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ENERGY HIGHLIGHTS

Content

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Role of windfarms for national grids – challenges, risks, and chances for energy security

by **Ms Marju Kõrts**

EXECUTIVE SUMMARY AND KEY RECOMMENDATIONS

Rapid growth of wind energy worldwide has led to the increased installation of wind farms that are more efficient, powerful, and have taller wind turbines. As wind development continues to grow and expand to new areas of the country, so does the possibility that some turbines would be located within the line of sight of radar systems. This could have potential effect on national flight safety, weather forecasting, and national defence radar operations. Wind turbines can cause radar interference whereby the blades appear as „clutter" on radar screens and can be mistaken for aircraft. Plans to set ambitious renewable energy targets have been impacted by the objections of the Ministries of Defence that wind turbines interfere with military radars. In a number of cases the military has claimed that the wind farms are an encroachment on military radar facilities, and have stalled construction on the wind farm. Similar problems have arisen in other countries wher wind power is expanding.

There is no fundamental physical constraint that prohibits the accurate detection of aircraft and weather patterns around wind farms. On the other hand, the aging radar infrastructure significantly increases the challenge of distinguishing wind farm signatures from airplanes or weather. On one hand, wind turbines are getting bigger and more powerful to harvest more energy, on the other hand there will be more challenges for the defence radars to cope with this situation. Thus, the probability for wind development to present conflicts with radar missions related to air traffic control, weather forecasting, national security and defence is also likely to increase, as is the potential severity of those conflicts. Certainly, the positioning of aviation infrastructures such as airports and helipads, and wind infrastructures such as wind farms and turbines, will continue to be a challenge. Therefore, a justified

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question can be posed whether wind farms can co-exist with radar installations?

Progress forward requires the development of mitigation measures, and quantitative evaluation tools and metrics to determine when a wind farm poses a sufficient threat to a radar installation for corrective action to be taken. Mitigation measures may include modification to wind farms (such as methods to reduce radar cross-section; and telemetry from wind farms to radar), as well as modifications to radar (such as improvements in processing; radar design modifications; radar replacement; and the use of gap fillers in radar coverage).

Establishing the optimal mitigation strategy for a specific case requires in-depth analysis of the particular site. However the most common technological solutions currently employed also include *blanking* where radar returns within the wind farm boundary are not shown on the radar screen. This eliminates the issue of wind turbines showing up as targets on a radar screen, but it also means that an aircraft overflying the wind farm will not be displayed. In the United Kingdom for example, the industry together with the aviation sector has also looked at changing the turbine design, but that is not always possible or it has not always given the desired results.

Collaboration is the key as the wind industry recognizes the need for technical solutions so that the presence of turbines does not have any impact on radars. In some countries (e.g. UK, USA) the dialogue has been ongoing for years. Government and the aviation authorities recognize the crucial need to develop renewable energy to tackle climate change, and the wind industry recognizes the need for technical solutions so that the presence of turbines does not have any impact on aviation radar (both civilian and military). With appropriate planning, coupled with funding the deployment of appropriate mitigation solutions, the impact of wind turbines on radar systems may be minimized or eliminated for the near, mid,- and long-term.

To preserve critical radar missions as well as to accommodate future wind development, new technologies to mitigate wind turbine radar interference are required. Although a great deal is now understood about the potential effects of wind turbines on many types of radar as well as their impacts on the missions those radars support, nevertheless new issues are likely to arise. One class of mitigation solutions is the augmentation or „infill" radars. Where a potential siting conflict manifests itself, an impacted legacy radar's performance loss may be restored by placing one of these infill radars, with advanced clutter suppression techniques, closer to wind farms to restore the lost surveillance coverage. Another approach is to improve the wind turbine interference mitigation capabilities of existing radars through signal processing, software upgrades and minor hardware modifications, which are likely to result in lower-cost solutions to wide-scale deployment of short-range infill radar systems. New design and operational methods for future wind turbines deployed in close proximity to vital radar assets could reduce radar impacts either independently or in conjunction with mitigation measures applied at the impacted radar systems.

Beyond radar-absorbing materials, there are additional at-the-turbine solutions, e.g. reduced radar impact lightning protection systems, materials, and structures are especially important for over-the-horizon radar systems. New operational methods in which data from individual turbines are combined with data in real time could also be explored as a potential mitigation method for current or newly deployed wind farms.

Besides radar interference, obstruction and safety can be considered as additional concerns for the Ministries of Defence that are related to wind turbines. A single wind turbine or wind farms which has the potential to endanger aviation in navigable airspace or has the potential to interfere with the operation of navigation, should be lighted. The number of light levels recommended depends on the height of the structure. The obstacle lights should be installed on the nacelle to provide an unobstructed view for aircraft approaching from any direction.

The so-called radar objections mentioned above are not the only impediment to the development of wind energy. In many countries and communities, there is still quite a lot of resistance to the wind developments due to the environmental and societal reasons. The local residents often claim about the noise or light pollution. Noise emissions may be heard, felt, or sensed. Some of them are in the audible range, the others are in the low frequency range and those may be heard. There are mainly two sources of noise in a wind turbine: aerodynamic that is generated by the motion of air around the blades, and mechanical caused by the motion of the mechanical and electrical components. Light pollution occurs in the form of strobing (also known as „shadowflickering") or from aircraft warning lights mounted on the towers. Improving warning lights to lit up the wind turbine only when there is an actual aircraft to warn in its vicinity is not a new idea, and individual tests to achieve this has been successfully carried out in the past. Due to the large number of wind farms, Germany is especially interested in this issue and is at present implementing new regulations to enforce an on-demand warning light system as requirement for wind farms.

All in all, wind energy developments can also be seen as an opportunity and not as a problem as the experience of Belgium shows. Namely, with the use of new generation mine-sweepers that also rely on drone technology, the offshore wind farms matrix can be used for the logistical support of this network (e.g. recharging the drones' batteries).

Once the potential for different mitigation measures are understood, there is no hurdle for establishing regulations that are technically based and simple to understand and implement.

Based upon the factors discussed above, some **recommendations** can be given how to foster the development of wind energy and ensure that the national defence needs are not compromised.

1. It would be recommendable that the Government move beyond a policy of unilaterally blocking wind farms on the basis of any observable impact on existing radars, and move to a collaborative and mutually agreed, technically based rule system for determining the severity of the interference.
2. The evaluation system should include a cost benefit analysis of mitigation strategies. Once the potential for different mitigation measures are understood, there is no hurdle for establishing regulations that are simple to understand and simple to implement, with a single government entity taking responsibility for overseeing the process.

INTRODUCTION

By the end of this year European countries are due to deliver on their 2020 renewable energy targets and will start implementing their 2030 National Energy & Climate Plans (NECPs) towards the 32% renewable energy goal. The depletion of conventional energy sources and the rising greenhouse gas emissions are fueling the adoption of renewable energy sources across the world. Wind is one of the most abundant and efficient sources of power generation. Countries such as Denmark, Spain, Germany, and the United Kingdom produce more than 10% of their power from wind energy.

Several studies, e.g "Wind Energy in Europe: Outlook to 2022" prepared by WindEurope reinforce the idea that wind energy will play a key role in the necessary energy transition to meet the challenges of climate change and produce clean energy. The study "Utility of the Future"[1] by Massachusetts Institute of Technology points out the key factors that can be seen in the electricity sector in the future: decarbonisation, combating climate change, new technologies, digitization, and the advancement of renewable energy.

According to the estimates of the WindEurope's study mentioned above, the installed capacity will grow an average by 17.4 GW per year between 2018 and 2022, due to the development of wind farm projects both onshore and offshore. Germany, Spain and the United Kingdom will continue to being the countries with the largest fleet of wind turbines in Europe.

Growth is expected to slow in Germany and will accelerate in Spain and Sweden. In terms of total installed capacity, wind power is the leading renewable energy technology after hydropower,

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[1] MIT Energy Initiative "Utility of the Future", 2016, Massachusetts, USA

with more than half a terawatt installed globally as of the end of 2018. Global installed wind-generation capacity onshore and offshore has increased by a factor of almost 75 in the last past two decades, jumping from 7.5 gigawatts (GW) in 1997 to some 564 GW by 2018, according to the International Renewable Energy Agency's (IRENA) latest data[2].

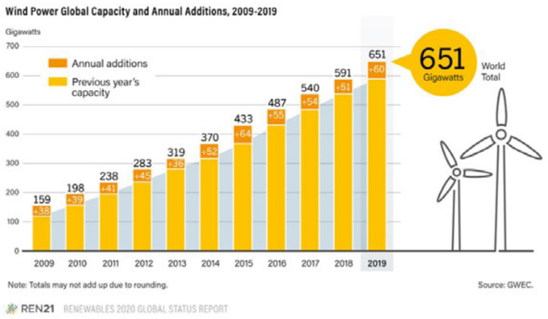

Figure 1. Wind Power Global Capacity and Annual Additions, 2009-2019

Europe could install 90 GW of new wind energy capacity over the next five years, if governments adopt clear and ambitious NECPs, resolve their current issues around wind farm permitting and continue investing in grid infrastructure. This would give Europe 277 GW of installed wind capacity by 2023 (WindEurope 2019)[3]. By 2023 Germany will remain the country with the largest wind fleet (72 GW), followed by Spain (32 GW) and the United Kingdom (29 GW). These three countries will account for just half of Europe's cumulative installed wind capacity by 2023. The decline in costs for renewable technology and other key technologies, such as batteries and electrolyzers, will impact the entire energy sector going forward.

There are also challenges that come with the benefits of wind energy generation. Wind farms can cause a number of problems on air traffic radar displays such as clutter (also known as interference), reduced sensitivity and overloading of processing functions. Wind turbines have significant electromagnetic reflectivity, as large structures and blade cause large and numerous Doppler returns due to their motion relative to the affected radars[4].

The Doppler Effect[5], specifically the shift in frequency of the reflected signal that occurs when an object is moving, was first discovered by Christian Doppler, an Austrian physicist and mathematician who carried out experiments with both moving sources and moving observers. Doppler shift applies to all propagating waves and is particularly useful for radars. This Doppler shift results from the fact that the frequency of a signal received by an observer will depend upon whether the source of that signal is stationary, moving forward, or moving away from the observer. For radar applications, the "source" of the signal is the radar wave reflected by the target. If the target is moving away from the radar, the frequency of the reflected signal will be lower than the originally transmitted frequency.

As the size and number of wind turbines increase, their operation can affect the military readiness of the surveillance radar installations near wind farms and the proper functioning of other civilian systems such as Air Traffic Control (ATC) Radar and Weather Radar, especially when the wind farms are within the radar line-of-sight (LoS). The electromagnetic waves follow the rules of optics in higher frequencies (>100 MHz). All radar unit systems almost without exception work in this frequency domain. Therefore, the wave fronts also propagate to quasi-optical rules. The earth's curvature may prevent the radar seeing a target within the maximum range (distance) given by the radar range equation[6]. This results in a "dead zone" for every radar system in which certain targets cannot be detected. However, in the atmosphere, electromagnetic waves are generally bent or refracted downward (e.g *diffraction effects*) that reduces the "dead zone" but causes fault in the distance and height measuring simultaneously. Several studies have also underlined the possibility that wind turbine structures, if positioned with certain geometries and distances relative to ATC radars, might cause those radars to fail to detect desired targets with adverse implications for safety-of-life and national security. Various studies have been carried out to determine minimum safe distance between a wind farm and radar system but without success. Due to numerous different constructions, and individual site circumstances, it is not possible to determine a universally accurate minimum distance where interactions between a turbine and a radar would occur. It is however, possible to determine a minimum distance where effects from wind turbines would not be anticipated.

The impact of wind farms, particularly on ground based aviation radars such as those operated for air defence and military and civil air traffic control purposes are likely to become particularly acute as the governments of the EU Member States strive to meet the requirements for energy generation under the renewables targets by 2030. The assessment of Member States' National Energy and Climate Plans shows that Member-States are accelerating their energy and climate transition. It indicates that the share of renewable energy in the EU could reach 33.7% by 2030, going beyond the current target of at least 32% (European Commission, 2020)[7].

The co-existence of wind farms and military radars is a topical issue in Estonia. The Estonian long-term objective is transition to a low carbon emission economy, which would mean purposeful reorganization of the economy and energy system to make them more resource efficient, productive and greener. This would entail changes *inter alia* in energy production, transport, forestry and agriculture. This also means that the role of renewable energy solutions in the energy portfolio, including production of electricity from wind energy will increase in the future (Estonian NECP 2030)[8]. For a number of years, the Estonian Ministry of Defence has denied permits for onshore wind projects on the grounds of national defence needs. Especially problematic for the military are wind farms located close to the state border or those wind farms located close to the air defence radar. The same tendencies can be seen in the neighboring countries, for example, Sweden recently denied permit for the Blekinge offshore wind farm, located 17 km off the southern coast of Sweden. This area was of strategic importance for the Swedish defence forces as they needed it for practicing military maneuvers.

Thus, erecting a wind farm involves many considerations including consultation with various civil or military aviation stakeholders. Radar beam blocking is the most serious effect that wind turbines have on radar. Beam blockage occurs when radar beams are partially or totally blocked by nearby obstacles. On land, beam blockage is usually caused by terrain and buildings, including wind turbines if they are located close enough to the radar. As a result, the radar is unable to "see" behind the turbine because it blocks the pulses of energy. Beyond the wind farms, the signal is attenuated[9] to varying degrees which in case of weather radars leads to underestimation of precipitation measurements and a loss of sensitivity of Doppler measurements. To limit these effects it is recommended to maintain the blockage ratio of radar beams below 10%, which corresponds to a maximum underestimation of 20 to 30% of the measurement of rainfall intensity located at 100 kilometers.

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[2] IRENA, 2019, Renewable Capacity Statistics 2019, International Renewable Energy Agency (IRENA), Abu Dhabi

[3] "Wind Energy in Europe: Outlook to 2023", WindEurope, October 2019

[4] Radar is a system for detecting the presence or position or movement of objects by transmitting radio waves, which are reflected back to a receiver.

[5] A Doppler radar is a specialized radar that uses the Doppler Effect to produce velocity data about objects at a distance. It does this by bouncing a microwave signal off a desired target and analyzing how the object's motion has altered the frequency of the returned signal. This variation gives direct and highly accurate measurements of the radial-component of a target's velocity relative to the radar. Doppler radars are used in aviation sounding satellites.

[6] If the echo signal is having the power less than the power of the minimum detectable signal, then radar cannot detect the target since it is beyond the maximum limit of the radar's range. The range of the target is said to be maximum range when the received echo signal is having the power equal to that of the detectable signal.

[7] The European Commission. "State of the Union: Commission raises climate ambition and proposes 55% cut in emissions by 2030", press release, 17 September 2020, Brussels, Belgium.

[8] Estonian National Energy and Climate Plan (NECP 2030), 2018.

[9] Attenuation is the scattering and absorption of energy as it passes through a medium. Gases and water vapor in the atmosphere absorb some of the radio waves energy. The higher the frequency, the greater the absorption of energy.

Electromagnetic radiation is a form of energy exhibiting wave like behavior as it travels through the space. A wave is a disturbance that propagates through space and time, usually with the transference of energy from one point to another without permanent displacement of particles of the medium (Malik, 2013)[10]. In the atmosphere, the wave propagates with a speed slower than the speed of light. The wave's speed, direction of propagation, and amplitude are dependent upon several atmospheric variables including temperature, moisture, and pressure (Ford, 1995)[11]. The atmospheric refractivity gives rise to bending of radio waves. The diffraction of the radar waves will reduce the intensity of the propagating wave directly behind the turbines as well as the reflected signal from a target. This two-way reduction in signal strength will increase the difficulty in detecting and tracking targets flying in low altitude in the immediate vicinity of the wind turbines. This effect will be most pronounced for targets with a small Radar Cross Section[12]. The surface area of simple geometric bodies depends on the shape of the body and the wavelength, or rather on the ratio of the structural dimensions of the object to the wavelength. In practice, some energy is absorbed and the reflected energy is not distributed equally in all directions. Therefore, the Radar Cross-Section is quite difficult to estimate. This means that some targets at the radar's screen are inherently the most challenging in all circumstances, and this added burden will result in a noticeable reduction in probability of detection for them.

As a result, all these aspects can lead to raising the so-called "radar objections" from air traffic control and military authorities, asking for example, to downsize or relocate planned wind farms. This hinders wind energy development, at a time where there is significant push to expand the energy production from renewable sources. Consequently, there is a conflict of interest between the desire to encourage wind farm development as a renewable energy source and the desire to maintain the performance of existing radar systems.

Even though both radars and wind turbines have been in use for many decades it is only in the last few years that the interference problem has received substantial attention. The reason for this is simple; in recent years wind turbines have increased in number and in size at the same time radar systems have become increasingly sensitive.

In recent years, important research projects have been carried out, in order to characterize the signals scattered by the wind turbines and to determine the impact these reflected signals may cause on the detection capability of the radars. Additionally, a significant effort has also been put into developing various mitigation techniques, some of them based on the wind turbine designs, but the others in signal processing in the receiver or in the development of specific techniques for filtering the interfering signals.

A number of technologies are being pursued to assist in mitigating the impact of wind turbine on both aviation and marine radars. These include additional post-processing of radar returns, the use of gap filler radars to improve coverage, physical obscuration to remove radar-wind farm line of sight, antenna tilting or modification to ensure that wind farms are not illuminated by elevation side lobes, and the lay-out of wind turbines within a farm to reduce coherent summation of returns for radars at fixed locations. The application of so-called "stealth" technology[13] has the potential to reduce both aviation and marine radars interference.

The aim of this study is to get further insight into the radar- and military related concerns raised around wind turbines, and to discuss alternative options that may be introduced to mitigate the impact of utility-scale wind turbines on defence and security. The research objectives are to answer the following questions: (1) how significant are the wind turbine related radar and military site concerns that have been raised by the military; (2) how viable are the proposed solutions to these concerns? (3) What is required (e.g. governance and resources) to implement the most viable solution so that wind farms can co-exist with the radar installations?

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[10] H. Malik. "Electromagnetic Waves and Their Application to Charged Particle Acceleration", Intech, 2013

[11] B. Ford. "Atmospheric refraction: how electromagnetic waves bending in the atmosphere and why it matters", U.S Naval Postgraduate School., Monterey, California, 2005

[12] Radar cross-section is a measure of how detectable an object is by radar. Therefore it is called electromagnetic signature of the object. It is a specific parameter of a reflective object that depends on many factors, and which has units of m².

[13] It is also termed as low observable technology that is a sub-discipline of military tactics, passive and active electronic countermeasures, which covers a range of methods used to make personnel, aircrafts, ships, submarines, satellites, and ground vehicles less visible.

The research methodology of this study uses a synthesis of literature analysis and industry interviews. In the study, there is a separate chapter where the energy policies and wind energy developments are viewed in depth. The interviews with selected representatives from the field of radar, the wind industry, and governmental agencies were conducted either via phone or other online devices. In order to give a broader energy policy perspective, both on- and offshore wind energy were covered in particular countries, although the study in itself focuses on onshore wind energy. The phone or online interviews were semi-structured with a transcript of the interview being scribed throughout, and responses and conversational leads were later reviewed with the person interviewed. Only non-classified information was sought, and included subsequent detailed questioning.

The study "*Role of wind farms for national grids – challenges, risks, and for energy security*" consists of 7 chapters and its structure is the following. **Chapter 1** is dedicated to wind formation and different types of wind turbines. **Chapter 2** provides a detailed overview of the radar concepts and systems with a special focus on wind turbines' electromagnetic footprint. **Chapter 3** addresses potential mitigation approaches that can be used to reduce the negative impacts wind turbines have on air defence. **Chapter 4** deals with environmental and societal aspects of wind energy. **Chapter 5** in turn focuses on the noise pollution and provides an overview of some reduction technologies. The focus on **Chapter 6** is on different energy storage technologies that can be used for storing wind energy. **Chapter 7** includes several case studies (Belgium, France, Switzerland, Poland, and the United Kingdom) focusing on specific energy policy options and measures to foster wind energy development. Conclusions of this study can be found at the end of the report.

CHAPTER 1 – WIND ENERGY SYSTEMS AND TECHNOLOGIES

Wind power capacity has increased dramatically in the recent years – and accompanying that, the turbines have become more efficient and more affordable for power producers. Wind energy generation is power generation that converts wind energy into electric energy. The wind generating set absorbs wind energy with a specially designed blade and converts wind energy to mechanical energy, which further drives the generator rotating and realizes conversion of wind energy to electric energy. A typical modern turbine will start to generate electricity when wind speeds reach six to nine miles per hour (mph), known as the cut-in speed. Another common feature of wind energy production is called capacity factor. This measures the amount of electricity a wind turbine produces in a given period of time (typically a year) relative to its maximum potential.

Although wind energy is a clean and renewable source of electric power, many challenges must be addressed. Wind turbines are complex machines, with large flexible structures working under turbulent and unpredictable conditions, and are connected to a constantly varying electrical grid with changing voltages, frequency, and power flow. Wind turbines have to adapt to those variations, so their efficiency and reliability depend heavily on the control strategy applied. As wind energy penetration in the grid increases, additional challenges are being revealed: response in grid disturbances, active power control and frequency regulation, restoration of grid services after power outages, and wind prediction, for example.

The present chapter focuses on wind formation, also covering the design and construction of wind turbines A separate section is dedicated to the new emerging technologies (e.g. smart grids) that are going to play a more important role in the future energy systems.

1.1. FORMATION OF WIND

Wind is atmospheric phenomenon due to the heating of the sun. The sun radiates on the Earth a power of 1.74 x 10^{17} Watts and about 2% of it is converted into wind energy. The Earth releases the heat received from the Sun, but this is hardly homogeneous. In those areas where less heat is released, the pressure of atmospheric gases increases, while in those areas where more heat is released, the air becomes hot and the gas pressure is reduced. As a consequence, high pressure areas and low-pressure areas are formed, which are also influenced by the Earth's rotation. When different masses of air get in contact, the area with a higher pressure tends to transfer air towards the area with lower pressure. It is the same as when we let a balloon deflate. The high pressure inside the balloon tends to transfer air outside, where the pressure is lower, originating a small airflow. Therefore wind is a more or less rapid air transfer between different pressure areas. The higher is the pressure difference, the faster is the displacement and the stronger is the wind.

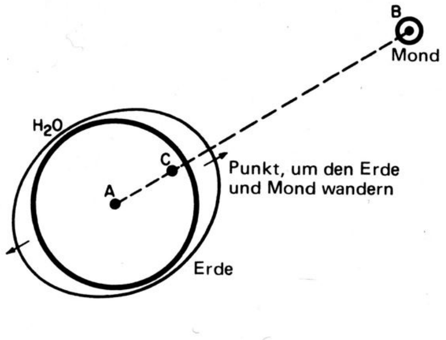
On weather maps, pressure is indicated by drawing isolines of pressure, called isobars, at regular 4 millibar intervals (e.g., 996 mb, 1000 mb, 1004 mb, etc.). If the isobars are closely spaced, it can be expected that the pressure gradient force to be great, and wind speed to be high. In areas where the isobars are spaced widely apart, the pressure gradient is low and light winds normally exist. High speed winds develop in areas where isobars are closer.

Wind is the result of a limited number of accelerating and decelerating forces, and that the action of these forces is controlled by specific fundamental natural laws. Sir Isaac Newton formulated these laws as several laws of motion. The first law suggests that an object that is stationary will remain stationary, and an object in motion will stay in motion as long as no opposing force is put on the object. This law also suggests that once in motion an object's path should be straight. Newtons' second law of motion suggests that the force put on an object equals its mass multiplied by the acceleration produced. The term force in this law refers to the total or net effect of all the forces acting on an object. From this natural law of motion it can be seen that the acceleration of an object is directly proportional to the net force pushing or pulling that body and inversely proportional to the mass of the body.

Gravitational force, pressure and gradient force are the most important forces responsible for such a change in the state of motion. Gravitational force is the force that describes the mutual attraction of masses. For example, objects fall to the ground, because it ensures that all masses are drawn towards the center of the earth. Pressure is the force that indicates the force acting on surface. In this particular case, it is an opposing force to the gravitational force, because the pressure on the particle near-earth is higher than the one far away from the earth, so the force towards the air masses above must be higher, since the number of particles pressing down decreases with increasing height. Since the two forces mentioned are directed against each other, they equilibrate each other, typically without any vertical movement. The gradient force is therefore of importance for the formation of wind. In the event of a difference in air pressure in an environment, this force ensures a compensating current along the pressure gradient. This compensation always takes place from higher to lower pressure, with the compensating force.

Thus, wind is created until the difference in air pressure has dissolved. The air pressure decreases with increasing altitude. Similarly, the gravitational force is also responsible for a change in air pressure, as the mutual attraction of earth and moon changes periodically. As a result, air particles rise/sink as they are more strongly attracted/repelled by the Moon. The emergence of the tides can again be attributed to attraction force. The gravitational pull of the Moon acts on the Earth, applying force not only on the tides of the sea, but also on the body of the Earth and the atmosphere. By movement of the Moon and Earth around a common central position, the mutual forces of attraction balance each other out. This means that the water and air on the side facing away from the Moon are less strongly attracted, because the Moon's gravitational pull is weaker than in the Earth's interior, where it equilibrates the centrifugal force. Thus, the body of the Earth is deformed by the tidal forces and tidal abdomen are formed as can be seen in Figure 1. The Earth's own rotation relative to the sun and moon leads to periodic change and hence makes the Earth's body elastic (Feynman et al., 2001)[14]

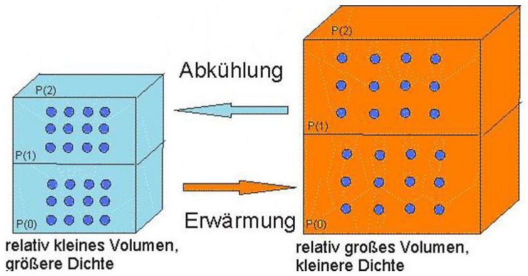
Figure 2: Effects of the gravitational pull of the Moon on the atmosphere and water cover of the Earth.



Source: Feynman et al., 2001

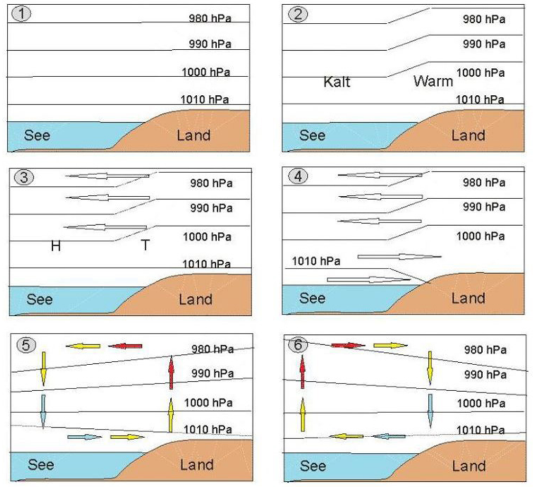
As a result, there are slight changes, especially in the tropics, since the Earth's atmosphere moves at a frequency of two oscillations per day. Another important reason for pressure differences lies in the temperature dependence. Due to an increase in temperature, the air molecules are able to move faster and thus cause the force per area to rise, as can be seen in Figure 3.

Figure 3. Relation between temperature and density of air. As the temperature increases, the volume of a body increases, i.e. the density decreases, as it is defined as mass per unit volume.



Due to the fact that the wind is located near the coast, the differences in air pressure caused by temperature differences are to be explained using the example of the sea-land breeze in Figure 3. To form a body, it is necessary to heat energy, which in the case of the Earth comes from the Sun. The higher and quicker warming of the land compared to the sea, which has a higher heat capacity, causes the air above it to expand (2). This expansion causes the density of the air to change, resulting in a pressure difference. Therefore, a compensating flow from the land side follows, as the higher pressure moves to the lower one (3). The higher the pressure difference, the greater the initial flow. Above the sea, this results in overpressure and above the land in a lack of air particles, so that in addition to the upper movements towards the sea, there is a lower movement away from the sea (4). This in turn, creates a cycle that moves the cold air near the ground to the land, warms it up there, so that it begins to rise and moves back to the sea (5). At night, there is a reverse cycle, as the air cools down more quickly on land than over the sea, whereby less differences can be found during the day and there is less wind (6). Thus, the temperature near the coast should have a significant influence on the presence of wind in coastal regions.

Figure 4: Example of land and sea wind



Source: Feynman et al., 2001

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[14] R. P. Feynman; R.B. Leighton (2001). "Feynman vorlesungen über physik band i: Mechanik, strahlung, wärme". Oldeburg Wissenschaftsverlag GmbH

1.2. WIND POWER GENERATION AND WIND FARMS

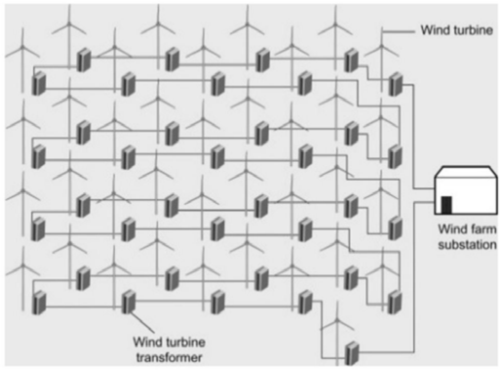
The commonly used wind power generation systems include the direct-driven wind power generating set and the double-fed wind power generating set; the direct-driven wind power generating set is connected to the grid through a full power converter, while the double-fed wind power generating set is connected to the grid through a double-fed converter.

There are three main types of wind energy:

- Utility-scale wind: Wind turbines that range in size from 100 kilowatts to several megawatts, where the electricity is delivered to the power grid and distributed to the end user by electric utilities or power system operators.
- Distributed or "small" wind: Single small wind turbines below 100 kilowatts that are used to directly power a home, farm or small business and are not connected to the grid.
- Offshore wind: Wind turbines that are erected in large bodies of water, usually on the continental shelf. Offshore wind turbines are larger than land-based (onshore) turbines that can generate more power.

A wind farm is a collection of wind turbines that operate as a single power station. Depending upon its size, a wind farm will normally have a dedicated substation into which power from all the wind turbines is fed and from which it is carried to the nearest access point to the grid system. Currently, increasingly larger wind farms are being deployed, and the continued spread and expansion of these farms poses a challenge since the required land area will increase. A major goal of current energy research is thus to increase the wind-farm power density, i.e. how much energy can be produced per unit land area used.

Figure 5. A layout of a wind farm



Source: Adapted from Paul Breeze article "Wind Power", in Power Generation Technologies, 2019.

In a wind farm, turbines should be far enough apart to allow wind speeds to recover, through lateral or vertical momentum entrainment, after deceleration by the upwind generator (Cortina et al, 2016)[15]. Spacing the turbines also reduces the fatigue load generated by turbulence from the upstream turbines and thus increases turbine lifetime (Chamorro and Porte-Agel, 2009)[16]. The large majority of existing farms use horizontal-axis wind turbines (HAWTs); the behavior of horizontal-axis turbines in large wind farms, and the required spacing between, have been extensively studied. Calaf et al (2010)[17] investigated the vertical transport momentum and kinetic energy in a fully-developed HAWT-array boundary layer (defined as the internal boundary layer developing above a wind farm). They showed that, for large wind farms, regeneration of the kinetic energy is mainly from downward vertical fluxes across the plane delineating the top of the farm, unlike farms with a limited number of wind-turbine rows where the stream-wise advection of kinetic energy dominates.

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[15] G.Cortina, M. Calaf, and R.B.Cal (2016). "Distribution of mean kinetic energy around an isolated wind turbine and a characteristic wind turbine of a very large wind farm". In Phys Rev Fluids 1:74402, https://doi.org/10.1103/PhysRevFluids.1.074402

[16] L. Chamorro; F. Porte-Agel (2009), "A wind-tunnel investigation of wind turbine wakes: boundary-layer turbulence effects. Boundary-Layer Meteorol 136:515-533. https://doi.org/10.1007/s10546-009-9380-8

[17] G.Cortina, M. Calaf, and R.B.Cal (2016). "Distribution of mean kinetic energy around an isolated wind turbine and a characteristic wind turbine of a very large wind farm". In Phys Rev Fluids 1:74402, https://doi.org/10.1103/PhysRevFluids.1.074402

All of the above, and other previous work, have focused on wind farms consisting of horizontal-axis wind turbines (Chamorro and Porte-Agel 2010; Lu and Porte-Agel 2011)[18]. However, recently Dabiri[19] (2011) has suggested the possibility of an order of magnitude increase power for wind farms when vertical-axis wind turbines (VAWTs) are used. Due to their axis of rotation, VAWT wakes and the flow in a VAWT farm are distinctly different from their HAWT counterparts.

Professor John Dabiri and his team used fish-schooling pattern to inspire wind farm design for optimal energy harvesting. Rather than following the conventional horizontal-axis approach and spacing turbines far apart, they placed vertical-axis turbines in close proximity. Dabiri and his team found that if neighboring turbines are staggered and rotate in opposite directions, the alteration of wind speed and direction by adjacent turbines can actually be beneficial for collective performance of the wind farm. Dabiri (2011)[20] and his collaborators (Kinzel et al., 2012)[21] performed experiments on various counter-rotating configurations of 9 meter tall vertical-axis wind turbines and demonstrated that, unlike the typical performance reduction of horizontal-axis wind turbines with close spacing, there is an increase in VAWT performance when adjacent turbines are arranged to interact synergistically. However, high experimental costs and time requirement prevent the extension of these field investigations to large farm scales or the assessment of a large number of configurations. The previous findings thus only pertain to limited number of turbines where the mean kinetic energy is primarily replenished by stream-wise advection and cross-stream turbulent transport, rather than by vertical transport as in large farms.

While these techniques can improve the energy produced by horizontal-axis wind turbine (HAWT) arrays, vertical-axis wind turbines (VAWTs) have been shown to facilitate additional strategies for performance. They can also include blades, or be bladeless. The top-heavy nature of conventional wind turbines requires high-quality components to avoid structural damage. On the other hand, with the recent innovation of bladeless wind turbines, the risk of structural damage to the system can be reduced significantly. Bladeless wind turbines do not include rotating blades and are designed in such a way that they stand erect and oscillate in response to the vortices. Bladeless wind turbines contain only a few moving parts. They not only help in eliminating noise, but also do not pose a threat to birds. On the other hand, bladeless wind turbines at a nascent stage, are less efficient in the conversion of captured wind power into electrical energy, thus limiting their implementation on a large scale (Evwind, 2019)[22].

1.3. WIND TURBINES

A wind turbine is a machine that converts kinetic energy from the wind into electricity. The blades of a wind turbine turn between 13 and 20 revolutions per minute, depending on their technology, at a constant or variable velocity, where the velocity of the rotor varies in relation to the velocity of the wind in order to reach a greater efficiency.

Nowadays, modern wind turbines are reliable, quiet, cost-effective and commercially competitive as the wind turbine technologies are proven and mature. At present, technical challenges are generally associated with ever-growing wind turbine size, power transmission, energy storage, energy efficiency, system stability and fault tolerance. The power converter malfunction will cease the operation of wind turbine and gener-

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[18] L. Chamorro; F. Porte-Agel (2009), "A wind-tunnel investigation of wind turbine wakes: boundary-layer turbulence effects. Boundary-Layer Meteorol 136:515-533. https://doi.org/10.1007/s10546-009-9380-8

[19] J. O. Dabiri (2011). "Potential order-of magnitude enhancement of wind power density via counter-rotating vertical-axis wind turbine arrays", In Renewable Sustainable Energy.

