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CHALLENGES OF WIND POWER IN COLD CLIMATES: THE IMPACT AND PREVENTION OF ICING

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ABSTRACT

Challenges of wind power in cold climates: The impact and prevention of icing
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The global energy sector has begun a transition towards cleaner energy production due to comprehensive climate targets set by nations. Wind power is one of the low-emission and renewable forms of energy as its only fuel is the motion of air – the wind. The use of wind power is expected to increase significantly in the next decades, posing a strong demand for solutions addressing the challenges of wind power in non-conventional sites such as cold climates. Icing and cold environments can adversely affect wind power operation in multiple ways. This sets a requirement for research on the matter in order to assure safety and efficiency of wind power units in these areas.

This thesis aims to present the impact of icing on wind power production. Both the effects of icing and solutions for preventing or reducing icing risks are examined. The operating principle of a wind turbine is studied to form an understanding of wind power technology. The current and future status of wind power in Finland and Scandinavian countries is also presented as their cold weathers, occurring particularly during wintertime, can impact local wind power production. These research questions are addressed through a literature review. In addition to icing issues, low temperature challenges and adaptations are assessed to provide an overview of wind power projects in cold climates. The main types of wind turbines, the concept of wind farms, and siting of wind power units are also introduced. The topic is approached by dividing wind power into onshore and offshore technologies.

The conclusions of the thesis indicate that wind turbines and other site infrastructure can be notably affected by icing and low temperatures. Typical consequences are power losses, detrition of turbine structure, and safety risks caused by ice throw. Icing risks can be mitigated with commercially available ice protection systems and cold climate packages. The share of wind power in the electricity supply of Nordic countries is expected to increase notably towards 2030. In the discussion section of the thesis it is inferred that despite of possible additional costs of ice mitigation systems, these solutions can advance wind power production in cold climates and therefore bring environmental and financial benefits.

Keywords: wind power, wind turbines, icing, cold climate

TIIVISTELMÄ

Tuulivoiman haasteet kylmässä ilmastossa: Jäätymisen vaikutukset ja ehkäisy
Kaisa Kankaala
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Energia-ala on siirtymässä globaalisti puhtaampaan energiantuotantoon valtioiden asettamien kattavien ilmastotavoitteiden myötä. Tuulivoima on vähäpäästöinen ja uusiutuva energiamuoto, sillä sen ainoana polttoaineena toimii liikkuva ilmavirta eli tuuli. Tuulivoiman käytön odotetaan lisääntyvän merkittävästi lähivuosikymmeninä. Tämä kasvattaa haastaviin tuotantopaikkoihin, kuten kylmiin ilmastoihin, sopivan tuulivoimateknologian tarvetta. Jäätyminen ja kylmä ilma voi vaikeuttaa tuulivoiman tuotantoa monin tavoin. Aihetta on syytä tutkia, jotta tuulivoimaloiden turvallisuus ja tehokkuus kylmillä alueilla voidaan taata.

Tämän kandidaatintyön tavoitteena on esitellä jäätymisen vaikutusta tuulivoiman tuotantoon. Työssä tarkastellaan sekä jäätymisen seurauksia että jäätymisen riskejä vähentäviä ja estäviä ratkaisuja. Tuuliturbiinin toimintaperiaatetta tutkitaan pohjakäsityksen muodostamiseksi tuulivoimateknologiasta. Tuulivoiman nykyinen ja ennustettu tilanne Suomessa ja skandinaavisissa maissa esitellään, sillä niissä erityisesti talviaikaan esiintyvät matalat lämpötilat ja lumisateet voivat vaikuttaa paikalliseen tuulivoimatuotantoon. Näitä tutkimuskysymyksiä käsitellään kirjallisuuskatsauksena. Jäätymisen vaikutusten lisäksi mataliin lämpötiloihin liittyviä haasteita ja ratkaisuja käydään läpi, jotta voidaan muodostaa yleiskuva tuulivoimaprojekteista kylmissä ilmastoissa. Työssä tutustutaan lisäksi tuuliturbiinien päätyyppeihin, tuulipuiston käsitteeseen ja tuulivoimaloiden sijoittamiseen. Aihetta käsitellään sekä maatuulivoiman että merituulivoiman kannalta.

Työn johtopäätökset viittaavat, että jäätyminen ja matalat lämpötilat voivat vaikuttaa huomattavasti tuuliturbiinien toimintaan ja tuotantopaikkojen muuhun infrastruktuuriin. Tyypillisiä seurauksia ovat muun muassa tuotannonmenetykset, turbiinirakenteen kuluminen ja lavoilta putoavasta jäästä aiheutuvat turvallisuushaitat. Jäätymiseen liittyviä riskejä voidaan alentaa kaupallisesti saatavilla olevilla jäätymissuojausjärjestelmillä ja kylmään ilmastoon soveltuvilla varusteilla. Tuulivoiman osuuden pohjoismaisessa sähköntuotannossa odotetaan lisääntyvän merkittävästi vuoteen 2030 mennessä. Työn lopputuloksista pääteltiin, että jäätymissuojausmenetelmät voivat edistää tuulivoiman tuotantoa kylmissä ilmastoissa olennaisesti. Seurauksena voi olla niin ympäristöhyötyjä kuin taloudellisia etuja huolimatta menetelmistä mahdollisesti aiheutuvista lisäkustannuksista.

Asiasanat: tuulivoima, tuuliturbiinit, jäätyminen, kylmä ilmasto

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1 INTRODUCTION

Climate change, caused greatly by the rapidly growing CO_2 emissions from fossil fuels, is a constant challenge in the modern society. To attain the objectives set in the Paris Agreement, which aims to limit the increase in average global temperatures close to 1.5 °C in the present century, the EU should acquire more than 80 % of its electricity from renewable energy sources by the year 2050 (European Union 2019). The global energy market is consequently shifting towards renewable energy sources, and there are several motives for this energy transformation in addition to reducing carbon emissions. The costs of renewable power production have faced a rapid decrease regarding all commercially available renewable energy technologies. This can increase economic feasibility and availability for energy projects. The use of cleaner energy sources also improves air quality, which majorly influences public health and the environment. Additionally, renewable energy production can improve local energy security significantly and bring notable socio-economic benefits such as new employment. (IRENA 2019)

Wind and solar energy are the major contributors in transforming the global energy generation (IRENA 2019). Wind power production has the advantages of being practically emission-free and affordable, and it does not require highly frequent maintenance operations (Jha 2011). Rapidly decreasing costs have made wind power the least expensive source of renewable energy in an increasing number of markets around the world (REN21 2019). It has been estimated that wind power could provide more than one-third of total electricity demand by 2050, becoming a highly prominent source in the world's electricity supply (IRENA 2019).

As wind power has become more common in the late 20th and early 21st century, the number of wind power sites constructed in cold climates has also increased. Large cold regions are planned to be developed for wind power utilisation in the Northern and Eastern Europe, North America and Asia. (Battisti 2015) Wind power in cold climates generally refers to wind turbines constructed in locations facing severe icing and/or temperatures below a standard wind turbine's operational limit (Krenn et al. 2016). Wind turbines in cold climate sites can typically be exposed to circumstances including air temperatures below 0 °C for extended periods during the year, clouding near the ground surface, high water content originating from atmosphere and/or sea water sprays, complex terrains, high altitudes of sites or extreme conditions such as severe turbulence and wind gusts, hail and lightning strikes. The growing amount of individual wind turbines and wind farms and the related failure and maintenance records in these areas have recently increased the need for studying the impacts of cold climates on wind power operation. (Battisti 2015) There is a demand for increasing wind power production due to national and global climate targets, yet cold environments pose challenges that may adversely impact wind power projects in such areas. Research is therefore required in order to secure efficient power production and safety regardless of icing and other cold climate issues.

