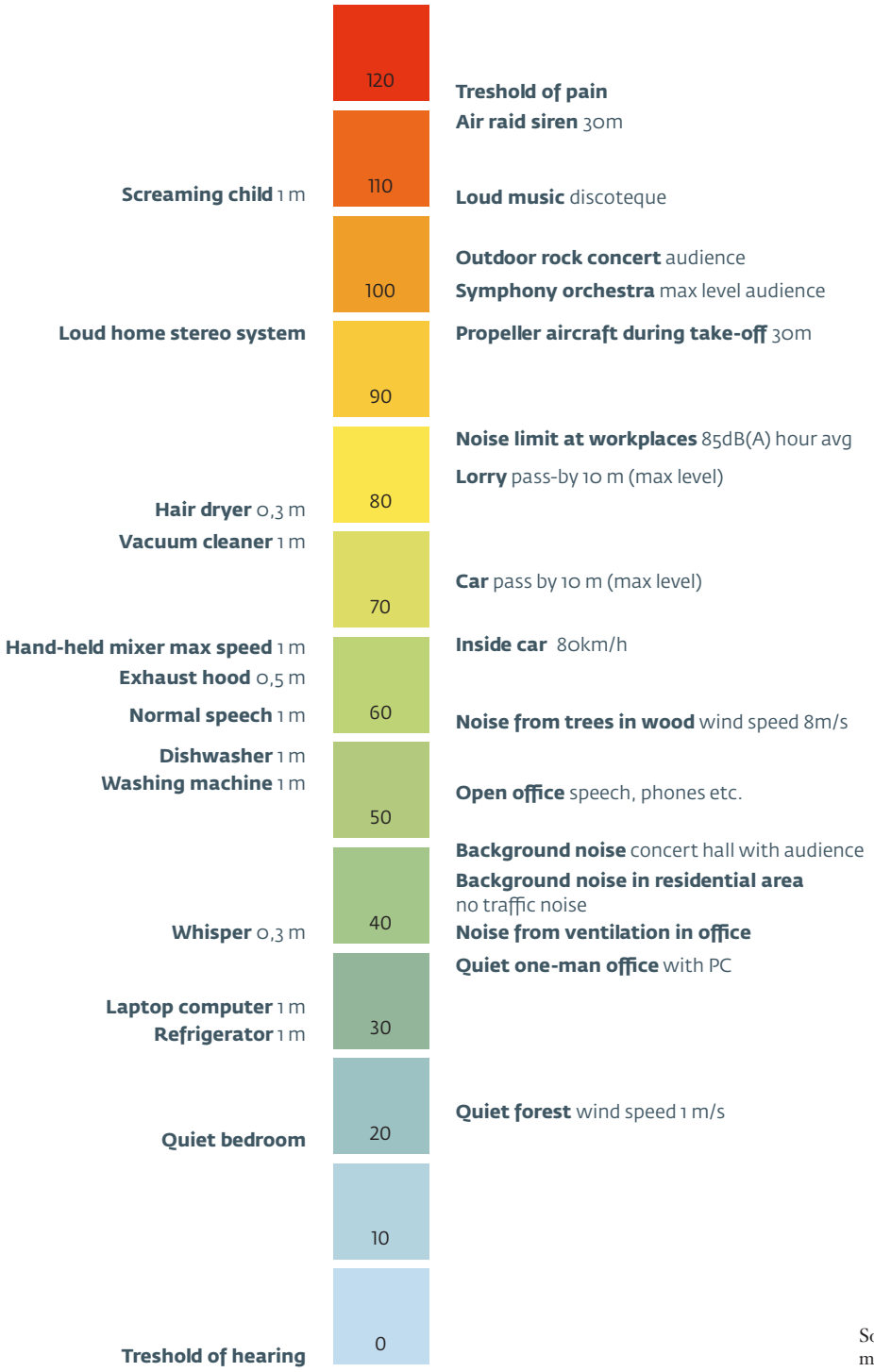
During hours of bright sunshine wind turbines will cast a shadow on the neighbouring area and during hours when the sun is low above the horizon (morning or evening) shadows get longer and may impact a house. Shadow flicker describes the pulsing change in light intensity that is observed when the blades of the wind turbine pass periodically through the sunlight. In Denmark the distance from the wind turbine to the house should be less than 2 km to qualify as shadow flicker. The guideline in Denmark is that up to 10 hours per year is tolerated. For nearshore wind farms it has no practical relevance due to the distance. The existing technological solution for calculation of annual hours with shadow impact is the software WindPRO by EMD International A/S[19].