[20] Ibid, 2011

[21] M. Kinzel; Q. Mulligan and J.O. Dabiri. "Energy exchange in an array of vertical-axis wind turbines". In Journal of Turbulence, vol. 13, No.38, 2012, pp. 1-13. Graduate Aeronautical Laboratories, California Institute of Technology, Pasadena, CA, USA

[22] "Bladeless Wind Turbines – Less Efficient in the Conversion of Captured Wind Power Into Electrical Energy", Evwind press release, 31 May, 2019

ate disturbance to the grid. Recently, it has been widely accepted in wind industry that the power converter should be robust, and have good capability of fault tolerance.

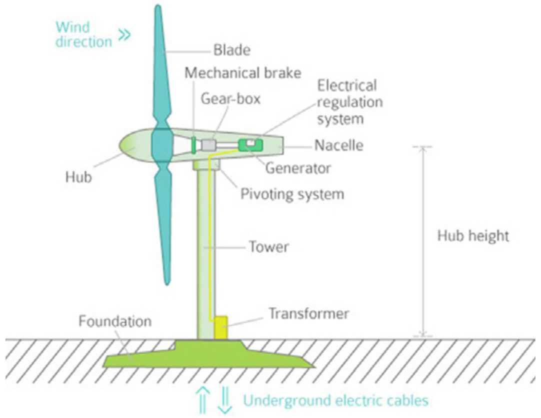
Wind turbines first emerged more than a century ago. Following the invention of the electric generator in the 1830s, engineers started attempting to harness wind energy to produce electricity. Wind power generation took place in the United Kingdom and the United States in 1887 and 1888, but modern wind power is considered to have been first developed in Denmark, where horizontal-axis wind turbines were built in 1891 and a 22.8 meter wind turbine began operation in 1897.

Tall, tubular steel towers support a hub with three attached blades and a "nacelle", which houses the shaft, gearbox, generator, and controls. Wind measurements are collected, which direct the turbine to rotate and face the strongest wind, and the angle or "pitch" of its blades is optimized to capture energy. Modern wind turbines are large structures, many reach more than 150 meters above the ground. Clusters of densely spaced with wind turbines, so called wind farms, are being built both on- and offshore. Wind farms vary in size from a small number of turbines to several hundred wind turbines covering an extensive area.

The smallest turbines are used for applications such as battery charging for auxiliary power for boats or caravans or to power traffic warning signs. Larger turbines can be used for making contributions to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Arrays of large turbines, known as wind farms, are becoming an increasingly important source of intermittent renewable energy and are used by many countries as part of a strategy to reduce reliance on fossil fuels.

An onshore wind turbine is made up of three main parts as seen in Figure 4: the tower, the rotor, and the pivoting nacelle. The tower is most often metallic and cone shaped, it is usually white and meets aeronautical requirements. It is 40 to 110 meters tall, with a base diameter of 4 to 7 meters. It contains an opening on the ground to allow access to variety of equipment. The rotor is located upwards where the wind is strongest, and which allows for a lengthy blade. The pivoting nacelle is located at the peak of the tower, it houses the generator that transforms the mechanical wind energy into electric energy. The nacelle is made by a ladder and/or a lift is located inside the tower.

Wind turbines come with different topologies, architectures and design features. The schematic of a wind turbine generation system is shown in Figure 6.



Source: Futuren Group (2020).

Wind turbines include critical mechanical components such as turbine blades and rotors, drive train and generators. In general, wind turbines are intended for relatively inaccessible sites placing some constraints on the designs in a number of ways.

The part of the wind turbine that converts the energy contained in the wind into a mechanical rotary motion is the **rotor.** It consists of one or more rotor blades of composite material from 25 to 60 meters in length and it is connected by the rotor hub. The number of rotor blades is related to the rotor speed in order to achieve the best possible wind speed reduction. For this reason, modern plants have from one to three rotor blades. The rotor pivots 360 degrees to face the wind and to allow a maximum production of electricity. The height at the tip of the blade varies between 90 and 150 meters for the largest wind turbines. The blades of a wind turbine turn at an average speed of 10 to 20 rotations per minute. The rotor blades extract kinetic energy from the moving air masses according to the buoyancy principle as seen in Figure 5. Here the upper side of the wing is larger than the lower side, due to the different distance the air must move at a higher speed at the upper side than at the lower side.

In order to convert the kinetic energy into electrical energy at a rotor speed of 30 to 50 rotations per minute (rpm), a speed of approximately 1500 rpm is required for most four-pole generators in the network specification (50 Hz). Usually, the gearbox forms a part of the drive train, which divides the drive shaft into a slow and a fast generator shaft. The gearbox is located in the nacelle of the wind turbine. The friction of the gearwheels results in low energy losses, which manifest themselves through heat radiation and acoustic noises.

One of key components in the wind turbine is its drive train, which links aerodynamic rotor and electrical output terminals. Optimization of a wind turbine generators cannot be realized without considering mechanical, structural, hydraulic and magnetic performance of the drive train. Generally, drive train technologies can be broken down into four types according to their structure:

- Conventional: gearbox and high speed generator with few pole pairs;
- Direct drive: any drive train without a gearbox and low speed generator with many pole pairs;
- Hybrid: any drive train with a gearbox and the generator speed between the two types mentioned above;
- Multiple generators: any drive train with more than one generator.

Drive train topologies may raise the issues such as the integration of the rotor and gearbox/bearings, the isolation of gear and generator shafts from mechanical bending loads, the integrity and load paths. Although, it may be easier to service separate wind turbine components such as gearboxes, bearings and generators, the industry is increasingly in favor of system design of the integrated drive train components.

1.3. TYPES OF WIND TURBINES

Wind turbines can be categorized by the orientation of their axis of rotation into two groups: horizontal axis wind turbines (HAWTs) and vertical axis wind turbines (VAWTs). The latter typically have fewer moving parts and a generator located at ground level which could ultimately lead to higher availability and lower maintenance cost (Eriksson, 2008)[23]. Furthermore, it has been shown that the concept is more suitable for upscaling than the HAWT concept. And of special interest for this work, VAWTs has potentially lower noise emissions.

1.3.1. HORIZONTAL AXIS WIND TURBINES

Horizontal axis wind turbines (HAWTs) are the most common wind machine design is use today. It may produce less than 100 kW for basic applications and residential use, or as much as 6 MW. The HAWT is a wind turbine in which the main rotor shaft is pointed in the direction of the wind to extract power. The principal components of a basic HAWT are shown in Figure 8. HAWTs utilize aerodynamic blades (i.e. airfoils) fitted to a rotor, which can be positioned either upwind or downwind. HAWTs are typically either two- or three-bladed and operate at high blade tip speeds. Machines with upwind rotors require a yaw, or tail vane, to help them orient into the wind while downwind rotors have blades that are coned allowing turbine to orient on its own. One drawback identified with downwind rotors, however, is that they have been known to "walk" around when trying to line up with winds during low speed energy production (Gipe, 2009)[24].

Modern HAWTs use the aerodynamic lift force to turn each rotor blade, in a manner similar to

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[23] S. Erikkson (2008). "Direct driven generators for vertical axis wind turbines", Doctoral dissertation, ACTA UNIVERSITATIS UPSALIENSIS, Uppsala

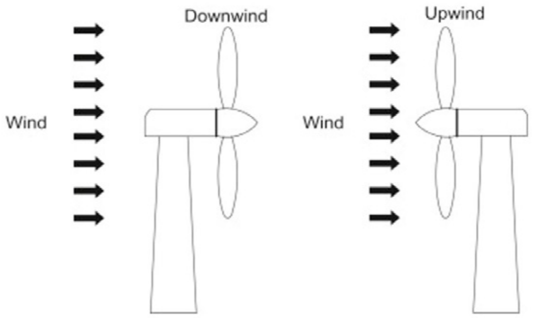
[24] P. Gipe (2009). "Wind energy basics: a guide to home and community scale wind energy systems", Chelsea Green Publishing.

the way an airplane flies. The lift force generally works as follows. When exposed to winds, air flows around both the upper and lower portions of a blade. As a result of the blade's curvature, however, air passes over the top of the blade more quickly (owing to a longer fetch length) than the lower portion, producing a low-pressure area on the topside. The pressure difference created between the top and bottom sides of the blade produces a force in the direction of the top blade.

Horizontal-axis wind turbines (HAWTs) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind, the turbine is usually positioned upwind of its supporting tower as seen in Figure 7. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed at a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

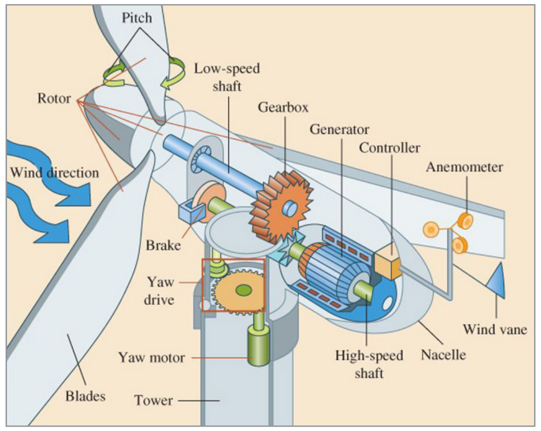
Figure 7. Configuration of HAWTs



Source: Modified from Boulouiha & Denai (2017) in "Clean Energy for Sustainable Development.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they do not need an additional mechanism for keeping them in line with the wind, as well as in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

Figure 8. Basic parts of a HAWT



Source: Electrical Academy 2020

The main design principle of horizontal axis wind turbine is almost exclusively a propeller design. One of the advantages of this propeller type is that by adjusting the rotor blades around their longitudinal axis, the rotor speed and the power output of the wind turbine can be controlled. The adjustment of the rotor blades is the most effective means of protection against over-speed, especially in case of extreme wind speeds. With an optimal design of the rotor blade shape, maximum utilization of the principle of aerodynamic lift can be achieved. Systems of such a propeller design, as shown in Figure 8, consist of the following components: foundation, nacelle and rotor.

An industry and academic focus on large, utility-scale horizontal-axis wind turbines (HAWT) has led to the development of HAWTs capable of efficiencies near the theoretical Betz limit of maximum wind energy extraction, 59.3%[25]. However, when HAWTs are arrayed in a wind farm, downstream turbines perform less efficiently than in isolation due to the incoming turbulent wake created by upstream turbines. Studies have shown that a HAWT spacing on the order of 20 turbine rotor diameters, D, is needed to provide space for the flow to re-energize sufficiently for downstream turbines to achieve performance levels similar to those demonstrated in isolation. Despite this, modern HAWT farms typically space turbines approximately 3-5 D in the cross-wind direction and 6-10 D in the stream-wise direction[26].

A variety of solutions have recently been proposed to effectively manage the tradeoff between turbine efficiency and wind farm footprint. Instead of optimizing for individual turbine efficiency, optimization can focus on the total power production of turbine arrays. More recently, a row-offset arrangement was demonstrated to allow for a greater wake recovery due to the increased stream-wise spacing within the array. Moreover, by decreasing the power output of upstream turbines, the performance of downstream turbines and the power output of the array as a whole can be increased[27].

Even though the HAWT has by far been the most successful concept with the large and economically feasible turbines of today the VAWT concept has some advantages that are explained more detail in the next section of this chapter.

A variety of solutions have recently been proposed to effectively manage the tradeoff between turbine efficiency and wind farm footprint. Instead of optimizing for individual turbine efficiency, optimization can focus on the total power production of turbine arrays. More recently, a row-offset arrangement was demonstrated to allow for a greater wake recovery due to the increased stream-wise spacing within the array. Moreover, by decreasing the power output of upstream turbines, the performance of downstream turbines and the power output of the array as a whole can be increased[28].

1.3.2. VERTICAL AXIS WIND TURBINES

Stanford University researchers created a cutting edge lab model of vertical wind turbine (VAWT) arrangements that will help with design and implementation in the future. VAWT is a wind turbine design where the generator is vertically oriented in the tower, rather than sitting horizontally on top. Vertical Axis Wind Turbine (VAWT) are a type of wind turbine used to convert kinetic energy from moving air into electrical power by means of lift producing blades. They differ to the conventional Horizontal Axis Wind Turbines (HAWT) by having the main shaft transversely aligned with the wind direction. Vertical Axis Wind Turbines are seen as a viable solution to urban and peri-urban power generation requirements leading into 2020.

This type of wind turbines could be either arranged in groups or interspersed within horizontal-axis wind turbines (HAWT) arrays. A VAWT has an overall cylindrical shape, with the blades aligned parallel to, and rotating around, the pole on which the rotor is mounted. These "egg-beater" VAWTs tend to be much smaller than the "propeller" HAWTs, typically about 10 times shorter in height, and output about 0.1 percent as much power per turbine.

While a single VAWT is not as energy-producing as an individual HAWT, the wind flow synergies created in a closely-spaced array of VAWTs can potentially generate up to 10 times more power per unit of land area than an array of widely-spaced HAWTs.

There are two different ways of converting wind energy into mechanical energy for the vertical axis converters. Here, either the thrust or the suction of the wind is used to generate a rotary motion, hence a closer look at the two most important representatives of this design will be taken.

The Savonius wind turbine is a type of vertical-axis wind turbine invented by the Finnish engineer Sigurd Savonius in the 1920s. It consists of

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[25] According to Betz' law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. The factor 16/27 is known as Betz' co-efficient. Practical utility-scale wind turbines achieve at peak 75-80% of the Betz limit.

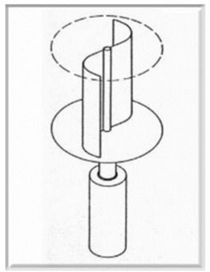
[26] Brownstein et al (2016), Performance enhancement of downstream vertical-axis wind turbines, Journal of Renewable Energy, 8

[27] Ibid

[28] Ibid

two to three "scoops" that employ a drag action to convert wind energy into torque to drive a turbine. When looked at from above in cross-section, a two scoop Savonius turbine looks like an S-shape. Due to the curvature of the scoops, the turbine encounters less drag when moving against the wind than with it, and this causes the turbine to spin in any direction of wind regardless of facing. Aerodynamically it is the simplest wind turbine to design and build which reduces its cost drastically compared to the aerofoil blade designs of the other VAWTs and HAWTs.

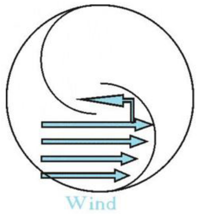
Figure 9. Savonius wind turbine



The air is trapped in the concave part and pushes the turbine. The flow that hits the convex part does produce a drag that is lower than the one on the concave part. It is the differential of the drag force that causes this turbine to rotate. This lowers the efficiency of the turbine as some of the wind's power is used pushing the convex part and is hence "wasted". More blades can be added to the S shape design, and the same principle causes it to spin as shown in figure 9.

According to Wilson et al[29], "a Savonius rotor requires 30 times more surface for the same power as a conventional rotor blade wind-turbine. Therefore, it is only useful and economical for small power requirements". This makes Savonius ideal for small applications with low wind speeds. Savonius are hence desirable for their reliability, as they are able to work at several magnitudes of wind speed.

Figure 10. Functioning of a Savonius wind rotor. Here the wind is first pressed into one of the counter-rotating, curved, overlapping shells and then deflected into the second shell, so that a drive movement is created.



After the First World War, G.J.M. **Darrieus,** a French aeronautical engineer, invented a VAWT by adopting airfoil profile for the blades. He patented the design in France in 1925 and in the USA in 1931 and put the working principle as a biomimicry of birds' wings which enabled to give the blades a stream line section analogous to that of the wings of birds. It offered the minimum resistance to forward movement. As well it was capable of converting it into mechanical energy the maximum available amount of energy of the fluid by means of the useful component of the traverse thrust which this section underwent[30]. The patent covered two major configurations: curved and straight blades.

Most wind turbines designed for the production of electricity have consisted of two or three bladed propeller rotating around a horizontal axis. These blades tend to be expensive, high technology items, and the turbines has to be oriented into the wind, another expensive task for the larger machines. These problems have led many researchers in search of simpler and less expensive machines. One that has seen considerable development is the **Darrieus wind turbine.**

Unlike the Savonius wind turbine, which accumulates the energy for rotation, the Darrieus is a lift-type VAWT. Rather than collecting the wind in cups *dragging* the turbine around, a Darrieus uses *lift forces* generated by the wind hitting aerofoils to create rotation.

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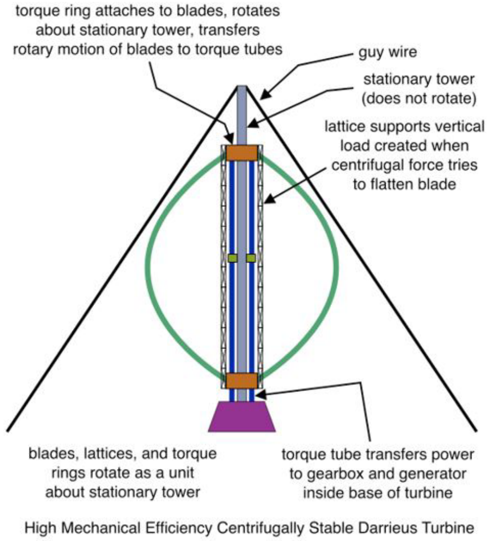
[29] R. Wilson; P. Lissaman. "Applied Aerodynamics of Wind Power Machine", National Science Foundation, 1974

[30] W. Tiju; T. Marnoto; S. Mat; M. Ruslan; K. Sopian. "Darrieus vertical axis wind turbine for power generation I: Assessment of Darrieus VAWT configurations", In Renewable Energy, volume 75 (2015), pp. 50-67

A Darrieus wind turbine can spin at many times the speed of the wind hitting (i.e. the tip speed ration is greater than 1). Hence a Darrieus wind turbine generates less torque than a Savonius but it rotates much faster. This makes Darrieus wind turbines much better suited to electricity generation rather than water pumping and similar activities. The centrifugal forces generated by a Darrieus turbine are very large and act on the turbine blades which therefore have to be very strong – however the forces on the bearings and generator are usually lower than the case with a Savonius.

A disadvantage of the Darrieus turbine is that it is not a self-starting wind turbine. Therefore a small powered motor is required to start off the rotation, and then when it has enough speed the wind passing across the aerofoils starts to generate torque and the rotor is driven around by the wind. Two small Savonius rotors are mounted on the shaft of the Darrieus turbine to start rotation. As a result it slows down the Darrieus turbine when it gets going however these two small rotors make the whole device a lot simpler and easier to maintain. Variants of the Darrieus wind turbine are the giromill and cycloturbine.

Figure 11. Darrieus wind turbine.



Source: Wordpress 2017.

1.4. WIND TURBINE GENERATORS

One of limiting factors in wind turbines lies in their generator technology. A generator converts the mechanical rotary motion of the drive train into electrical energy. This is done by alternating current generators, which achieve efficiencies of 90 to 98% depending on the load range. There is no consensus among academics and the industry on the best wind turbine generator technology. Traditionally, there are three main types of wind turbine generators (WTGs) which can be considered for the various wind turbine systems, these being direct current (DC), alternating current (AC) synchronous and AC asynchronous generators. In principle, each can be run at fixed or variable speed. Due to the fluctuating nature of wind power, it is advantageous to operate the WTG at variable speed which reduces the physical stress on the turbine blades and drive train, and which improves system aerodynamic efficiency and torque transient behavior.

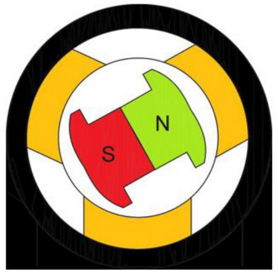
The advantages of asynchronous generators are its robustness and low maintenance costs. Furthermore, they can ensure simple synchronization with the mains, which they load with reactive current. Asynchronous generators can be coupled to the grid smoother as compared to their synchronous counterparts, but they have a lower efficiency. However, for the synchronous generators with a higher efficiency, power inverters are required to be connected to the grid.

AC Synchronous Generator Technologies

Since the early time of developing wind turbines, considerable efforts have been made to utilize three-phase synchronous machines. AC synchronous WTGs can take constant or DC excitations from either permanent magnets or electromagnets and thus termed PM synchronous generators (PMSGs) and electrically excited synchronous generators (EESGs), respectively. When the rotor is driven by the wind turbine, a three-phase power is generated in the stator windings which are connected to the grid through transformers and power converters. For fixed speed synchronous generators, the rotor speed must be kept at exactly the synchronous speed. Otherwise synchronisation will be lost.

Synchronous generators are a proven machine technology since their performance for power generation has been studied and widely accepted for a long time. In theory, the reactive power characteristics of synchronous generators, random wind speed fluctuations and periodic disturbances caused by tower-shading effects and natural resonances of components would be passed onto the grid.

Figure 12. Structure of a Synchronous Generator. With stator (in black color), rotor (in green and red), and slip rings (in orange)



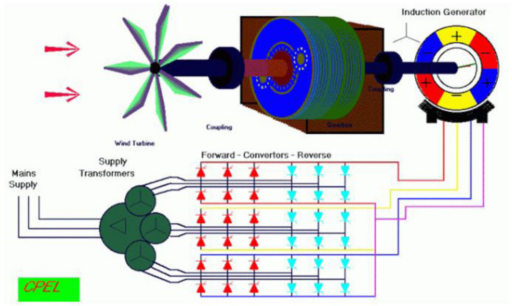
AC Asynchronous Generators

Whilst conventional power generation utilizes synchronous machines, modern wind power systems use induction machines extensively in wind turbine applications. One reason for choosing this type of generator is that it is very reliable and tends to be comparatively inexpensive. The generator also has some mechanical properties which are useful for wind turbines, like the generator slip and a certain overload capacity.

The key component of the asynchronous generator is the cage rotor that makes the asynchronous generator different from its synchronous counterpart. The rotor consists of a number of copper or aluminium bars which are connected electrically by aluminium end rings. When the current is connected, the machine will start turning like a motor at a speed which is slightly below the synchronous speed of the rotating magnetic field from the stator. There is a magnetic field which moves relative to the rotor. This induces a very strong current in the rotor bars which offer very little resistance to the current, since they are short circuited by the end rings. Therefore the rotor develops its own magnetic poles, which in turn become dragged by the electromagnetic force from the rotating magnetic field in the stator.

These induction generators fall into two types: fixed speed induction generators (FSIGs) with squirrel cage rotors, and doubly-fed induction generators (DFIGs) with wound rotors.

Figure 13. Doubly-fed induction generator



Source: Adapted from CPEL Energy (2020)

When supplied with three-phase AC power to the stator, a rotating magnetic field is established across the airgap. If the rotor rotates at a speed different to synchronous speed, a slip is created and the rotor circuit is energized. Generally speaking, induction machines are simple, reliable, inexpensive and well developed. They have high degree of damping and are capable of absorbing rotor speed fluctuations and drive train transients (i.e fault tolerant). However, induction machines draw reactive power from the grid and thus some form of reactive power compensation is needed such as the use of capacitators or power converters. For fixed-speed induction generators, the stator is connected to the grid via a transformer and the rotor is connected to the wind turbine through a gearbox. The rotor speed is considered to be fixed (in fact, varying within a narrow range).

The asynchronous system has one rather interesting mode of operation that electric utilities do not have. The turbine speed can be controlled by the load rather than by adjusting the turbine. Electric utilities do have some load management capability, but most of their load is not controllable by the utilities. The utilities therefore adjust the prime mover input (by a valve in a stream line, for example) to follow the variation in load. That is, supply follows demand. In the case of wind turbines, the turbine input power in is just the power in the wind and it is not subject to control. Turbine speed still needs to be controlled for optimum performance, and this can be accomplished by an electrical load with the proper characteristics, as can be seen.

It can be expected that the use of asynchronous electricity to continue, and perhaps even to grow, for a number of reasons. The use of wind power at remote communication sites for charging batteries can be expected to increase as less expensive, more reliable wind turbines are developed. Space heating and domestic hot water heating are natural applications where propane or oil are now being used. Another large potential for market would be the many thousands of villages around the world which are not interconnected with any large utility grid. Economics may preclude the possibility of such a grid, so each village may be forced to have its own electric system.

One final reason for having asynchronous capability on wind turbines would be the possibility of its being needed if electrical grid should fall apart.

1.5. FUTURE TRENDS IN WIND TURBINES TECHNOLOGIES

As the technology matures, advancements are on the horizon that will extend wind project lifespan whilst simultaneously lowering the operational costs. Some of the main areas of innovation are: (1) longer and lighter rotor blades – with some reaching 95 meters long; (2) blades with curved tips that are designed to take maximum advantage of all wind speeds; (3) more reliable gearboxes; and (4) digitalization of processes.

Turbines at present, are not very digital. But as technology, in general, evolves to become more sophisticated. Use of drones is also another technological advance the wind industry is leveraging. With drones, photo can be taken remotely and autonomously without the need for a pilot, cloud computing can then stitch these images together, before finally passing them over to an AI (artificial intelligence) system that is programmed to identify any problems with the blade i.e. – cracks, for example. The highly digitalized process means maintenance issues can be identified at an early stage, enabling technicians to be deployed before the problem becomes serious enough to warrant shutting down the turbine.

Digitalization is not only restricted to the technology of the wind turbine itself, it expand across the industry with ideas such as an intelligent "smart grid" developing. In essence, the smart grid is a digital technology that enables communication between the utility provider and the customer. The smart grid can be conceptualized as an extensive cyber-physical system that supports and facilitates significantly enhanced controllability and responsiveness of highly distributed resources within electric power systems. Smart grids consist of series of computers, automated process and new technologies working together to create a responsive grid. For example, if there is an emergency such as a blackout, the smart grid technologies can detect this and isolate the problem, containing it before it grows to become a large-scale blackout.

The uncertainty and intermittency of wind and solar generation are major complications that must be addressed before the full potential of these renewables can be reached. Smart grid concepts – an evolution of electricity networks towards greater reliance on communications, computation, and control – promises a solution. The term gained prominence through the U.S Energy Independence and Security Act (EISA) of 2007, the European Technology Platform for the Electricity Networks of the Future, and similar initiatives across numerous other countries. The current grid structure reflects carefully considered trade-offs between cost and reliability. The responsiveness achievable through smart grid concepts will, however, play a vital role in achieving large-scale integration of new forms of generation and demand. Renewable generation will make an increasingly important contribution to electric energy production into the future. Integration of these highly variable, widely distributed resources will call for new approaches to power system operation and control. Likewise, new types of loads, such as plug-in electric vehicles and their associated vehicle-to-grid potential, will offer challenges and opportunities. Establishing a cyberinfrastructure that provides ubiquitous sensing and actuation capabilities will be vital to achieving the responsiveness needed for future grid operations. Sensing and actuation will be pointless, though, without appropriate controls. The premise of the smart grid is a huge industry-level change that will take a decade to implement, but it will bring great rewards such as, the ability to predict demand and coordinate storage at multiple levels. It could be used to tell the turbines in a wind farm when to run; dependent on what the current demand for energy is, meaning energy usage becomes much more efficient and cost-effective.

A smart power grid can be characterized by four different features: collecting (real-time) information, its transfer and aggregation, evaluation and analysis as well as making adjustments. At first, a smart power grid enables to gather information at the different parts of the grid. As an example, a sensor at a turbine measures the current power generation and indicates when it has to be maintained. Other potential use can be gathering information about the power demand of a city or the current wind speed or level of sunshine at a specific location. This information is transferred and aggregated at a central point, for example a data center where the data is further processed and can be finally observed by a human or computer who evaluates and analyses the data by using different methods, for example a machine learning algorithm which categorizes the maintenance level of a wind turbine. Based on the analysis, adjustments can be made, for example the shut-down of the turbine as it is seriously damaged when further operated. In this way, actions can be taken in advance to increase the efficiency of the grid and its parts. This can be applied on the power grid of a country as well as micro-grids of for example single buildings (Ricalde et al., 2011)[31].

Different systems can be integrated into the smart grid to provide a more efficient and more stable network. This also includes the data transmission of sensors on wind turbines to get the actual generation information as well as data related to maintenance issues. As renewable energy by its nature is fluctuating, a precise observation is necessary to prevent blackouts. Further, the smart grids can be used for optimization of the grid to make adjustments in case, the power demand increases or decreases. Basis for this is the fast communication between all parts of the grid (Li et al., 2010)[32].

However, smart grids do not only feature high level observation and fast communication they also yield a high amount of data, which can be used to predict events even before they occur. Since more than two decades researchers try to find the most efficient way to predict the wind generation in different scenarios. This can be done by traditional time series models or other probabilistic approaches. Currently artificial intelligence (AI) algorithms are the most commonly used method for wind generation predictions. These algorithms take advantage of a complex system which is weighting different factors of influence and is optimized by powerful computers to provide the best prediction results (Di Piazza et al., 2016)[33]. They can also be used for other forecasts, for example the power demand of private households. This part of the power demand is another factor of volatility which can be reduced by predictions besides solar and wind power (Raza et al., 2017)[34].

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[31] L. J. Ricalde; E. Ordoñez; M. Gamez and E.N. Sanchez. "Design of a smart grid management system with renewable energy generation". In 2011 IEEE Symposium on Computational Intelligence Applications In Smart Grid (CIASG), Paris, 2011, pp. 1-4., www.doi.org/10.1109/LIASG.2011.5953346

[32] F. Li; F. Wu and J. Zhong. "Communications Requirements for Risk-Limiting Dispatch in Smart Grid". 2011 IEEE International Conference on Communications Workshops, Capetown, South – Africa, 2010, pp. 1-5

[33] A. Di Pizza; C. Di Piazza and G. Vitale. "Solar and wind forecasting by NARX neural networks". In 2016 Renewable Energy and Environmental Sustainability, volume 1, Issue 39. https://doi.org/10.1051/rees/2016047

[34] M. Raza; M. Nadarajah; D. Hung; Z. Baharudin. "An intelligent hybrid short-term load forecasting model for smart power grids". In 2017 Sustainable Cities and Society, 31, pp.264-275

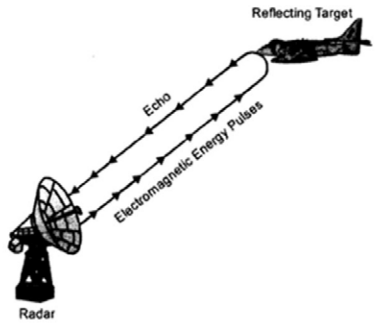
The characteristic features of wind energy as its volatility and unpredictability can cause different problems. On one hand, to keep the provided power at a steady level the power feed in of other sources has to be adjusted or the wind power generation itself has to be controlled in some way. Therefore making predictions on the wind power feed in is essential to solve the issue. The most common models for forecasting wind are time series models and machine learning approaches. Thus, wind power can be predicted on short and medium time intervals from minutes to a few days. Based on these forecasts, adjustments can be made to ensure a stable grid. On the other hand, fluctuations on very short time intervals like a couple of seconds cannot be accounted for in the same way. Instead, other approaches have to be taken. One of them is to evaluate the effects of this short term fluctuation via simulation and take adjustments in the grid to prevent blackouts (Zhang et al., 2019)[35].

CHAPTER 2. RADAR SYSTEMS AND WIND FARMS

A radar is an electromagnetic system for detection, location and recognition of target objects, which operates by transmitting electromagnetic signals, receiving echoes from target objects within its coverage volume, and extracting location and other information from these echo signals. Detection involves directing a beam of radio-frequency waves over a region to be searched. When the beam strikes a reflecting object, some of the beam's energy is reflected. A very small part of this reflected energy is returned to the radar system.

Using the coordinate systems, radar systems provide early detection of surface or air objects, giving extremely accurate information on distance, direction, height, and speed of the objects. Radar measurement of range (or distance) is made possible because of the properties of radiated electromagnetic energy. Modern radars, however, are sophisticated transducer/computer systems that not only detect targets and determine target range, but also track, identify, image, and classify targets while suppressing strong unwanted interference such as echoes from the environment (known as *clutter*) and countermeasures (*jamming*). Radar jamming and deception is a form of electronic countermeasures that intentionally sends out radio frequency signals to interfere with the operation of radar by saturating its receiver with noise or false information.

Figure 14. Basic principle of a radar



Radar originally was developed to meet the needs of the military services, and it continues to have critical applications for national defence purposes. For instance, radars are used to detect aircraft, missiles, artillery and mortar projectiles, ships, land vehicles, and satellites. In addition, radar controls and guides weapons; allows one class of target to be distinguished from another; aids in the navigation of aircraft and ships; and assists in reconnaissance and damage assessment. Military radar systems can be divided into three main classes based on platform: land-based, shipborne, and airborne. Within these broad classes, there are several other categories based mainly on the operational use of the radar system. There is also a trend to develop multimode radar systems.

In 1904 the German engineer, Christian Hülsmeyer obtained a patent for a device capable of detecting ships. This device was demonstrated to the German navy, but failed to arouse interest probably due in part to its very limited range. In 1922, Guglielmo Marconi drew attention to the work of Hertz and repeated Hertz experiments and eventually proposed in principle what is now

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[35] X. Zhang; C. Ma; M. Timme (2019). "Dynamic Vulnerability in Oscillatory Networks and power Grids" ort-term load forecasting model for smart power grids". In 2017 Sustainable Cities and Society, 31, pp.264-275

known as marine radar. It was a pulsed radar, radiating differentiated video pulses, generated by a spark gap. Hülsmeyer's ideas were based on the experiments by Heinrich Hertz in 1888, when he detected the polarization dependent reflection of electromagnetic waves. Radar systems have evolved tremendously since their early days when their functions were limited to target detection and target range determination.

The radar technology, also known as microwave technology is based on the Doppler Effect: the radar sensor continuously emits microwaves with a certain frequency in a defined area. These microwaves are reflected back to the sensor by all of the objects present in its environment. If the objects in this area do not move, the microwaves come back to the sensor with the same frequency as the initial one. Once a movement occurs in the detection field, the microwaves come back to the sensor with a different frequency and this results in a detection.

The phenomenon of electromagnetic radiation is caused by the mutually reinforcing interaction of charged electrical and magnetic fields operating perpendicular to each other and that travel through space at the speed of light. Each pulse emanating from the interplay of the electrical and magnetic fields' results in a force that creates a wave of energy. Electromagnetic wavelength refers to the measured distance between the crest and trough of each adjacent wave generated by the electromagnetic disturbance. Radio waves, television broadcasts, X-rays, visible and invisible light, and microwave radiation are each discrete components of the electromagnetic spectrum that can be defined and categorized by the respective electromagnetic wavelengths.

Figure 15. Radar frequencies and Radar Bands

Band Designation	Frequency Range	Usage
High frequency (HF)	3-30 MHz	OTH surveillance[36]
Very high frequency (VHF)	30-300 MHz	Very-long-range surveillance
Ultra high frequency (UHF)	300 MHZ – 1 GHz	Very-long-range surveillance
L	1-2 GHz	Long-range surveillance En route traffic control
S	2-4 GHz	Moderate-range surveillance Terminal traffic control Long-range weather
C	4-8 GHz	Long-range tracking Airborne weather detection
X	8-12 GHz	Short-range tracking Missile guidance Mapping, marine radar Airborne intercept
Ku ("under" K-band)	12-18 GHz	High-resolution mapping Satellite altimetry
K	18-27 GHz	Little use (water vapor) 24.65-24.75 GHz
Ka ("above" K-band)	27-40 GHz	Very-high resolution mapping Airport surveillance
Millimeter	40-100+GHz	Experimental

Source: Adapted from Skolnik, M. "Radar Handbook", 3rd ed. NY: McGraw-Hill, 2008.