This thesis is a literature review on the impact and prevention of icing on wind power production. The primary objective is to overview icing-related challenges and technical solutions in use and under development regarding wind power operation. Technical principles of wind energy conversion, the fundamental types of wind turbines, and status of wind power utilisation in northern Europe are additionally introduced. Accordingly, the research questions addressed in this thesis are the following:

- What is the operating principle of a wind turbine?
- What is the current and future status of wind power in Finland and Scandinavia?
- What is the impact of icing on wind power production?
- How can icing risks be prevented or reduced?

2 OVERVIEW OF WIND POWER

This chapter describes the fundamentals of wind, wind energy utilisation by wind turbines, and the main types of machinery used in wind power production. Wind farms, siting of wind turbines, and offshore wind power technology are additionally presented in their respective chapters.

2.1 Principles of wind energy conversion

The phenomenon of wind is essentially air masses' constant motion deriving from varying thermal conditions of these masses. The motion of air masses is not only a regional or a local occurrence, but also a global phenomenon. Prevailing regional winds are therefore always determined by the global wind patterns in addition to orographic conditions such as the surface structure of the area. Wind turbines harness the wind energy near the ground called the boundary layer. Owing to the rough texture of the surface, the local wind stream close to the ground is turbulent. In other words, the wind speed fluctuates repeatedly as a function of time and height. (Ackermann 2005)

Fluctuations of wind speed inflict variation in the produced power. Considering wind power production, wind speed can be divided into three categories. The minimum wind speed at which a wind turbine will produce useful power is called the cut-in speed, typically 3–4 m/s (Awasthi 2018; Manwell et al. 2009). The rated capacity of a wind turbine is achieved at the rated wind speed, which is usually in the range of 12–16 m/s, depending on the turbine type. The maximum wind speed at which a wind turbine will deliver power is the cut-out speed, commonly the wind speed between 20–25 m/s. (Manwell et al. 2009; Ackermann 2005) In the event of the cut-out wind speed being exceeded, the wind turbine will shut down, cease power production and disconnect from the grid (Wizelius 2007; Ackermann 2005). To summarise, if the wind speed is below the cut-in speed or above the cut-out speed, power production will be zero (Ackermann 2005).

Due to air having a mass and wind being air in motion, the wind has kinetic energy. The kinetic energy can be converted into mechanical-rotational energy, and further electric power, by wind turbines. The basic principle of wind energy conversion can be described briefly as follows: the wind pushes the rotor blades of a wind turbine, inflicting the rotor axis of the turbine to rotate. The axis is connected to an electric generator, which converts the rotational energy into electric energy. (Wizelius 2007; Ackermann 2005) However, in order to construct a power-producing wind turbine, a variety of other components with different functions are required in addition to a rotor and a generator.

Broadly, a typical horizontal axis wind turbine consists of a rotor, a drive train, a nacelle and a yaw system, a tower and a foundation, a control system and a selection of other electrical components. The rotor comprises the turbine blades, commonly two or three, and the supporting hub, which are often recognised as the foremost components of a wind turbine. The rotor harnesses kinetic energy from the wind, converting it into rotational energy for the gearbox to utilise. The drive train encases the rotating parts of a wind turbine exclusive of the rotor, such as shafts, the gearbox, a mechanical brake and the generator. The gearbox's function is to accelerate the rate of the rotor's rotation to a value sufficient for a standard generator. The generator then transforms the rotational energy provided by the gearbox into electricity. Wind turbines are commonly equipped with one of the two: an induction or a synchronous generator. These particular devices entail a fairly continuous rotational speed when connected to the grid. The nacelle is a hard cover shielding the drive train and the control system from the weather. The control system, being a principal subsystem considering both machine operation and power production, contains power amplifiers, controllers, actuators, and intelligent devices such as sensors and computers. The produced power can be controlled aerodynamically by a pitch, stall or yaw system. The yaw system, for instance, retains the rotor shaft properly aligned with the wind direction. The rotor can be turned away from the wind to avoid overproduction. (Manwell et al. 2009)

2.1.1 Betz's law

Conversion of kinetic energy of the wind into rotational energy induces a reduction in wind speed. This is a result of energy extraction from the wind. Wind turbines cannot utilise all the power in the wind, given it would result in a total stop of air flow, and ultimately, operation of wind turbines. (Awasthi 2018; Ackermann 2005) The theoretical limit for utilising the power of wind by decreasing its speed was found by Albert Betz in the early 1900s. As attested by Betz, laws of conversion of energy and mass allow a maximum of 16/27 or approximately 59 % of the kinetic energy to be harnessed by a wind turbine. Contemporary wind turbines are able to attain performances between 42-48 %. (Awasthi 2018)

2.2 Types of wind turbines

There are numerous options in wind turbine design and construction, such as axis and rotor orientation, rotor speed, selection of control and yaw systems, materials, hub design, and generator and gearbox types (Manwell et al. 2009). This chapter introduces technologies which are divided by the axis of the turbine (horizontal or vertical) and speed of the rotor (fixed-speed or variable speed), however, discussion of other wind turbine topologies is beyond the scope of this thesis.

2.2.1 Axis of the turbine: horizontal or vertical

Most wind turbines today have horizontal-axis rotors, rotating by the lift force of wind. Horizontal axis wind turbines are typically equipped with a yaw orientation system, which adjusts the direction of the turbine according to the prevailing wind direction. (Awasthi 2018; Manwell et al. 2009) There are two major advantages to horizontal-axis operation. Firstly, costs usually remain rather moderate on a production capacity basis as the overall blade mass relative to swept area is lower with a horizontal rotor axis. Secondly, the rotor and thus the height of the rotor swept area can be placed fairly high above the ground, which typically enhances productivity as wind speeds tend to increase in the upper air levels. (Manwell et al. 2009)

Vertical axis wind turbines operate relatively independent of the wind as the rotor is able to utilise winds blowing from any direction. Consequently, they do not obligate orientation with changes in wind direction. (Awasthi 2018; Manwell et al. 2009) Yaw orientation systems are therefore not required, which is an advantage considering wind turbine design and construction. In addition, the blades of the turbine can be fabricated quite simply and inexpensively, and the drive train components such as the generator and gearbox can be placed fairly close to the ground. (Manwell et al. 2009)

The vertical axis wind turbine has not received extensive support despite of these advantages. Fatigue detriments have occurred particularly at connection points of the blades to the rest of the rotor as a result of the cyclic aerodynamic stress on the blades during rotation, and properties of materials used in manufacture. (Manwell et al. 2009)

2.2.2 Rotor speed: fixed or variable

Standard grid-connected wind turbines have formerly operated at fixed-speed. This implies that the turbine's rotor speed is not dependent of the speed of wind, but rather determined by turbine and grid design. Fixed-speed wind turbines are typically fitted with an induction generator designed to obtain the highest possible efficiencies at a specific speed of wind. The benefits of fixed-speed wind turbines include their simplicity, reliability, and sturdiness. Furthermore, their construction is relatively inexpensive due to low costs of their electrical components. There are, however, disbenefits to fixed-speed operation, such as mechanical stress, restricted power rate quality control and intractable reactive power consumption. Varying wind speeds induce fluctuations in the mechanical torque and, consequently, in the produced electrical power. This may generate major voltage fluctuations and line losses. (Ackermann 2005)

The majority of modern wind turbines, especially large models, operate at variable speed, allowing the rotational speed of the turbine to be adjusted to the speed of wind (Wizelius 2007; Ackermann 2005). With variable-speed wind turbines it is possible to maximise power production at lower wind speeds and additionally decrease loads in the drive train at higher wind speeds (Manwell et al. 2009). A variable-speed wind turbine is commonly equipped with a power converter, which regulates the speed of an induction or a synchronous generator. The mechanical generator torque therefore maintains relatively constant, and fluctuations in winds are absorbed by changes in the generator speed, contrary to a fixed-speed turbine. Variable-speed wind turbines also have the advantages of decreased mechanical stress, higher power quality and enhanced energy capture. (Ackermann 2005) On the other hand, more complex and thus expensive equipment may be required, increasing the overall cost of construction (Manwell et al. 2009). Additionally, losses in power electronics may appear (Ackermann 2005).