19 www.emd.dk

Appendix B:
Examples of typical noise levels

Typical noise levels

Sound pressure level dB(A)



Source: Acoustics
madebydelta.com

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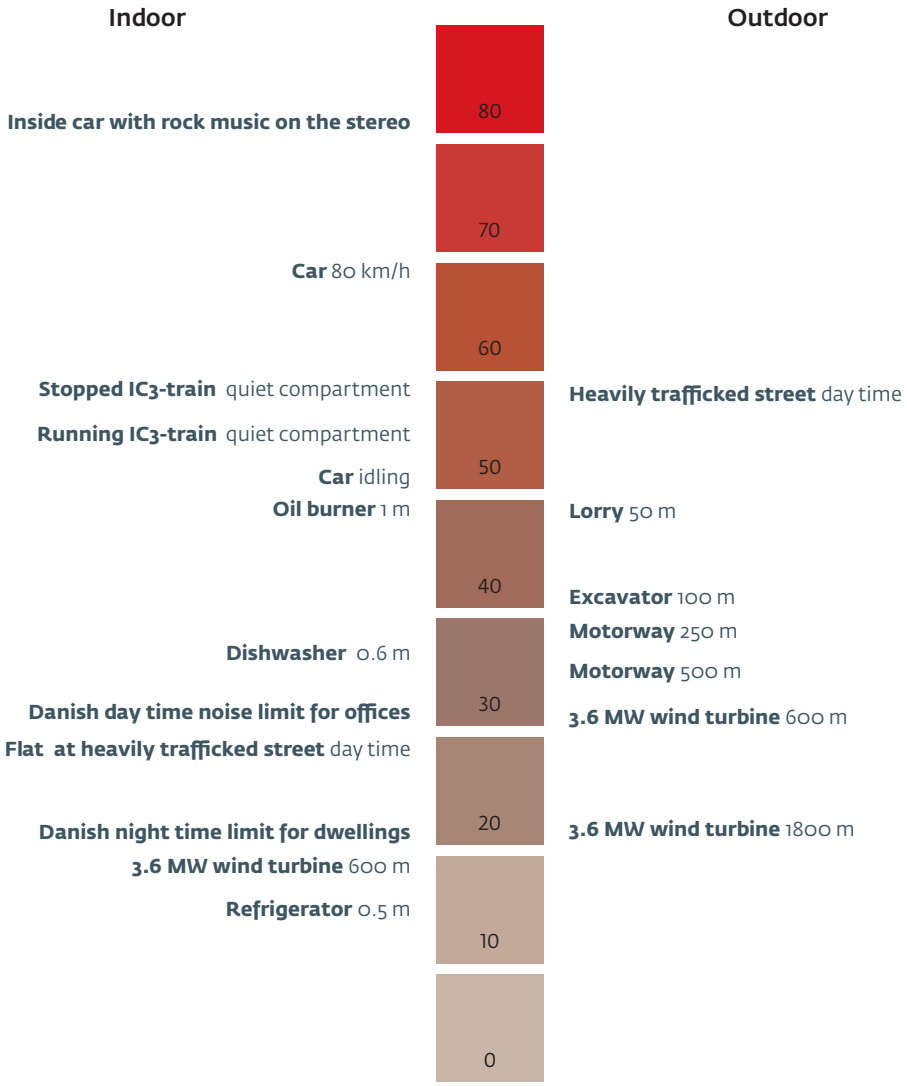
Low frequency noise

Low-frequency aound pressure level
dB(A) - LF



Source: Acoustics
madebydelta.com

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