Electromagnetic waves can be grouped according to the direction of disturbance in them and according to the range of their frequency. This means that there are two things going on: the disturbance that defines a wave, and the propagation of wave. In this context the waves are grouped into the following 2 categories:

- **Longitudinal waves** – a wave is called longitudinal when the disturbances in the wave are parallel to the direction of propagation of the wave. For example, sound waves are longitudinal waves because the change of pressure occurs parallel to the direction of wave propagation.
- **Transverse waves-** a wave is called a transverse wave when the disturbances in the wave are perpendicular (at right angles) to the direction of propagation of waves.

The intensity of electromagnetic radiation is a function of the frequency of the waves generated in each second. Specific frequencies are identified by the number of cycles generated each second. The spectrum of electromagnetic waves has frequencies up to 10^{24} Hz. This very large range is subdivided into different subranges due to different physical properties. There are different working frequencies ranging from S-band (2.0-4.0 GHz) to X-band (8.0-12.0 GHz) in the case of weather and marine radars, and L-band (1.0-2.0 GHz) as seen in Figure 15.

2.1. THE RADAR CONCEPT

A radar system measures the distance and direction to the object, its velocity and some signatures for the purpose of classification. There are two sources for the distance measurement: a coarse but unambiguous information by measurement of the wave travelling time and a fine but ambiguous information by phase measurement. The accuracy is in the order of meters down to decimeters for the first kind and in the order of fractions of the wavelength (millimeters) for the second. By using the phase modulations over time (Doppler frequency) the radar can measure also the radial velocity with a high accuracy (Ender, J, 2005)[37].

There are two different basic concepts of radar: the first aims at the detection and localization of targets; here the resolution cell size (range, direction, Doppler) is greater or equal to the extensions generated by the object. Target classification can be achieved via the signal strength (radar cross section, RCS), Doppler modulations by moving parts of the object, polarization[38], and the dynamics of motion. The second concept is that of radar imaging. The aim is to generate a quasi- optical image (SAR, ISAR)[39]. In this case the resolution cells have to be much smaller than the objects extension. Information about the target can be extracted from the two- or three-dimensional images or even one-dimensional images (range profile, micro-Doppler).

Radar systems in its simplest form can be seen in Figure 16. Radar is a sensor system utilizing electromagnetic radiation in the radio frequency (RF) special region, spanning from approximately 3 MHz to around 100 GHz. An elementary form of radar consists of a transmitting antenna emitting electromagnetic radiation generated by an oscillator of some sort, a receiving antenna, and an energy-detecting device, or receiver.

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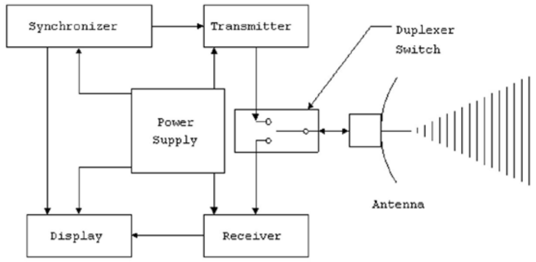
[36] Over-the-horizon radars (OTH), sometimes called beyond the horizon (BTH), is a type of a radar systems with the ability to detect targets at very long ranges, typically hundreds to thousands of kilometers, beyond the radar horizon, which is the distance limit for ordinary radar.

[37] Ender, J. "Introduction to Radar, Part I: Scriptum of a lecture at the Ruhr-Universität Bochum, Frauenhofer Institute for High Frequency Physics and Radar Techniques.

[38] In all electromagnetic radiation, the electric field is perpendicular to the direction of propagation, and the electric field direction is the polarization of the wave. Radars use horizontal, vertical, linear, and circular polarization to detect different types of reflections.

[39] SAR – Synthetic Aperture Radar is a form of radar that is used to create two-dimensional images or three-dimensional reconstructions of objects, such as landscapes. SAR uses the motion of the radar antenna over a target region to provide finer spatial resolution than conventional beam-scanning radars. Inverse synthetic aperture radar (ISAR) is a radar technique imaging to generate two-dimensional high resolution image of a target. It is analogous to conventional SAR, except that ISAR technology uses the movement of the target, rather than the emitter to create a synthetic aperture.

Figure 16. Basic elements of a radar system



Source: Federation of American Scientists (FAS, 2020)

The electronic principle on which radar operates is very similar to the principle of sound-wave reflection. Radio-frequency energy is transmitted to and reflected from the reflecting object. A portion of the transmitted signal is intercepted by a reflecting object (target) and is reradiated in all directions. It is the energy reradiated in the back direction that is of prime interest to the radar. The receiving antenna collects the returned energy and delivers it to a receiver, where it is processed to detect the presence of the target and to extract its location and relative velocity. The distance to the target is determined by measuring the time taken for the radar signal to travel to the target and back. The direction, or angular position, of the target may be determined from the direction of arrival of the reflected wave front. The usual method of measuring the direction of arrival is with narrow antenna beams. If relative motion exists between target and radar, the shift in the carrier frequency of the reflected wave (Doppler Effect) is a measure of the target's relative (radial) velocity and may be used to distinguish moving targets from stationary objects.

2.2. TYPES OF RADARS

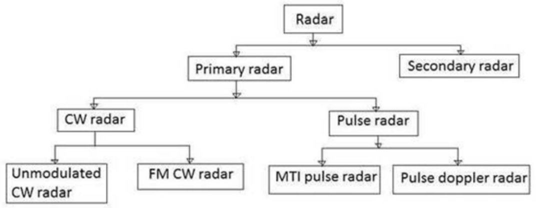
Radar systems have been designed for a variety of applications and missions. These systems include radars for air defence, air traffic control, missile warning, weather, etc. Generally, they may be classified depending on:

- Technology, in imaging and non-imagine radars: Primary, Secondary, Continuous Wave, Frequency Modulated, Frequency Modulated Interrupted Continuous Wave, Pulse, Bi-static, and Side-looking Airborne;
- Design used in radars: Air Defence, Fly Surveillance, and Ground penetrating;
- Data monitoring used: Weather radars, Noise radar, etc.

Each of the radar systems described is designed to detect a specific kind of target, and therefore, they feature different working regimes and frequency bands, operation ranges, etc. Weather radars aim at detecting meteorological phenomena like clouds, rain, or storms, while air traffic radars (ATCs) aim at detecting aircrafts, and maritime radars at ships and boats.

Radar systems can also be classified into many types based on specific radar characteristics, such as system configuration (mono-static, bi-static or multi-static), desired application, waveform used (continuous wave and pulse radars) and frequency bands (Skolnik, 2008)[40]. The monostatic radar has a common antenna used for both transmitting and receiving, while the bistatic radar has transmitting and receiving antennas separated by a considerable distance. According to the waveforms transmitted, radars can be classified into continuous wave (CW) radars or pulsed radars. A CW radar's transmitter operates continuously as seen in Figure 17. A pulsed radar transmits a relatively short burst of pulses, and after each pulse, the receiver is turned on to receive the echo. According to the primary missions, radars can be classified into search radars and tracking radars. Search radars continuously scan a volume of space without dwelling at any location. Their primary missions are detecting targets and determining a target's range and direction.

Figure 17. Radars classification



Source: Radar Tutorial (2020)

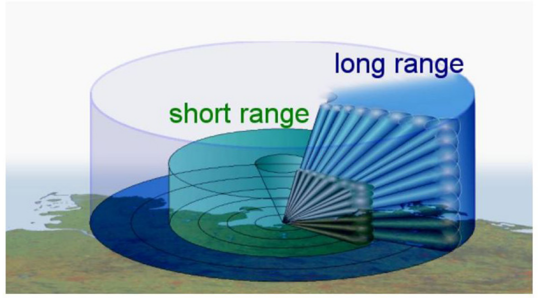
2.2.1. PRIMARY SURVEILLANCE RADARS

Air defence radars typically operate in what is termed a "Primary Surveillance" mode. When operated in that manner they are referred to as "Primary Surveillance Radar" (PSR). This type of radar will send out radio frequency waves (radar energy) focused by the antenna to provide an "illuminated" volumetric region of coverage. Radar coverage describes the space controlled by a radar or a network of radars.

Primary Surveillance Radar is generally rotated about a vertical axis to extend the volume of coverage. The angle of rotation may be as little as a few degrees to observe a small sector or up to 360 degrees to cover the entire airspace surrounding the radar. Alternatively, the antenna may oscillate back and forth over a small angle to cover only a sector of airspace. Systems of this type able to rotate a full 360 degrees can often be observed in use around airports.

Radars of this type are often referred to as 2-D radars since they are able to determine the position of an aircraft in terms of range and bearing angle (angular position of the aircraft with respect to north) but are unable to determine the height at which the airplane is above the surface of the earth. In contrast, most radars designed to inherently determine aircraft range, bearing, and altitude employ multiple beams. Radars able to determine all three aircraft parameters are typically referred to as being three-dimensional (3-D) radars as seen in Figure 18. In addition to range, the more common two-dimensional radar provides only azimuth for direction, whereas 3-D radar also provides elevation. Applications include weather monitoring, air defence, and surveillance.

Figure 18. Diagram of a typical 3-D radar, a mix of vertical electronic beam steering and mechanically horizontal movement of a pencil-beam.



Source: Christian Wolf (2003)

The main disadvantage of Primary Surveillance Radar (PSR) is the necessity of a large power radiated as to ensure the returning from the target. This is especially needed if long range is desired. Another disadvantage refers to the small amount of energy returned at receiver, which may be easily disrupted by changes of targets, attitude of the turbine blades, signal attenuation due to heavy rain, etc. This may cause that the displayed target to "fade".

The information provided by 3-D radar has long been required, particularly for air defence and interception. Interceptions must be told the altitude to climb to before making an intercept. Before the advent of single unit 3-D radars, this was achieved with separate search radars (giving range and azimuth) and separate height finding radars that could examine a target to determine altitude. This type of radars had little search capability, so they were directed to a particular azimuth first found by the primary search radar.

There are 2 different types of multi-beam 3-D radars, the first employs several "stacked" transmit units to produce overlapping illumination lobes. Similar to the 2-D radar, the entire antenna would be rotated about a vertical axis to sweep the illuminated area over the volume of airspace to be covered. The second type of 3-D radar is known as a phased-array radar as seen in Figure 18. In a phased-array radar, hundreds of thousands of

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[40] M. Skolnik. "Radar Handbook", 3rd ed. NY: McGraw-Hill, 2008.

small transmitters and receivers make up the face of the antenna. Radar beam patterns are formed by precisely adjusting (shifting) the phase angle of the signal sent to each transmit element. Employing a similar technique, the receive beam can also be "electronically steered" over an area to cover a specific volume of airspace. Mechanical steering can also be employed to increase the "field of regard" for a phased array radar.

2.2.2. SECONDARY SURVEILLANCE RADAR

Secondary Surveillance Radar (SSR) is an "interactive" radar in a sense that it requires the cooperation of the target aircraft. The SSR systems are considered to be tracking systems. It operates by sending out a coded signal (interrogation) that is received by a transponder system on an aircraft. The airplane's transponder system translates the interrogation and responds by transmitting a coded signal back to the radar. This coded signal will contain information about the aircraft and other data such as its flight altitude. The frequencies of the interrogation and response are different and both are different from the primary radar frequency so that this signals do not interfere with each other. The operating frequencies, signal strength, message format, and other key parameters influencing the performance of transponders are defined by published standards.

A major advantage of SSR is that the return from the aircraft transponder is much stronger than the typical primary (skin) radar return and it is generally unaffected by clutter sources that can affect the primary radar return. This is because the SSR system does not depend upon the "reflection" of its interrogation message. Instead, it receives a different signal actually broadcast by the aircraft. Thus, wave propagation losses in each direction are minimized. This in turn allows much smaller antenna to be employed for SSR.

A disadvantage of the SSR is that the aircraft must have a functioning transponder. Not all aircraft are required to have transponders. Additionally, even for transponder-equipped airplanes, if the transponder fails or is turned off, the SSR will not be able to track the airplane. Under these circumstances, only a primary radar will be able to detect or track the aircraft.

2.3. RADAR FUNCTIONS

Modern systems apply these major radar functions in an expanding range of applications, from the traditional military and civilian tracking of aircraft and vehicles to two- and three-dimensional mapping, collision avoidance, Earth resources monitoring, and many others.

2.3.1. AIR TRAFFIC CONTROL (ATC)

Air Traffic Control Radar is the umbrella term for all radar devices used to secure and monitor civil and military air traffic. They are usually fixed radar systems that have a high degree of specialization. Common applications of air traffic control radars include: (1) en route radar systems; (2) Air Surveillance Radar (ASR) systems; (3) Precision Approach Radar (PAR) systems; (4) surface movement radars, and (4) special weather radars. Radar performs two functions for air traffic control:

a) Airport surveillance radar allows air traffic controllers to provide air traffic services to aircraft in the vicinity of an airport. This service may include vectoring aircraft to land, providing radar service to departing aircraft, or providing service to aircraft either transiting through the area or in the airfield circuit;

b) En route (or area) radar is used to provide services to traffic in transit. This includes commercial airliners and military traffic. Area radar has a longer range than airport radar, particularly at high altitudes. En route radars monitor the air traffic outside the special airfield areas. En route radar sets initially detect and determine the position, course and speed of air targets in a relatively area. En route radars are Primary Surveillance Radars that are coupled to a Secondary Surveillance Radar.

2.3.2. AIR DEFENCE

Air defence radar is used in two ways. On one hand, it performs a function similar to its Air Traffic Control (ATC) counterparts, being used by air defence controllers to provide control services to military (usually air defence) traffic. It is however, also used to monitor all air traffic activity within the country and it approaches to produce a recognized air picture (RAP) with the aim of preserving the integrity of airspace through air policing. The RAP is produced by allocating track identities to each radar return (or "plot" of interest). A radar plot can often fade from a radar display for a period of time due to a number of factors, but the track identity will remain, indicating that the associated plot is actually still present (Upton & Thurman, 2001)[41].

2.3.3. WEATHER RADAR

Weather radar, also called weather surveillance radar and Doppler weather radar, is a type of radar used to locate precipitation, calculate its motion, and estimates its type (rain, snow, hail etc.) Modern weather radars are mostly pulse-Doppler radars, capable of detecting the motion of rain droplets in addition to the intensity of the precipitation. Both types of data can be analyzed to determine the structure of storms and their potential to cause severe weather.

Weather radars usually work with three main types of data. In the reflectivity mode, return echoes from targets are analyzed for their intensities to establish the precipitation rate in the scanned volume. In the Doppler mode, the precipitation's motion is calculated. Finally, in the polarization mode, orthogonal polarization pulses are used to evaluate drop shapes and distinguish amongst different precipitation types, such as rain, snow, or hail.

2.4. ELECTROMAGNETIC INTERFERENCE AND ITS IMPACT ON RADARS

Electromagnetic radiation is energy propagating in the form of an advancing disturbance, or wave, in the electrical and magnetic fields. As electromagnetic energy propagates through the atmosphere, it is attenuated (i.e., undergoes a loss in overall energy) by absorption and scattering. In the case of data path, these effects can range from an increase in error rate to a total loss of the data.
The principle of superposition states that when two or more waves having the same frequency are present at the same place and at the same time, the resultant waves is the complex sum, or superposition, of the waves. This complex sum depends on the amplitudes and phases of waves. For example, two in-phase waves of the same frequency will produce a resultant wave with an amplitude that is the sum of the two waves' respective amplitudes (*constructive interference*), whilst two out-of-phase waves will produce a resultant wave with an amplitude that is less than the sum of the two amplitudes (*destructive interference*).

Two waves of equal amplitude that are out of phase will produce a null result (i.e., no wave). The importance of the concept of superposition is seen in many topics related to radar. Among these are the formation of a defined beam produced by an antenna, the total Radar Cross Section (RCS) of a target as a result of the many scatters, and the effects of multipath.

Wind turbines can cause electromagnetic interference via three principal mechanisms, namely near field effects, diffraction and reflection/scattering. Near-field and far-field diffraction effects were studied by the Danish physicist Christian Huygens and the French physicist Augustin-Jean Fresnel. Whenever a travelling wave encounters a line of objects, the objects will disrupt the propagation of the wave in that location. This phenomena can be illustrated as propagation of spherical waves from each of the objects. These waves will combine constructively and destructively on the far side of the objects. In the zones of the disrupted waves the reflection of the radar signal is significantly different from areas where it has not been disturbed. These differences include variations in intensity and phase angle and are a function of original frequency and the spacing of the objects causing disruption. Wind turbines cause three types of problems for Doppler radars: clutter, blockage, and erroneous Doppler measurements.

2.4.1. BLOCKAGE OF THE RADAR'S BEAM

This is the main anticipated effect on air defence surveillance radar. Such radar works at high radio frequencies and therefore depends on a clear

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[41] L.O. Upton; L.A. Thurman (2001). "Radars for the Detection and Tracking of Cruise Missiles". Massachusetts Institute of Technology (MIT), Lincoln Laboratory, MA, USA

"line of sight" to the target object for successful detection. It follows that any geographical feature or structure lying between the radar and the target will cause a shadowing or masking effect; military aircraft wishing to avoid detection readily exploits indeed this phenomenon.

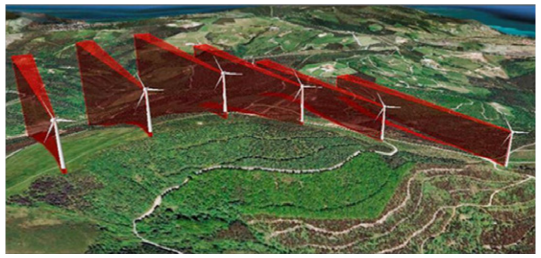
Objects in the path of an electromagnetic wave affect its propagation characteristics. This includes actual blockage of wave propagation by large individual objects and interference in wave continuity due to diffraction of the beam by individual or multiple objects. The effect caused by either of these is often termed to cause "shadowing" of the radar beam.

The presence of a single tall building within the radar field of view provides a typical example for blockage. Since the tall building effectively blocks all propagation of radar radio frequency wave, the zone immediately behind the building will not be illuminated by the radar. If the building is close to the radar there will be zones of complete and partial shadowing. This is illustrated in Figure 19. It shows an example of assessment of the volume behind the wind turbines where the radar beam is blocked, causing the misidentification of precipitation phenomena in case of weather radars.

Blocking of the beam occurs when the radar is pointing in direction of the wind turbine and there is direct line of sight (e.g distance) between them. If the physical area of a wind turbine blocks part of the radar beam, this obstruction, even if partial, can lead to errors in the precipitation monitoring.

The Meteorological Office is also concerned with the effect of shadowing on their sensors as the weather radars look at a relatively narrow altitude band that is a near to the earth's surface as possible. Due to the sensitivity of the radar, wind turbines, if they are poorly sited, have the potential to significantly reduce weather radar performance (Novak, 2009)[42].

Figure 19. Blocking of the radar beam and "shadow volume" (in red) generated behind each wind turbine.



Source: Adapted from the article by de la Vega D., Fernandez C., and Wu Y., et al "Software tool for the analysis of potential impact of wind farms on radio communication services" (2011).

2.4.2. WIND TURBINE CLUTTER

Radar returns may be received from any radar-reflective surface. In certain geographical areas, or under particular meteorological conditions, radar performance may be adversely affected by unwanted returns, which may mask those of interest. Such unwanted returns are known as "clutter". It is displayed to a controller as "interference" and is primarily a problem for air defence and airport radar operators as it occurs more often at lower altitudes.

For military surveillance radar clutter can for example consist of precipitation echoes whereas for weather radar echoes from, e.g aircraft are unwanted. Echoes from wind turbines are considered clutter by most radars. Blockage occurs when obstacles such as buildings or terrain obscure the radar line of sight. Measurements behind such obstacles become incomplete or non-existing. Wind turbines located near a radar may block substantial part of the radar's measurement region. In addition, there is another concern. Namely, if the turbine generates clutter on the radar screen, and the controller recognizes it as such, he may choose to ignore it. However, such unwanted returns may obscure others that genuinely represent aircraft, thereby creating a potential hazard to flight safety. This may be of particular concern in poor weather.

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[42] A. Novak. "Wind Farms and Aviation". In Aviation 2009, 13 (2): 56-59.

For a weather radar, clutter refers to all non-meteorological radar echoes. Typical examples of clutter include echoes from terrain, buildings, and clear-air targets (e.g insects, birds, atmospheric turbulence). Clutter can further be divided into two categories: static and dynamic. Static clutter typically originates from terrain and buildings, whereas dynamic clutter is caused by moving targets such as clear-air returns. Static clutter has zero or near-zero radial velocity and can be removed by built-in clutter filter whereas dynamic clutter originates from targets having radial velocities larger than the clutter filter limits. Dynamic clutter can therefore not be suppressed by conventional clutter filters.

Operating wind turbines generate both static and dynamic clutter. Since the static clutter from the wind turbines is suppressed by clutter filters the dynamic wind turbine clutter, mainly originating from the rotating blades, has the largest impact on weather radar measurements. Dynamic wind turbine clutter is often difficult to separate from precipitation echoes and may therefore incorrectly be interpreted by the weather radar as precipitation. In addition, wind turbine clutter is highly variable in time since the amplitude of the scattered signal depends sensitively on the wind turbine's yaw- and tilt angle.

Several turbines in close proximity to each other and painting on radar could present particular difficulties for long-range air surveillance radar. A rotating wind turbine is likely to appear on a radar display intermittently. Multiple turbines, in proximity to each other, will prevent several returns during every radar sweep, causing a "twinkling effect". As these will appear at slightly different points in space, the radar system may interpret them as being one or more moving objects and a surveillance radar will then initiate a "track" on the returns. This can confuse the system and may eventually overload it with too many tracks.

2.4.3. "SCATTERING", "REFRACTION" AND/OR FALSE RETURNS

The concepts of diffraction and scattering are considered fundamental in optics and other wave phenomena. For any type of wave, one way to define diffraction is the spreading of waves, i.e., no change in the average propagation direction, while scattering is the deflection of waves with a clear change of propagation direction. However, the terms "diffraction" and "scattering" are often used interchangeably, and hence a clear distinction between the two is difficult to find (Berg & Sorensen, 2018)[43]. They conclude that diffraction is the spreading of waves but demonstrates that all diffraction patterns are the result of scattering.

Scattering is a term used in physics to describe a wide range of physical processes where moving particles or radiation of some form, such as light or sound, is forced to deviate a straight trajectory by localized non-uniformities (including particles and radiation) in the medium through which they pass. Electromagnetic waves are one of the best known and most commonly encountered forms of radiation that undergo scattering. Several different aspects of electromagnetic scattering are distinct enough to have conventional names. For example, Rayleigh scattering, named after the 19th century British physicist Lord Rayleigh, is the predominantly elastic scattering of light or other electromagnetic radiation by particles smaller than the wavelength of the radiation. Scattering occurs when the rotating wind turbine blades reflect or refract radar waves in the atmosphere. These are then subsequently absorbed either by the source radar system or another system and can then give false information to that system. It may affect both primary and SSR radars. This effect as yet not quantified but is certainly possible.

Diffraction phenomenon is the most pronounced when the wavelength of the radiation is comparable to the linear dimensions of the obstacle. When sound of various wavelengths or frequencies is emitted from a loudspeaker, the loudspeaker itself acts as an obstacle and casts a shadow to its rear so that only the longer bass notes are diffracted there. When a beam of light falls on the edge of an object, it will not continue in a straight line, but will be slightly bent by the contact, causing a blur at the edge of the shadow of the object; the amount of bending will be pro-

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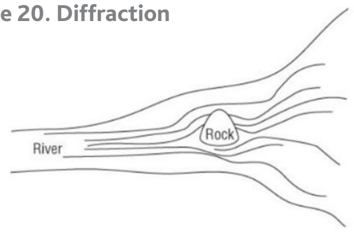
[43] M. Berg; C. Sorensen. "A Review and reassessment of diffraction, scattering and shadows in electronics", In Journal of Quantitative Spectroscopy and Radiative Transfer, Volume 210, May 2018, pp. 225-239

portional to the wavelength. Due to diffraction, radio frequency shadow can occur causing dead coverage zones or receive degraded signals.

Figure 20. Diffraction

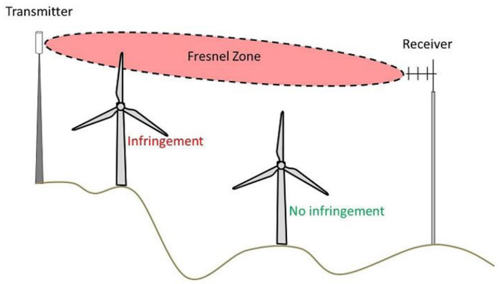


Source: WordPress (2020)

Because of the point-to-point nature of these links, and the frequency range they use, unobstructed line of sight between both ends of the links is intended. Diffraction effects occur in the forward scattering zone of the wind turbines, where the turbine obstructs the path between transmitter and receiver, located at the two end points of the link. The criterion for avoiding diffraction effects is based upon an exclusion volume around the radio path of a fixed link. In the specific case of a wind farm, an exclusion zone equal to the second Fresnel zone is proposed in (Bacon, 2002)[44].

A Fresnel zone, named after physicist Jean Fresnel, is one of a series of confocal prolate[45] ellipsoidal regions of space between and around a transmitter and a receiver as seen in Figure 21. Transmitted radio, sound, or light waves can follow slightly different paths before reaching a receiver, especially if there are obstructions or reflecting objects between the two. The waves can arrive at slightly different times and will be slightly out of phase due to the difference path lengths. Depending on the magnitude of the phase shift, the waves can interfere constructively or destructively. The size of the calculated Fresnel zone at any particular distance from the transmitter and receiver can help to predict whether obstructions or discontinuities along the path will cause significant interference.

Figure 21. Fresnel zone



Source: Pager Power (2020)

To determine if an obstruction of the Fresnel zone will exist, the volume occupied by the turbine due to the blade rotation and the rotor orientation must be considered, together with the terrain conditions. If there is no intersection between the exclusion zone and the volume occupied by the turbine, no impact due to the link obstruction is expected.

Changes in temperature, moisture, and pressure in the atmospheric column cause a change in atmospheric density, which in turn causes variations in the speed of the electromagnetic waves in both the vertical and horizontal. These changes in speed lead to changes in the propagation direction, or bending, of the waves. The bending of electromagnetic waves as they pass through the atmosphere is an example of **refraction.** It is always such that the waves turn toward the medium in which they ravel more slowly, as they pass from a faster speed medium into a slower speed medium. Refraction causes waves to turn back toward the slower speed medium as they pass from the slower into the faster medium.

Some amount of refraction is always present in the atmosphere, however, when the structure of the atmosphere causes abnormal bending of the energy waves, anomalous propagation occurs. It takes place when an unusual, other than normal vertical distribution of temperature, moisture, and pressure exists within the atmosphere. Anomalous propagation occurs in many forms.

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[44] D.F. Bacon. "Fixed-link wind turbine exclusion zone method", OFCOM: 2002

[45] The prolate spheroid is the approximate shape of the ball in several sports, such as in rugby football.

One type of refractive condition can extend the normal detection range of radar and, if conditions intensify, produce false echoes or ghosting. The latter can cause returning echoes to fool the radar equipment into displaying far away echoes as though they are much closer than they actually are.

With another type of refractive condition, anomalous propagation may produce a shadow zone (commonly referred to as a radar hole), sometimes allowing an aircraft or ship to approach within visual range but to remain undetected by radar. In this case, the radar equipment operated properly.

To calculate this exclusion zone, the interference caused by a wind turbine should be assessed by means of the bistatic radar equation, where the wind turbine is characterized in terms of its maximum RCS. In case the wind turbine causes interference, it should be moved away from the link path, in order to decrease the interference level. The proper location for the turbine to not disturb the radio link can be assessed by applying the bistatic radar equation in suitably small increments of the distance of the wind turbine to the radio path until the required value of C/I is obtained (Bacon, 2002).

2.5. NAVIGATION AIDS

Many aircrafts are fitted with a variety of navigation aids, such as Automatic direction finder (ADF), inertial navigation, compasses, radar navigation VHF omnidirectional range (VOR), and Global navigation satellite system (GNSS).

VOR (VHF omnidirectional radio) is a radio-navigation system which enables aircrafts to determine their position and stay on course, to support both approach and departure procedures and navigation on route. VOR operational frequency band is between 108.0 and 117.95 MHz. VOR transmitters, located on the ground, radiate two VHF radio signals: a reference signal that is omni-directionally broadcasted, and a signal of variable amplitude that sweeps around a vertical axis 30 times a second. Doppler VOR systems are based on VOR systems, but they use the Doppler shift of an electronically rotating antenna to generate the variable signal, and therefore, to improve the accuracy. The variable signal is modulated such that it is in phase with the directional signal only when detected from the north in the aircrafts. From other directions, the phase difference between the two signals indicates the receiver's bearing from the beacon (Kayton et al., 1997)[46].

ILS (Instrument Landing System) is a collection of radio transmitting stations used to guide aircraft to a specific airport runway for landing, especially during times of reduced visibility. Typically, an ILS includes a localizer antenna centered on the runway beyond the stop end to provide lateral guidance, a glide slope located beside the runway near the threshold to provide vertical guidance, and marker beacons located at discrete positions along the approach path to alert pilots of their progress along the glide-path and radiation monitors[47].

For the VOR receiver on-board the aircraft, depending on the importance of the multipath, some azimuth direction shift may occur. If the total bearing error rises above 3 degrees, the service will be no longer available. Doppler VOR seems to be less susceptible to multipath interference (Morlaas et al., 2008)[48]. For ILS systems, flight calibration results may be worsened.

The International Civil Aviation Organization (ICAO) defines safeguarded distances named as Building Restricted Areas (BRAs) the shape of which and dimension are dependent upon individual facility types. These protected areas are also applicable to the deployment of wind farms. In case of a wind farm infringing these limits, potential issues concerning wind turbines should be dealt with on a case by case basis (ICAO, 2009)[49]. The Civil Aviation Authority (CAA), a public and

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[46] M. Kayton; W. Fried; J. Wiley. "Avionics navigation systems", 1997.

[47] Ibid, 1997

[48] C. Morlaas; M. Fares; B. Souny. "Wind turbine effects on VOR system performance". In IEEE Transport Aerospace Electronic Systems, 2008; 44 (4); 1464-76

[49] International Aviation Organization. "European guidance material on managing building restricted areas", ICAO EUR Doc 015: 2009.

independent specialized aviation regulator and provider of air traffic services in the United Kingdom, suggests a similar criterion not based on BRAs, but on the following rule of thumb: a wind farm whose blade tips at their maximum height are below the visual horizon when viewed from a point located 25 m above an aeronautical radio station site may be acceptable (CCA, 1998)[50].

According to ICAO, proposed wind farms should be assessed to a distance of 15 km from the VOR facility, with special attention to any turbines within the BRA delimited by the flowing criteria: any turbine infringing a 600 m distance or a 1 degree slope from the center of the antenna at ground level to a distance of 3 km, or a 52 m horizontal surface from a distance of 3 km to 15 km. The consultation zone of 15 km is also proposed by Radio Advisory Board of Canada and Canadian Wind Energy Association.

In practice, most cases of single wind turbine developments are acceptable at distances greater than 5 km, and wind farms of less than 6 turbines are acceptable at distances greater than 10 km from the facility. Wind turbine developments to a distance of 15 km from the facility should be analyzed, and further assessment is required for any turbine within the BRA. In cases where there are existing wind turbines within the 15 km zone, the evaluation of new proposals needs to consider the accumulative effect of all the turbines (ICAO, 2009)[51].

2.6. RADIO LINKS

A radio link is a telecommunication facility between two fixed points located over terrain that aims at two point data transmissions by means of radio waves, featuring specified characteristics of quality and availability. Radio-links use different frequency bands between 800 MHz and 22 GHz, depending on their data transmission capacity. Therefore, they are sometimes called microwave links.

The performance of a fixed radio link might be degraded due to obstruction or scattering of radio waves by a wind turbine and the effect of large blades rotating. Wind turbines can cause large fades in the signal received by one of the ends of the link, thus reducing the power of the received signal (obstruction), or generated interfering reflected signals that reduce the wanted-to-unwanted protection (scattering)[52]. Other effects such as near-field effects are not probable in the UHF (ultra-high frequency) band or higher frequencies. Therefore, two main degradation mechanisms may have an effect on a radio-link and must be considered in the impact studies: diffraction effects and refraction or scattering.

To sum it up, definitely, there is no single "gold bullet" solution to the wind turbine/radar service problem that could be applied to all scenarios and make the problem disappear. In reality, it is not simple. Each wind farm is unique in the layout, type and number of turbines, the surrounding terrain, the orientation and range with respect to the radar systems and the aircraft flight paths. Apart from the technical issues, of course there are also financial issues; the overall profitability of the site may take certain options more attractive than others, for example. Each case, therefore requires detailed analysis to determine the impact of the wind farm on the radar system and the likely efficacy of potential mitigation options, and any agreed mitigation action is likely to be the output of negotiations with a number of stakeholders.

CHAPTER 3 WINDFARMS INTERFERENCE MITIGATION

Radar objections to wind turbines have been the source of the most intractable source of the safeguarding disputes for over a decade. Wind turbines can have a safeguarding impact due to their physical impact or their technological impact. On one hand, a wind turbine can be an aerodrome obstacles, if it is within reasonably close proximity to the aerodrome, e.g within 15 km, and infringes the Obstacle Limitation Surfaces. It defines the airspace surrounding an airport that must be protected from obstacles to ensure aircraft flying in good weather during the initial and final stages of flight, or in the vicinity of the airport. On the other hand, wind turbines are most problematic to primary surveillance radar (PSR), which is either used for air traffic control or air defence – Primary Surveillance Radars (PSR) that detect non-cooperative, i.e. all, targets. As the capacity of each wind turbine is expected to grow in the future, the inevitable size increase will result even higher Radar Cross-Section (RCS), which means careful selection of proper sites to install wind turbines, needs to be conducted.

A number of recent trials in wind turbine clutter have demonstrated the adverse impact that it has on the air defence capability. Analysis of these trials has concluded that current mitigation methodologies are insufficient to meet the agreed aviation specification. In addition, many of the mitigations applied to civilian radar systems cannot be applied to Ministry of Defense's primary surveillance radar assets, in part due to the age and type of these assets. Further, Air Defence staff cannot rely on transponder data, standard flight paths, and standard flying heights on potential enemy aircraft who may intend to remain hidden.

The current state-of-the art mitigation solutions can be largely grouped into two areas; radar-based solutions (radar hardware upgrades or new installations) and material solutions ("stealth windfarms"). An example of the former would be the acquisition of new radar equipment capable of distinguishing wind farms from aircraft. However, the high upfront cost of this is not viable for all wind farm applications, particularly small wind farms or those in unique geographical locations. Only with a complete suite of solutions available, will energy developers be able to mitigate all objections to wind farm applications. Indeed, many radar experts believe that the only solution to this emerging issue of wind turbine electromagnetic interference saturation is a combination of radar and material-based strategies, necessitating innovation in both areas.

Mitigations measures may include modifications to wind farms (such as methods to reduce radar cross-section; and telemetry[53] from wind farms to radar). This list of mitigation techniques also includes modifications to radar (such as improvements in processing radar design modifications; radar replacement; and the use of gap fillers in radar coverage). For the purpose of this section, the word "mitigation" is specifically defined to include either an approach that completely prevents any negative impact from occurring or an approach that sufficiently attenuates any negative impacts so that there is no significant influence on the capability of an air defence.