2.3 Wind farms

Wind farms are essentially wind turbines forming a power production unit in which they are constructed adjacent to each other. These installations have several advantages in comparison to single wind turbines. Favorable wind resources are only provided in specific geographic areas and hence it is profitable to site multiple wind turbines in such locations, naturally increasing the produced wind energy. Furthermore, in larger wind farms, devoted maintenance staff can be employed in order to decrease costs of labor of an individual wind turbine. Storing of maintenance and repair equipment as well as replacement parts can be concentrated, possibly resulting in financial benefits. (Manwell et al. 2009)

2.3.1 Wake effect

The rotor of a wind turbine momentarily reduces the speed of wind as it harnesses energy, and the wind may only achieve its initial speed approximately ten rotor diameters behind the turbine (Wizelius 2007). In addition to lower wind speeds, vortices occur behind the turbine due to interaction of the rotor blades and the wind. This turbulence caused by wind turbines is called the wake turbulence. Wind turbines downwind of others are highly affected by the increased turbulence, experiencing weakening of materials as well as decreased turbine life and energy capture. Furthermore, turbine loads resulting from wind gusts are limited by control actions which may cause turbines to shut down, reducing overall power production. (Manwell et. al 2009) The wake effect must be taken into consideration when designing the layout of a wind farm. The turbines should be placed adequately far apart from each other, commonly a distance of five rotor diameters if the turbines are set in one row, to decrease the influence of wake turbulence. (Wizelius 2007)

2.4 Offshore wind power

Wind turbines can be installed both onshore and offshore. The EU’s total wind power capacity at the end of 2018 was 178.8 GW of which 160.3 GW was onshore and 18.5 offshore wind power (REN21 2019). Onshore wind turbines are located on land, whereas offshore wind power refers to wind turbines installed in aquatic environments such as seas, oceans or lakes. There has been growing interest in offshore wind power in recent years, the primary motive being the inadequacy of land suitable for wind power production, particularly in northern Europe. (Manwell et al. 2009)

In addition to shortage of land, offshore wind resources are one of the prime causes of the appeal of offshore operation. The speed of wind is consistently higher over open water, increasing with distance from coast. This generally tends to increase productivity. In addition to higher speeds, offshore winds are typically less turbulent in comparison to onshore sites, which usually improves a standard wind turbine’s performance. Further, offshore sites provide sufficient areas for larger wind power projects, and owing to less wind shear, tower height offshore can be lower than would be necessary onshore. (Manwell et al. 2009) Wind farms can also be constructed in close proximity to heavily populated coastal areas, which would typically not be the case with onshore wind power. The North Sea and Atlantic Ocean are currently the primary locations for offshore wind farms, having as much as 90% of the global offshore capacity. (IRENA 2019)

However, offshore wind power production is rather expensive due to transport, specialised equipment, the grid connection to shore, and costly support structures and turbines (IRENA 2019; Manwell et al. 2009). The special offshore turbines account for approximately 45% of total installed costs of an offshore wind farm. Despite the challenge, development of offshore wind turbine technology and wind farms as well as increasing experience in the industry have been able to decrease offshore wind power costs. There has been a decrease of 5 % in the average installed costs since 2010, and they are expected to fall significantly by 2050. (IRENA 2019)

The offshore wind turbine is fairly similar to the onshore model apart from the support structure, consisting of a tower, a substructure and a foundation. The substructure is a component which extends vertically upward from the seafloor and connects the tower to the foundation submerged into the seabed. There are multiple support structure options for offshore turbines, yet the monopile has generally been the most prevalent type. Monopiles are steel tubes with a diameter between 2.5 and 4.5 meters, usually driven 10–20 meters below into the seabed. (Manwell et al. 2009)

The offshore wind turbines with these conventional foundation types are currently only limited to waters up to 60 metres deep, restricting the potential deployment of offshore wind especially in areas with few shallow-water sites. The floating wind farm is an emerging technology that could enable a rapid growth in the offshore wind power capacity in the future, since it allows access to deeper waters and facilitates turbine installation. There are three principal floating foundation designs under development and testing: tension-leg platforms, spar-submersibles and spar buoys. (IRENA 2019) The spar buoy, for example, is a floating cylinder with a ballast at the bottom for stabilisation. The buoy is additionally equipped with mooring lines and anchors that keep it steady and in place. (Manwell et al. 2009)

2.5 Siting

This chapter is a brief overview of the siting phase of a wind power project. Both onshore and offshore wind power sites are addressed, including possible limitations and recommendations to consider when planning to install wind power capacity in these areas.

2.5.1 Onshore wind power

When searching for an onshore site suitable for a wind farm, several factors should be considered, the wind resource naturally being the foremost aspect. Contrary to offshore sites, the onshore winds are highly influenced by local conditions such as hills, mountains, vegetation and buildings, thus the wind conditions should be carefully evaluated by surveying wind resource maps, for instance. This information may be used for a vague estimation of expected production of a wind farm. Production could be increased by installing wind turbines on top of a hill or a slope, but such roughness of the terrain around the site may also reduce production due to a decrease in the speed of wind. This and many other factors are then noted when calculating the expected power production of a site more specifically by using the wind atlas method. The method utilises wind data from existing meteorological masts. (Wizelius 2007)

A wind farm should not disturb nearby residents with noises or rotating shadows from the rotor, thus a minimum distance of 500 meters to the closest dwellings must be secured. There are software available for the calculation of sound emissions as well as plotting shadow diagrams, which are useful tools for the feasibility study of a specific site. Visual impact of wind turbines can be surveyed by embedding the turbines into pictures of the landscape taken from different viewpoints. Access to roads and costs of building service routes, distance to the grid, and the ground conditions of the site must additionally be assessed in order to enable the transportation, installation and maintenance of wind turbines. (Wizelius 2007)

2.5.2 Offshore wind power

Various issues should be considered in siting an offshore wind farm. These include, for instance, sea lanes, fish, mammal and bird breeding and feeding habitats, fishing areas, existing underwater cables, seabed characteristics, storm tides, underwater currents, transportation for maintenance, and the available infrastructure for construction. If the wind turbines are located distant from the coast, the wind speed and thus electricity production will possibly be higher. On the other hand, the installed expenses will be higher since the transmission cable to shore must be quite long. The waters are typically deeper far from the coast, and thus larger and more expensive support structures may also be required. (Manwell et al. 2009)

There are typically extensive feasibility studies and permitting activities prior to building an offshore wind farm, hence comprehensive site investigations are often required in the process. In addition to the study of wind conditions, these include bathymetry, sea floor imaging, magnetometry, acoustic sub-bottom profiling and soil borings, among others. Bathymetry is a measurement of the depth of water, and it can be executed with a device called an echosounder. The results of bathymetry measurements are usually more correct than values accessible from nautical charts. Sea floor imaging can be implemented with side scan sonars, and the intention of the imaging is to observe what is visible on the sea floor. This could be structures such as shipwrecks which may impact the siting of the turbines. Shipwrecks and unexploded ordnance can also be detected with magnetometry, which is used to discover any magnetic material in the area. Acoustic sub-bottom profiling is based on sound waves and is done as a part of the preliminary geophysical investigation to determine the quality of the soil under the sea floor. Soil borings are required to decide the design of the support structure. They are implemented with an offshore drilling rig which bores holes and takes soil samples over the full length of the predicted support structure if attainable. (Manwell et al. 2009)

3 STATUS OF WIND POWER IN COLD CLIMATES

This chapter addresses the current status of wind power, projects under development and the estimated outlook for the near-term future in Finland and Scandinavia.