In recent times, significant research has gone into characterizing the signals scattered by the wind turbines and determining the impact of these reflected signals on the detection ability of these radars to detect and track aircraft flying in the vicinity of wind farms. Additionally, there has been significant research underway into developing various mitigation techniques in the radar receiver to suppress the windfarm returns while preserving aircraft target components. Some of these techniques are also based on the design and site installation of the wind turbines, but the others include development of specific techniques for filtering these interfering signals at various detection stages in the signal processing chain of the radar receiver.

Various companies have tried to fix the problem, for example, there are at least 50 mitigation solutions that have matured at some point in the past 10 years. Many of these solutions are developed in order for the radar to become "Windfarm Compliant", which will prevent blocking wind energy development because of radars. As an illustration, the radar manufacturer Thales has installed a STAR 2000 PSR in Scotland at Inverness, an airport which is surrounded by many windfarms.

For air surveillance radar, where airplanes are separated from wind turbines by altitude, con-

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[50] United Kingdom Civil Aviation Authority. "CAP 670 ATS safety requirements", 1998

[51] International Aviation Organization. "European guidance material on managing building restricted areas", ICAO EUR Doc 015: 2009.

[52] B. Randhawa; R. Rudd. "RF measurement assessment of potential wind farm interference to fixed links and scanning telemetry devices", Ofcom report 2008-0568: 2009.

[53] Telemetry is the in situ collection of measurements or other data at remote points and their automatic transmission to receiving equipment (telecommunication) for monitoring. Telemetry is used in complex systems such as missiles, spacecraft, oil rigs, and chemical plants since it allows the automatic monitoring, alerting and record-keeping necessary for efficient and safe operation.

[54] Constant false alarm rate (CFAR) detection refers to a common form of adaptive algorithm used in radar systems to detect target returns against a background noise, clutter an interference.

current beam processing and enhanced Constant False Alarm Rate (CFAR) detection algorithm[54] are planned for future system upgrades. The role of the CFAR circuitry is to determine the power threshold above which any return can be considered to probably originate from a target. If this threshold is too low, then more targets will be detected at the expense of increased numbers of false alarms. Conversely, if the threshold is too high, then fewer targets will be detected, but the number of false alarms will also be low. In most radar detectors, the threshold is set in order to achieve a required probability of false alarm. The methodology behind is radar Line of Sight (LoS) avoidance, which may work for cooperative aircrafts, but could also lead to loss of track for low-altitude non-cooperative targets.

Three development axis, depending on the type of situation to tackle can be identified:

- The upgrade of existing radars: software processing can be improved, in particular by adding wind farm filters which allow to filter out the wind turbine spurious signals once they are classified as such,
- Gap-filler radars: in the case of existing radars for which such an upgrade is not envisaged or yet for solving specific issues such as masking, then gap-filler radar solutions (e.g. installed on the wind turbine itself) can be proposed.
- Next generation radars: windfarm "clutter" will be considered as a requirement, and new architectures are already studied for proposing the best solutions. Among these architectures, Multi-Static Primary Surveillance Radar (MSPSR)[55] shows built-in good features for mitigating windfarm effects.

Recently, multi-static primary surveillance radar (MSPSR) has attracted the attention of researchers. MSPSR can cover the shadow areas of the conventional primary surveillance radar (PSR) and can be used as an alternative variant. As the MSPSR is classified into passive bistatic radar, it can select illuminators of opportunity, e.g. present radar signals (e.g. PSR and SSR), digital terrestrial television broadcasts (DTTB), mobile communications, global navigation satellite system, and so on. Looking at Multi-static Primary Surveillance Radar techniques and ongoing trials, MSPSR might be tested as a potential low-cost replacement for the aging primary surveillance radar system. Recently, there have been both passive and active MSPSR trials in England, Germany and Japan.

This chapter will describe a number of potential mitigation approaches that could be employed to reduce or eliminate the adverse impacts wind turbines can have on air defence and missile warning radars.

3.1.1. GUIDELINES PUBLISHED BY REGULATORY BODIES

Some regulatory bodies have published guidelines to estimate and avoid the impact of wind farms on radar services. Most of them aim to define rules-of-thumb and safeguarding zones that are easy to understand by a non-technical audience (from a radar perspective), such as wind farm developers.

Regarding the Air Surveillance Radars (ASR), the Eurocontrol has published a document aimed at both providers of air navigation services and wind farms developers (Borely, 2014)[56]. This document defines a number of zones and provides guidelines within each of these zones. These range from "safeguarding zones", within which no wind turbines should be placed, through zones requiring an impact assessment to be conducted, to zones in which no impact is expected. The first step in the assessment is to determine if any part of a turbine is within line-of-sight of the radar. If this is not the case, then it is stated that there will be no impact to the radar. The definition of these zones is reproduced in Figure 22. It should be noted that the radar line-of-sight depends on atmospheric refraction, which at some locations may deviate from standard propagation conditions.

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[55] Such systems differ from typical modern active radar systems through consisting of multiple spatially diverse transmitter and receiver sites. Due to this spatial diversity, these systems present challenges in managing their operation as well as in usefully combining the multiple sources of information to give an output to the radar operator.

[56] M. Borely. "EUROCONTROL Guidelines for Assessing the Potential Impact of Wind Turbines on Surveillance Sensors". Technical Report EUROCONTROL-GUID-130. Eurocontrol: Brussels, Belgium, 2014.

Figure 22. Primary Surveillance Radar (PSR) recommended ranges.

Zone	Zone 1	Zone 2	Zone 3	Zone 4
Description	0-500 m	500 m – 15 km and in radar line of sight	Further than 15 km but within maximum instrumented range and in radar line of sight	Further than 16 km or not in radar line of sight
Assessment Requirements	Safeguarding	Detailed Assessment	Simple Assessment	No assessment

Source: Adapted from EUROCONTROL Guidelines for Assessing the Potential Impact of Wind Turbines on Surveillance Sensors". Technical Report EUROCONTROL-GUID-130.

The Primary Surveillance Radars (PSR) safeguarding range where no wind turbine shall be built is derived from the ICAO recommendations provided in the ICAO EUR 015 document[57] which is applicable for any obstacle.

PSR radar designs vary considerably and the design choices made the PSR manufacturers influence the susceptibility of their radars to wind turbines. The figure for the PSR recommended limit between detailed and simple assessment is therefore derived from the best practices collected from the ECAC[58] member states and it is also a figure recognized in the ICAO EUR 015 document. Therefore, these figures are applicable to current wind turbine design, e.g 3-blades, 30-200 m height, and horizontal rotation axis. For other types of turbines, it is recommended to undertake the detailed assessment as long as the wind turbine is in radar line of sight.

Both the World Meteorological Organization (WMO) and the Network of European Meteorological Services have issued general guidelines for the development of wind turbines near weather radars, based on safeguarding distances (WMO, 2010)[59]. According to these guidelines, no wind turbine should be deployed closer than 5 km to a weather radar, and wind farm developers are recommended to submit plans of wind farms located at a distance within 20 km from the radar for the development of an impact study. The International Telecommunications Union (ITU) has also recognized the problem, but it has not yet stated any specific guidelines; only recommended protection level for weather radars is stated, as an interference over noise level of – 10dB[60]. Although all these above-mentioned guidelines provide safeguarding distances and rules-of-thumb, they all propose the development of a case-by-case analysis, based on a detailed modeling of the scenario.

3.1.2. WIND FARM LAYOUT

Wind turbines are usually installed in so called wind farms consisting of a group of wind turbines located at a site to generate electricity. Nowadays, the progress of technologies, such as power electronics, wind speed forecasting, coordinated control, together with the increased experience of wind farm construction and operation have enabled the development of modern wind farms. These are larger, smarter wind farms, which are typically consisted of hundreds of utility-scale (multi-MW sized) wind turbines and with a total capacity of hundreds MW. For space and cost rea-

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[57] International Civil Aviation Organization. 'European Guidance Material on Managing Building Restricted Areas". ICAO EUR DOC 015, 3rd Edition.

[58] ECAC- European Civil Aviation Conference was founded in 1955 as an intergovernmental organisation that seeks to harmonise civil aviation policies and practices amongst its members. Currently is composed of 44 Member-States, e.g. Estonia joined ECAC in 1995.

[59] World Meteorological Organization (WMO). "Commission for Instruments and Methods of Observation". Technical Report, WMO-No 1046, WMO, Helsinki, Finland, 2010

[60] International Telecommunications Union (ITU-R). "Technical and Operational Aspects of Ground-Based Meteorological Radars. Recommendation ITU-R". Technical Report M.1849; ITU; Geneva, Switzerland, 2009.

sons, the wind turbines should be as close as possible to each other, but not mutually influence each other. To avoid mutual interference, the wind turbines need to be arranged in a layout according to the prevailing wind direction, in order to harvest the maximum energy.

Wind turbines can be adapted to meteorological conditions due to their aerodynamic shape. In order to take the site condition into account, the potential location of a wind turbine must be examined in advance. For the selection of suitable locations, numerical simulations are mostly used which examine the meteorological and orographic conditions in advance.

Taking this into account, each wind farm is unique in the layout, type and number of turbines, the surrounding terrain, the orientation and range with respect to the radar systems and the aircraft path. Apart from the technical issues, of course there are also financial issues; the overall profitability of the site may make certain options more attractive than others, for example. Each case, therefore requires detailed analysis to determine the impact of the wind farm on the radar system and the likely efficacy of potential mitigation options, and any agreed mitigation action is likely to be the output of negotiations with a number of stakeholders.

The first step in the analysis is usually to estimate if the wind farm is in the line-of-sight of the radar system, considering altimetry data, wind turbines dimensions and layout, which can be used for initial site optimization. The next step is to perform detailed modeling of the scenario, including technical specifications of the radar services and threshold values for evaluating the potential degradation of each service. As radars are stochastic systems, it is not practical to "turn-off" the effect of the wind farm but rather it is necessary to agree on threshold level, below which the interference is considered insignificant. The results of the analysis must provide numerical values regarding the clutter level generated by the turbines, as well as additional outcomes that help to modify the wind farm layout for minimizing the impact on the radar.

A variety of mitigation approaches are available to help minimize wind energy's impact on radar, including the following siting practices:

- Designing the windfarm layout to minimize the impacted area of radar coverage or to allow for maximum radar coverage within the project, such as by increasing the spacing between turbines within the project;
- Eliminating proposed turbines located in areas that result in high radar interference impacts.

Wind turbine siting alone may not eliminate impacts or reduce them to an acceptable level. In these cases, other mitigation techniques, including the deployment of new radar-related software upgrades and/or hardware can also reduce potential wind energy impacts on radar operations. Examples include:

- Adding infill radars in or around the wind project to maintain existing radar coverage;
- Modifying the existing radar system software's constant false alarm rates, clutter maps, or other filtering and/or preliminary tracking routines;
- Upgrading the hardware or software of the affected radar to implement advanced filtering techniques that can remove interference from turbines.

The wind farm layout could potentially be modified in some cases in order to reduce the impact to the radar system. This clearly needs to be achieved without affecting the viability of the wind farm. The effectiveness of such an option is dependent on terrain effects. A typical rule adopted is that if the wind turbine is not in the line-of-sight of the radar, it will not cause an impact on the radar. Alternatively, increasing the spacing between wind turbines in a farm in such a way that they are individually resolvable will help with the detection of targets within the farm.

3.1.3. LINE OF SIGHT MITIGATION TECHNIQUES

Line-of-sight propagation is a characteristic of electromagnetic radiation or acoustic wave propagation which means travel in a direct path from the source to the receiver. The rays of waves may be diffracted, refracted, reflected or absorbed by the atmosphere and obstructions with material and generally cannot travel over the horizon or behind obstacles.

The performance of a radar will not be affected by objects that do not appear within its line of sight unless exceptional circumstances exist. With respect to objects projecting upward from the surface of the earth, such as wind turbines, radar line of sight is determined by four factors when there is no intervening terrain. These factors are the height of the focal point of the radar above the earth's surface, the height of the wind turbine, its distance from the radar, and how much the atmosphere will refract the radar beam.

The curvature of the earth influences the line of sight. As an estimating rule, radar engineers often use a "4/3rds earth" approximation to account for the effect of atmospheric refraction near the surface of the earth. When doing this, they multiply the radius of the earth by the factor 4/3 when performing the tangent line calculation to determine if an object is in a radar line of sight (US Department of Defence report to the Congressional Defence Committees, 2006)[61].

Line-of-sight problems if potential interference issues are identified during the formal review process, can be avoided by:

- Regulating wind turbines' proximity to radar systems based on their elevation and the corresponding height of its tallest blade;
- "Terrain masking", or placing turbines on the opposite side of elevated terrain in relation to the radar, thereby redirecting the line of sight to avoid most of the turbines which would otherwise fall within the line of sight;
- "Terrain relief", which places the radar system on a high elevation such as a mountain/or hillock overlooking a valley that contained wind turbines;
- Software which would allow aircraft radar signatures to be injected into digital processors on modern radars, allowing the "assessments" of the ability of that radar to detect and track aircraft under real world conditions which may otherwise hinder performance.

In most cases, siting and other mitigations have solved conflicts and allowed wind projects to coexist effectively with radar missions. The best mitigation technique is to avoid locating wind turbines in the radar line of sight (LoS). This strategy may be achieved by distance or terrain masking. Mitigation of impacts, if turbines are located in the LoS, can be achieved by reducing the number of turbines in the LoS, the amount of blade penetration into the LoS, greater separation from the radar, or through selective turbine siting, e.g. to reduce the azimuthal extent of the turbines with respect to the radar. However, in some proposed locations, wind turbines will cause disruptive radar interference that cannot be effectively mitigated. At such sites, wind development would probably not proceed.

3.1.4. WIND TURBINE SUPPRESSION CONCEPTS

The second potential mitigation area is the suppression of wind turbine radar signatures. An alternative approach, heretofore not technically feasible to great extent, is to reduce the radar cross-section of wind turbine to extent that they can be installed near existing radar installations. The radar cross-section (RCS) is a figure of merit that can serve to estimate the effect of a wind turbine on a system's performance. Since the development of radar in the 1930s and 1940s, avoiding detection by reducing radar signature has been an area of significant military interest. The development and deployment of radar signature suppression technologies for military aircraft naturally leads to the question of whether or not a similar approach could be employed to suppress the radar signature of a wind turbine.

Traditionally, there are three approaches to reducing RCS: (1) shaping, (2) application of radar

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[61] Department of Defence. "Report to the Congressional Defence Committees: The Effect of Windmill Farms On Military Readiness", Office of the Director of Defence Research and Engineering, Washington D.C, 2006.

absorbing materials, and (3) cancellation techniques.

Shaping alters the geometry of a plane, missile, or other object to direct radio frequency energy away from the radar. It can only reduce RCS over a limited range of angles, which is often an effective solution when the target is illuminated by a single radar, and the radar location relative to the target is known (as is often the case for plane flying over radar). Shaping applied to the tower and nacelle could be somewhat effective, but it would have to be done with knowledge of the transmitter and receiver directions. Although, it could reduce the RCS in some desired monostatic or bistatic directions, it would likely increase it in the others. Shaping of wind turbine structures to reduce RCS has been investigated in (Pinto et al., 2000)[62]. Most RCS reduction techniques use a combination of shaping and radar absorbing materials (RAM). Only RAM was considered for this effort because the wind turbine-blade geometry has significant mechanical and aerodynamic constraints that prevent significant shaping.

Thus, the most promising approach is the application of radar absorbing material (RAM) that seeks to reduce Radar Cross-Section (RCS) by absorbing the incident radio-frequency energy and converting it to heat (McDonald et al., 2012). The material would have to be lightweight, thin, durable, inexpensive, and provide sufficient RCS reduction to make it economically viable. Most commercial RAM materials give a specular RCS reduction in the range of 15 to 20 dB (e.g., Emerson and Cuming Eccosorb FGM)[63]; however, it varies widely with frequency and angle incidence. A RAM coating might make sense if the wind turbine was at a fixed location from a facility, such as an airport radar. However, the bistatic RCS is so large that the aerodynamic degradation of the blades and cost of adding RAM would not generally be merited.

Stealth coating, as a technique for reducing the RCS of the turbines, as it reduces the clutter generated by the wind turbines (Matthews, 2007)[64] is well established in military world, as it has been studied extensively since the early days of radar. Stealth techniques are based, mainly, on modifying the object by shaping and coating with radar signal absorbing materials, in order to reduce the power scattered towards the radar antenna. Much of this research can be transferred into the civil domain and applied to wind turbines, although there are various constraints. First, a wind turbine represents a very large surface area, and therefore, the cost per square meter of stealth treatment must remain low. Additionally, any significant increase in mass of turbine components is prohibitive due to the overall impact on the structure (for example, the impact on the gearbox loading due to the impact on blade mass). Stealth technologies can be applied to the main elements of the turbine (mast, nacelle and blades) in a different way.

The wind turbine tower is typically an electrically large cylinder and provides a very directive, large radar return. The directivity, however, results in a large return only when the radar stares directly at the tower. In cases where this does not occur, the tower can remain unchanged. If the large return from the tower is received by the radar, much of the return will be significantly reduced to the Doppler processing, which will attenuate the returns from a stationary object. Nevertheless, a radar system will not necessarily completely cancel a very large return from a stationary object, and some of the tower return may be detected[65]. In such a case, shaping of the tower into a more conical shape may be an option to direct the specular return away from the radar. Application of radar absorbing materials on the mast is also an option, but it can be expensive, due to the large surface area and potential for increased service costs.

Most work in the literature on stealth treatments for turbines has concentrated on the blades. These are large objects and their movement produces a large, non-zero Doppler return that can affect the radar (Matthews et al, 2006)[66]. The aerodynamic shape and the elevation angle of the blades mean that a time varying return is seen by the radar with a "flash" of high RCS for certain blade rotation angles. Stealth treatment for the blades is not trivial due to the blade structure and composition (they are made of various material layers incorporated to make a light, strong structure, and typically include some form of lightning protection, either a mesh or a rod), and because the blade shape is determined by aerodynamic factors. As an example, a 40 m turbine blade may cause RCS flashes of around 45 dBsm. Theoretically, stealth technologies may reduce these flashes by 15-20 dB, still two orders of magnitude greater than a typical light aircraft, but recent studies only show a reduction of 10 dB (Rashid et al., 2010)[67]. The reason of this divergence comes from the fact that the stealth treatment is applied in a way that minimizes the changes of the existing blade design, which leaves very little room for the stealth material to be incorporated. A blade design that considers the radar material application from the beginning may well achieve better reductions in RCS.

With a particular emphasis on blade fabrication, for example, Sandia National Laboratories in the USA demonstrated the technical feasibility of integrating radar-absorbing materials into the standard construction methods currently used for manufacturing wind turbines (McDonald et al., 2012)[68]. The study identified multiple pathways to apply radar-absorbing material to a blade in a targeted way that could minimize the added cost leading to an economically viable mitigation option for the wind industry. Vestas, one of the largest global wind turbine manufactureres, developed a „stealth blade" based on a similar concept (Vestas, 2014)[69].

The current leading technology in the "stealth windfarm" sector was deployed in Perpignan in 2016 in Southwest France[70]. It is known to be an effective solution for weather radar, and successfully reduced the average wind turbine radar cross-section by 90%. However, the solution suffered from several drawbacks that prevented wider adoption within the wind industry, including single-band absorption, high upfront cost, narrow absorption bandwidth and insufficient absorption strength for large wind turbines. In order for stealth windfarms to become truly viable for wind developers across the world, a solution must provide multi-band absorption at L&X-band and S&X-band (suitable for windfarm impinging on both civilian and military airports), wide absorption peaks (up to 1 GHz bandwidth) and high strength absorption (up to 40dB reduction), all designed from the ground up to minimize cost.

3.2. MITIGATION TECHNIQUES ASSOCIATED TO THE RADAR SERVICES

Mitigation options can also be applied to the radar services. The main options are adaptive clutter filters, the installation of gap filler radars, radar processing techniques, and the use of adaptive scanning in the radar antennas.

A variety of approaches have been suggested for both hardware and software modifications to radars that would reduce their sensitivity to wind farm generated clutter. These include use of finer clutter cells, use of more and/or adaptive Doppler filters, use of special post-processor track file maintenance routines to prevent track drops, use of enhanced adaptive-detection algorithms, and the use of special clutter suppression algorithms developed for other applications.

All these techniques are aimed to remove the clutter and ghost targets from the wind turbines.

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[62] J. Pinto; J. Matthew; G. Sarno. "Stealth technology for wind turbines". In IET Radar Sonar Navigation, vol 4 (1), pp. 126-133, 2000

[63] Emerson and Cuming, October 2012, http://www.eccosorb.com/products-eccosorb-fgm

[64] J. Matthews. "Stealth Solutions to Solve the Radar Wind Farm Interaction Problem". In Proceedings of the 2007 Loughborough Antennas and Propagation Conference, Loughborough, UK, 2-3 April 2007; pp. 101-104

[65] Ibid, 2003

[66] J. Matthews; J. Lord; J. Pinto. "RCS Prediction for Stealthy Wind Turbines". In Proceedings of the European Conference on Antennas and Propagation, Nice, France, 6-10 November, 2006

[67] L. Rashid; A. Brown. "Partial Treatment of Wind turbine Blades with Radar Absorbing Materials (RAM) for RCS Reduction". In Proceedings of the 4th European Conference on Antennas and Propagation", Barcelona, Spain, 12-16 April 2010

[68] J. McDonald; B. Brock; W. Patitz; S. Allen; H. Loui; P. Clem; J. Paquette; W. Miller; D. Calkins. "Radar-Cross-Section Reduction of Wind Turbines (Part 1) (Technical Report)". SAND2012-0480. Sandia National Laboratories (SNL), Albuquerque, NM, USA (2012).

[69] Vestas (2014). "Vestas proud to install 1st large-scale wind farm using stealth blade technology. Big technological step but other options also available", Statement.

[70] In 2014, EDF Energies Nouvelles started the construction of the windfarm where it installed the new Vestas-built turbines at the "Ensemble Eolien Catalan".

Echoes from wind turbines are a stochastic phenomenon, and therefore, the goal of completely removing this clutter and avoiding a reduction in the probability of detection is unrealistic. Nonetheless, these mitigation techniques have provided significant advances in the detection capacity in presence of wind farms.

3.2.1. DATA PROCESSING IN AIR SURVEILLANCE RADARS

Various aspects related to the data processing in the reception chain of an air surveillance radar (ASR) can be modified to reduce the effect of wind farms. Each options were often applied in the post-detection stage (once the radar has determined the presence of the turbine). They include inhibiting track initiation in the vicinity of the wind farm or range-azimuth gating (Sergey et al., 2008)[71]. The main drawback of these options is that they will also inhibit the detection of wanted targets around the wind farm, and a "blind area" is generated around the wind farm area.

Pre-detection options are those applied to raw data, before the presence of an object is determined by the radar. They include the use of elevation beam information to discriminate higher altitude aircraft from lower altitude wind farms. This data information is included further along the processing chain. Additional techniques such as enhanced CFAR, moving target detector processing, high resolution clutter maps and plot/track filters (Perry & Biss, 2007)[72].

3.2.1. ADAPTIVE CLUTTER FILTERS

Adaptive clutter filters have been applied in weather radars to remove clutter signals from wind turbines. Clutter suppression is essential to radar signal processing, but it still suffers from severe problems. The moving target indication (MTI) is a commonly used approach in clutter cancellation, and is very effective when radar detects moving targets in clutter interference environment.

Such filters ideally identify the wind turbine signature, remove the corrupt measurements, and interpolate over the non-corrupt data to reconstruct the signal. The difficulty lies in identifying the wind turbine signature as it is time varying and highly complex. Furthermore, the wind turbine signature often resembles the actual weather signal. Nonetheless, several adaptive filter techniques for removing or educing effects of wind turbine clutter have been suggested (Norin & Haase 2012)[73]. Such adaptive clutter filters can also help to mitigate erroneous wind measurements. If clutter is removed from signal, the average wind velocity as well as the spectrum width can easily be estimated.

Adaptive clutter filters use in-phase and quadrature phase (I/Q) measurements of the electric field as input. Since weather radars normally do not transmit I/Q data, but only the products based on it (reflectivity, radial velocity, etc.), the adaptive clutter filter should be implemented in the radar's signal processor. The main challenge of this mitigation technique is that it requires fast, reliable, and computationally effective filters.

To speed up filtering, only radar cells containing wind turbines should ideally be processed. This may be achieved by keeping maps of all wind turbines near a weather radar, or by using automatic detection schemes (Hood et al., 2009)[74].

3.2.2. ADAPTIVE SCANNING

For weather radars, which primarily scan the sky for precipitation, the influence of wind turbines can be mitigated by adapting the scan strategy of the radar antenna. Changing the radar scan strategy to pass over areas with wind turbines could limit the amount of wind turbine clutter received and, therefore, reduce the undesired signal in the data processing. The drawback is that data obtained in the direction of the wind farm area would be gathered from higher altitudes, which may shorten the effective range of the radar.

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[71] L. Sergey; O. Hubbard; Z. Ding; H. Ghadaki; J. Wang; T. Pondsford. "Advanced Mitigating Techniques to Remove the Effect of Wind Turbines and Wind Farms on Primary Surveillance Radar". In Proceedings of 2008 IEEE Radar Conference, Rome, Italy, 26-30 May, 2008; pp. 1-6.

[72] J. Perry; A. Biss. "Wind Farm Clutter Mitigation in Air Surveillance Radar". In Proceedings of the 2007 IEEE Radar Conference, Boston, MA, USA, 17-20 April 2007; pp. 93-98.

[73] L. Norin; G. Haase. "Doppler Weather Radars and Wind Turbines". In Doppler Radar Observations –Weather Radar, Wind Profiler, Ionospheric Radar, and Other Advanced Applications: Bech, J.; Chau, J., Eds.; InTech: Rieka, Croatia, 2012

[74] K. Hood; S. Torres; R. Palmer. "Automatic detection of wind turbine clutter for weather radars. Journal of Atmospheric Oceanic Technologies, 2010, 27, pp. 1868-1880

A more advanced version of adapting the scanning strategy may be possible using phased array radars (Yosikawa et al., 2012)[75]. It has been suggested that the beam shape of the phased array radar can be altered in such a way that a null in the antenna radiation pattern is created in the direction of the wind turbine. For such radars, this technique could provide an elegant way to reduce wind turbine clutter, but at the expense of a heavy computational cost.

3.2.3. CONCEPTS FOR GAP FILLER MITIGATION APPROACHES

When a wind farm has caused an unacceptable loss of coverage, a supplementary gap filler radar could be installed, with appropriate data fusion. The gap filler, by allowing a second view of the wind farm radar interference, makes it considerably easier to process this interference out through data/or sensor fusion (Aarholt &Jackson, 2010)[76].

In the case a new radar is deployed, it may be a relatively simple, low-cost radar, specifically designed to provide enhanced detection in such small regions. For example, holographic radars have been proposed to achieve "unambiguous differentiation between aircraft and turbines. Over-the-horizon radars and AWACS (airborne warning and control systems) are even more promising. The latter consist of large radar and computation, display, and control systems, housed in large aircraft. First introduced for naval defence, they have become potentially effective over land with new developments in clutter-rejection circuitry.

An alternate approach would be to use a "gap filler" radar positioned within the wind farm but sufficiently high above the arcs of rotation of the turbine blades so as not to be affected by the clutter they can create. Certain types of small tactical radars developed for other applications may be suitable candidates. Analysis, including the susceptibility of such radars to clutter generated beneath them as well as the capability of the air defence system to accept the additional input, need to be performed to determine if there are merits in pursuing this concept further.

The underlying idea for the gap-filling radar concept is exceptionally simple: if one radar cannot see an object due to obscuration created by a wind farm, a second radar can be used that provides overlapping coverage. In addition to large conventional radars, small distributed radars (known as gap fillers) are used to detect low-flying aircraft penetrating gaps in large radar coverage. It is possible to employ more than one radar to provide additional coverage where the probability of detection of the original radar has been reduced by the introduction of a wind farm, and combine the radar plots in a plot fusion process. The additional data may come from an existing radar system or through the deployment of a new radar. Current market leaders in this regard in the UK for example are the Terma Scanter 4002 and the Avellant Theia series. They are being or have been installed at East Midlands, Chester Hawarden/Liverpool John Lennon, Edinburgh and Newcastle airports[77].

Sensor fusion brings the data from each of these sensor types (e.g multiple radars, LIDARs, and cameras) together, using software algorithms to provide the most comprehensive, and therefore accurate mode possible. This improves perception by taking advantage of partially overlapping fields. As multiple radars observe the environment around a vehicle, more than one sensor will detect objects at the same time. Interpreted through global 360 degrees perception software, detections from those multiple sensors can be overlapped or fused, increasing the detection probability and reliability of objects around the vehicle and yielding a more accurate and reliable representation of the environment.

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[75] E. Yoshikawa; T. Ushio; Z. Kawasaki; S. Yoshida; T. Morimoto; F. Mizutani; M. Wada. "MMSE beam forming on fast-scanning phased array weather radar". In IEEE Transport, Geoscience, Remote Sensors, 2012, volume 51; pp. 3077-3088.

[76] E. Aarholt; C. Jackson. "Windfarm Gapfiller concept solution". In Radar Conference (EuRAD), 2010 European, 2010, pp. 236-239

[77] Terma announced in summer 2016 contracts with NATS to mitigate windfarms at 3 airports – and https://www.terma.com/press/news-2016/terma-provides-wind-turbine-mitigation-radar-for-nats

and Avellant announced on 22 September 2016 the competition of the safety case and the CAA operational approval for its Theia 16A radar at East Midlands Airport in respect of the Spondon Reservoir Windfarm – http://www.aveillant.com/news/aveillant-radar-receives-caa-operational-approval-east-midlands-airport/

Each sensor type, or "modality" has inherent strengths and weaknesses. Radars are very strong at accurately determining distance and speed – even in challenging weather conditions – but they cannot see the color of a stoplight. Cameras do well reading signs or classifying objects, such as pedestrians or other vehicles. However, they can easily be blinded by sun, snow or darkness. Lidars can accurately detect objects, but they do not have the range or affordability of cameras or radar.

Coordinating two radars by software does present a number of challenges. First, a radar can locate the position of a target only within a finite level of accuracy determined by the size of the resolution cell. The resolution cell for one radar unit will never align with those of the other due to the offset positioning. Thus, inherent uncertainties are created in actual position when returns from one must be compared with returns from the other.

Second, it is unrealistic to expect that the radar beams from each unit will sweep the exact same area of interest at precisely the same moment. As such, relative target motion will always occur between the observations made by each radar. The coordination software would need to account for that as well.

If the "blocking area" is a wind farm, each radar will also experience false returns due to the rotation of the turbine blades and bleed through from the clutter map. There are no data available at present to determine if such false returns will be seen by both radars concurrently. If they are not, then the coordination software also will face the challenge of determining if the changes in observed position are due only to positional uncertainty and relative motion of the target or represent track "seductions" caused by false returns seen by one radar but not the other. This further increases the coordination challenge.

CHAPTER 4 - ENVIRONMENTAL AND SOCIETAL IMPACTS OF WIND ENERGY

Most people have a positive attitude towards alternative sources of energy. The association between wind turbines and human responses is a complex one, and many factors play a role in the public debate. Wind turbines can change the landscape, generate noise and can cause shadow-flicker. It is the effect of the sun shining through the rotating blade of a wind turbine, casting a moving shadow.

To ensure the safety of air traffic, aviation authorities require wind turbines over a certain height (typically a tip height of 150 meters) to be fitted with obstacle lights. Although essential for air traffic flying at low altitudes, these lights cause significant residential annoyance, especially at night, reducing public support for wind energy. As next generation wind turbines have become increasingly higher over the years, the majority of newly planned windfarms will require obstacle lights. As a result, these plans encounter more and more resistance from local communities. Especially in populated regions, this public resistance forms a serious challenge for wind farm developers and national wind energy ambitions (van der Zee, 2016)[78].

At the beginning of this year, the German Bundesrat, a legislative body that represents Germany's 16 regions at the national level, has approved amendments to a general administrative regulation that will stop lights continually flashing on wind turbines to warn aircraft. To reduce light pollution and thereby energy consumption, the German – AVV introduced Anfang 6 for BNK (*Bedarfgesteuerte Nachtkennzeichnung von Windenergieanlagen*, also known as Aircraft Detection Lighting Systems or ADLS). It makes BNK systems mandatory for existing and new wind farms, with the intention of ensuring the adoption of technologies that further reduce light pollution. BNK systems combine the obstruction lighting with a system that detects when an aircraft at night is within a radius of 4 km and an altitude of less than 600 meters of the wind farm, and turning the lights on at that time. This specific regulation will apply for German onshore turbines from 31 December 2022 and for German offshore turbines from 31 December 2023. This means that the blinking of wind turbines will soon be over, at least in Germany. The introduction of night markings for wind turbines is one of the measures of German wind action plan with the aim to reinvigorate the wind energy sector that declined last year (ReNews Biz, 2020)[79].

The awareness of the consequences of a wind farm can lead to intense, and sometimes emotional discussions about the need for wind energy, the suitability of the area, the visual and aesthetic aspects and noise-related issues are not uncommon. The most persistent criticism levelled at onshore wind farms is their aesthetic effect on the local landscape. The concept of "not-in-my-backyard", or NIMBY-ism, comes to mind when stakeholders generally support a technology, but do not want it located near them. People often feel a strong attachment to their local area and value its aesthetic qualities. Wind projects are particularly challenging in this respect because they can be seen for much greater distances.

The assessment of suitability of a certain location for the installation of a wind turbine requires the consideration of multiple impact issues: visual aspects, environmental effects such as the impact on wildlife and birds, and shadow flicker from wind turbines to name a few. The present chapter will touch upon visual impact, wind energy and land use conflicts and impacts on birds and bats. As environmental aspects of renewable energy are wider, they also require some mitigation strategies to find a right balance between wind energy development and biodiversity. The impacts of noise pollution are dealt in the next chapter.

4.1. VISUAL IMPACT

The advent of utility-scale wind energy is having a profound impact on scenic resources. Wind turbines are large structures and taken together with associated development, such as access tracks and associated buildings have the potential to create significant visual and landscape impacts. These impacts will be influenced by the distance from which the turbines will be viewed and whether the turbines are seen in isolation or with other features in the landscape, including the other wind farms. Utility-scale wind farms may cover large area, and the individual wind turbine generators are very large structures incorporating visually conspicuous, reflective surfaces and obviously non-natural geometry that contrasts strongly with natural landscapes. Concerns regarding the visual impacts of utility-scale windfarms have emerged as major factors in the delay or cancellation of planned windfarms.

Optimal siting to reduce potential visual impacts requires an accurate understanding of the visual characteristics of the different types of energy facilities, including their visibility under the different lighting conditions that occur at proposed project locations. Lightning conditions at a given location vary by season, time of day, sun direction and angle above the horizon, and atmospheric factors, including the presence or absence of clouds and the level of haze, which varies by region and by time of a day.

One of the first published analyses of the impact of distance on turbine visibility was conducted for the environmental statement for the Penrhyddlan and Llidartywaun facilities in Wales (European Commission, 1995)[80]. These wind energy facilities (managed as one site) were installed in the early 1990s. From a visual assessment undertaken at 22 locations around the 103-turbine site, 20 km was determined as the limit of visibility. Owing to the size of this wind energy facility and its early development, this distance became a general standard for measuring the visibility of turbines and determining their relative impact.