3.1 Finland

In the end of 2019, the electricity demand of Finland amounted to approximately 86 TWh. Net imports of electricity aggregated 20 TWh, and 66 TWh was generated in Finland. A total of 6.025 TWh or 9 % of the electricity generation was produced by wind power. By comparison, nuclear power contributed 35 % and hydro power 19 % of the electricity production in Finland. (Energiateollisuus 2020; Official Statistics of Finland 2020)

There were 756 wind turbines in operation at the end of 2019, comprising a capacity of 2288 MW. Over the year 2019, 56 turbines with a combined capacity of 243 MW were installed across the country, the largest wind farm consisting of 18 turbines located in Närpiö, Ostrobothnia. There was a considerable decrease in new installed capacity compared with the year 2017 during which a total of 154 wind turbines were constructed in Finland. (Finnish Wind Power Association 2020a) In 2018, however, there was zero new wind power installed (Komusanac et al. 2019). The Finnish support scheme for wind power called the feed-in-tariff system was closed for new wind farms in November 2017 and replaced with a tendering process in 2018 (Finnish Wind Power Association 2021). This is likely the reason for the deficiency of new installed capacity in 2018. The cumulative capacity and production of wind power in Finland are presented in Figure 1, indicating a significant increase in production during the past decade.

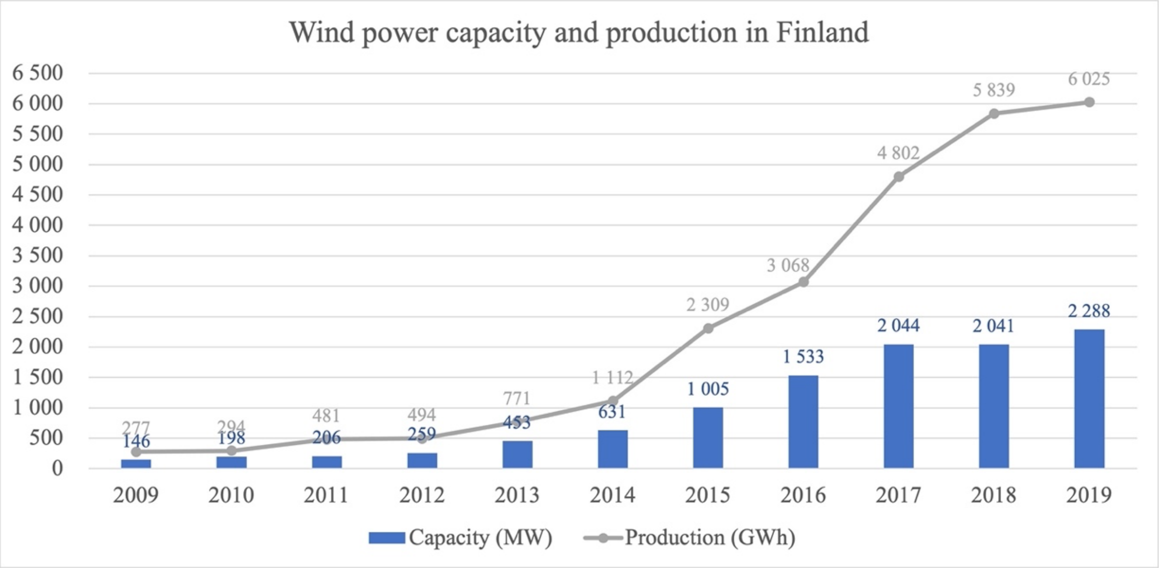

Figure 1. The wind power capacity and production in Finland in the years 2009–2019 (Finnish Wind Power Association 2020a; Official Statistics of Finland 2020; Official Statistics of Finland 2019; Komusanac et al. 2019; Peltola et al. 2018).

3.1.1 Projects under planning and construction

There were 212 new wind power projects, having a combined capacity of approximately 18 500 MW, under development in February 2020. Offshore wind power accounted for 2700 MW of the capacity under planning. (Finnish Wind Power Association 2020b). All the projects planned are not presumably to be executed due to, for instance, wind resources of the areas or environmental issues (Finnish Wind Power Association 2020c). However, in January 2020, 69 projects had already been fully permitted and 22 were under construction. Northern Ostrobothnia appears to be a favored location for new wind power projects as more than 30 % of the projects under development are sited in its municipalities, especially in coastal areas such as Pyhäjoki (nine projects), Raahe (eight projects), Ii (six projects) and Kalajoki (four projects). (Finnish Wind Power Association 2020b) One of the projects is a fairly large offshore wind farm planned by The Finnish wind power company Suomen Hyötytuuli. The power unit would comprise 25–50 wind turbines and be constructed to Ulkonahkiainen, located at Bothnian Bay near the coast of Raahe and Pyhäjoki. This project was, however, only in its early stages in January 2020. (Finnish Wind Power Association 2020b, Suomen Hyötytuuli 2020) In September 2020, the most recently completed wind power installation in Northern Ostrobothnia was the Hirvineva wind farm in Liminka (Finnish Wind Power Association 2020d).

3.1.2 The future of wind power

There is a growing interest in wind power in Finland, and the capacity could be increased significantly in the future. Nghiem et al. (2017) predict the Finnish wind power capacity to be between 5000 MW and 10 000 MW in 2030 according to a central and a high scenario, respectively. The wind power industry aims at a generation of 30 TWh of annual production by the year 2030, which would contribute roughly one third of the country's electricity consumption then. In addition, the size of wind turbines is expected to increase particularly in offshore wind farms. (Finnish Wind Power Association 2020e)

Regional land use plans do not currently propose a significant increase in wind power sites as only a small share of potential sites have been allocated. It has therefore been advised to take the possible increase in wind power construction into consideration when composing future plans and modifying current plans. (Finnish Wind Power Association 2020c) The national grid appears to be quite reliable and flexible, thus moderate additions in wind power plants do not require improvement of the power grid (Finnish Wind Power Association 2020f). However, if many new power plants are constructed, the system must be developed and strengthened (Finnish Wind Power Association 2020c).

The wind resources in Finland, both onshore and offshore, are adequate to attain larger wind power capacities in the future (Finnish Wind Power Association 2020c). The average wind speed is fairly high especially in coastal areas and on the sea, although variations in wind speeds are more frequent in such areas compared with inland. The winds in Finland are variable in speed according to the time of year, and the strongest winds typically occur during the wintertime. Essentially, Finnish winters are windier than summers. (Finnish Wind Atlas 2020a,b)

3.2 Scandinavia

Scandinavian countries typically have cold weathers during the wintertime, which can impact current and future wind power installations. This section overviews the status of wind power in Scandinavia, and possible interests of research and development.