In 1996, Gareth Thomas, a planning officer in Montgomeryshire, Wales, attempted to define the potential visual impacts of wind turbine using descriptors, which could be assessed in the field and could be repeated with constant observations. His analysis was based on observations of the Cemaes and Llandinam windfarms located in Wales. As a result of his initial evaluations, Thomas concluded that a distance of 15 km was appropriate for evaluating the visibility of the windfarm. Using the information from his

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[78] H.T.H van der Zee (2016). "Obstacle lighting of onshore wind: Balancing aviation safety and environmental aspects". The Netherlands Aerospace Center, Amsterdam, NL

[79] ReNews Biz. "Germany advances turbine light relief", newsletter, 14 February, 2020

[80] European Commission (1995). ExternE. Externalities of Energy, Vol 6. Wind & Hydro

observations of the two windfarms, Thomas developed a matrix that incorporated nine bands of visual impacts ranging from "dominant" to "negligible". The matrix accounted for turbine heights of approximately 25-31 m and overall heights of 41-45 m.

Subsequent evaluations of the visual impact of windfarms often utilized standard guidelines, building from these early studies for reference, in determining the largest distance at which wind turbine was visible. One such standard includes a division of the landscape into three areas – a distant area (a radius of over 10 km), an intermediate area (a radius of 1 km), and an immediate area (a radius of less than 1 km). Within the distant area, wind turbines would be visible, but the nearest objects generally would dominate perception. However, within an "empty" landscape, the wind turbines could become the visual focus of observers. In the intermediate area, wind turbines would be extremely dominant because of their size and the rotational movement of the blades (Jallouli and Moreau, 2009)[81].

Additional research has been conducted to determine the influence of wind turbine blade movement in conjunction with distance. In general, the human eye can detect movement at large distances. The rotary and very regular movement of wind turbine blades is not a common type of "natural" movement, especially at the scale of large windfarm. Instead, this type of movement has been found to be highly noticeable, and Coates Associates (2007)[82] suggested that it may enhance the visibility of wind farms within the landscape. Some studies of onshore wind farms, for instance, have suggested that motion can extend the viewshed of wind turbines to beyond 8 km (Tsoutsos et al., 2007)[83] and up to 17 km in clear weather, or when conditions of strong contrast between the rotors and the sky are present (University of Newcastle, 2002)[84]. At times, the blades may not be visible, but a slight "pulse" in the intensity of light can be seen as the blade passes across the wind turbine tower (Coates Associates, 2007).

4.2. WIND ENERGY AND LAND USE

Even though people like wind power in the abstract, some object to large projects near their homes, especially if they do not financially benefit from the project. The NIMBY (Not-in my-backyard) discussion seriously affects the transition process towards a decentralized energy supply, as residents feel restricted in their quality of life by renewable technology systems installed nearby. Power plants and transmission lines will be located in areas not accustomed to industrial development, potentially creating opposition. Siting of wind farms is especially challenging as modern wind turbines are huge.

The land footprint of wind farms varies considerably, based on the wind conditions, topography and other factors. Thus, wind power similar to solar, has a comparatively small land footprint and similarly low greenhouse gas intensity compared to fossil electricity. Direct land use measures the area occupied by wind turbines and other infrastructures, excluding the land between infrastructure elements. This takes into account that overall land use of wind farms does not prevent this land from fulfilling other functions such as agriculture for example. Within the wind farm boundaries, approximately 90 percent of the land is not occupied by wind power equipment so that land is available for grazing or cultivation. Wind turbine nevertheless, can cause noise up to 100 decibels, depending on the type of turbine, power capacity, and wind speed (Kaza & Curtis, 2014)[85]. This can restrict land use, especially if human settlements are nearby.

Technological and policy solutions can lessen the land use impact of renewable power and the resulting public opposition. A number of technologies may help lessen the land use impact and public opposition to renewable development. One potential solution to overcome land use concerns is to move these projects away from land entirely. Wind is particularly amenable to moving offshore where winds are generally stronger, and wind speed and direction are more consistent, leading to greater potential generation and greater efficiency[86]. Although offshore wind eliminates land use, but it raises opposition among those concerned with the impact on the environment and scenic views. Community involvement in project planning and regulation for land use and zoning can help to alleviate these concerns.

[81] J. Jallouli; G. Moreau. "An Immersive Path-Based Study of Wind Turbines' Landscape: A French Case in Plouguin". In Renewable Energy, Vol. 34; pp. 597-607

[82] Coates Associates, 2007. "Cumbria Wind Energy Supplementary Planning Document: Part 2. Landscape and Visual Considerations". Prepared for the Cumbria County Council.

[83] T. Tsoutsos; G. Zacharias; K. Stefanos; P. Elpida. "Aesthetic Impact from Wind Parks", 2007

[84] University Of Newcastle. "Visual Assessment of Windfarms Best practice". Scottish Natural Heritage Commissioned Report F01AA303A

Zoning refers to placing turbines a predetermined distance from a radar to avoid interference. The U.S Department of Defence report[87] recommends a distance of 30 nautical miles for turbines with blade tips that protrude over 90 meters above the local terrain. Zoning is a common mitigation measure supported by policies pertaining to wind turbine siting in many European countries. In Austria, wind farms greater than 10 km from an air defence radar will receive no objections. In the Netherlands, only wind farms within 24 km from a military radar require review. In Germany, policy enforces a protection zone of 10 km around all Air Traffic Control (ATC) radars, with an area of interest up to 18 km from ATC radars. These zoning policies address both military and civilian concerns over radar shadowing (for Germany and the Netherlands), and electromagnetic interference and obstacles to low flying routes (in Austria). Zoning is also a mitigation measure used in UK Civil Aviation Authority policy as a means to manage shadowing and false plots on secondary surveillance radar (Auld et al., 2014)[88].

Wind development may also be in conflict with biodiversity, since bats, birds and insects can be affected. Analyses for California found that areas with the highest quality wind resources tend to be those with high biodiversity values. Planning and respective siting can avoid negative biodiversity impacts. Development of land with lower conservation value could lead to lower capacity factors and, hence, increase the specific land footprint, although this also provides opportunity for the co-location of different generation technologies to improve land use efficiency and reduce permitting, leasing and transmission costs (Gross, 2020)[89].

4.3. IMPACT ON BIRDS

For wind electricity, one of the most vociferous environmental concerns relates to the death of birds, and other avian species that can fatally collide with turbine towers, blades, and power lines, an issue termed "avian mortality". Many ecologists, biologists, ornithologists, and environmentalists at large have spoken out against wind power on the grounds that it presents too great a risk to avian wildlife. Studies have generated that onshore and offshore wind turbines present direct and indirect hazards to birds. Birds can smash into a turbine blade when they are fixated on perching or hunting and pass through its rotor plane: they can strike support structures; they can hit parts of towers; or they can collide with associated transmission and distribution lines. Some species, face additional risks from the rapid reduction in air pressure near turbine blades, which can cause internal hemorrhaging through a process known as barotrauma (Baerwald et al., 2011)[90]. Indirectly, wind farms can positively and negatively physically alter natural habitats, the quantity and quality of prey and the availability of nesting sites. It has been suggested that some species, such as migratory bats, raptors and seabirds, may be particularly impacted, which may at least be partly linked to visual acuity (Green, 2012)[91].

[85] N. Kaza; M. Curtis. "The land use energy connection". In Journal of Planning Literature, 29 (4): 1-16

[86] "Offshore Wind Research and Development", U.S Office of Energy Efficiency and Renewable Energy, https://www.energy.gov/eere/wind/offshore-wind-research-and-development

[87] U.S. Department of Defence. "Report on Congressional Defence Committee: Effect of windmill farms on military readiness". 2006, Washington D.C, USA

[88] T.Auld; M.P. McHenry and J.Whale (2014). "Options to mitigate utility-scale wind turbine impacts on defence capability, air supremacy, and missile detection". In Renewable Energy, Issue 63, pp. 255-262

[89] S. Gross. "Renewables, Land Use, and Local Opposition in the United States", Brookings Institution (2020), Washington D.C, USA

[90] E. Baerwald; R. Barclay. "Patterns of Activity and Fatality of Migratory Bats at a Wind Energy Facility in Alberta, Canada". In Journal of Wildlife Management, 2011, 75 (S), pp. 1103-1114

[91] M. Green. "Through birds' eye: insight into avian sensory ecology". In Journal of Ornithology, 153, 2012; pp. 23-44

The collision of birds with wind turbines has been noted since the 1970s though only in light of the recent wind energy expansion has the problem been seriously recognized. One of the major studies recording bird strikes from wind turbines quote collision rates per turbine from 0 to over 60 collision fatalities per year, which equals 0 to 20 birds per MW per year. Many bird species feature in the collision records, including gulls, raptors, such as griffon vulture, golden eagle, red kite, kestrels, and red-tailed hawks, though it is suggested that limited information existent on passerines collisions with wind turbines is probably due to a combination of fewer studies, lower detection rates, rapid scavenger removal.

The characteristics of collision with operating turbines have been extensively studied in the Western Europe. Collision risk is primarily influenced by the location of a wind farm. Indeed, farms located at certain landscape features, such as coastlines, hill tops, or large rivers have been associated with higher rates of mortality as birds are known to use these linear features for navigation, especially during migration. Weather conditions also affect collision risk: nights with low wind speed, relatively warm temperatures, and no precipitation are associated with the highest collision risk. In North America, it has been observed that large-scale weather phenomena, such as high pressure and low humidity, were more accurate in predicting collisions than local weather conditions (Arnett et al., 2008)[92]. Fatalities occur mainly during autumn migration, roughly from August to mid-September, and a smaller peak can also occur during spring migration in certain parts of Europe. The exact timing of fatalities varies latitudinally, e.g in Southern Europe the period of higher collision risk is longer.

The most bird collisions are with the rotating turbine blades, although collisions with turbine towers are also possible. For birds, adjusted fatality rates from most studies range from three to six birds per MW per year[93] for all species combined, and no publicly available study has reported more than 15 bird fatalities per MW year (Strickland et al., 2011; Loss et al., 2013a)[94].

Some studies have suggested that bird fatalities increase with tower height (Barclay et al., 2007; Baerwald and Barclay 2011)[95]. However, tower height was found not to affect levels of bat fatalities at Canadian facilities (Zimmerling and Francis, 2016)[96], and studies on birds suggest that the relationship between tower height and bird collisions is more nuanced (Smallwood and Karas, 2009)[97]. Taller turbines often have much larger rotor-swept areas, and it has been hypothesized that collision fatalities will increase due to the greater overlap with flight heights of nocturnal-migrating songbirds. The vast majority (<80%) of avian nocturnal migrants typically fly above the height of the most common rotor-swept zone (<150 m).

Important factors associated with elevated collision risk identified to date at onshore wind farms include topography, turbine location, design, and configuration, including spacing, and land use close to turbines. In particular there is a significant interaction between the prevaling wind and topography for raptors. When siting a wind farm all these factors need to be considered in light of the local bird population and their flight behavior and thereby minimize the impact of the wind turbines.

4.4. IMPACTS ON BATS

Bats are long-lived mammals with low reproductive potential and require high adult survivorship to maintain populations. The recent phenomenon of widespread fatalities of bats at utility scale wind turbines represents a new hazard with the potential to detrimentally affect entire population. Most fatalities reported from turbines in the United States, Canada, and Europe are of species that evolved to roost primarily in trees during much of the year ("tree bats"), some of which migrate long distances in spring and late summer to autumn.

It is estimated that hundreds of thousands die at wind turbines each year in North America alone (US Geological Survey, 2019)[98]. Unfortunately, it is not clear why this is happening. Several hypotheses have been proposed to explain why bats are killed by wind turbines (Kunz et al., 2007, Cryan and Barclay 2009, Rydell et al., 2010a)[99]. These include accidental encounter, particularly by migrating or juvenile animals; deliberate foraging around the blades; and deliberate use of tall structures as display sites by bats in the breeding season. Recent research has shown that migrating bats preferentially visit tall structures in the landscape, potentially explaining their high turbine collision rates (Jameson and Willis, 2014)[100]. In addition, the use of thermal imaging has shown tree-dwelling bats preferentially orientating towards turbines and approaching turbines from the leeward side (Cryan et al., 2014)[101]. It has been suggested that tree bats use streams of air flowing downwind from wind turbines while searching for roosts and insect pray, similar to those produced around trees at night[102].

The reasons for bat presence in the vicinity of wind turbines have also been investigated, with the initial hypothesis that collisions between bats and turbines are random. Another hypothesis suggests that bats are at a greater risk of collision while expressing certain behaviors, such as flying high while migrating or hunting migratory insects. Finally, there is also a hypothesis that turbines could attract bats into their vicinity (Cryan et al., 2009)[103]. The main reason for this attraction appears to be the presence of great numbers of prey insect close to the turbines, lured by the turbine's color and heat emission.

While it is still unclear why bats frequent wind turbine installations, recent research has shown that bats appear to actively investigate turbine rotors. Some species may be assessing them as potential roost sites[104], however there is also some evidence of foraging behavior around turbines. Bats tend to be concentrated in areas of high insect density and are much more likely to begin hunting when large numbers of insects are congregating. Reports into bat-turbine interactions frequently state the importance of investigation into the possibility of insect attraction to turbines (e.g Johnson & Kunz, 2004; Ahlen, 2004; Rodriquez et al., 2006)[105], particularly since the recent loss of feeding habitats may be pressurizing bats to feed in alternative areas. Turbine color may play an important part in insect attraction (Ahlen, 2004)[106], although to date this has not been closely investigated. Turbines are mostly painted white (Johnson & Kunz, 2004)[107] or shades thereof; the reasoning behind painting turbines in light colors appears to be connected with making turbines "visually unobtrusive", against the skyline, to make them "blend well into the landscape", or to make them easier to locate for meteorological purposes.

The species with the highest collision numbers in Europe are *Pipistrellus pipistrellus, Pipistrellus nathusii, and Nyctalus noctula.* However, this finding is derived mainly from Central Europe. In total, there are eight species that account for 98% of all the dead bats found at wind turbines

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[92] E.B. Arnett; M. Schirmacher; M.M. P. Huso; J. P. Hayes. "Effectiveness of changing wind turbine cut-in speed to reduce bat fatalities at wind facilities", Final Report submitted to the Bats and Wind Energy Cooperative, Austin, TX, USA: Bat Conservation International

[93] Fatality rates are typically reported on a per turbine basis or per nameplate capacity (MW).

[94] S. Loss; T. Will; P. Marra. "Estimates of bird collision mortality at wind facilities in the contiguous United States". In Biological Conservation, Volume 168 (2013), pp. 201-209

[95] E. Baerwald; R. Barclay. "Patterns of Activity and Fatality of Migratory Bats at a Wind Energy Facility in Alberta, Canada". In Journal of Wildlife Management, 2011, 75 (S), pp. 1103-1143

[96] J.R. Zimmerling; C. M. Francis (2016). "Bat mortality due to wind turbines in Canada". In Journal of Wildlife management, volume 80, pp. 1360-1369

[97] K. W. Smallwood and B. Karas (2009). "Avian and bat fatality rates at old generation and repowered wind turbines in California". In Journal of Wild-

[98] US Geological Survey. "Bat Fatalities at Wind Turbines – Investigating the Causes and Consequences", U.S Department of the Interior, 2019; Washington D.C

[99] J. Rydell; L. Bach; M. Dubourg-Savage; M. Green M; L. Rodrigues; A. Hedenström (2010). "Mortality of bats at wind turbines links to nocturnal insect migration". In European Journal of Wildlife Research, 56 (6), pp. 823-827

[100] J. Jameson; C. Willis. „Activity of tree bats at anthropogenic tall structures: implications for mortality of bats at wind turbines". In Animal Behavior, Volume 97, November 2014, pp. 145-152

[101] P. Cryan; P. Gorresen; C. Hein; M. Schirmacher; R. Diehl; M. Huso; D. Hayman; P. Fricker; F. Bonaccorso; D. Johnson; K. Heist; D. Dalton. "Behavior of bats at wind turbines", PNAS, 2014Geological Survey

[102] Ibid, 2014

[103] P. Cryan; R. Barclay. "Causes of Bat Fatalities at Wind Turbines: Hypothesis and Predictions". In Journal of Mammalogy, Volume 90, Issue 6, 15 December 2009, pp. 1330-1340

[104] Ibid, 2009

[106] I. Ahlen. "Wind turbines and bats – a pilot study". Final report, 11 December 2003, Swedish National Energy Administration

[107] T. Kunz; E. Arnett; W. Erickson; A. Hoar; G. Johnson; R. Larkin; M. Strickland; R. Thresher and M. Tuttle. "Ecological Impacts of Wind Energy Development on Bats: Questions Research needs, and Hypothesis". In Frontiers in Ecology and the Environment, Volume 5, No 6 (August 2007), pp. 315-324

in northwestern Europe (Rydell et al, 2010)[108], and these are defined as "high-risk species" because they face a higher probability of colliding with the turbines. In addition to the three aforementioned species, the high risk species include *Vespertilio murinus, Eptesicus nilsonii, Pipistrellus pygmaeus, Nyctalys leisleri, and Eptesicus serotinus*[109]. Other species or species groups such as the *Myotis* spp. and *Rhinolophus* spp. are rarely found dead at wind turbines. Species that are the most prone to collisions are predominantly aerial hawkers with wings and echolocation calls adapted for movement in open space: they are the species that hunt on flying pray, usually far from the ground or any structures (Barclay et al., 2017; Foo et al., 2017)[110]. In turn, the low-risk species such as *Myotis* spp. and *Rhinolosophus* spp. hunt close to surfaces or directly in the vegetation, which decreases the time that they spend in the rotor sweep zone, and further reduces the probability of colliding with the turbines. Despite the earlier belief that only migratory bats were affected by collisions (Arnett et al., 2008; Kunz et al., 2007)[111], it was discovered that both resident and migratory species are prone to collisions with wind turbines throughout Europe (Rydell et al., 2015)[112].

Individuals are either killed by direct collision (blunt-force trauma) with the moving blades or by barotrauma (tissue damage provoked by rapid pressure change) when flying close to the blade (Baerwald et al., 2008)[113]. Bat scientists speculated that bats would experience sudden pressure changes as they passed through rotating turbine blades. An implication of the barotrauma hypothesis was that bats might avoid collision, but still suffer debilitating injury or die from either over-pressure (damage to tympanic membranes) or under-pressure (damage to lungs) in proximity to the rotating blades, thus adding to the risk of wind energy to bats.

The hypothesis that barotrauma was an important source of bat mortality at wind facilities was quickly accepted, although the evidence was largely circumstantial and there have been few efforts to evaluate this hypothesis empirically. Rollins et al. (2012)[114] observed that many of the symptoms associated with barotrauma were also consistent with traumatic injury as well as postmortem processes occurring before the carcasses were discovered. Simulations conducted at the National Renewable Energy Laboratory (NREL; presentation at 2015 BWEC Science meeting) suggested that there is a very limited area along a rotating turbine blade that creates pressure differentials sufficient to cause barotrauma, and that bats would have to be in such close proximity to the blade to experience barotrauma-causing pressure changes that the risk of collision was almost certain[115].

Barotrauma continues to be cited as an important source of mortality for bats in both the popular and scientific literature (e.g., USFWS, 2016, Barclay et al., 2017)[116]. Whether it is important to resolve questions around the significance of barotrauma depends on whether it leads to an underestimation of bat fatalities, particularly in some species, from bats flying out of the search area before dying for example, or whether the risk of barotrauma leads to different strategies for mitigating bat fatalities.

Another reason might be that bats are drawn to tall structures, which are easy to perceive in the landscape and which they confuse with

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[108] J. Rydell; L. Bach; M. Dubourg-Savage; M. Green; L. Rodrigues; A. Hedenström (2010). "Mortality of bats at wind turbines links to nocturnal insect migration". In European Journal of Wildlife Research, 56 (6), pp. 823-827

[109] Ibid, 2010

[110] C. Foo; V. Bennett; A. Hale; J. Korstian; A. Schildt and D. Williams. "Increasing evidence of bats actively forage at wind turbines". In Animal Behavior, Conservation Biology, 2017

[111] T. Kunz; E. Arnett; W. Erickson; A. Hoar; G. Johnson; R. Larkin; M. Strickland; R. Thresher and M. Tuttle. "Ecological Impacts of Wind Energy Development on Bats: Questions Research needs, and Hypothesis". In Frontiers in Ecology and the Environment, Volume 5, No 6 (August 2007), pp. 315-324

[112] J. Rydell; A. Wickman. "Bat Activity at a Small Wind Turbine in the Baltic Sea" Acta Chiroterologica 17 (2), pp. 359-364

[113] E. Baerwald; R. Barclay. "Patterns of Activity and Fatality of Migratory Bats at a Wind Energy Facility in Alberta, Canada". In Journal of Wildlife Management, 2011, 75 (S), pp. 1103-114.

[114] K. Rollins; D. Meyerholz; G. Johnson; A. Capparella; and S. Loew. "A Forensic Investigation into the Etiology of Bat Mortality at a Wind Farm: Barotrauma or Traumatic Injury?" In Journal of Veterinary Pathology, Volume 49, Issue 2, 2012

[115] The NREL study has not been published in the peer-reviewed literature.

[116] USFWS – U.S Fish &Wildlife Service

large trees. Further, the exploration of wind turbines for roosting possibilities by bats (Kunz et al.,2007)[117], or their utilization as social and mating sites, have also been proposed to explain the presence of bats nearby turbines, but so far, they have still not seen examined in detail. It is important to keep in mind that the relative importance of each factor attracting bats to wind turbines fluctuates depending on the considered species, the sex and age of the individuals, the time of year, or the location of the wind turbines.

It is possible that wind turbines interfere with seasonal migration and mating patterns in some species of bats. More than three quarters of the bats fatalities at wind turbines are from species known as "tree bats", which tend to migrate long distances and roost in trees. These bats migrate and mate primarily during late summer and early autumn, which is also when the vast majority of bat fatalities at wind turbines occur. It is also possible that bats mistake slow or stopped turbine blades for trees.

The impacts of wind farms on bats vary in nature and duration, and can occur at all stages from the construction to the dismantling phase. The first impact to possibly take place is the loss of habitat and the following changes in bat fauna during the construction phase of a wind farm. However, the fatalities observed during the operating time of a farm are the most visible impact (Mascarenhas et al., 2018)[118]. Furthermore, among the newly investigated topics in this field is the avoidance of operating wind farms and their vicinity by bats, which could severely affect species in Europe by decreasing their habitats' availability.

4.5. AVOIDANCE AND MITIGATION STRATEGIES IN MINIMIZING WIND FARMS IMPACT ON WILDLIFE

Many methods have been developed to avoid or to reduce the impacts of wind turbines on birds and bats, but only a few proved to be efficient (Gartmann et al., 2016)[119]. Possible mitigation options to reduce collisions between birds, bats and wind turbines in existing wind-power plants can be categorized as either turbine-based or bird-based. Mitigation options on turbines encompass wind-power plant design, micro-siting of turbines, repowering and operation. Such measures have small or only indirect effects on bird mortality. The other approach is to directly affect bird behavior. The mitigation options affecting bird behavior encompass turbine design, deterrence/harassment and habitat alterations. The latter may be either inside (decreasing the attractiveness of the area), or outside the wind-power plant area (increasing the attractiveness of other areas). The objective of this section is to focus on the methods currently used in Europe on operating turbines that have shown to be effective. Some of the methods presented decrease the collision risk and therefore the fatality rate of the wind farm, others attempt to avoid destruction of important habitats and features for birds and bats.

4.5.1. TURBINE-SPECIFIC MITIGATION OPTIONS

The first and probably the most effective way to avoid impacts is the choice of the wind farm site itself as there are multiple factors to consider just regarding bats and birds. General opinion is that the most effective way to lessen impacts on birds and bats is to avoid building wind farms in areas of high avian abundance, especially where threatened species or those highly prone to collision at present. Therefore, guidance suggests that strategic planning should be based on detailed sensitivity mapping of bird populations, habitats and flight paths, to identify potentially sensitive locations.

General guidelines recommend avoiding areas which are extensively used by the involved spe-

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[117] T. Kunz; E. Arnett; W. Erickson; A. Hoar; G. Johnson; R. Larkin; M. Strickland; R. Thresher and M. Tuttle. "Ecological Impacts of Wind Energy Development on Bats: Questions Research needs, and Hypothesis". In Frontiers in Ecology and the Environment, Volume 5, No 6 (August 2007), pp. 315-324

[118] M. Mascarenhas; A.T. Marques; R. Ramalho; D. Santos; J. Bernardino; and C. Fonseca. "Biodiversity and Wind Farms in Portugal". Springer, 2018

[119] V. Gartman; L. Bulling; M. Dahmen; G. Geissler and J. Köppel. "Mitigation Measures for Wildlife in Wind Energy Development, Consolidating the State of Knowledge – Part 1: Planning and Siting, Construction". In Journal of Environmental Assessment Policy and Management, Volume 18, Number 3 (September 2016)

cies or which play an important role in their life cycle, principles that can also be utilized for birds and other species. For bats, this means avoiding, for example, hedgerows, forest edges, and other wooded linear features, as they are extremely used for commuting and foraging. Wetlands are also important sites for foraging. Summer and winter roosts can be in various location types, but caves, forests and old trees, ridges and cliffs can be highlighted. Migration flyways are often located on the coast or in fluviatelle valleys along rivers. Another recommendation is to avoid natural reserves, national parks or any protected areas, as they are designed to protect important sites for numerous endangered or vulnerable species, including bats. These zones usually have defined limits and specific regulations, often forbidding the construction of wind turbines inside their perimeter anyway (Drewitt &Langston, 2006)[120]. Buffer zones around these sensitive areas are recommended (Arnett & Baewald, 2013; Marx[121], 2017).

Studying flight corridors is essential to understand their importance for migratory and commuting bats, and to choose the position of wind turbines accordingly: keeping a distance from the flyways and placing turbines parallel to them (Drewitt &Langston, 2006[122]; Baerwald &Barclay[123], 2011). A simple wind farm design, such as turbine rows or clusters has been found to be effective in keeping the impact on habitats low. The adequate distance between each tower is difficult to assess on both tight and wide spacing have pros and cons: turbines closer to each other can reduce the cumulative avoidance effect of turbines (Gartmann, 2016)[124] and footprint on habitats (Drewitt & Langston, 2006)[125], but also decreases the commuting possibility between each turbine, because of the aforementioned avoidance effect, while a longer distance would result in the opposite.

Wind turbines have a relatively short life cycle (ca 30 years) and equipment remodeling must be undertaken periodically. Repowering is considered an opportunity to reduce fatalities for the species of greatest concern: (1) wind farm sites that have adverse effects on birds and bats could be decommissioned and replaced by new ones that are constructed at less problematic sites or (2) wind turbines of particular concern could be appropriately relocated. It is essential that monitoring studies are carried out first, before undertaking such potentially positive steps.

Also, as technology has rapidly progressed in recent years, there is a trend to replace numerous small wind turbines by smaller numbers of larger ones. The main changes have been a shift toward higher rotor planes and increased open airspace between the wind turbines. Despite taller towers having larger rotor swept zones, and therefore a higher collision risk area than an old single wall wind turbine, there is increasing evidence that fewer but larger, more power-efficient wind turbine may have a lower collision rate per megawatt (Barclay et al., 2007; Smallwood & Karas, 2009)[126]. However, repowering has been raising major concern for bats, so a trade-off analysis must be conducted.

A similar approach to avoiding sensitive areas can also be adopted for micrositing, i.e., the positioning of turbines and other facilities – roads, power lines, and substations – within the wind farm area. Micro-siting options (i.e. removing or relocating turbines) aim at identifying locations with increased risk for collisions. In wind-power plants where turbines were placed at more hazardous locations to bird collisions, these were either removed or relocated. Micro-siting has been proposed in agricultural areas, wetlands and along ridges with many soaring raptors. Removing "problem" turbines will specifically reduce mortality at that location, but may possibly lead to a shift of the problem to other turbines. Relocation of "problem" turbines instead may create increased collision risk elsewhere: and has therefore a lower expected efficacy. It has for example been suggested that outer turbines and turbines at the end of each row may experience higher risk of collision. Unless 'problem" turbines were placed at specific hazardous locations, such as breeding sites, migration bottlenecks or topography creating thermals, the collision risk may be expected to be reduced when such turbines are removed or relocated. The efficacy of micro-siting options is likely very site-specific and should preferably be done prior to the construction of the wind-power plant.

To date, wind turbine shutdown on demand seems to be the most effective mitigation technique. It assumes that whenever a dangerous situation occurs, e.g birds flying in a high collision risk area or within a safety perimeter, the wind turbine presenting greatest risk stop spinning. This strategy may be applied in wind farms with high levels of risk, and can operate year-round or be limited to a specific period.

De Lucas et al. (2012)[127] demonstrate that wind turbine shutdown on demand halved Griffon vulture fatalities in Andalucia, Spain, with only a marginal (0.07%) reduction in energy production. In this region, wind farm surveillance takes place year-round, with the main objective being to detect hazardous situations that might prompt turbine shutdown, such as presence of endangered species flying in the wind farm or the appearance of carcasses that might attract vultures. However, this approach requires a real-time surveillance program, which requires significant resources to detect birds at risk.

In addition to human observers, there are emerging new independent-operating systems that detect flying birds in real-time and take automated actions, for example radar, cameras or other technologies. These systems may be particularly useful in remote areas, where logistic issues may constrain the implementation of surveillance protocols based on human observers; or during night periods. These new systems are based on video recording images such as DTbird® (May et al., 2012)[128], or radar technology such as Merlin SCADA™ Mortality Risk mitigation System. For example, an experimental design at Smøla wind farm in Norway showed that the DTbird® system recognized between 76% and 96% of all bird flights in the vicinity of the wind turbine. Analyzing the characteristics of these technologies and taking into account factors influencing the risk of collision, cameras can be particularly useful in small wind farms. Radar systems appear to be more powerful tool for identifying large-scale movements like pronounced migration periods, particularly during night periods.

Turbine operation may be restricted to certain times of the day, seasons or specific weather conditions (Smallwood & Karas, 2009)[129]. This curtailment strategy is distinct from that described beforehand in that it is supported by collision risk models. This approach may imply a larger inoperable period and, consequently, greater losses in terms of energy production. As a result, it has not been well-received by wind energy companies.

Restrict turbine operation revealed to be very effective for bats. Arnett et al. (2010) showed that reducing turbine operation during periods of low wind speeds reduced bat mortality from 44% to 93% with marginal annual power loss (≤ 1% of total annual output)[130]. For birds it might not

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[120] A. Drewitt; and R. Langston. "Assessing the Impacts of Wind Farms on Birds: impacts of Wind Farms on Birds". Ibis 2006, 148, pp.29-42.

[121] G. Marx. "Le Parc Eolien Français et Ses Impacts Sur l'avifaune – Étude Des Suivis de Mortalité Réalisés En France de 1997 à 2015; LPO, France: Rochefort, 2017; p.92

[122] A. Drewitt; and R. Langston. "Assessing the Impacts of Wind Farms on Birds: impacts of Wind Farms on Birds". Ibis 2006, 148, pp.29-42.

[123] E. Baerwald; R. Barclay. "Patterns of Activity and Fatality of Migratory Bats at a Wind Energy Facility in Alberta, Canada. In Journal of Wildlife Management, 2011, 75 (S), pp. 1103-1114.

[124] V. Gartman; L. Bulling; M. Dahmen; G. Geissler and J. Köppel. "Mitigation Measures for Wildlife in Wind Energy Development, Consolidating the State of Knowledge – Part 1: Planning and Siting, Construction". In Journal of Environmental Assessment Policy and Management, Volume 18, Number 3 (September 2016)

[125] A. Drewitt; and R. Langston. "Assessing the Impacts of Wind Farms on Birds: impacts of Wind Farms on Birds". Ibis 2006, 148, pp.29-42.

[126] K. W. Smallwood and B. Karas (2009). "Avian and bat fatality rates at old generation and repowered wind turbines in California". In Journal of Wildlife Management, Volume 73, pp. 1062-1071

[127] M. De Lucas; G. Jans; and M. Ferrer. "Birds and Wind Farms: Risk Assessment and Mitigation", University of Madrid, 2007

[128] R. May; O. Hamre; R. Vang; T. Nygard. "Evaluation of the DTBird Video-system at the Smøla Wind-Power Plant. Detection Capabilities for Capturing Near-turbine Avian Behavior". NINA Report 910, 2012

[129] K. W. Smallwood and B. Karas (2009). "Avian and bat fatality rates at old generation and repowered wind turbines in California". In Journal of Wildlife Management, Volume 73, pp. 1062-1071

[130] E. B. Arnett; M. Schirmacher; M.M.P. Huso; J.P. Hayes. "Effectiveness of changing wind turbine cut-in speed to reduce bat fatalities at wind facilities", A final report submitted to the Bats and Wind Energy Cooperative, Austin Texas, USA: Bat Conservation International;

be so easy to achieve such results. However, restricting turbine operation could be implemented when particularly high risk factors overlap. For example, wind turbine on migratory routes could be shut down on nights of poor weather conditions for nocturnal bird migration.

Temporary shutdown has been tested in periods with high bird activity, or when birds moved too close to the turbines. Methods used to assess when birds flew too close to turbines were either through visual observations or avian radar. An effective use of this measure, however, depends on a good monitoring scheme to limit unnecessary shutdown and thereby loss of energy generation. Especially when shutdown is restricted to specific events of near-collisions, the efficacy will likely improve as this will limit possible habituation effects. Too large shutdown periods may cause birds to adjust to this new situation, leading to reduced avoidance of the turbines. However, other studies indicated that birds may primarily be affected by the actual turbine structures (Smallwood, KS et al., 2007; Muñoz et al., 2011[131]).

4.5.2. BIRD-SPECIFIC MITIGATION OPTIONS

Another option for mitigation of collisions is to alert birds to the turbines or affecting bird behavior. Alerting birds to the turbine structure may encompass making the rotor blades more visible, where reduction motions smear has been the major incentive. Alternatively mitigation measures have been proposed to dissuade birds from coming too close to the turbines through sensory cues. The efficacy of such measures is dependent on the birds' perception and response to the sensory cues (i.e. stressors). It is therefore crucial to take into account the sensory constraints placed upon the species of focus (Green, 2012)[132]. Mitigation options include passive and active visual cues (e.g painting or lightning), audible deterrence/harassment, and to a lesser extent other sensory cues (olfaction[133], microwaves). In addition, habitat alterations either within or outside of the wind-power plant may affect the birds' behavior. Although great difference exist among species, generally birds' hearing is inferior to humans while their visual acuity and temporal resolution is higher. Consequently, most measures are based on visual cues.

When turbine blades spin at high speeds, a motion smear (or motion blur) effect occurs, making wind turbines less conspicuous. This effect occurs both in the old small turbines that have high rotor speed and in the newer high turbines that despite having slower rotor speeds, achieve high blade tip speeds. Motion smear effect happens when an object is moving too fast for the brain to process the images and, as a consequence, the moving object appears blurred or even transparent to the observer. The effect is dependent on the velocity of the moving object and the distance between the object and the observer. The retinal-image velocity of spinning blade increases as birds get closer to them, until it eventually surpasses the physiological limit of the avian retina to process temporally changing stimuli.