3.2.1 Sweden

Approximately 165.6 TWh of electricity was generated in Sweden in 2019, wind power supplying roughly 12 % of the national electricity production as the total electrical energy output from wind was 19.8 TWh. Hydro and nuclear power each contributed around 39 % of the produced electricity. (Official Statistics of Sweden 2020)

At the end of 2019, Sweden’s total wind power capacity amounted to 8984 MW from 4099 wind turbines. There was 1588 MW of capacity installed throughout the year 2019, contributing 10 % of new wind power installations in the EU. The total offshore capacity remained at 190 MW since there was zero new offshore wind power constructed in 2019. (Gustafsson & Rigole 2020; Komusanac et al. 2020)

There has been increasing interest in siting new wind power projects especially in Northern Sweden and forested areas due to great wind potential of these locations. It is, however, uncertain if local conditions enable efficient wind power production in such areas. Northern Sweden’s cold climate poses many challenges to wind power operation, one of them being turbine blade icing. Energy capture and loads of turbines caused by turbulence in forested areas are also topics of discussion which research projects aim to gain further knowledge of. (Gustafsson & Rigole 2020)

Sweden has a market-based support system for the production of renewable energy referred to as the electricity certificate. Electricity producers are granted a certificate by the government per each MWh produced from renewable energy sources in new or renovated power plants. The certificates are then sold to electricity consumers on an open market. Sweden and Norway have operated at a common electricity certificate market, in which certificates are traded across borders, since 2012. (Gustafsson & Rigole 2020)

The country has a target of 100% renewable energy production by the year 2040. It is estimated that 2.5–6 TWh worth of renewable power should be added every year between 2030 and 2040 in order to achieve the goal, wind power supplying a significant share of the new capacity. (Gustafsson & Rigole 2020) The annual output of wind power would have to expand to 70 TWh and the capacity to 21 000 MW by 2040 (Swedish Wind Energy Association 2018). There is, however, some uncertainty surrounding future installations since the joint Swedish-Norwegian electricity certificate is set to end after 2021 (Komusanac et al. 2020).

3.2.2 Norway

In 2019, a total of 134.9 TWh of electricity was produced in Norway. Wind power was the second-largest source of electricity, contributing approximately 5.5 TWh or 4 %. This implies an increase in wind-based electricity of nearly 43 % from the year 2018. Hydro power is the foremost source of electrical energy in Norway as it generated more than 93 % of the national electricity production in 2019. (Statistics Norway 2020)

There was 2444 MW of installed wind power capacity in total at the end of 2019. 785 MW of new capacity was installed and 31 MW decommissioned throughout the year. Furthermore, over 2200 MW of onshore projects were under construction at the end of the year. Similarly to Sweden, none of the new installed capacity was offshore wind power, thus the total capacity of offshore wind sites maintained at 2.3 MW in 2019. (Østenby 2020; Komusanac et al. 2020)

Research and development activities in Norway are primarily focused on icing challenges onshore, and floating offshore wind turbines. Floating offshore wind power is physically more suitable compared to bottom-fixed offshore turbines due to the large amount of deep waters in Norway. However, the evaluated cost of building offshore wind power, both floating and bottom-fixed, is currently high compared to the country's grid parity. There is also not a significant wind turbine manufacturing industry in Norway, but there appears to be growing interest in offshore wind on the Norwegian market. Some companies experienced in the offshore oil and gas industry are increasing their engagement to offshore wind power. They have begun to offer wind turbine substructure solutions for offshore sites, utilising their knowledge from operating at sea. (Østenby 2020)

Norway does not currently have any specific target for wind power production, however, the amount of onshore wind power is expected to increase significantly in the near-term-future. Furthermore, the national wind power capacity is estimated to reach nearly 5000 MW by the end of 2021. After 2021, Norway will not continue in the electricity certificate scheme, thus Norwegian wind power will need to be profitable independently without potential income provided by the arrangement. A shift towards offshore wind power activities in the future seems likely. (Østenby 2020)

3.2.3 Denmark

A total of approximately 29.3 TWh of electricity was produced in Denmark in 2019. Wind power was evidently the largest electricity provider as it generated around 16.2 TWh or 55 % of the national electricity production. (Danish Energy Agency 2020) In 2019, Denmark had the largest proportion of wind energy in its electricity demand in Europe. The second-largest and third-largest sources of electricity in Denmark were combustible renewables and coal, contributing 19 % and 10 % of the electricity production, respectively. (Remler et al. 2020)

At the end of 2019, Denmark's wind power capacity aggregated around 6000 MW. There was 402 MW of new capacity established throughout the year, and 39 MW was decommissioned. New offshore wind power installations had a combined capacity of 374 MW in 2019, and thus the total capacity of offshore wind power amounted to 1700 MW. The wind power capacity in Denmark is relatively old. In the year 2000, the national capacity was approximately 2000 MW, and therefore over 30 % of the total wind power capacity was nearly 20 years old in 2019. (Remler et al. 2020; Komusanac et al. 2020)

The Danish Parliament approved a programme called the Danish Climate Act in February 2020. One of the key elements of the national Climate Act is the goal to reduce the country's greenhouse gas emissions by 70 % in 2030. The climate programmes released in each update of the Climate Act are predicted to accelerate wind energy deployment towards 2030. The specific role of wind power in the national goal will be settled in the future. (Remler et al. 2020)

In September 2019, the height limit of 150 meters for onshore wind turbines was removed in Denmark. This change will allow municipalities to construct fewer but larger wind turbines, possibly producing significantly more green energy per year. The Danish Energy Agency has projected the annual offshore wind power electricity production to increase with five times to 33 TWh and onshore production with two times to 20 TWh by 2030. It has been estimated that Denmark would have an offshore wind power capacity of 2650 MW in 2023, followed by an additional amount of 2400 MW by 2030. The future research projects are expected to concentrate on system integration and digitalisation of wind energy. (Remler et al. 2020)

4 THE IMPACT OF ICING

Low air temperatures and a wet environment may result in ice formation on wind turbines and other infrastructure on the site (Battisti 2015). The phenomenon of icing occurs when water droplets cool below the freezing temperature 0 °C and freeze as a result (Xue & Khawaja 2016). Icing essentially originates from either atmospheric icing or sea water sprays. Atmospheric icing includes all icing events due to rain or snow, whereas sea spray icing is a result of sea water sprays splashing on the turbine structure or sea water droplets transferred by wind contacting the turbine. Atmospheric icing is formed in three different processes: precipitation icing, in-cloud icing and hoar frost. Precipitation and in-cloud icing are the primary factors in wind turbine icing. Precipitation icing is caused by freezing rain or wet snow, and the accretion rate is typically higher than in cloud-icing. In-cloud icing occurs as supercooled liquid droplets, usually cloud droplets, contact with moving structures and freeze on them. In-cloud icing often results in thick ice layers. (Battisti 2015)

4.1 The impact of icing and low temperatures on the wind turbine structure

Ice can accumulate over both stationary and moving parts of a wind turbine (Battisti 2015). The appearance and physical properties of ice accretion vary depending on the weather conditions during the ice growth (Xue & Khawaja 2016). The two primary types of accreted ice are rime and glaze ice. Rime ice typically accumulates in temperatures well below 0 °C, and it can occur in two forms: soft rime or hard rime. Glaze ice appears as hard, high in density and difficult to remove from objects. Glaze is commonly transparent, and it can form large uniform ice sheets over surfaces. (Battisti 2015; Manwell et al. 2009)

4.1.1 Blades

Icing of wind turbine blades can generally occur in three situations: power production, idling and standstill. Idling is the operational state in which the wind turbine blades are rotating but the turbine is not connected to the grid, whereas standstill indicates that the rotor is at rest and the blades are not in motion. In horizontal-axis wind turbines, the ice accumulation during power production is more prevalent at the outer part of the blade.

The ice at the blade tip usually detaches and accumulates again during operational actions in storms, forming a type of saw-tooth ice distribution. Icing challenges are more severe in idling and standstill states where ice spreads on significantly larger areas of the blade than in the power production state. In vertical-axis wind turbines, the joints between the turbine blades and arms are highly exposed to ice and snow accumulation due to the effect of centrifugal forces and the specific turbine structure. (Battisti 2015) However, this chapter focuses primarily on ice accretion on horizontal-axis wind turbine blades.

Atmospheric icing decreases the aerodynamic performance of a wind turbine rotor considerably since the blade aerodynamics are sensitive to additional roughness on the surface (Baring-Gould et al. 2009). Ice accretion mainly on the leading edge of the blade results in differences in the aerodynamic profile shape of the blade and impacts its structural dynamics as a result of added masses. This causes a considerable increase in aerodynamic drag and a decrease in aerodynamic lift. In addition, the icing of blades could induce premature air flow separation. All of the above-mentioned, for instance, can result in severe power losses on the wind turbine operation. The extent of power loss is dependent mainly on the amount of ice accretion, blade design and turbine control. (Yirtici et al. 2019; Afzal & Virk 2018)

Ice structures on blades can also cause additional vibrations and loads on the wind turbine. Ice accretion can excite edgewise vibrations on the blade, and the increase in blade mass weakens its natural frequencies. The change in frequencies may consequently induce resonance, especially for smaller wind turbines and blades light in weight. Asymmetrical icing does not only affect the blades, but also induces vibrations and loads in the turbine tower and nacelle. Ice can accumulate rather unevenly on the blades, meaning one blade may have more ice mass and shapes than the other. These differences in asymmetric ice masses between individual blades may cause imbalances in the rotor, resulting in fatigue loads and reduced lifetime for all components of the wind turbine. (Gantasala et al. 2019; Afzal & Virk 2018) The increased surface roughness of turbine blades also results in higher noise levels compared to clear blades (Baring-Gould et al. 2009).

4.1.2 Wind turbine machinery

Low temperatures and icing impact the materials used in the manufacturing of a wind turbine, such as glass fibre structures, steel, plastics, grout, concrete, and lubricants. Materials have a tendency to become brittle in low temperatures, implying that their ability to deform without damage is reduced. (Krenn et al. 2016; Baring-Gould et al. 2009) Additional vibrations induced by mass imbalance and possible large ice chunks detaching from the blades and contacting the turbine structure can cause stress and hardly visible damage on various components. This can result in micro-cracking and delamination of the wind turbine materials. The micro cracks reduce rigidity and impermeability of the materials, possibly hastening the deterioration process which could eventually cause structural failure of the wind turbine. Crack growth due to both the cold climate and general fatigue are one of the primary factors impacting structural integrity of wind turbines in such conditions. (Afzal & Virk 2018)

Thermal expansion of materials in different temperatures should also be noted as it can affect the operation of various components. For example, concrete or grouted structures' thermal cracking can have an impact on permeability associated with the possibility of water infiltration, increasing the risk of corrosion. Electrical equipment such as generators, transformers, yaw and pitch drive motors and control electronics have also been reported to be adversely affected by low temperatures and thermal expansion. For instance, when a pitch drive motor is activated in cold temperatures, the stator can be damaged due to the abrupt increase in heat and differential thermal expansion in the cold motor. This could lead to failure or decreased motor lifetime. (Krenn et al. 2016; Baring-Gould et al. 2009)

Wind turbine nacelles are usually not airtight structures since they typically have several openings to enable cooling. Snow is easily transported by wind and it can accumulate in the nacelle, damaging particularly electrical equipment. It can also block openings and limit normal air circulation in the nacelle. (Baring-Gould et al. 2009)

The heat generated by internal losses inside a liquid-filled transformer may not evacuate quickly enough in cold-start scenarios. As temperature decreases, the viscosity of the lubricants and hydraulic fluids increases. Liquid-filled transformers can cool down to even –40 °C according to the location of the transformer: in the nacelle, in the base or the mid-section of the tower, or outside. Due to the viscosity of the cooling liquids increasing at such temperatures, the natural convection cooling of the internal windings can become limited as the fluid is too rigid to circulate and thus remove heat. This poses both a reliability and safety risk for the turbine operation. (Krenn et al. 2016)

Unsuitable lubrication oils and greases have also been observed to damage, for instance, gearboxes and bearings and during low temperature operations (Baring-Gould et al. 2009). The excessive stiffness caused by higher viscosity of the fluids in low temperatures can prevent pumping and therefore unable sufficient lubrication the components. Inadequate lubrication can damage the machine quickly. Furthermore, the higher viscosity of lubricants decreases the power transmission capacity of the gearbox and consequently adversely impacts the efficiency of the turbine. Seals of components in contact with greases usually lose flexibility at lower temperatures, possibly causing leakages. (Krenn et al. 2016)

Cup anemometers and wind vanes, measuring the speed and direction of wind, are highly affected by icing (Battisti 2015; Manwell et al. 2009). Small quantities of ice can severely reduce the measured wind speed – it has been observed that accumulation of rime ice on the cups and shaft of an anemometer functioning at a wind speed of 10 m/s causes a speed underestimation of approximately 30 %. Larger ice structures may even totally prevent the operation of the anemometer. A complete stop can result in malfunctioning of the turbine due to controller insufficiency to monitor the intensity of wind and changes in direction. Additional vibrations, energy yield losses, and ultimately, shutdown could consequently occur due to the wind turbine rotor not being able to follow shifts in wind direction. If the turbine is in standstill state, it can start in the wrong rotational direction or unwantedly remain in standstill caused by wrong or underestimated measurement of wind speed. Large power fluctuations can also eventuate if the turbine is in its operational state with a partly iced anemometer. (Battisti 2015)

4.2 Site access and infrastructure

Wind turbines may be located at remote sites, and access roads are probable to face seasonal restrictions due to icing and snow drifts. Snow and ice may complicate or even prevent site access without snowmobiles or other specialised vehicles. Moreover, if the access is limited to a snowmobile, only light repair instruments can be transported to the site. Poor accessibility can also force construction or maintenance personnel to stay at the site for longer periods of time, and expanded snowstorms can block access roads and even completely isolate wind power sites. It has been remarked that icing and snow have expanded the duration of maintenance and repair operations significantly. Low temperatures and turbine inaccessibility can also result in higher downtime between repairs and increased maintenance costs. (Laakso et al. 2010; Baring-Gould et al. 2009)

Seasonal and climatic restrictions of site access likely impact the overall logistics of wind power site construction projects. In remote and possibly snowy areas, the length and weight of the turbine tower and other components may face limitations due to weight and turning radius limits of bridges and access roads for large trucks and cranes. Seasonal access restrictions may force wind site construction to be executed over more than one season, possibly increasing mobilisation expenses for construction crews and cranes and affecting the selection of wind turbines. (Baring-Gould et al. 2009)

Snow and ice accumulating on doors and hatchways can prevent access inside wind turbines or toolsheds. Icing on turbine towers and climbing structures can cause the surfaces to be unserviceable, complicating maintenance and causing safety risks. Ice can also accumulate inside the turbine and make moving more dangerous for personnel. The human capacity to concentrate on safety and problem solving is lower in disadvantageous conditions such as low temperatures and high winds. This may pose a considerable safety hazard as well. Furthermore, even brief exposure to low temperatures can cause frostbites and other injuries. (Baring-Gould et al. 2009)