As a consequence, the blades may appear transparent and perhaps the rotor swept zone appears to be a safe place to fly (Hodos, 2003)[134]. The ex-situ experiments by Hodos indicated that painting one of the three blades black reduced motion smear most. Depending on whether decreased visibility of rotor blade tips is the cause of collisions, reducing motion smear may enhance the exposure potential. As for all measures based on passive visual cues, UV-coating only works during daytime. UV-coating on rotor blades to increase their visibility has been proposed and tested in the USA with unclear conclusions on its efficacy. Reflectors in the form of mirrors and aluminium/silvered objects – e.g holograms may also provide to be an effective way of scaring birds. However,

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[131] A. Muñoz; M. Ferrer; M. de Lucas; E. Casado. "Raptor mortality in wind farms of southern Spain: mitigation measures on a major migration bottleneck area". Proceedings of the conference on wind energy and wildlife impacts, 2-5 May 2011, Trondheim, Norway: Norwegian Institute for Nature Research

[132] M. Green. "Through birds' eye: insights into avian sensory ecology", Journal of Ornithology, 153, 2012; pp.23-48

[133] Olfaction, the sense of odor, is the detection of chemicals dissolved in air (or in water, by animals that live under water).

[134] W. Hodos (2003). "Minimization of Motion Smear: reducing Avian Collisions with Wind Turbines". University of Maryland/National Renewable Energy Laboratory NREL/SR-500-33249, Colorado, USA

reflectors will only be effective when they reflect (sun) light and lose their efficacy between sunset and sunrise, they were recommended in combination with other methods of scaring. At daytime, when also most birds are active, they may create an ever-moving myriad of lights reflecting off the blades. Due to these changing reflections, the blades may become more visible and may attract attention to them resulting in increased responsiveness in the birds.

Mitigation measures based on active visual cues include minimal use of turbine lighting, adjustment of turbine lightning regimes, visual deterrence or laser. Minimal use of turbine lightning has been proposed especially for bats and nocturnal migrating birds. However, observations showed no difference in fatality rates between lit and unlit turbines (Johnson et al., 2003, 2004)[135]. Even though nocturnal (migrating) birds may be attracted to the (red) flashing or steady-burning safety lights (Hötker et al., 2006)[136]. Although the implementation costs - air safety implications aside - should be limited, minimal use of lighting may have limited impact for reducing collisions. Although nocturnal birds may be prevented being attracted to the turbine lights, they are also not alaerted their presence.

Visual deterrence includes the use of strobing, flashing, revolving lights causing a temporary blinding and thereby confusion effect. This measure will be most effective at low lights levels, and may therefore mainly help mitigate collisions of nocturnal birds. Habituation may be reduced through randomized selection of a least two strobe frequencies; however use of bright lights may cause visual nuisance for local residents. Also, its efficacy will be enhanced greatly when the visual deterrents are emitted only in situation when birds are in close vicinity of a turbine. This requires a functional, e.g based on video or avian radar, system to continuously monitor bird flight behavior. Depending on the exact wavelength, luminance and exposure regime used this activity will likely result in high levels of evasive responses. However, the implementation may be more challenging as such deterrence systems should be installed on all („problem") turbines and require trustworthy triggering of the deterring stimulus. Using laser renders similar efficacy as for visual deterrence. The difference being that laser may be directed more accurately at an approaching bird (Clark, 2004)[137]. However, this accuracy may also be with its limitation as it assumes that it will be possible to pinpoint a flying bird. The visual nuisance of laser may however be less pronounced than for lights. Lasers also work best under low light levels. Something that has not been proposed is to utilise UV lasers that sweep upwards during night time encircling the rotor swept zone. UV lasers are invisible to the human eye but may deter nocturnal birds from entering the rotor swept zone.

Deterrent devices that scare or frighten birds and make them move away from a specific area have been broadly used as tools for wildlife management. Auditory deterrents are considered the most effective, although their long-term use has been proven to be ineffective due to habituation by birds to certain stimuli (Bishop et al, 2003; Dooling, 2002)[138]. Biacoustic techniques are thought to be the most effective because they use the birds' natural instinct to avoid danger. Preliminary data on the use of the acoustic deterrent LRAD (Long Range Acoustic Device) in wind farms showed that 60% of Griffon vultures had strong reactions to the device, and its efficacy depended on the distance between the bird and the device, the bird's altitude and flock size.

Deterrents can also be activated by automated real-time surveillance systems as an initial mitigtion step and prior to blade curtailment (May et al., 2012; Smith et al, 2011)[139]. Systems such as

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[135] G. D. Johnson; M. K. Perlik; W.P. Erickson; and M. D. Strickland (2004). "Bat activity, composition, and collision mortality at a large wind plant in Minnesota". In Wildlife Society Bulletin, 32 (4), pp. 332-342

[136] H. Hötker; K. Thomsen; H. Jeromin. "Impacts on biodiversity of exploitation of renewable energy sources: the example of birds and bats – facts, gaps in knowledge, demands for further research, and ornithological guidelines for the development of renewable energy exploitation", p. 65, Berghausen, Germany: Michael-Otto-Institut in NABU: 2006.

[137] T. L. Clark. "An autonomous bird deterrent system. [Dissertation]. University of Southern Queensland; 2004.

[138] R. Dooling. "Avian hearing and the Avoidance of Wind Turbines", National Renewable Energy Laboratory, Colorado, USA

[139] R. May; O. Hamre; R. Vang; T. Nygard. "Evaluation of the DTBird Video-system at the Smøla Wind-Power Plant. Detection Capabilities for Capturing Near-turbine Avian Behavior". NINA Report 910, 2012

DTBird®or Merlin ARS™incorporate this option in their possible configurations. Although the results are preliminary, this type of methodology may have an unpredictable effect on the flight path of a bird, so caution is needed, if it is applied at a short distance from a wind turbine or within a wind farm. Nevertheless, it may be used as a potential measure to divert birds from flying straight at a wind turbine.

CHAPTER 5 - WIND TURBINE NOISE

Wind energy development is inevitably related to certain negative environmental impact, since when operating, wind turbines generate acoustic noise that can be defined as any unwanted sound. Distinguishing noise from sound is to a large extent subjective but generally sound from wind turbines is considered as unwanted and therefore it is referred to as noise in this chapter.

Wind turbine noise emissions are generated by blades, as the blade tip passes through the air at rather high speed (250 km/h). A lot of focus has been given to the issue over the years and this noise has been reduced by clever design and blade add-ons[140]. When stricter noise limits are enforced to legacy wind turbines already deployed, actions need to be taken. One solution is retrofitting wind turbine blades with additional outer layer skins that change their aeroacoustic footprint. Although the technology has advanced, wind turbines have got much quieter, but noise from wind turbines is still a public concern. It is one of the major hindrances in the development of wind industry[141][142].

Noise levels can be measured, but similar to other environmental concerns, the public's perception of the noise impact of wind turbines is in part a subjective determination. The concerns about noise depend on 1) the level of intensity, frequency distribution and patterns of the noise source; 2) background noise levels; 3) the terrain between the emitter and receptor; and 4) the nature of the noise receptor. The effects of noise on people can be classified into three general categories (National Wind Coordinating Committee, 1998)[143]:

1) Subjective effects including annoyance, nuisance, dissatisfaction
2) Interference with activities such as speech, sleep, and learning
3) Physiological effects such as anxiety, or hearing loss.

In almost all cases, the sound levels associated with wind turbines produce effects only in the first two categories. Workers in industrial plants, and those who work around aircraft can experience noise effects in the third category.

World Health Organization (WHO) recommends when estimating wind turbine environmental impact to evaluate the noise impact as low, average and high frequencies. Low frequency sounds and infrasound, excite individual human body parts and worsen general human well-being[144]. It is known that the noise of 32 dB (A) for some people is a strong irritant for their nervous system, whereas the noise of 40 dB (A) and higher for most people evokes strong discomfort (Taylor et al., 2016)[145].

The process of developing stress begins with the perception of possible stressors (e.g. wind turbine noise as an ambient stressor), followed by the evaluation of those stressors (e.g., they are annoying), then psychological and physical reactions to it. However, to date, the predominant wind turbine impact indicator relied upon has been annoyance, while symptoms of wind turbine noise have been studied. These studies revealed a pattern of stress symptoms due to wind turbine noise including sleep disturbance, irritability, negative mood and a lack of concentration (e.g. Bakker et al., 2012, Hübner and Löffler, 2013; Pohl et al., 2018)[146].

To understand what influences the perceived annoyance and stress reactions due to wind turbine noise, several moderators must be considered: the visibility of wind turbine by residences seems to increase annoyance. These decrease, however, when residents have a financial interest in the wind farm project (e.g Health Canada, 2014)[147]. Annoyance induced by the planning and construction of wind farms appears related to wind turbine noise annoyance as well as reported stress symptoms. Several studies also indicate that residents with negative attitudes towards wind energy or their local wind farm are more likely to experience wind turbine noise annoyance and vice versa (e.g Pawlaczyk-Luszczynska et al., 2014; Pohl et al., 2012, 2018)[148][149]. Remarkably, the distance of residences from wind turbine has been inconsistently correlated to wind turbine noise annoyance and stress impact (increased annoyance with decreased distance).

The present chapter focuses on noise problems as they are the most frequently discussed stress impact on residents. A number of mitigation strategies are available for wind farm project developers to reduce this effect, and in any case to comply with applicable noise regulations. Noise is generally regulated in national legislation which restrains potential locations when planning for wind power. The mitigation strategies range from keeping a certain distance from dwellings, carefully selecting the adequate turbine type, going for blade add-on elements to reduce aerodynamic noise or applying noise curtailment modes. However, these strategies often impact the project cost, and pretty much of all of them would impact expected revenues, making it all the more important to apply them carefully and correctly.

5.1. WIND TURBINE NOISE SOURCES

It is well established that the dominant noise mechanisms for modern, industrial scale wind turbines are aeroacoustic. Mechanical noise sources in modern designs can be reduced to a point where their contribution to total noise levels is nominally negligible relative to aeroacoustic noise sources. Aeroacoustic noise is produced by several mechanisms, each ultimately caused by various forms of unsteady aerodynamic flow about the blades (Wagner et al., 1996)[150]. Some of these mechanisms are not relevant for modern industrial-scale turbines. Blade tip-vortex interaction noise is minimized by the design of blade tip geometry.

Aeroacoustic noise (i.e. the noise of turbine blades passing through the air) is a limiting factor on performance of wind turbines. Aerodynamic i.e. flow-induced noise from the rotor is generally considered to be the most dominant noise source for a modern large wind turbine, provided that mechanical noise is adequately treated. There are three main aerodynamic noise sources for wind turbines, turbulence inflow noise, trailing-edge noise and separation noise. Blade tip noise can also be a problem, but for modern wind turbines tip noise is not contributing to the overall noise as it can be controlled by tip shape design.

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[140] Blade add-ons are used to improve blade performance, they increase power input and reduce noise.

[141] M. Dröes; H. Koster. „Renewable Energy and Negative Externalities: The Effect of Wind Turbines on House Prices". In Journal of Urban Economics, vol. 96, pp 121-141 (2016), www.doi.org/10.1016/j.jue.2016.09.001

[142] J. L. Davy; K. Burgenmeister; D. Hillman. "Wind turbine sound limits: Current status and recommendations based on mitigating noise annoyance". In Applied Acoustics, vol. 140, pp. 288-295 (2018); www.doi.org/10.1016/j.apacoust.2018.06.009;

[143] National Wind Coordinating Committee. "Permitting of Wind Energy Facilities: A Handbook, "RESOLVE". NWCC, Washington D.C, USA, 1998

[144] It describes sound waves with a frequency below the lower limit of audibility (generally 20 Hz). Hearing becomes less sensitive as frequency decreases, so for humans to perceive infrasound, the sound pressure must be sufficiently high.

[145] J. Taylor; C. Eastwick; C. Lawrence; R. Wilson. "Noise levels and noise perception from small and micro wind turbines". In Renewable Energy, volume 55, July 2013, pp. 120-127

[144] It describes sound waves with a frequency below the lower limit of audibility (generally 20 Hz). Hearing becomes less sensitive as frequency decreases, so for humans to perceive infrasound, the sound pressure must be sufficiently high.

[145] J. Taylor; C. Eastwick; C. Lawrence; R. Wilson. "Noise levels and noise perception from small and micro wind turbines". In Renewable Energy, volume 55, July 2013, pp. 120-127

[146] G. Hübner., J. Pohl; B. Hoen; J. Firestone; J. Rand (2019). "Monitoring annoyance and stress effects of wind turbines on nearby residents: A comparison of U.S and European samples", Environment International 132 (2019) 105090

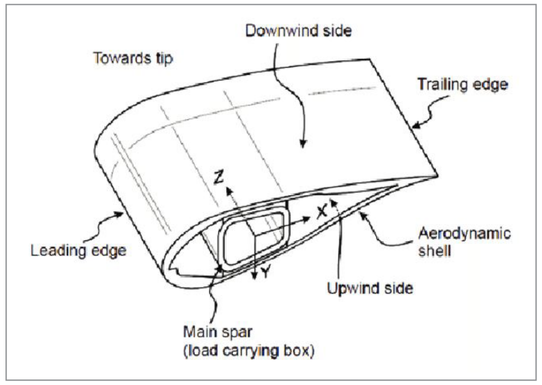
[147] Health Canada (2014). "Summary of Health Canada study on wind turbine noise and health impacts"

[148] M. Pawlaczyk-Luszczynska; K. Zaborowski; A. Dudarewicz; M. Zamojska-Daniszewska; M. Waskowska. "Response to Noise Emitted by Wind Farms in People Living in Nearby Areas". In International Journal of Environmental Research and Public Health, vol. 15, no. 8 (2018), www.doi.org/10.3390/ijerph15081575

[149] M. Pawlaczyk-Luszczynska, M; Dudarewicz, A; Zaborowski K; Zamojska-Daniszewska, M. "Annoyance Related to Wind Turbine Noise". In Acoustics, Volume 39, No 1, pp. 89-102 (2014)

[150] S. Wagner; R. Bareib; and G. Guidati (1996). "Wind Turbine Noise". Springer, Berlin, Germany

Figure 23. The main elements of a wind turbine blade



Source: Sørensen et al., 2004

Turbulent inflow noise is reported as an important aeroacoustic wind turbine broadband noise source, coexistent with the airfoil self-noise sources (e.g., airfoil trailing edge noise and the low-frequency noise). Trailing edge noise is produced by the scattering of convected turbulent sources by a sharp edge. The Aero/Hydro-acoustics Laboratory in the USA has studied conventional methods of treating trailing edge noise focused on modifications to the trailing edge geometry (e.g. serrations). Most recently, they have developed a novel method of reducing trailing edge noise by treating the boundary layer instead[151].

In order to reduce noise, most wind turbine designs limit their rotational speed because of noise constraints, which reduces aerodynamic efficiency. With quieter gearbox and generator designs, aeroacoustic noise is now considered the dominant noise source for wind turbine operation. This type of noise is more difficult to mitigate, and it is the dominant noise source on modern wind turbines (Oerlemans et al, 2007)[152].

Operating conditions and maintenance of the wind turbine also affect noise production. Efforts to quantify wind turbine noise have been ongoing for the past three decades. There are two primary classes of noise sources on a wind turbine. These include mechanical noise due to vibrations in the drive train and gear noise, and aeroacoustic noise due to unsteady aerodynamic processes on the rotor. Mechanical noise, while it can potentially be a large contributor to overall wind turbine noise, is usually relatively straightforward to reduce using techniques to dampen or isolate mechanical vibrations in the nacelle, or by employing sound absorbing material (Wagner et al, 1996)[153].

5.1.1. MECHANICAL NOISE

Mechanical noise is generated from components within the wind turbine, such as the generator, the hydraulic systems and the gearbox. Other elements such as fans, inlets/outlets and ducts also contribute to mechanical noise. The type of noise produced by these mechanical components tends to be more tonal and narrowband in nature, which is more irritating for humans than broadband sound. There are four types of noise that can be generated by wind turbine operation: tonal, broadband, low frequency, and impulsive. Tonal noise is defined as noise at discrete frequencies. Low-frequency noise with frequencies in the range of 20 to 100 Hz is mostly associated with downwind turbines (turbines with the rotor on the downwind side of the tower). Impulsive noise is a category of acoustic noise that includes unwanted, almost instantaneous (thus impulse-like) sharp sounds, typically caused by electromagnetic interference. High levels of such a noise (200+ decibels) may damage internal organs, while 180 decibels are enough to damage human ears.

While the total wind turbine sound pressure level only incurs a minor increase due to this noise, the penalty it places on wind turbines and the nearest buildings is much greater. Many countries have regulations which stipulate distances between wind turbines and the nearest buildings must be increased, or in some cases, outright refusal of installation, due to the negative impact of this noise to humans. There are two ways in which mechanical noise is transmitted: airborne or structural. Airborne noise is straightforward, as the sound is directly emitted to the surroundings. Structural noise is more complex as it can be transmitted along the structure of the turbine and then into the surroundings through different surfaces, such as the casing, the nacelle cover, and the rotor blades. The drive gearbox is a significant source of noise in wind turbines. The mechanical noise is of less importance in modern wind turbines because of improved sound insulation of the hub (van den Berg, 2005, Oerlemans et al., 2007)[154].

5.1.2. AERODYNAMIC NOISE

The most remarkable noise source of wind power plants is their rotor blades that cause mainly aerodynamic noise. The broadband aerodynamic sound of rotor blades is composed of four major components caused by flow turbulence: the trailing edge sound (turbulence boundary layer – trailing edge interaction), blunt trailing edge sound, the tip vortex sound and the inflow turbulent sound. The trailing edge sound among them seems to be the most remarkable (van den Berg, 2006)[155]. The angle of attack plays an important role in the action of a wind turbine and in broadband wind turbine noise generation. It is an important parameter in most three-dimensional aerodynamic models of rotating wind turbines (Maeda &Schepers, 2011)[156]. However, the definition of the angle of attack is based on the wind tunnel environment as the angle between the chord line and the wind velocity vector, which has the same direction as the uniform flow among the wind tunnel walls. When the angle of attack increases from its optimal value, the turbulent boundary layer on the low pressure side of the blade grows in thickness, decreasing power performance and increasing sound level.

Mainly associated with the interaction of turbulence with the blade surface, aerodynamic noise can be divided into three main types: low frequency noise, turbulent inflow noise and airfoil self-noise. Low frequency noise occurs due to the passage of the blades through the tower's wake. In turn, turbulent inflow noise is generated due to the interaction of turbulence of the incoming flow with the turbines blades. Airfoil noise is the total noise produced when an airfoil encounters smooth non-turbulent inflow and the noise is produced as this turbulence passes over the trailing edge. It is further divided into various noise mechanisms; the two most relevant mechanisms are turbulent boundary layer-trailing edge noise (or, "trailing edge noise"), and blade tip vortex. At the tip of the blade the air flows from three different directions causing a tip vortex which generates sound, especially when the vortex is interacting with the trailing edge.

Turbulent boundary layer – trailing edge noise is considered to be one of the major contributors to airfoil self-noise. It is the main source of high frequency noise, especially for medium and large wind turbines (Oerlemans et al., 2007)[157]. For installed fans, trailing edge noise corresponds to the minimum achievable noise level. Rotors and propellers are subject to other noise sources. Some of these are broadband, for example leading edge noise due to upstream turbulence, tip vortex-induced noise and stall noise[158]. Others are tonal, as in the case of steady loading in the reference frame of the rotor, periodic unsteady loading produced by stationary distortions in the flow.

In any airfoil subject to a flow, a boundary layer develops on its surface, starting from the stagnation point close to the leading edge. As certain angle of attack and Reynolds number conditions are met, the boundary layer transitions from laminar to turbulent at a certain chordwise po-

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[151] This research is inspired by the silent flight of certain species of owls that have a fine downy coating on their feathers that is used to attenuate the strength and reduce the spanwise correlation of turbulence in the wind boundary layer.

[152] Oerlemans, S., Sijtsma, P., Mendez-Lopez, B. "Location and quantification of noise sources on a wind turbine", In Journal of Sound and Vibration, 299, pp. 869-883, 2007

[153] S. Wagner; R. Bareib; and G. Guidati (1996). "Wind Turbine Noise". Springer, Berlin, Germany

[154] G. Van den Berg. "Criteria for a wind farm noise: Lmax and Lden", In The Journal of the Acoustical Society of America, June 2008

[155] G. Van den Berg (2006). "The Sounds of High Winds, the Effect of Atmospheric Stability on Wind Turbine Sound and Microphone Noise". Groningen: University of Groningen.

[156] T. Maeda; G. Schepers. "Wind turbine performance assessment and knowledge management for aerodynamic behavior modelling and design: IEA experience". In Wind Energy Systems, 2011

[157] S. Oerlemans; P.Sijitsma; B. Mendez-Lopez (2007). "Location and quantification of noise sources on a wind turbine". Report, National Aerospace Laboratory, Amsterdam, the Netherlands

[158] This is noise due to a non-zero angle of attack of the wind turbine blade creating a boundary layer separation wake at the trailing edge. Very high angles of attack lead to large-scale separation (deep stall) at the trailing edge causing the airfoil to radiate low-frequency noise. At high angles the airfoil is acting similar to that of bluff body in the flow.

sition. At higher Reynolds numbers[159] turbulent boundary layers develop over much of the airfoil and the noise occurs at the turbulent eddies pass over the trailing edge. Beneath this boundary layer, the turbulence induces a fluctuating pressure field. Turbulent boundary layer trailing edge noise is perceived as a swishing sound i.e. broadband. Its peak frequency is typically in the order of 500 – 1500 Hz (Wagner et al., 1996)[160].

The turbulent flows coming from different sides of the blade strike at the trailing edge generating a turbulent flow wake (Di Napoli, 2007)[161]. The turbulence in the boundary layer generates sound, particularly when it interacts with the trailing edge. The increase in the turbulence over the blade is the higher the larger the change in the blade profile is. The turbulence can be increased by the geometry of the trailing edge (blunt), the roughness (dirtiness, icing) of the blade surface, and turbulence and the flow speed of the oncoming flow. In modern blade profiles the area of the blade narrows towards the blade tip in which case most of the noise is not generated at the tip but in region situating in the blade 0.75 – 0.95 from the base of the blade. The source region moves outwards with increasing frequency and it is larger with rough blades. The roughness of the blade surface raises the radiated sound level especially at low frequencies. The bluntness of the trailing edge causes a clear maximum (narrow band) in the sound spectrum (Oerlemans & Lopez, 2005)[162].

Turbulence can be defined as temporal and spatial changes in wind velocity and direction, resulting velocity components normal to the airfoil causing in-flow turbulent sound. The maximum of its spectrum is typically in the infrasound region (van den Berg, 2006)[163].

Highest broadband sound levels have been measured in the upwind and downwind directions, and lowest ones in the crosswind directions. According to Hubbard et al (1991)[164], levels measured at night time are generally lower, particularly in the crosswind directions, and the lower night time levels are believed to be associated with less intense inflow turbulence. According to van den Berg, the above is only valid for small wind turbines, tall wind turbines produce on average more sound in night time than in day time. This is due to the atmospheric conditions presented above. In near field most of the noise is produced when the blades are moving downwards.

Besides, aerodynamic pulsations are developed due to rotating interaction of blades with construction elements of wind turbine tower. Noise may be broadband and tonal whereas broadband noise is characterized by a continuous distribution of sound pressure with frequencies greater than 100 Hz. It is often caused by the interaction of wind turbine blades with atmospheric turbulence, and also described as a characteristic “swishing” or “whoosing” sound. Besides aerodynamic and mechanical noise, there always exists the environmental background noise, which is conditioned by wind flows of the plants, relief incongruities and other obstacles, transport means, birds, industry objects, etc. The background environment noise intensifies during the day, whereas at night, it sometimes diminishes due to lower side effect impact (evoked by transport, factories, fauna, etc.) (Moeller &Pedersen, 2011)[165].

Noise limits for wind turbines are more usually given for a range of wind speeds. The reason for this is that wind turbines produce more sound at higher wind speeds and it was thought that the

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[159] The Reynolds number is a commonly used non-dimensional parameter in fluid mechanics, which describes the inertial forces to viscous forces. With increasing Reynolds number the boundary layer gets thinner, which results in a lower drag. Increasing the Reynolds number also has a destabilizing effect on the boundary layer flow, which results in the transition location moving towards the leading edge, leading to a turbulent boundary layer over a longer part of the airfoil surface.

[160] S. Wagner; R. Bareib; and G. Guidati (1996). "Wind Turbine Noise". Springer, Berlin, Germany

[161] C. Di Napoli. "Tuulivoimaloiden melon syntytavat ja leviärninen". Helsinki: Ympäristöministeriö, Suomen ympäristö 4, 2007

[162] S. Oerlemans and B. Lopez. "Localization and quantification of noise sources on a wind turbine". First International Meeting on Wind Turbine Noise, proceedings. Berlin, 2005

[163] G. Van den Berg. "The Sounds of High Winds, the Effect of Atmospheric Stability on Wind Turbine Sound and Microphone Noise". Groningen: University of Groningen, 2006

[164] H. Hubbard & K. Shepherd. "Aeroacoustics of large wind turbines". In Journal of Acoustic Society of America, 1991, Volume 89, No 6, pp. 2495-2508

[165] H. Moeller; C. Pedersen (2010). "Low frequency noise from large wind turbines". In Journal of the Acoustics Society of America, Volume 129, Issue 3727

higher wind speeds would provide more background sound which in turn would mask the increasing wind turbine noise level. It has been shown, especially for modern, tall turbines – that this assumption is incorrect when the atmosphere is stable, which is a common situation in the temperate climate zone after sundown. The reason for this is that a stable atmosphere the wind at higher altitude is decoupled from the near-ground wind. Then, high hub height wind speeds can occur with simultaneous low near-ground wind speeds and thus high turbine sound levels occur at low background sound levels. In fact, tall wind turbines in relatively flat land can produce (near) maximum sound power at any near-ground wind speed except the very lowest. As a result the masking potential of background sound is not very different from what it is for other industrial sources. In complex terrain the situation is more complicated, though it may lead to the same conclusion.

5.2. WIND TURBINE NOISE REDUCTION TECHNOLOGIES

Acoustic emissions of wind farms have a negative impact on social acceptance of wind energy and can be a barrier for the future spread of this source of renewable energy. To comply with local regulations governing community noise, wind turbines are often designed to curtail their operation, degrading efficiency, reducing energy capture, and effectively increasing the cost of wind energy. Thus, development of high quality noise prediction tools and innovative noise reduction technologies are key objectives for wind turbine manufacturers.

Various experimental and numerical techniques have been developed for noise mitigation by taking advantage of our understanding of the noise mechanisms which provide the insight into the aero-acoustic characteristics of wind turbines. Researchers are focused on reducing noise without affecting the power generated by the wind turbine. Lately companies have started looking for different strategies in order to suppress noise without affecting the power output. These strategies have been inspired from the owl's feathers and consist in the modification of the airfoil at the trailing edge. Strategies for reducing mechanical and aerodynamic noise will be discussed in this section.

5.2.1. MECHANICAL NOISE REDUCTION

One source of mechanical noise is vibration induced by rotating components. Vibration control is used to suppress or eliminate unwanted vibrations. Depending on the case, different laws can be chosen in order to minimize unwanted vibration. Additionally, dampening or increasing the effective mass can be realized by the controller (Kelly, 2000)[166]. Inferentially, the absorber works as an active system. This includes the use of sound isolating materials, insulation, and closing the holes in the nacelles which would decrease the sound transmitted to the air. Aside from loss of power and increased maintenance costs, faulty gearboxes also increase noise levels in wind turbines. As a result, researchers are developing fault diagnostic systems for gearboxes with applications to wind turbines. A system has been developed to integrate singular value decomposition noise reduction, time-frequency analysis and order analysis methods in order to identify weak faults objectively and effectively (Wang et al., 2011)[167]. More recently, efforts have been taken to develop intelligent techniques for online condition monitoring in machinery systems such as wind turbines.

5.2.2. AERODYNAMIC NOISE REDUCTION

There are a number of adaptive noise reduction approaches for aerodynamic noise, including varying the speed of rotation of the blades. Since the increase in rotational speed will also lead to increased noise production, lowering the rotational speed will lead to decreased sound. However, the rotational speed decreases power output, and therefore should only be implemented within a certain range of wind velocities, since high winds also have the added benefit of masking the sound of the wind turbine with the sound

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[166] S. Kelly. "Fundamentals of Mechanical Vibrations", Second Edition, McGraw Hill, 2000

[167] F. Wang; L. Zhang; B. Zhang; Y. Zhang; L. He. "Development of wind turbine gearbox data analysis and fault diagnosis system", Power and Energy Conference (APPEEC), 2011, Asia-Pacific

of the wind itself. The pitch angle of the wind turbine blades also have an important role in noise production. An increase in pitch angle will lead to a reduction in the angle of attack. As the angle of attack increases, the size of the turbulent boundary layer on the suction side of the airfoil grows, thereby increasing noise production in the wind turbine. Therefore, if the pitch angle is reduced, a thinner boundary layer results on the suction side, which is considered the strongest source of noise production (Brooks et al., 1989)[168]. This also implies that, on the pressure side, the effect is the opposite; therefore when using this method for noise control, it is important to find the appropriate pitch angle range for optimal noise control. As with the previous method, the major drawback to this adaptive noise control method is the corresponding reduction of power since the angle of attack is decreased. Despite the loss in power, the main advantage if wind turbines with optimized operating conditions is that the acoustically affected areas are much smaller, allowing more wind turbines to be built in a specified area, e.g., a wind farm (Romeo-Sanz & Matesanz, 2008)[169].

The main drawback to adaptive methods (an overall reduction of power) is a hindrance to that method of noise control. By breaking down the noise sources it can be seen that the maximum noise contribution occurs within the trailing edge. The region between about 75-95% span is exposed to the maximum flow velocities and it has the highest aero-acoustic noise levels (Oerlemans et al., 2001)[170]. Furthermore experimental tests showed that most of the noise is generated when the blade is moving downwards in a clockwise rotation. Therefore, the majority of modification procedures are aimed at reducing the noise in this area.

Turbulent boundary layer - trailing edge noise is one of the dominant sources of airfoil self-noise emitted by well-designed modern wind turbines. This source of noise limits both the installation of new wind turbines and the operational regimes of existing ones, thus reducing the power production and increasing the overall cost of energy. Wind turbines, depending on their manufacturer, may come equipped with low-noise operational modes, which basically is an application of this method. The trade-off is a loss in energy production by a less efficient capturing of the wind's energy. Depending on the economic viability of using these settings, which might be better than, for example, shutting down a wind farm during the night because of stricter noise regulations (common in countries like Germany), they may prove useful without becoming a loss to the operator (Arce Leon, 2012)[171].

Noise reduction is an important development direction for aircrafts and wind turbines. Owl wings have three unique morphological characteristics (leading edge serrations, trailing edge serrations and velvet-like surfaces) that effectively suppress aerodynamic noise in low Reynolds numbers. Among them, trailing-edge serrations are widely considered the most effective noise-reduction method. Trailing edge serrations provide a way to reduce the angle between eddy path and edge below 90 degrees, thus decreasing the scattering of sound. Experimental observations on full scale wind turbine of 94 meter diameter with serrations have reported reductions of 3.2 dB (Oerlemans et al., 2009)[172]. However, since the serrations cannot always be aligned to the flow direction due to variable incoming flow velocity, they lead to increased sound level at higher frequencies.

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[168] T. Brooks; D. Pope; M. Marcolini. "Airfoil Self-noise and Prediction", NASA Reference Publication 1218, National Aeronautics and Space Administration, 1989, USA

[169] I. Romeo-Sanz; A. Matesanz. "Noise management on modern wind turbines". In Wind Engineering, 2008, 32, pp. 27-44.

[170] Oerlemans, S.; Schepers, J.; Guidati, G.; Wagner, S. "Experimental demonstration of wind turbine noise reduction through optimized airfoil shape and trailing edge serrations". Proceedings of the European Wind Energy Conference and Exhibition, 2001, Copenhagen, Denmark

[171] C. Arce Leon. (2012). "Study on the near-surface flow and acoustic emissions of trailing edge serrations (for the purpose of noise reduction of wind turbine blades)", Delft Technical University, the Netherlands

[172] S. Oerlemans; M. Fischer; T. Maeder and K. Kögler. „Reduction of wind turbine noise using optimized airfoils and trailing-edge serrations". In AIAA Journal 2009; 47 (6), pp. 1470-1481

To overcome this problem of flow alignment with serrations, the concept of trailing edge brushes was introduced. Experimental investigations by Herr (2007)[173] and Finez et al (2010)[174] prove the advantage of trailing edge brushes over serrations in reducing airfoil noise. Porous trailing edge works similar to trailing edge brushes for reducing sudden change in acoustic impedance encountered at the abrupt edge by near blade flow. Trailing edge brushes and porous trailing edges are potential technologies which can help gain extra trailing edge noise reduction. Studies by Geyer et al (2009)[175] and Kinzie et al (2013)[176] show potential in this technology for noise reduction, however, conclusive full scale experimental studies are required.

Most of the noise with trailing edge as the source is generated from outbound portions of the blade where the flow velocity is higher. Methods like serrated trailing edges for trailing edge noise reduction are already being used in some wind turbines but more effective methods for noise control are needed. Lot of work has been done in identifying and mitigating inflow turbulence noise. Bio-mimicry has yielded leading edge serrations and slits for reduction of noise from this source. Leading edge slits have been shown to outperform serrations and provide very significant noise reduction. Tip noise reduction can be achieved by optimizing tip shape for reduced vortex strength and less interaction of vortex with tip edges. Computational aero-acoustics can help in faster optimization blade shape to reduce noise by introducing less computationally expensive numerical techniques. Most of these technologies require further experimental validation.

With the goal of reducing turbulent boundary layer- trailing edge noise of already existing wind turbines, many passive noise modification solutions, based on the modification of the trailing-edge geometry with attachable add-ons, have been proposed (Arce-Leon et al, 2016)[177]. Among others, sawtooth add-ons are widely used for their simplicity of manufacturing and installation. More recently, Oerlemans (2016)[178] proposed a variation of the conventional sawtooth geometry, named as combed-sawtooth serration, with solid filaments filling the empty spaces between the teeth. This design showed additional 2 dB noise reduction during in-field measurements for the frequency range of practical interest.

The prediction of the scattered noise in the presence of sawtooth serrations is not straightforward because of the complex three-dimensional flow generated by the spanwise varying geometry (Arce-Leon et al., 2016[179]; Avallone & Ragni 2016[180]). Several analytical and semi-analytical models were developed to obtain reliable prediction for different trailing-edge shapes. While predictions based upon analytical models require only details of the geometry, semi-analytical ones need additional information on the boundary-layer characteristics and on the spatial and temporal distribution of the surface pressure fluctuations.