Heavy ice or snow accumulation on meteorological masts and aerial power lines located on the wind power site may cause breaking of the structures. Meteorological masts are typically very thin, as slender masts influence the atmospheric measurements less than wider constructions. The mast can collect ice masses of even five times its own weight. Ice loads, particularly combined with high wind speeds, can critically damage the mast structure. Ice accumulation on the guy wires supporting the mast may slide down and damage cable clamps or anchor rods. Overhead power cables can be strained by ice loads or the impact of permafrost soil's freezing cycles on power poles. However, the use of buried cable is also typically restricted by permafrost or solid rock due to the costs of trenching and the possibly cable-damaging dynamic behavior of permafrost soil. (Baring-Gould et al. 2009)

Permafrost soil impacts the development and construction of wind turbines in cold climate sites as well. Permafrost can be classified into two categories: ice-poor and ice rich. The construction and type of the support structure of a wind turbine depends on the permafrost layer prevalent on the specific site. Ice-poor permafrost conditions are perhaps the most challenging due to the need of excavation to a more stable ground layer. Foundations of a standard design can be used after this procedure. Ice-rich permafrost typically consists of fine grain soils containing a large amount of frozen water. A significant part of the structural durability then actually relies on the ice structure. The frozen soil must therefore be protected from possible heat induced by wind turbine heaters in order to keep the foundation stable. In some areas the active layer of permafrost, the part that thaws during summertime and freezes during wintertime, can be fairly large, requiring special foundations to guarantee that the turbine tower is properly anchored. (Baring-Gould et al. 2009)

4.3 Ice throw

Ice accretion on turbine blades and other components does not only decrease system performance, but it also affects the safety of wind power sites. As a result of either natural conditions or de-icing actions, ice pieces of different weights and shapes may suddenly detach from the blade surfaces, tower and nacelle during standstill, idling or operation. (Battisti 2015) However, it has been recognised that when a wind turbine with ice accumulation on the blades is stopped and turned on again, shedding of ice appears to be more prevalent. This could be caused by, for instance, vibrations induced by the stoppage or bending of the turbine blades. Bending of the blade tips has been observed to occur when the blades are rotating, and the wind turbine is in operation. The deflection is on average approximately 2 ±0.5 m in length and is caused by wind load. (Xue & Khawaja 2016)

Ice shedding is essentially associated with mechanical failure of ice. Since ice is a brittle material, it can crack when a certain amount of stress is applied. This can be connected to ice throw during turbine operation as bending strains the ice structures accumulated on the blades. It has also been recognised that when ice on the blades extends to a certain thickness, it begins to loosen. The prominence of this phenomenon is dependent on weather conditions, turbine dimensions and rotational speed. (Xue & Khawaja 2016)

When the ice cracks and loosens, the detached fragments are thrown off the blade by gravitational, aerodynamic and centrifugal forces. Rotating blades may even project ice pieces to a distance of several hundred meters from the turbine. The area covered by the ice fall around the wind turbine depends, in addition to rotational speed and other turbine parameters, on the strength and direction of wind and on the size and mass of the detached ice fragments. Ice throw poses a significant safety and economic risk for the surroundings of the wind turbine if protection measures are not established. Falling ice can cause injuries for maintenance personnel and damage vehicles, equipment and other structures on the site. (Xue & Khawaja 2016; Battisti 2015)

4.4 Offshore challenges

In offshore locations, icing poses a challenge for wind turbine operation for two primary reasons: the impact of icing on structures caused by atmospheric icing and sea spray, and also the mechanical actions of sea ice. (Battisti 2015; Battisti et al. 2006)

The prevalence of sea spray originating from sea water is naturally emphasised in offshore sites. However, the relative importance of sea spray and atmospheric icing does vary according to, for instance, the turbine components' height above the sea surface. Depending on the speed of wind, sea sprays typically do not reach to a height of more than 15–30 meters. That is, they can usually only reach the lower parts of the turbine such as the bottom structure of the tower and the blade tips when they are pointing downwards. (Battisti 2015; Battisti et al. 2006)

Sea ice causes additional static and dynamic forces on the wind turbine structure, inducing mechanical shocks and enhanced vibrations which may result in additional operational loads. Field experiences have strongly indicated that offshore turbines suffer from these actions less at areas where sea ice is mainly land-fast ice compared with areas of drifting ice. (Battisti 2015; Battisti et al. 2006) Fast ice generally refers to motionless ice anchored to the shore or the ocean or sea bottom, whereas drifting ice is ice moving from winds or currents (National Snow & Ice Data Center 2021a,b).

The land-fast ice surrounding the wind turbine is usually fairly consistent. The ice sheet does, however, have an impact on the wind turbine as the stationary contact between the ice and the turbine tower induces static loads on the structure. The ice sheet is gradually pushed against the structure by winds, currents drags, and thermal expansion. The tower can be seen as an isolated pinning point resisting the driving force which can be distributed over the tower surface. (Battisti 2015; Battisti et al. 2006)

Dynamic loads on the structure can occur as floating ice blocks or large ice fields hit against the turbine foundation with considerable velocity, even more than 1 m/s. The duration of contact and the forces exchanged with the turbine structure are dependent on the kinetic energy of the moving ice and on its features. Structural vibrations can, however, be a result of both drifting ice colliding with the turbine and the turbine structure's ice caused by atmospheric icing or sea spray. (Battisti 2015; Battisti et al. 2006)

Sea ice gradually accumulating on the turbine tower could modify the tower weight and aerodynamics and therefore alter loads on the foundation. The ice can also accelerate the corrosion process of the tower and support structure if corrosion protection techniques are not applied. (Battisti 2015; Battisti et al. 2006) Finally, if the sea is completely frozen, access for maintenance can be limited or impossible for long periods of up to several months. This could possibly have negative impacts on the estimates of offshore wind energy output. (Battisti et al. 2006)

5 SOLUTIONS

This chapter provides and overview of solutions used to mitigate icing and low-temperature risks. Tools for both wind turbine structure and wind power site issues are presented.

5.1 Ice detection

Ice detection should be addressed both in the wind power project development stage and during wind farm operation. Ice detection tools are targeted at detecting and measuring meteorological and instrumental icing, ice load and the intensity of icing. The detection and measurement of ice are needed to evaluate the impacts of ice on wind turbines and power production, and to enable adequate control of anti- and de-icing systems. Ice detection also helps to provide a safe working environment for site personnel. Ice detection instruments can be installed on wind turbine blades, the nacelle or on a meteorological mast. (Krenn et al. 2016)

Ice detection instruments would ideally be able to measure icing automatically and accurately, supplying information about duration and intensity of meteorological and instrumental icing and ice load estimations. Instruments able to measure liquid water content and the droplet size distribution would also be ideal to certify results from numerical weather models. However, modern ice detection technologies are not currently quite as developed as described above, and many ice detection tools are waiting for formal verification. (Krenn et al. 2016) The detection of ice on turbines is complicated since the accumulation is dependent not only on the current meteorological conditions, but also the structures exposed to icing. It has been suggested that ice detectors can be categorised as direct icing sensing techniques and indirect icing sensing techniques. (Battisti 2015)