Selection of an appropriate airfoil for performance is key to energy production of a wind turbine. An airfoil is a structure designed to obtain reaction upon its surface from the air through which it moves or that pass such a structure. Van Treuren and Hays (2017)[181] studied the four wind turbine airfoils for their aerodynamics and noise generation. Airfoils can be made quieter by designing them in such a way that the boundary layer flow results in less noise compared to airfoils that perform aerodynamically similar. Nev-

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[173] M. Herr. "Design criteria for low-noise trailing edges". 13th AIAA/CEAS Aeroacoustics Conference, 2007

[174] A. Finez; M. Jacob; E. Jondeau; and M. Roger. "Broadband noise reduction with trailing edge brushes. 16th AIAA/CEAS Aeroacoustics Conference, 2010

[175] T. Geyer; E. Sarradj; and C. Fritzsche. "Measurement of the noise generation at the trailing edge of porous airfoils". In Experiments in Fluid, 2009; 48 (2), pp. 291-308

[176] K. Kinzie; R. Drobietz; B. Petitjean and S. Honhoff (2013). "Concepts for wind turbine sound mitigation". AWEA Wind Power

[177] C. Arce Leon; R. Merino-Martinez; D. Ragni; F. Avallone; M. Snellen. "Boundary layer characterization and acoustic measurements of flow-aligned trailing edge serrations". In Exp Fluids (2016), volume 57, Issue 182

[178] S. Oerlemans. "Reduction of Wind Turbine Noise using Blade Trailing Edge Devices". 22nd AIAA/CEAS Aeroacoustics Conference, 30 May – 01 June, 2016, Lyon, France

[179] F. Avallone F; van der Velden; D. Ragni. "Benefits of curved serrations on broadband trailing –edge noise reduction". In Journal of Sound and Vibration, Volume 400, 21 July 2017, pp. 167-177

[180] Ibid, 2017

[181] K. Van Treuren. (2018). "Wind Turbine Noise: Regulations, Siting and Noise Reduction Technologies". Proceedings of Montreal 2018 Global Power and Propulsion Forum 7th- 9th May, 2018, Canada

ertheless, the similarity of airfoils (for the purpose of stating that one in low-noise compared to another) is a broad and open question that is purpose driven.

By looking at a typical airfoil profile, such as the cross section of a wing, several obvious characteristics of design can be seen. The major objective in wind turbine airfoil design is to achieve a high aerodynamic performance that ensures wind turbine blade to operate with high-power performance. When it comes to societal acceptance, the noise aspect becomes very important in particular onshore turbines, such that low-noise wind turbine design is an important competitive parameter. Therefore, the overall objective behind the design work is to make wind energy production more efficient, while at the same time lowering noise emissions through gaining fundamental insight into the airfoil noise generation mechanism.

The use of serrated trailing edges for wind turbine noise reduction has now become a mature technology, academic-research institutions and wind turbine manufacturers demonstrating its effectiveness in wind tunnel and turbine tests leading to commercial products. Researchers from the National Aerospace Laboratory (NLR), Energy Research Center of the Netherlands (ECN) and Institute of Aerodynamics and Gas Dynamics (IAG) at University of Stuttgart tried to reduce turbulent boundary layer – trailing edge noise by modifying the airfoil shape and/or implementing serrated trailing edge, during the European project SIROCCO. In this project, acoustic field measurements on a 94 m diameter, three-bladed wind turbine has been conducted. One standard blade, one blade with acoustically optimized airfoil shape, and one standard blade with serrated trailing-edge were fitted on a HAWT. Test results for the baseline blade showed that the dominant source was turbulent boundary layer-trailing edge noise from the outer 25% of the blade. The outcome of the SIROCCO project shows very encouraging results on noise reduction with serrated trailing-edge blades. Roughly 3.2 dB overall sound power level reduction is observed compared to the noise of baseline blades (Kamaruzzamann et al., 2017)[182].

Alternatively, a slower rotating rotor could be manufactured that would capture the same amount of energy from the wind, but this must be done at the design stage of the blades and turbine. With slower rotating blades, to capture the same amount of energy, the torque that they produce must be increased. The trade-off is therefore found in having to increase the safety limits of the entire system, including blades, tower and, very critically, the drivetrain. This results in a very steep hike in the cost of the turbine, often making it prohibitively expensive for the expected return and benefit of having lower noise emissions.

Extensive research has been presented regarding noise from wind turbines. For example, interesting work can be found in (Bolin, 2009)[183] where noise, sound masking and propagation modelling has been studied, in (Pedersen, 2007)[184] where the human response to wind turbine noise has been investigated and in (Baath, 2013)[185] where a substantial investigation of wind turbine noise in forestry areas is performed. However, most research has been aimed at the more common HAWTs and little attention has been given to the alternative VAWTs which have shown potential for lower noise levels. VAWTs usually has lower tip speed ratio than HAWTs and should therefore produce less aerodynamic noise and furthermore the drive train of a VAWT can be placed at ground level which limits mechanical noise propagation (Ericksson et al., 2008)[186]. Work that has been done regarding noise from VAWTs include (Iida et al., 2004)[187] and (Dumitrescu et al., 2010)[188] where numerical methods are used to simulate aerodynamic noise from VAWTs and which for both studies indicates lower noise levels compared to HAWTs. This is further supported by results of (Dessoky et al., 2019)[189], (Ghasemian et al., 2015)[190] and Möllerström et al., 2014)[191]. In combination with a wind farm system proposed by (Dabiri et al., 2011)[192] or (Hazavet et al., 2018)[193] VAWT may be used at least similar power density as HAWT with less acoustic and visual annoyances. Further (Hui et al., 2018)[194] find that the public acceptance of VAWT is mostly higher than for HAWT.

CHAPTER 6 – ENERGY STORAGE TECHNOLOGIES AND WIND POWER

One of the distinctive characteristics of the electricity power sector is that the amount of electricity that can be generated is relatively fixed over short periods of time, although demand for electricity fluctuates throughout the day. Developing technology to store electrical energy so it can be available to meet demand whenever needed would represent a major breakthrough in electricity distribution. In theory, energy storage is a viable solution: it can absorb peaks in output from variable sources, such as wind and solar power, and provide energy for when there are peaks in demand. In practice, however, energy storage is held back by high costs of implementation. Also, many proposed energy storage solutions are still immature technologies.

Some technologies provide short-term energy storage, while others can endure for much longer. Regardless of where energy is generated, it will end up at the point of consumption. If storage capacity is located at a few large-scale facilities, energy must be delivered there first, which comes at a cost because the power grid is not 100% efficient. Then that energy must be delivered again to the point of consumption. On the other hand, with distributed storage it is only necessary to deliver energy once. Distributed energy storage is currently dominated by hydroelectric dams, both conventional as well as pumped. Grid energy storage is a collection of methods used for energy storage on a large scale within an electrical power grid.

Energy storage systems provide a wide array of technological approaches to managing power supply in order to create a more resilient energy infrastructure and bring cost savings to utilities and consumers. There are diverse approaches currently being deployed worldwide, in broad they can be divided into five main categories as seen in Figure 24:

- **Batteries** – a range of electrochemical storage solutions, including advanced chemistry batteries, flow batteries, and capacitators;
- **Thermal** – capturing heat and cold to create energy on demand or offset energy needs;
- **Mechanical storage** – other innovative technologies to harness kinetic or gravitational energy to store electricity
- **Hydrogen** – excess electricity generation can be converted into hydrogen via electrolysis and stored
- **Pumped hydropower** –creating large-scale reservoirs of energy with water.

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[182] M. Kamaruzzaman; J. Hurault; K. Madsen. "Wind turbine Rotor Noise Prediction &Reduction for Low Noise Rotor Design", 7th International Conference on Wind Turbine Noise, Rotterdam, 2 to 5th May, 2017

[183] K. Bolin. "Wind Turbine Noise and Natural Sounds: Masking, Propagation and Modeling". PhD thesis: Royal Institute of Technology; 2009

[184] E. Pedersen. "Human response to wind turbine noise: Perception, annoyance and moderating factors". PhD thesis: University of Gothenburg; 2007

[185] L. Baath. "Noise spectra from wind turbines". In Renewable Energy; 2013; volume 57, pp. 512-519

[186] S. Ericksson; H. Bernhoff; M. Leijon. "Evaluation of different turbine concepts for wind power". In Renewable and Sustainable Energy Reviews; 2008; volume 12 (5); pp. 1419-34

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[189] A. Dessoky; T. Lutz; G. Bangga; E. Kraemer. "Computational studies on Darrieus VAWT noise mechanisms employing s high order DDES Model". In Renewable Energy, vol. 143, pp. 404-425

[190] M. Ghasemian; A. Nejat. "Aeroacoustics prediction of a vertical axis wind turbine using large Eddy Simulation and acoustic analogy". In Energy, vol. 88, pp. 711-717 (2015)

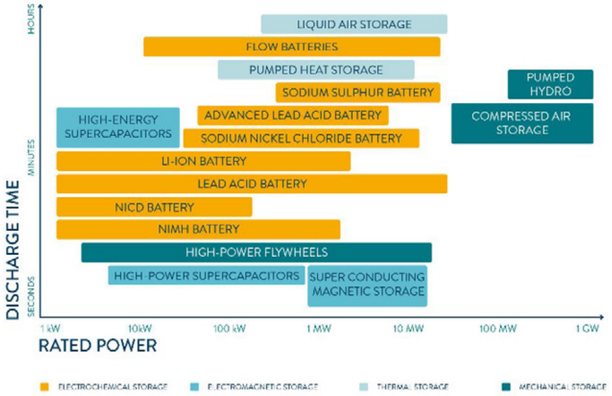
[191] E. Möllerström; S. Larsson; F. Ottermo; J. Hylander; L. Baath. "Noise Propagation from a Vertical Axis Wind Turbine". Presented at the International Noise (2014)

[192] J. O. Dabiri. "Potential order-of-magnitude enhancement of wind farm power density via counter-rotating vertical-axis wind turbine arrays". In Renewable Sustainable Energy 3, 043104 (2011); www.doi.org/10.1063/1.3608170

[193] S.H. Hezaveh; E.Bou-Zeld; J. O. Dabiri; M. Kinzel; G. Cortina; L. Martinelli. "Increasing the power production of Vertical-Axis Wind Turbine Farms using Synergistic Clustering". In Boundary-Layer Meteorology, vol. 169, no 2, pp. 275-296 (2018)

[194] I. Hui; B.E. Cain; J.O. Dabiri. "Public receptiveness of vertical axis wind turbines". In Energy Policy, vol 112, pp. 258-271 (2018)

Figure 24: Types of energy storage technologies



Source: Modified from De Oude Bibliotheek Academy (2017)

The length of time the energy must be stored will also affect the technology choice. For very long-term storage of days or weeks, a mechanical storage system is the best, and pumped hydro storage is the most effective method provided water loss is managed carefully. Batteries are also capable of holding their charge for extended periods. Energy loss in other systems will make them less practical for long-term storage. For daily cycling of energy, both pumped hydro storage and compressed air energy storage are suitable, while batteries can be used to store energy for periods of hours.

Much of the current growth in energy storage is battery systems, helped by plunging battery prices. Battery technologies are becoming more mature with significant reduction in their costs. The role of batteries in balancing power grids and saving surplus energy represents a concrete means of improving energy efficiency and integrating more renewable energy sources into electricity systems.

There is a rapid growth of stationary utility-scale storage projects, mostly used as stand-alone installations. Wind power can be used in off-grid systems, also called stand-alone systems, not connected to an electric distribution system or grid. In these applications, small wind electric systems can be used in combination with other components – including a small solar electric systems – to create hybrid power systems. These include batteries, flywheels, power-to-gas, thermal storage and compress air energy storage. Lithium-ion batteries represent most of the electrochemical storage projects. The recycling of such systems should be taken into consideration, as well as their effective lifetime. In the EU, the segment of operational electrochemical facilities is led by UK and Germany (European Commission, 2020)[195]. However, the number of projects used in combination with wind farms, the so-called co-located wind and storage projects is increasing too.

This chapter identifies the numerous different types of energy storage devices currently available that can be used with wind energy. Finally, a brief comparison of the various technologies is provided.

6.1. MECHANICAL ENERGY STORAGE

Mechanical energy storage technologies (such as **flywheel**, **compressed air,** and **pumped hydro**), while each performing quite different roles, have greater industrial applicability in a net-zero carbon scenario, due to their lower installation costs when compared to supercapacitors and superconductors. Despite their high energy density (80-200 Wh/l) and round-trip efficiency (0-95 per cent)[196], flywheels are approximately similar to electrical types of energy storage in terms of low capacity (about 0.0001GWh) and extremely high daily energy loss (self-discharge of 5-15 per cent/hour) (Fuchs et al., 2012)[197]. Therefore, although currently assisting with fast response ancillary services, flywheels do not seem to be suitable candidates for storing energy in large quantities and for a long time. On the other hand, though rarely used despite its low cost and self-discharge rate, compressed air complements pumped hydro (currently described as one of the most prevalent method of grid-scale energy storage (Bañares-Alcántara et al., 2015)[198]. Indeed, apart from offering ancillary services requiring short-term electricity storage, both technologies can also serve for long-term large-scale energy storage, as they can cater for periodic and seasonal storage as well as emergency back-up. This is not surprising as, notwithstanding their relatively low energy density, compressed air and pumped hydro can provide significant storage capacity (ibid, 2015). However, the downside is that neither of these storage technologies is transportable. In this sense, even if they could potentially solve the problem of decarbonizing on-land grids, pumped hydro and compressed air will not be able to deliver energy over distance. That is why mechanical applications do not seem to be suitable for providing the ultimate solution to the challenge of large-scale, long-term, and transportable energy storage.

6.1.1. PUMPED-HYDRO ENERGY STORAGE

The pumped- hydro energy storage (PHS) is the world's largest battery technology, accounting for over 94 per cent of installed energy storage capacity, well ahead of lithium-ion and other types of batteries (International Hydro-energy Association, 2020)[199]. This technology is an ideal complement to modern clean energy systems, as pumped storage can accommodate for the intermittency and seasonality of variable renewables such as wind and solar power. Hydro power is not only a renewable and sustainable energy source, but its flexibility and storage capacity also make it possible to improve grid stability and to support the deployment of other intermittent renewable energy sources such as wind and solar.

Figure 25. Bear Swamp Pumped Storage in South Korea

Source: Modified from Emerson (2020)

Pumped hydro storage uses two water reservoirs which are separated vertically as seen in Figure 25. In times of excess electricity, often off peak hours, water is pumped from the lower reservoir to the upper reservoir. When required, the water flow is reversed and guided through turbines to generate electricity. Pumped hydroelectric storage (PHS) projects generally involve an upper and lower reservoir. Some projects use a river as the lower reservoir; others have used massive lakes or even a sea or ocean. Another interesting concept being developed is to locate one or both reservoirs below ground (sub-surface). While a project utilizing sub-surface reservoirs has yet to be completed, these types of projects are attractive due to their perceived site availability and their potential for reduced environmental risks.

The flexibility of pumped storage hydro-power that it provides though its storage and ancillary grid services is increasingly important in securing stable power supplies. PHS provides flexibility through system inertia, frequency control, voltage regulation, storage and reserve power with rapid mode changes, and black-start capability. All of these are vital to support the ever-growing proportion of variable renewable energy in grid systems.

Pumped storage excels at long discharge duration and its high power capacity will be crucial in avoiding renewables curtailment, reducing transmission congestion, and reducing overall costs and emissions in the power sector.

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[195] European Commission. "Study on energy storage – Contribution to the security of the electricity supply in Europe". Final report, March 2020, Brussels

[196] Energy storage typically consumes electricity and saves it in some manner, then hands it back to the grid. The ratio of energy put in (MWh) to energy retrieved from storage (in MWh) is the round efficiency (measured as a percentage). The higher the round trip efficiency, the less energy was lost due to storage.

[197] G.Fuchs, B.Lunz, M. Leuthold, and D. U. Sauer (2012). "Technology overview on electricity storage: Overview on the potential and on the deployment perspectives of electricity storage technologies". Aachen: ISEA

[198] R. Alcántara et al., (2015). "Analysis of islanded ammonia-based energy storage systems". Oxford, UK: University of Oxford.

[199] According to their estimates pumped storage hydro-power projects now store up to 9, 000 gigawatt hours (GWh) of electricity globally.

Multiple studies have identified vast potential for pumped storage sites worldwide and there is growing research on possibilities for retrofitting disused mines, underground caverns, non-powered dams and conventional hydro plants. Abandoned mines, caverns, and man-made storage reservoirs have all been proposed as potential project reservoir options, and there are examples of several projects under initial phases of development. The underground excavation or material-handling costs, construction risks, and time required for underground excavation and construction could make the economics of such a project difficult, so most developers are looking to utilize existing subsurface structures or minimize underground costs through the sale of excavated materials (ore, aggregate, etc.).

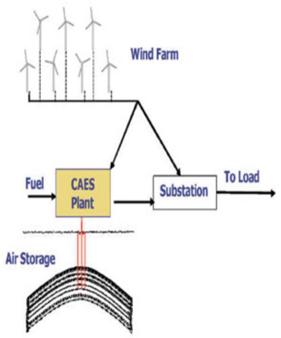
As a result of resurgence of interest in this technology, with more than 100 projects in the pipeline, IHA estimates that pumped hydro storage capacity is expected to increase by almost 50 percent – to about 240 GW by 2030.

Underground pumped storage electricity (UPSH) could be an alternative means of increasing the energy storage capacity in flat areas where the absence of mountains does not allow for the construction of pumped hydro storage (PHS) plants (reservoirs must be located at different heights requiring location in mountainous regions). UPSH plants consist of two reservoirs, with the upper one located at the surface or possibly at shallow depth underground, while the lower one is underground. These plants provide three main benefits: (1) more sites can be considered in comparison with PHS plants (Meyer, 2013)[200], (2) landscape impacts are smaller than those of PHS plants, and (3) the head difference between reservoirs is usually higher than in PHS plants; therefore, smaller reservoirs can generate the same amount of energy (Uddin & Asce, 2003)[201]. Underground reservoirs can be excavated or can be constructed using abandoned cavities such as old deep mines or open pits. The former possibility has been adopted to increase the storage capacity of lower lakes at some PHS plants (Madlener & Specht, 2013)[202] and allows full isolation of the lower reservoir mitigating the interaction between the used water and the underground environment. While the reuse of abandoned works (deep mines or open pits) is cheaper, the impacts on groundwater can be a problem. Consequently, the interaction between UPSH plants and local acquifers must be considered to determine the main impacts of such a system. Acqifer is an underground layer of water-bearing permeable rock, rock fractures or unconsolidated materials (gravel, sand, or slit). Any detailed studies on this interaction have not been published before.

6.1.2. COMPRESSED AIR ENERGY STORAGE

Compressed air energy storage is the second biggest form of energy storage currently behind pumped storage. It involves converting electrical energy into high-pressure compressed air that can be released at a later time to drive a turbine generator to produce electricity. This means that it can work along with technologies such as wind turbines to provide and store electricity 24/7. There are a number of storage options, but the best option is to store the compressed air in existing geographical formation such as disused salt mines. Salt caverns are usually free of cracks and fissures as any ingress of water through cracks will dissolve salt, which then crystallizes and creates air-tight seals.

Figure 26. Compressed air energy storage



Source: U.S Department of Energy (2020)

Compressed air storage (CAES) plants are largely equivalent to pumped-hydro power plants in terms of applications. But, instead of pumping water from a tower to an upper pond during periods of excess power in a CAES plant, ambient air or another gas is compressed and stored under pressure in an underground cavern or container. When electricity is required, the pressurized air is heated and expanded in an expansion turbine driving a generator for power production.

There are two major problems associated with CAES. The first is that when air is compressed, it heats up. Unfortunately the warmer the air, the less will be the amount of air that can be stored. The second problem is that on releasing the compressed air, the pressure in the cavern is slowly reduced and this affects the amount of electricity produced in the turbine. The first problem can be dealt with in three ways: adiabatically, by storing the heat and reusing it when the air is expanded to produce power; isothermally, with the aid of heat exchangers; and diabatically, by dissipating the heat to the atmosphere. The second problem can be dealt with by controlling the rate at which the air is discharged and thus creating a constant supply of electricity. Another solution being researched by Seamus Garvey at Nottingham University is to store the air in large energy bags deep in lakes or in the sea. In this way, the pressure of the air leaving the bags remains constant, being the hydrostatic pressure.

New technology is being developed by companies to try to increase the heat retained from the compression process. For example, SustainX from the USA has working on a process to remove the heat by injecting water vapor into the compressed air. The water absorbs the heat which then gets stored and reapplied to the air during the expansion process.

6.2. ELECTROCHEMICAL ENERGY STORAGE

Electrochemical energy storage is represented by four main types of batteries (**redox-flow**, **lead-acid**, **lithium-ion**, and **high temperature**). With electrification set to be one of the main pathways to decarbonisation of energy systems, batteries as electricity storage devices will become one of the key enablers of a low-carbon economy. Stationary devices that use chemical interactions between materials to store electricity at a set location for later use. *Li-ion* batteries predominate in the stationary battery market, mainly because they have been around longer and have had more time to mature as a technology. *Lithium-ion* technology has the highest round-trip efficiency and storage capacity among batteries and could dominate the energy storage future as its continuing decline in price, along with improved performance, it will likely open new markets (Renewable Energy World, 2019)[203]. There are also arguments in favor of vanadium *redox flow batteries*, due to the fact that there is much vanadium in the earth's crust than lithium, which makes this technology more scalable (Energy Post, 2019)[204]. The other two technologies (*lead-acid* and *high temperature*), however, are not suitable for large-scale use as their energy capacity is several times smaller in comparison with lithium-ion and redox-flow (Fuchs et al., 2012)[205]. Although *lithium-ion* and *redox-flow* are potential candidates for global utility-scale storage capacity, none of these technologies has progressed sufficiently to increase its energy storage capacity to a level comparable with that of fossil fuels, in order to make the transportation of batteries over long distances economically feasible. Thus, electrochemical energy storage will have to be further advanced to address the long-term large-scale energy storage dilemma.

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[200] F. Meyer (2013). "Storing wind energy underground", FIZ Karlsruhe – Leibniz Institute for Information Infrastructure, Eggenstein Leopoldshafen, Germany

[201] N. Uddin; M. Asce. (2003), "Preliminary design of an underground reservoir for pumped storage", Geotech Geological Engineering, vol 21: 331-355

[202] R. Madlener; J.M. Specht. (2013). "An exploratory economic analysis of underground pumped-storage hydro power plants in abandoned coal mines", FCN working paper no. 2/2013, Institute for Future Energy Consumer Needs and Behavior, RWTH Aachen University, Aachen, Germany.

[203] Renewable Energy World (2019). Why lithium-ion technology is poised to dominate the energy storage future. [Online]. Available from: https://ww.renewableenergyworld.com/2019/04/03/why-lithiumion-technology-is-poised-to-dominate-the-energy-storage-future/. (Accessed: 20 November 2020).

[204] Energy Post (2019). Can Vanadium Flow Batteries beat Li-ion for utility scale storage? [Online]. Available from: https://energypost.eu/can-vanadium-flow-batteries-beat-li-ion-for-utility-scale-storage/
(Accessed: 19 November 2020)

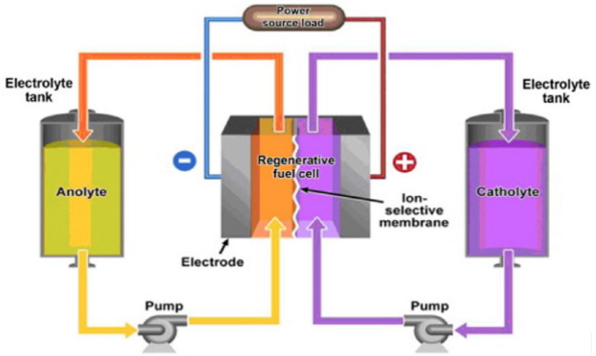
[205] G.Fuchs, B.Lunz, M. Leuthold, and D. U. Sauer (2012). "Technology overview on electricity storage: Overview on the potential and on the deployment perspectives of electricity storage technologies". Aachen: ISEA

6.2.1. REDOX-FLOW AND OTHER BATTERIES

Among the frontrunners for large-scale stationary storage of wind and solar power are flow batteries, which consist of two tanks of liquids that feed into electrochemical cells. The main difference between flow and conventional batteries is that flow batteries store the electricity in the liquid rather than in the electrodes. NASA studied the use of redox-flow batteries (RFB) for the space program during the 1970s, and the concept of using chemical reduction and oxidation reactions for energy storage dates back even further. The flow-batteries are far more stable than Li-ion, they have longer life-spans and the liquids are less flammable.

In RFBs, two chemical components are dissolved in liquids within the system, and are separated by a membrane. The membrane facilitates the ion exchange and the electric current flows, while the liquids are kept separate in anolyte and catholyte tanks. The chemical reduction and oxidation reactions that take place in these tanks store the generated energy in liquid electrolyte solution and are what the "redox" (reduction oxidation) name refers to it as seen in Figure 26.

Figure 26. Flow battery consists of two tanks of electrolytes pumped against each other separated by a membrane.



One type of flow battery, the vanadium flow battery, is already available commercially. A grid-scale 50 megawatt vanadium flow battery is planned for energy storage in the South Australian town of Port Augusta, and China is building the world's largest vanadium flow battery, expected to come online in 2020. There are two main downsides: the liquids can be costly, so there is a greater up-front cost for the batteries, and flow batteries are not quite efficient as Li-ion batteries. Similar to lithium batteries, there are multiple types of flow batteries with a variety of chemistries. For example, researchers at RMIT University in Melbourne are developing a proton battery that works by turning water into oxygen and hydrogen, then using the hydrogen to power a fuel cell. Several other research teams are exploring completely lithium-free ion batteries using materials such as graphite and potassium for the electrodes.

Zinc-hybrid technology is among the latest advanced chemistries with early field results in grid-scale storage use. The first rechargeable zinc-based batteries came in 1996 and were eventually used to power small and mid-sized buses in Singapore. The proliferation of electric vehicles and distributed energy resources have ramped up the demand for battery systems that are affordable to produce. Zinc-hybrid technology also holds the promise of a purpose-built battery for grid-scale solutions that could leapfrog competitive technologies with regard to cost. Zinc is widely available and typically less expensive than the materials used to create lithium-ion or flow batteries. Zinc-hybrid batteries are at an earlier stage in the commercialization process, so their costs have further to fall than most other emerging battery technology solutions.

6.3. CHEMICAL ENERGY STORAGE

Chemical energy storage is viewed as an important candidate for a large-scale, long-duration, and transportable form of energy storage as, apart from sources such as natural gas, energy can be stored in the form of hydrogen and ammonia. As natural gas does not fully align with environmental objectives in the absence of carbon capture, utilization, and storage (CCUS), the solution of the long-term large-scale energy storage dilemma seems to belong to either hydrogen or ammonia. Hydrogen and ammonia have roughly the same energy intensity and costs (Fuchs et al., 2012)[206]. However, as "liquid ammonia has over 50 per cent more volumetric energy than liquid hydrogen; more than twice the volumetric energy of hydrogen gas at 700 bar", it seems to be more economically advantageous (US Department of Energy, 2010)[207]. In addition, in comparison to hydrogen, ammonia is easier and less dangerous to handle. Specifically, its vapor pressure is much lower (10 bar at 25 degrees Celsius), which to a great extent simplifies the design of storage tanks for transportation purposes (Rivard, Trudeau, and Zaghib, 2019)[208]. Therefore (if it is generated through a carbon-free process), ammonia can be used for storing large amounts of energy for a long time in a transportable form because of its specific physical features; this is essential for achieving a low-carbon future.

6.3.1. HYDROGEN ENERGY STORAGE

Hydrogen energy storage is a process wherein the surplus of energy created by renewables during low energy demand periods is used to power electrolysis, a process in which an electrical current is passed through a chemical solution in order to separate hydrogen. Once hydrogen is created through electrolysis it can be used in stationary fuel cells, for power generation, to provide fuel for fuel cell vehicles, injected into natural gas pipelines to reduce their carbon intensity, or even stored as a compressed gas, cryogenic liquid or wide variety of loosely-bonded hydride compounds for later use. Hydrogen created through electrolysis is showing great promise as an economic fuel choice, with data from the International Energy Agency predicting that hydrogen generated from wind will be cheaper than natural gas by 2030.

The storage of hydrogen in pure, molecular form can be achieved in the gas or liquid phase. These are the only types of hydrogen storage that are currently employed on any significant scale. The storage of liquid hydrogen in the space industry and the large salt cavity storages in Texas, USA, and Teeside, UK, are notable examples (Crotogino, 2016)[209].

Power-to-gas (P2G) is another technology option for long-term energy storage that uses renewable or excess electricity to produce hydrogen (Power-to-Hydrogen) via water electrolysis. Hydrogen produced in this way can be used directly as a final energy carrier or converted to methane, synthesis gas, electricity, liquid fuels or chemicals, for example. The reasons for using P2G are diverse. The main purpose is to store energy long term by converting it to other easily storable energy carriers, and at the same time reducing the load of the electricity grid by controlled operation (flexible demand). Furthermore, the production of renewable fuels for transportation, households, or industry, as well as for chemical production, can be a main driver for Power-to-gas.

Neither electrolysis nor methanisation are yet close to cost competitive. These conversion processes are especially difficult and costly to run in an intermittent mode. They have low "round trip efficiency" of storing and then re-generating electricity an estimated 34-44% for the hydrogen pathway and 30-38% for the methane pathway. Research, development, and pilot deployment, and pilot deployment of these technologies is needed to drive down cost supported by carbon pricing that adequately values the climate benefits of power-to-gas (as well as "renewable gas" from sources like landfills and wastewater treatment facilities).

In Europe many hydrogen energy storage projects have been created, such as the Energiepark Mainz in Germany. The *Energiepark* uses excess wind energy to create hydrogen fuel, which is later used to generate electricity when wind power cannot match demand.

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[206] G.Fuchs, B.Lunz, M. Leuthold, and D. U. Sauer (2012). "Technology overview on electricity storage: Overview on the potential and on the deployment perspectives of electricity storage technologies". Aachen: ISEA

[207] US Department of Energy (2010). Alternatives to electricity for transmission and annual-scale firming storage for diverse, stranded, renewable energy resources: Hydrogen and Ammonia [Online]. Available from: https://www.osti.gov/etdeweb/servlets/purl/21396853

[208] E. Rivard, M. Trudeau, and K. Zaghib (2019). "Hydrogen storage for mobility: A review", MDPI, 12 (1973), pp. 1-22

[209] F. Crotogino. "Larger scale hydrogen storage". In: Storing energy. Elsevier; 2016, pp. 411-29

Orsted, Denmark's largest energy company, is planning to use excess energy from its proposed North Sea wind farms to power electrolysis and create renewable hydrogen energy. The proposed wind farms would have a nameplate capacity of 700 MW and be linked to the grid. During period of time where the wind farms oversupplied energy, this excess power would be used to generate hydrogen through electrolysis which would later be sold to large industrial customers.

Hydrogen production based on wind power can already be commercially viable today. Until know, it was generally assumed that this environmentally friendly power-to-gas technology could not be implemented profitably. Economists at the Technical University of Munich, the University of Mannheim and Stanford University have now described, based on the market situations in Germany and Texas, how flexible production facilities could make this technology a key component in the transition of the energy system. Today, most of hydrogen for industrial applications is produced using fossil fuels, above all with natural gas and coal. In an environmentally friendly energy system, however hydrogen could play a different role.

CHAPTER 7 – CASE STUDIES

Several European governments have developed policies and procedures to address the siting of wind turbines in locations to reduce their impact on air defence and air traffic control radars. The policies vary considerably, reflecting different degrees of understanding that government policymakers have of the effects that wind turbines have on radar, different radar systems employed by that country, and different relationships between the military and industrial communities. This chapter gives a brief overview of the current policies employed by each of several European governments in regulating/influencing the placement of wind turbines in the vicinity of radar systems.

As wind development continues to grow and expand to new areas, the likelihood that some turbines will be located within the line of sight of radar systems also increases. If not mitigated, such wind development can cause potential interference for radar systems involved in air traffic control, weather forecasting, national defence missions and the internal security. If potential interference issues are identified during the formal review process, a variety of approaches are available to help minimize wind energy's impact on radar (e.g designing the wind farm layout to minimize the impacted area of radar coverage or terrain masking). This chapter provides an overview of the approaches used in Switzerland, Poland, UK, France and Belgium to overcome the interference issue.

7.1. SWITZERLAND

Switzerland has the lowest carbon intensity among IEA countries, owing to a carbon free electricity sector dominated by nuclear and hydro power generation. However, following the 2017 decision of the Swiss people to gradually phase out nuclear power, Switzerland's energy sector is undergoing a considerable transition.

In 2017, the Swiss electorate approved a new energy law being part of an innovative strategy to be implemented by 2050. This new energy law also includes phasing out of nuclear energy. Hydroelectricity power, which provides just under 60% of total electricity production, is the most important domestic source of renewable energy. The Swiss "Energy Strategy 2050" (ES 2050) is a strategic policy package for advancing the energy transition of Switzerland towards a low-carbon economy. It consist of a comprehensive set of new and revised laws and ordinances, as well as policy measures that will be implemented in phases.

The complete revision of the Energy Act of 1998, which entered into force on 1 January 2018, jointly with related new and revised laws and ordinances, is central to the strategy. The ES 2050 has three pillars: (1) withdrawal from nuclear energy; (2) reduction of energy consumption and emissions per capita and (3) promotion of renewable energy sources and energy efficiency.

Hydropower and wind power are controversial topics in Switzerland, and public acceptance remains an issue. Small hydro projects below 1 MW capacity have now been banned by the ES 2050 from receiving public support, due to environmental impact. There are exceptions, but they are limited to specific project circumstances. The potential for wind power is limited by the country's mountainous topography. There are some excellent wind sites, but they are located in only a few regions. In 2016, a total of 37 wind power plants at ten locations produced around 140 gigawatt hours (GWh) of electricity (IEA, 2018)[210].

While the Swiss population is, in principle, supportive of wind power, there is local opposition to their construction once sites have been identified, with concerns for landscape, tourism, noise pollution and bird protection. Public opposition is well organized and has successfully prevented several large wind projects from progressing. Delays with obtaining permissions or the need to reduce the originally planned size of the installations have undermined the economic viability of some projects, which have been abandoned by project promoters.

No additional siting for new wind installations has been approved since 2012; expansion of existing facilities has been pursued instead. Just three new wind installations have become operational since 2015. There is extensive project at the advanced planning stage, but it has been delayed due to institutional and approval issues. Switzerland has only constructed 34 wind turbines over the last 20 years, which produce around 0.15% of the nation's electricity, according the experts at Swiss Federal Institute of Technology and UNIL, two universities located in Lausanne. According to their estimates around 100 high-potential locations could accommodate 700 turbines. Together they could generate 7 percent of Switzerland's electricity. Wind power is expected to increase to 1 760 GWh by 2035 and 4 300 GWh by 2050 (compared to 140 GWh in 2016) under the ES 2050. This is to be reached through the construction of 600-800 turbines. The Swiss Federal Office of Energy (SFOE) introduced a new tool, the so-called "wind energy concept", in 2017.

This tool identifies areas that may be suitable for wind developments, designates authorities to be involved in the early planning stages, specifies procedures and helps to integrate the spatial plans of the cantons. It also sets an unbinding wind energy target for each canton with wind power generation potential, with the cantonal department of energy should take into consideration in its cantonal energy plan. This tool, which applies only to turbines 30 meters or higher, shows high potential zones, and areas that would be protected. The document includes 3 maps: one showing wind speed, one showing high potential zones, and another showing restricted zones. In addition, the document specifies turbines should not be built within at least 300 m of homes.

The Swiss Federal Office of Energy (SFOE) is responsible for practical management of national energy policy within Federal Department of the Environment, Transport, Energy and Communications (DETEC). Cantons are consulted during federal energy policy and law-making processes. They have much leeway in adopting their own energy laws, policies and measures, within the boundary set by federal legislation. This results in a diversity of cantonal policies and measures. Cantons play an important role in energy policy making and implementation, zoning and permitting for energy infrastructure.

The SFOE has also established a dedicated one-stop window for wind energy questions, to serve permitting authorities and project developers.

7.1.1 SWISS APPROACH

The basic principle of the one-stop window means that the Swiss Federal Office of Energy is the main focal point for the formal review process in case of new wind farms planning process. They will carry out an evaluation procedure by sending the application submitted by the project developer to all relevant authorities (e.g. Federal Civil Aviation Authority, the Swiss Army, and the representatives of a canton and municipalities involved).

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[210] "Energy Policies of IEA Countries: Switzerland 2018 Review", IEA, Paris, 2018

The evaluation process is quite simple and the delegated authorities have to fill in the form of 1-2 pages and provide their feedback to the project under question. It is possible to approve the project, deny it or give a conditional approval. In case, a concrete project proposal will get a negative answer than the one-stop window actually asks grounds for not approving the proposal. In many cases, there are certain restrictions to the project, but it is possible to implement it by using certain additional mitigating solutions. For example, it is possible to build lower or smaller than previously planned wind turbines.

The impact on aviation needs further examination. The potential impacts of aviation from wind turbine developments can be assessed in 3 areas: those that have a direct impact, an indirect impact, or a cumulative impact on aviation interests and operations. It is not just wind turbines that require planning consideration for their potential effects on aviation. Aircraft may be re-routed in order to avoid flying over an area of clutter and therefore maintain the controller's understanding of the air situation. As well airplanes can fly higher in order to ensure flight security.

The following siting practices can also be used to minimize wind energy's impact on radar:

- Designing the wind farm layout to minimize the impacted area of radar coverage or to allow for maximum radar coverage within the project, such as increasing the spacing between turbines within the project;
- Terrain masking, or placing turbines on the opposite side of elevated terrain in relation to the radar so they will be blocked from view;
- Relocating proposed turbines or reducing their height so that they fall outside the radar line of sight;
- Eliminating proposed turbines located in areas that result in high radar interference impacts.

Another mitigation strategy is to hire flight managers at the wind farms who are entitled to stop the work of wind turbines in case there is a flight safety related danger. This can be organized in co-operation with the wind farms and the Swiss army. Although it should be highlighted the army has to support the Swiss energy policy which also means integrating more renewable energy, including wind into the energy mix.

7.2. FRANCE

France plans a massive expansion of renewables in order to reduce its reliance on nuclear, according the energy policy roadmap – known as "*programmation pluriannuelle de l'energie (PPE)*". The country is currently moving away from nuclear power, which previously delivered 75% of the country's energy needs, and will fill the gap by increasing its renewables share. Based on its 2030 National Energy and Climate Plan (NECP) France will aim for 33% renewable energy in its energy mix in 2030. This means approximately 40% renewables in the power sector – wind energy could deliver half of it. It foresees onshore wind reaching around 35 GW in 2028, compared to 15 GW today.

France has also confirmed plans to boost its capacity base and become a "world leader" in floating offshore wind under its multi-year energy plan (PPE). The development of offshore wind and large wind turbine technology has been a priority in the recent years. France has a favorable situation for floating wind, local harbor facilities, and a local naval and offshore oil and gas industry capable of addressing this market.

Wind power is an increasingly significant source of renewable electricity production in France, accounting for nearly 28% of all installed renewable power capacity. However, hostility to wind energy is "deeply rooted" in France, as much of the population considers wind turbines to be ugly and noisy.

Overall, the government will speed development of the most competitive technologies, while taking into account environmental issues, local feasibility and conflicts of use. Among other things, the government will encourage the repowering of existing sites, support citizen's participation and, in 2023, make it obligatory to recycle decommissioned turbines. It will continue to simplify the permitting process for onshore wind. The targets could have been more ambitious, but the government confirms that onshore wind energy, through its competitiveness, its reliability, its capacity to create jobs and its environmental coherence, is a pillar of the energy transition in France.

Despite this strongly developing market, the deployment of the technology is often slowed down or even stopped. In general, the highest barriers in France are seen to be administrative and legislative ones. New wind energy projects in France have come to a standstill due to the government's indecision over who should be responsible for delivering construction permits. In December 2017, the *Conseil d'Etat*, the highest administrative jurisdiction in France, annulled a decree giving the regional perfect authority for issuing environmental permits needed to build new wind farms. In addition, French wind farms have suffered from the cumbersome appeals process caused by a misplaced pessimism towards the technology both onshore and offshore. The country's stringent permitting process also means that while projects are constantly delayed in the courts, developers' are unable to alter the turbine choice. According to WindEurope data, projects in France could take up to seven years to be fully permitted as compared to three or four years in Germany.

Permitting takes so long due to a typical French phenomenon in which third parties can challenge wind projects in the courts. According to OPTRES, this is because renewable energy policies are not fully clear or consistent, and a large number of authorities are involved in granting the building permit. In 2018, the government of France announced a set of measures to simplify the wind project approval process and cut development times. These measures are expected to halve the average time for completing and connecting a wind farm to the national grid. This plan included 10 points, among which proposals to remove one level of jurisdiction in the appeal process, reduce the number of night-time lights on wind turbines, distribute a higher grid tax share to municipalities with onshore wind farms, give some sort of preference in tenders to onshore wind projects by local residents and ease repowering.

7.2.1. THE FRENCH APPROACH

Government policy is supportive of renewable energy with electricity market conditions favorable towards onshore wind developments. French onshore wind farms developments are increasingly receiving radar objections as developers seek to build projects closer to radar and also because safeguarding criteria are becoming more stringent. Radar objections prevent wind farm developments with Météo France and Ministère des Armées being the most prominent objectors in France. For military radar sites a new assessment process is being developed known as Dempere (*DEMonstrateur de Perturbation des* Éoliennes *sur les Radars* Électromagnétiques) project for assessing wind farm radar interference on French military radar. It is a process and software system that will predict the impact of wind turbine on radar. With the introduction of Dempere the 30 km safeguarding limit for wind farm developments is being lifted which means that objections to developments more than 30 km from French military radar are likely in future.

In the past developers would not have pursued sites with these objections - they would have simply moved on to an alternative development. However the number of developers and the demand for good wind farm sites is decreasing. The number of objections to wind farm radar interference in France is likely to increase substantially in the coming years if nothing is done.

For most radar types there are currently specific safeguarding distances beyond which wind turbine objections will not be made. These distances are shown below:

Radar Operator	Radar Type	Safeguarding Distance (km)
Directorate General of Civil Aviation (DGAC)	Primary	30
DGAC	Secondary	16
Météo France	C Band	20
Météo France	S Band	30
Ministère des Armées	Defence	30

fied safeguarding distance technical and operational assessments are undertaken to determine whether the proposed development will be acceptable. For DGAC civil radar sites proposed wind farms inside the safeguarding distance a subject to an operational assessment to determine whether the development should be allowed.

The situation in France is similar with the UK ten years ago for the following reasons: (1) the government strongly supported onshore wind; (2) there were a good market incentives for onshore wind development; (3) there was a very competitive market for wind farm sites; (4) the maximum distance at which radar operators objected increased following wind farm radar interference research and flight trails from the Ministry of Defence; (5) there was a large increase objections to wind farms due to radar.

The UK wind industry addressed this issue in a number of ways:

1. Within government between Defence, Transport and Energy departments;
2. Within industry via Renewable UK (formerly BWEA)
3. Research and development of technical mitigation solutions
4. On a case by case basis for each wind development facing an objection.

7.3. THE UNITED KINGDOM

Renewable electricity, is now a significant part of the UK's electricity mix providing over a third of annual generation. This ambition to become the leader in the renewable energy sector is clearly seen in the UK energy and climate legislation.

In June 2019 the UK Government laid the draft "Climate Change Act 2008 (2050 Target Amendment)" Order 2019 to amend the Climate Change Act 2008 by introducing a target for at least a 100% reduction of greenhouse gas emissions (compared to 1990 levels) in the UK by 2050. This is otherwise known as a net zero target because some emissions can remain if they are offset by removal from the atmosphere and/or by trading in carbon units. In addition, under the 2019 "Net Zero" legislation, the Committee on Climate Change (HMG's advisory body) has predicted a requirement at least 75 GW of electricity from offshore wind by 2050. It is expected that this will be achieved by a number of current offshore windfarm developers and operators installing additional, larger, offshore windfarms around UK. It is unlikely that these ambitious targets will be possible without a step-change in the technology of wind turbines; allowing developers to utilize new and more advanced manufacturing techniques.

The Offshore Wind Sector Deal published in March 2019 set out an ambitious partnership between government and industry to raise the productivity and competitiveness of UK companies to ensure that country continues to play a leading role as the global market grows in the decades to come[211]. The Offshore Wind Sector Deal confirmed the UK's aim to achieve 30 GW of offshore wind by 2030, up from 8 GW today. The UK Prime Minister, Boris Johnson, has recently set out new plans to "build back greener" by making the UK the world leader in clean energy – creating jobs, slashing carbon emissions and boosting exports[212]. That should set out the UK government plan to achieve its goals. Government's commitment in the 10-point plan also means that the target for offshore wind power capacity by 2030 will be set from 30 gigawatts to 40 gigawatts. These commitments are the first stage of a 10-point plan for a "green industrial revolution" from the government to accelerate the progress towards net zero emissions by 2050. The 10-point plan released on 18 November 2020 is not a detailed blueprint, the Government's commitment will be seen in the energy "white paper" (a policy document that precedes new legislation) due at the end of November 2020.

The UK is the world leader in offshore wind, with more installed capacity than any other country. With a third of the world's offshore wind installations and the first floating wind farm, the UK is a global leader in this sector. This lead will be reinforced when the world's largest offshore farm Dogger Bank, starts up off Yorkshire's coast in 2023. The cost of new offshore wind has fallen by 50% since 2015 and is now one of the lowest cost options for new power in the UK – cheaper than new gas and nuclear options. By 2030 wind and solar are expected to reach above 50%, more than any other country.

That will set the course for onshore wind, solar, and the two latest objects of prime minister's desire – hydrogen produced by surplus off-peak wind energy; and carbon capture, where emissions are caught and pumped into underground rocks. Like Japan and Germany, UK has increasingly looked to hydrogen as a way of lowering emissions. The cleanest form of hydrogen – the so-called green hydrogen, which is usually generated from water using clean electricity sources like offshore wind – is still expensive to make.

The government secures funding for large-scale renewables through contract-for-difference (CfD) auctions or agreements. CfDs fix a price per unit of power that a developer will receive. Renewables such as offshore wind have been successful in these auctions, and prices have fallen dramatically. However onshore wind and solar, some of the cheapest technologies, were not able to compete for funding in the last two auctions, due to Government manifesto commitments.

Recently, the UK Government announced turnaround on its land-standing ban on the onshore wind. It means that the government will reverse its block on onshore projects, overturning the public veto policy in England and introduced by David Cameron in 2015. Previous Conservative government policy on onshore wind development had allowed for communities to vote down projects based on their impact to the local area. The government will remove a block against onshore wind projects by allowing schemes to compete for subsidies alongside solar power developments and floating offshore wind projects, in a new auction scheme.

The UK's onshore wind capacity should increase by almost threefold in the next 15 years to meet climate goals at low cost. This would require the UK to grow its onshore wind capacity from 13,000 MW now to 35,000 MW, or an average of more than 1,400 MW a year.

At the moment, the UK government is conducting a review of current energy infrastructure at sea as it sets the sights on expanding offshore wind energy. The review will focus on improving the cabling and transmission infrastructure to reduce the costs and impacts of connecting of new wind farms to the onshore electric grid. It will also consider how hybrid projects could combine offshore wind turbine connections with interconnections to neighboring markets – helping export more green energy abroad.

7.3.2. UK'S APPROACH

The UK Government is committed to the development of wind energy in the country through the use of offshore and onshore wind farms. Wind turbines can have significant effects on radar, which in turn is a major barrier of development. Aviation radar objections to wind farms in the UK mainly arise from three distinct groups; the MoD (for air defence and military traffic control); NATS En Route in respect of its regulated en route air traffic control service; and terminal civilian air navigation service providers, namely airports. This conflict illustrates the constraint on aviation's ability to meet its commitment to Governments policies; international obligations and license conditions (Memorandum of Understanding, 2010)[213]. Department of Energy and Climate Change (DECC), Department of Transport (DfT), Ministry of Defence (MoD), RenewableUK, Civil Aviation Authority (CAA) and National Air Traffic Services (NATS/NREL) signed a memorandum of understanding (MoU) in 2008 which committed them to work together to identify mitigation solutions, and drive towards progress on projects corralled under an "Aviation Plan".

Offshore windfarms, when in the line of sight of radar, may have a detrimental effect on Ministry of Defense's (MoD) primary surveillance ra-

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[211] "Industrial Strategy; Offshore Wind Sector Deal", policy-paper, March 2019

[212] T. Raphael. "Welcome to Boris Johnson (Green) Revolution". Bloomberg news, 19 November 2020

[213] Policy paper: "Wind turbines and aviation radar mitigation issues", Memorandum of understanding, 2011 update

[214] It is a zone where a radar ignores interference.

dar capability used to deliver a recognized air picture for Air Defence. A number of trials have demonstrated the adverse impact that this has on the UK's air defence capability. The Doppler shift on ground radar returns mimics the signals of fast moving aircraft, curtailing the RAF' (Royal Air Force) ability to detect incoming, low-flying, aircraft threats. Analysis of these trials has concluded that current mitigation methodologies (including Non-Automatic Initiation Zones)[214] may be insufficient to meet future and to be agreed aviation specifications. When properly implemented interference is rejected whilst genuine targets (aircraft) are displayed. Non-Auto Initiation Zones (NAIZs) are sometimes used to mitigate the effects of wind turbines. For larger wind developments infill mitigation may be more suitable. Sometimes a mitigation scheme can combine radar blanking and Transponder Mandatory Zones by NATS and for Ministry of Defence (MoD) Air Traffic Control mitigation. In addition, some of the mitigations applied to civilian radar systems may not be suitably applied to MoD (Air Defence) primary radar surveillance assets. The detrimental effect of offshore windfarms may be exacerbated by the increasing size, number, and scale of future installations.

Given these challenges, more than half of the current offshore wind farm development pipeline are subject to objections from the aviation sector (civilian and military); potentially preventing the development of projects within radar line of sight of many air defence radar installations. With accelerated deployment of offshore wind farms needed to meet the goals set out in legislation, there is a clear need to mitigate the impact of wind turbines on radar and allow the wind farm developments to go ahead.

UK so far has relied on good cooperation within the government and the stakeholders. The dialogue between the aviation, defence and wind industries have been ongoing for many years. Proactive and collaborative approach has resulted in the identification of opportunities and solutions which enable mitigation measures to be implemented in a significant number of situations, including civil and defence radar and low-flying operations. However, there is not a "one-size-fits-all" solution, given the unique operational environment of air infrastructure.

It is also obvious that the existing mitigation strategy has to be reviewed in the light of the technological progress where wind turbines are becoming bigger and more efficient. To mitigate the negative effects of wind turbines of the next generation, additional methods are required, either technical, procedural or a combination of those two. Mitigation measures can be set at national, regional, cluster or project levels. The UK MoD will elaborate a new mitigation strategy next year to tackle air defence mitigation. There is a joint programme of work between stakeholders to support the development of this new strategy. Starting in August 2019, the Task Force's programme of studies and works includes the BEIS funded DASA Innovation Challenge, the sector funded MoD Air Defence Mitigation Feasibility Study, a MoD funded Next Generation Mitigation Study led by Defence Science & Technology Laboratory, and MoD leading on operational analysis through the Defence Science & Technology Laboratory and strategy development works. The Aviation Taskforce is planning a set of Concept Demonstration activities to better understand the capabilities of mature mitigation solutions. Informed by these inputs, the aim is to publish an initial Air Defence and Offshore Wind Mitigation Strategy & Implementation Plan in early 2021, with follow on studies and work planned in 2021-22 to update the Strategy & Implementation Plan for future offshore wind deployment.[215]

UK government and the wind industry have invested in the research and development which enable to get cutting-edge innovation off the ground. For example, Defence and Security Accelerator (DASA) recently organized competition that offered wide-range and complex ideas to tackle radar interference[216]. Thales, in collaboration with the University of Birmingham and SMEs, will develop surveillance to mitigate windfarm "clutter", whereas Saab is developing a radar mitigation system using Artificial Intelligence and Doppler filtering.

Therefore, future mitigation solutions should exist for Air Defence Radar, which may be applicable to new developments. There are technologies which have the potential to mitigate impacts at Air Traffic control radar installations. However, the high cost of mitigating impacts of (onshore) wind development on military radars may threaten to make some proposed (onshore) developments uneconomic.

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[215] https://cdn.ymaws.com/www.renewableuk.com/resource/resmgr/sector_deal_progress_update_.pdf

[216] Defence and Security Accelerator (DASA). "Offshore Windfarms development boosted by 2 billion GBP research". Press release, 28 October 2020.

7.4. BELGIUM

Renewable energy potential in Belgium is relatively low. The country is flat, densely populated and not particularly sunny, and large-scale use of hydro, onshore wind and solar solutions faces challenges in spatial planning and in public support. Under current technologies, biomass and offshore wind have the most potential (IEA, 2016)[217]. The first ocean (wave) energy facility (Mermaid, 20 to 61 megawatts) received a concession in 2012 and started operation in 2019.

Belgium's Government coalition has a strong focus on climate and energy policies. Today Belgium has 2.3 GW of onshore wind capacity and 1.6 GW of offshore wind capacity. To accommodate for a target of 55% or higher greenhouse gas reduction, the coalition agreement foresees to expand onshore wind capacity in Flanders to 2.5 GW up from 1.3 GW today and in Wallonia to 4.600 GW up from 1,500 GWh by 2030. It will also aim to double the country's offshore wind capacity to 4 GW in the next decade by exploring the potential for additional capacity in the North Sea.

In Belgium renewable energy is a regional matter, with exceptions for offshore wind power, hydropower and renewable energy sources used in transport which are governed by national regulations. Belgium will double the area of its North Sea waters made available to offshore wind farms after 2020 as part of its exit strategy from nuclear power. The country has 4 offshore wind farms that produce 871 megawatts of power and wants to increase that capacity to 2.2 gigawatts by 2020 and to 4 gigawatts by 2030. With the installation of Northwester 2, the country's largest offshore wind farm, Belgium – more specifically the northern region of Flanders – has achieved 1,775 MW in installed capacity and outranks Denmark as fourth – largest offshore wind energy producer worldwide. In Europe, Belgium ranks 3rd. With the Marine spatial planning 2020-2026, there has been established the framework for additional wind zone of 281 km^2 (at the frontier with France), in addition to the wind zone of 225 km^2 which already exists (at the border with the Netherlands).

When the government approved the reduced level of support for three last wind farms to be built by 2020, ministers decided to organize as from 2020 a competitive bidding procedure for the realization of new renewable energy projects in the North Sea, such as it is also the case in the neighboring countries and in accordance with the European state aid rules.

For that purpose, the Belgian Parliament has adopted a law on 4 April 2019 (ratified by the King on 12 May 2019) which establishes the general principles of the commitments at competitive bidding procedure. With this new legal framework Belgium aims at achieving commitments at European level and within the framework of the Paris Climate agreement. This legal framework should enable the federal government to realize the proposed 4 GW of offshore wind energy (inclusive the already operational or planned wind farms) in the inter-federal Energy Plan by 2030 at the latest. In addition, the new law also aims at realizing after 2029 the largest possible share of additional offshore electricity production capacity from renewable energy sources at the lowest possible societal cost.

Electricity from renewable sources is promoted mainly through a quota system based on the trade of certificates. The individual green certificate systems differ in many ways between regions. They vary according to the quota obligation, the basis for granting green certificates, technology specific support levels, calculation of minimum price levels, duration of support and tradability.

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[217] International Energy Agency. "Energy Policies of IEA Countries: Belgium 2016 Review", IEA, 2016, Paris, France

7.4.1. BELGIUM'S INTEGRATED APPROACH

Standing off the coast of Belgium are found enough wind turbines to generate more than 5 percent of the national energy demand, increasing to 20 percent beyond 2020. Despite its relatively small coastal zones, Belgium is third in Europe behind the United Kingdom and Denmark in wind energy production. Instead of solely complicated navigation, the cooperation with wind industry could prove very useful (Lundquist, 2019)[218]. The Belgium Navy that is responsible for coastal security (critical to offshore wind farms) has used three Cs: collaboration, coordination and counter-together. In terms of collaboration, the same radar system should be used, the same data protocol between military and wind farms. Cooperation means working together on common issues, while counter-together means developing measures to counter unidentified objects together.

Belgium's Navy is a blue-water navy that is capable of distant open-ocean operations. The new mine-sweeper ships will remain outside minefields and rely on a "toolbox" of off-board remote and unmanned systems to enter the danger zones while the ship remains at a safe distance. As drone technology matures, the newer capabilities can replace the older systems. These off-board systems can be controlled from the ships, or from containerized control stations that can be placed where needed ashore. These unmanned underwater vehicles can carry sensors such as synthetic aperture sonars and side scanning sonar, as well as neutralization charges to destroy mines. The matrix of wind structures can help create an underwater network to communicate with the drones, and even recharge their batteries. Therefore the co-existence of wind farms with military radars and other equipment can also be seen as an opportunity, not always as a technical challenge to overcome.

Belgium is not an exception and similarly to some other countries in Europe has certain problems or barriers that need to be overcome to boost the wind energy deployment to a greater scale. Such barriers include spatial planning limitations (i.e. military, aeronautical, or traffic-related restrictions) and lengthy permitting procedures. The federal administration has created a "one-stop shop" aimed at simplifying and speeding up the license procedures.

The Flemish government aims to speed up the planning process and decrease the large number of rejected permit requests. The goal is to integrate the environmental and building permit and establish more collaboration between the different levels and domains through the Wind Working Group. The Flemish Government also aims to focus on developing and facilitating zones in the harbor areas and next to highways where fewer people live, in order to limit the risk of local opposition. They also see a larger role for Wind Working Group in advising developers before they actually request a permit for their project and assisting the development of positively advised wind farms. To conquer "NIMBY" (not in my backyard) feelings, the FEA advises earlier involvement of the municipal council, financial participation for residents and more "objective" information to tackle misconceptions about wind turbines.

The simplification of the planning procedure is important step and improves the efficiency of wind power planning by decreasing the political distances between various policy levels, but it does not necessarily increase the acceptability of projects. For example, the Flemish government has not yet tackled the major current bottleneck in planning: the wind "rush" on the sparse zones for wind power development.

Lengthy legal procedures also affect the sector. For example, cases where local communities appealed against the construction of wind energy facilities have taken years to resolve. Such legal cases could potentially be avoided by involving the local communities more closely at the project planning stage and by offering them the opportunity to take part in investments through cooperatives.

The main issue affecting growth for wind is the number of judicial appeals at the State Council, which has severely hindered the development of land-based wind parks both in the Flemish and Wallonia regions. Belgium has limited space for wind energy compared to many other countries. However, because of their relatively high availability, offshore wind resources provide the most potential, according to an IEA in-depth review in 2015.

For the development process to be successful, it is necessary to have an integrated approach of the wind farm project from the very beginning of the process. It means that the way of working to identify potential sites is already part of a decision-making process, since all the stages of a wind farm life-cycle (development process, construction, deployment, operation and dismantling) are taken into account when site prospecting so that their impacts can be reduced to minimum levels.

At the local and provincial level, there is a better application of more participatory planning which allows discussion of different views, knowledge, values and interests of the various stakeholders.

7.5. POLAND

The development of renewable energy sources in Poland, including wind power is the priorities listed in the document "Polish Energy Policy until 2040". In addition to different tools for policy implementation, the document includes e.g., "hierarchy-based spatial planning ensuring the implementation of energy policy priorities. This means that the spatial planning system should involve the implementation of energy policy at all the government levels: national (country), regional (Voivodship) and local (municipal). Hence the regional and local authorities are expected to actively implement the energy policy. In Poland, just as in Sweden and the United States, local governments have a good deal of authority over spatial planning, and decisions on wind farm siting are taken at a local level.

Poland's government plans to "liberalize" a damaging distance rule from 2016 that has brought new wind power developments on land to a near stand-still, shutting down the largest onshore wind energy market. No draft for an amendment of the distance rule act has been presented yet, but according to the Polish Wind Energy Association (PWEA), legislative work on it could be completed by the end of the year.

The development ministry is finalizing work on provisions that would allow for shorter distances between new wind turbines and farm buildings or protected areas, which under current distance rule need to be 10 times the tip height – which in practice means a distance of 1.5 to 2 km.

So far the biggest role in increasing the share of renewable energy in the Polish electricity balance was played by private energy companies and companies-prosumers, who collectively built 81% of all renewable capacity installed between 2013 and 2019. The total capacity of halted projects in various stages of development in Poland amount to 4.1 GW, including 3.4 GW in projects that have a signed connection agreement. According to the estimates of PWEA, Poland has an onshore wind potential of some 22-24 GW, almost four times the 6.2 GW currently in operation.

Next to the enormous potential for wind on land, pressure from the EU to phase out coal (which currently accounts for more than 70% of polish electricity). And the hunger for green power by large state-owned firms, mid-term voter strategy aspect may also play a role for Poland's warming up to onshore wind.

The government led by the right-wing populist Law and Justice Party (PiS) had introduced the wind distance rule also to cater wind protesters in coal and rural constituencies that are important for its voter support. After winning elections for municipalities, parliament and president in 2018, 2019 and 2020 respectively, the PiS does not need to face another important vote for several years. Until then, renewables developers hope the government – together with the wind industry – can convince rural constituencies more of the beneficial aspects of wind farms, and offer local regions substantial support to ease possible job losses in coal in the wake of the energy transition. The government in 2018 and 2019 had carried out tenders that included a combined 3.2 GW in onshore wind projects in an advanced

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[218] E.Lundquist. "Belgian Navy Sees Cooperation Opportunities for Wind Farm Industry". Sea-power Magazine, 12 February 2019.

stage of development, which fetched record-low prices for winning bids. Another 1.2 GW of advanced projects have valid building permits, and could be auctioned off soon.

Poland's expansion targets for offshore wind turbines are ambitious. Poland does not have any offshore wind farms as yet, but by 2030 they aim to have installed 3.8 GW offshore wind energy – with 10 GW of new capacity awarded CfD by then. By 2050 they want a massive 28 GW, which would make Poland the largest operator of offshore wind power in the Baltic Sea. New agreements and the planned Offshore Wind Act could improve the conditions for developers, investors and lenders. Poland is ambitious where the development of offshore wind farms is concerned. Thanks to the legal framework the Polish government seeks to create, Poland will become a very interesting growth market for key players in the offshore wind sector.

The development of offshore wind is part of the Polish National Energy and Climate Plan for 2021 -2030 and also enshrined in the Polish Energy Policy until 2040. Poland believes that offshore wind is one of the key technologies for achieving the EU's renewable energy target for 2030. If Poland met its 28 GW target, it would be the largest operator of offshore turbines in the Baltic Sea. The Polish government's focus on offshore wind energy is very reasonable given the country's commitment to increase its share of renewable energy to 21% by 2030, from 10.9% in 2017.

In July, 2020, representatives of the Polish government and members of the offshore wind energy sector agreed to take joint action to develop the offshore energy market in Poland. The cooperation is set out to develop, sign and implement the so-called Polish Offshore Sector Deal. The declaration will be similar in character to the British sector deal for offshore wind energy, but it will take into account Polish reality and conditions. Poland's ambition is to become an offshore leader on the Baltic Sea and a net exporter of cheap and clean energy.

In July 2020, the Polish government published a new draft of the so-called Offshore Wind Act that also outlined a new subsidy scheme. According to the Polish Wind Energy Association (PWEA), offshore wind farms in the Baltic Sea with an overall capacity of 5.9 GW are set to "receive support under a two-sided contract for difference between the investor and the regulator". Awarding support under this formula will be time-limited until the end of June 2021.

CONCLUSIONS

Given the expected increase in the wind energy development, and the role of renewable electricity in the future, wind farms, both onshore and offshore, will play a vital part. This also means that wind farms are here to stay and they are expected to increase in size and number in the years to come. Unfortunately, wind farms may affect the proper operation and reduce the detection capability of the surrounding radars. If not mitigated, such wind development could cause clutter and interference for radar systems involved in air traffic control, weather forecasting, internal security, and national defence missions.

Wind turbines due to their physical characteristics (more powerful and bigger) are contributing evermore complex clutter interference to the ever noisier radio-frequency spectrum, therefore they give rise to the bigger surveillance challenge. This also means that the military have to adapt and evolve to operate in evermore "complex clutter interference". To solve the problem, wind turbines and surveillance systems must become more electromagnetically compatible – it is the ability of the devices and systems to operate in their electromagnetic environment without impairing their functions and without faults. In this context, the currently used approaches are not enough, and the existing siting processes as well as mitigation approaches need to be reviewed and enhanced. This enables to guarantee continued development of this important renewable energy resource while maintaining vital defence readiness. All these factors can give rise to a number of conflicts between the wind energy and aviation sectors (both civilian and military). Definitely, the co-existence of windfarms and radar installations is challenging, but possible. Therefore, the solutions have to be found how to mitigate the negative effects of wind turbine on radars.

The research found that genuine concerns have been raised in many countries in Europe and elsewhere about the impact of wind turbines on radar and military sites. The concerns are varied, however the research clarifies that each concern is theoretically plausible. Additional clutter, shadow, and flight obstructions are the main concerns that the Ministries of Defence have raised, and a particular concern is the use of radar clutter and shadow zones by unfriendly aircraft to move below the radar, enabling them to potentially conduct missions undetected. Air Traffic Control Radar providers, thus take a conservative view on a wind farm deployment and they often end up in conflict with wind farm developers.

The interference problems can be solved by using operational & procedural mitigation tools (e.g. procedurally safeguarding vital radars and areas or operationally amending activity routes and using mandatory transponder zones in wind farms areas). The other possibility is to use technical mitigation measures, e.g. maximizing current radar capabilities (clutter mapping, sector blanking). A common approach to create a clutter map is to divide the observation area into predefined clutter cells and to count the number of measurements appearing in the respective cell on a given time interval. Clutter map computation is of great importance in order to reduce the amount of false alarms by a tracking algorithm. The proposed solutions available to help resolve wind turbine interference with radar and military concerns are numerous, with gap filler radar, software upgrades, radar upgrades, and stealth technology as favored solutions. Initial research between government agencies and academia will focus on the viability of adaptive clutter mapping, in-fill radar, and concurrent beam radar to provide mitigation solutions.

A number of radar manufacturers are developing what they term "next-generation" radar which includes an element of "wind farm tolerance', which either comes in the form of a built-on "windfarm filter" or are inherent to the radar design. For example, no "windfarm tolerant" next generation radar has yet been installed in the UK and approved by its Civil Aviation Authority, but work continues and some airports have expressed an interest in such a holistic mitigation solution. Furthermore, some existing radars have advanced processing capabilities which afford a degree of "wind farm tolerance" in particular circumstances – for example, Raytheon S and L band radar (as used by NERL[219] at Lowther Hill and Great Dun Fell and, it is understood, Liverpool airport as well as at military bases in the Netherlands[220]. The conducted interviews highlighted the importance of co-operation between governmental agencies and wind developers, dedicated funding, a common research plan, and streamlining certification procedures as necessities for implementing and expanding the range of approved mitigation solutions available to address the impact of wind farms on radar and military operations. It is clear from the literature and the interviews that wind industry stakeholders seek "early engagement" from authorities with distinct requirements such as the Ministry of Defence, the Ministry of Energy, the Ministry of the Interior, Aviation Authority/Agency to ensure wind turbine projects are not unduly delayed or prevented, and that the defence capability is not compromised.

Certain countries have adopted wind turbine interference mitigation strategies (e.g the USA) or have concluded country level memorandum of understandings (e.g. U.K) to foster co-operation between the agencies and the wind industry. Under a Memorandum of Understanding signed in 2014 and building off the successful Interagency Field Test & Evaluation radar mitigation testing campaigns, in the USA, a consortium of federal agencies composed of the U.S. Department of Defence, Department of Energy, the Federal Aviation Administration, and the National Oceanic and Atmospheric Administration established the Wind Turbine Radar Interference Mitigation Working Group to address these conflicts.

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[219] NERL is the sole provider of civilian en-route air traffic control over the United Kingdom and is regulated by the Civil Aviation Authority (CAA) which, for example determines the charges NERL can make.

[220] "RenewableUK Members' Briefing Note: Aviation Safeguarding and Radar Mitigation: Introductory Overview". Issue 1, 13 October 2016, Amendment 1, 29 January 2019

Through collaborative activities and coordinated investments, this Working Group seeks, by 2025, to fully address wind turbine radar interference as an impact to critical radar missions, ensure the long-term resilience of radar operations in the presence of wind turbines, and remove radar interference as an impediment to future wind energy development. To address, the interference issue at early stage, several other countries use one-stop shop approach while reviewing the new windfarm applications. Whenever there is an impact for civilian or military radars, the mitigation options are sought.

There are a number of other hurdles on the way towards large-scale wind energy deployment, for example, there are different rules that have been established at different times regarding paint markings on turbines and the position of lights on turbines, etc. However, there is no overall trend on positioning and brightness adjustability (for example, brightening lights during search and rescue operations). This lack of EU regulation means there are major disparities in terms of how rules are interpreted and implemented, depending on the location. Wind industry, aviation regulators and the military should work together towards a more simple and uniform categorization to overcome these issues. Another important issue is the lighting regime of the wind turbines that different countries have used. Therefore, a proportional approach to this issue would be desired like Germany does by using transponder based solutions that do not disturb the local community so much. The harmonization of similar regulation at European Union level could be useful.

Some of the hurdles for successful co-existence between wind farms and radars can be hopefully solved by the adoption of the Estonian maritime plan that is a thematic plan of the marine area for the whole Estonian maritime area. It also includes planning and assessment of the inland sea and exclusive economic zone. For wind energy development, it will also give a clue for the wind energy developers where onshore windfarms can be planned (e.g. national defence restrictions).

A WAY FORWARD

The demand for sustainable offshore energy can encourage companies to establish offshore wind power plants. The introduction of offshore wind turbines helps to generate electricity, which as a result is expected to evolve the offshore wind power market. The mature offshore wind technology makes it possible to install wind turbines on the seabed in large projects that take advantage of strong and steady winds. Offshore wind has rapidly become a mature technology in Europe, and a significant growth of capacity is also forecasted in Asia and in the USA.

Europe is expected to lead the global offshore wind market with increasing number of investments in offshore wind projects. Furthermore, the region is likely to hold a major share in the global market owing to favorable governmental initiatives. Other factors likely to drive the market share are energy security initiatives and decarbonisation reforms in Europe.

New challenges may emerge as the next range of offshore wind turbines are introduced that may be floating in deeper waters and are likely to be further offshore; for example, what to do with cable in floating offshore wind installations and ground conditions.

Among the most promising innovations, floating offshore wind energy is the future solution for expanding the scope of offshore operations. In addition to traditional solutions, floating offshore wind power will allow projects to be installed in areas of great depth, further from the coast or in windy areas.

With respect to storage and batteries, significant progress has been made to drive costs down and enhance capacity. Various forms of storage will be needed, from very short durations to long-term durations. Storage will support market developments and help to manage peaks and drops in volatile markets.

As a follow-up to the present study, the challenges and potential for offshore wind power will be covered in a separate study by the NATO Energy Security of Excellence conducted in 2021. The focus of the study ““*The offshore wind farms – challenges, risks and opportunities for building more resilient national energy system”* would be on the main barriers in the deployment of offshore wind farms; it would also map the potential solutions and best practices to ensure national security on one hand, and making the energy transition possible on the other hand. Among other aspects, the study should give an overview on the current technological trends starting from radars and cables to turbines including power-to-X technology.

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