5.1.1 Direct icing sensing techniques

Direct icing sensing techniques are further classified as mechatronic systems, electric systems and optical systems, and they track changes of physical quantities induced by icing. An example of mechatronic systems is the measurement of the attenuation of a signal, in which an ultrasonic or a microwave signal's attenuation through a low acoustic attenuation mean is determined. The signal induced at the one end of a waveguide, typically made of steel or nickel tape, is collected at the other end, and the signal's damping rate is measured. Piezoelectric elements can be used for this procedure. The principle behind the technique is that ice causes a high attenuation of the signals, whereas the density and viscosity of water in its liquid form causes a considerably lower attenuation and can therefore be differentiated from ice on the structure. Another example of mechatronic systems is the measuring the shift of resonance frequency. This method is based on the variation of the resonant frequency of a vibrating mass, which changes as a result of ice accumulation on the structure. The natural frequency of the mass is predicted to decrease while the mass increases. This can be tracked by piezoelectric and magnetostriction instruments. (Battisti 2015)

The measurement of change in electric properties can be also used to determine the presence of ice. This method is based on tracking the impedance, inductance or capacitance variation due to the change of electric properties of the water-ice layer. The sensors are thin and can detect ice accumulation on a fairly large area, allowing them to be easily installed on blades afterwards. (Battisti 2015)

Optical systems include, for instance, direct measurement of reflected light, infrared spectroscopy, and web camera recordings. A source of light reflected or emitted by the structure can be measured in order to detect ice, since ice accretion changes the reflectance and emittance of the surface. The signal can be digitally inspected to connect the result with the absence or presence of ice. This method also allows executing icing rate measurements by the cyclic heating of the surface. (Battisti 2015)

The method of infrared spectroscopy measures infrared light reflection and absorption by the ice. The downside of this method is that it cannot determine the thickness of ice due to the reflection rate being affected by the ice type. The advantage of infrared spectroscopy is that the system does not require electrical wiring on the rotor blade surface being mounted to the hub. However, the sensor may become faulty if the reflection area is not clean, and the system is difficult to install afterwards since the fibre optics must be inserted inside the turbine blade. Web cameras facing the turbine blade combined with image analysis techniques can also be utilised to determine the presence of ice. This method has the disadvantage of requiring a light source to capture the images, and thus it cannot be effective in limited illumination conditions if artificial lighting is not implemented. (Battisti 2015)

5.1.2 Indirect icing sensing techniques

Indirect icing sensing techniques utilise measurements of parameters which can, compared with normal values, indicate probable icing conditions. These methods include measuring wind turbine-based parameters, noise, and thermodynamic status of the surface, for instance. (Battisti 2015)

Since blade icing has been observed to decrease the aerodynamic performance and thus the delivered power, these occurrences are possible signs of ice accumulation on the turbine. It is nevertheless important to combine the measure with the surrounding temperature reading and blade accelerations in order to dismiss the possibility of false signals caused by, for example, mechanical failure of the turbine. Measuring the increased weight of the turbine blades and the gyroscopic torque of the hub have also been introduced, addressing the fact that ice typically accumulates unevenly on the blades. However, any changes in aerodynamics can, in principle, result in misleading suggestions on ice accretion. The methods based on wind turbine parameters should therefore always verify if both the meteorological conditions and operational conditions can be associated with blade icing. (Battisti 2015)

Measuring blade surface and detecting the presence of liquid water are also methods to monitor the probability of icing. If there are drops of water on the blade surface and the surface temperature is below the freezing point, the risk of icing is naturally conceivable. Increased noise is also a possible indicator of blade icing. Noise measurement tools should always be customised for the specific wind power site to minimise the impact of background noises. (Battisti 2015)

5.2 Ice protection systems

Ice protection systems for wind turbines are aimed at mitigating ice accumulation and its adverse impacts on wind turbine blades. They are generally classified into two categories: active systems, including anti- and de-icing systems, for instance, and passive systems such as coatings. (Krenn et al. 2016)

In areas of heavy icing or long periods of mild icing, anti- or de-icing systems can be utilised to improve turbine performance. Anti-icing is a method in which considerable ice accretion is prevented while the wind turbine is operating normally. In de-icing operations, ice is allowed to accumulate on blades followed by stoppage of the turbine, and then the ice protection system is activated to erase the predetermined amount of accreted ice. (Krenn et al. 2016; Baring-Gould et al. 2009)

Active methods are typically based upon removing ice by applying heat to the wind turbine blades. An example of active systems is the electro-thermal heating system. It contains a heating membrane or element positioned on the outer surface of the blade. The heat is produced by electrical heating elements inserted inside the membrane, or from a heating element laminated into the turbine blade structure. (Baring-Gould et al. 2009)

Hot air ice protection systems consist of a heat source and an effective fan to circulate hot air inside the blade shell. Such systems are well suitable for milder climates in which icing is prevalent mainly at temperatures close to 0 C. However, as turbine size and blade length increases, blade shells thicken and their thermal resistance increases. Considerably high temperatures are therefore acquired inside the blades in order to retain the outer surfaces clear of ice accretion, even in mild icing conditions. (Krenn et al. 2016; Baring-Gould et al. 2009)

There are also microwave ice protection systems available, including an outer coating on the blade which heats up when exposed to microwaves induced by generators located inside the blade. Mechanical removal systems consist of manual and hot-fluid de-icing methods using rope access, a skylift, or a helicopter. Other active systems include, for example, precautious turbine shutdowns and safety related abbreviations and stoppages. (Krenn et al. 2016)

Some ice protection methods mitigate icing risks passively, meaning no energy is required in the mitigation process. Passive ice protection systems typically utilise the physical characteristics of the blade surface to prevent or eliminate ice. Passive methods include, for instance, black-colored blades and different types of coatings such as stick-free surface coatings. Coatings have the advantage of being relatively affordable and easy to implement, but there has been uncertainty surrounding their actual efficiency for ice prevention and removal. Flexible turbine blades may also naturally remove ice. Some semi-passive methods have also been introduced, one of them being facing the turbine blades towards sunlight. However, these methods may damage the turbines if used repeatedly. (Krenn et al. 2016; Baring-Gould et al. 2009)

5.3 Cold climate packages

Cold climate packages have been developed to expand the functional temperature range of wind turbines, and to increase the safety and reliability of low temperature operations (Krenn et al. 2016). The packages include wind turbine components modified for low temperatures, and they are available from companies engaged in manufacturing wind turbines for cold climates (Baring-Gould et al. 2009). The contents of cold climate packages differ depending on the turbine manufacturer, but they typically comprise low temperature adaptations for the nacelle, the gearbox, the control and yaw system, oils, greases and hydraulic fluids, turbine materials, wind speed and direction sensors, and more (Krenn et al. 2016; Baring-Gould et al. 2009).

5.3.1 Sensors

Heated wind sensors are recommended in sites experiencing frequent icing or snowfall. Both the sensing part, namely the cups or ultrasonic arms, and the supporting pole of the sensor should be heated in order to secure the quality of wind measurements. (Battisti 2015; Baring-Gould et al. 2009) There are several technical solutions available for this procedure, such as fully or partially heated anemometers and bearing heated cup anemometers (Krenn et al. 2016). It must be noted, however, that even fully heated sensors cannot guarantee to be 100 % ice-free, especially during severe icing or snow events (Battisti 2015). It is also possible to use a combination of one heated and one unheated anemometer. They measure almost identical values in normal conditions, but their data differs from each other during icing events. This information can be processed by the turbine control system to shut down the turbine, for instance. (Laakso et al. 2010)

5.3.2 Control system

A wind turbine controller should foremostly recognise the presence of ice with ice detectors, but there are also many other specific features in cold climate adapted wind turbine control systems. The system can, for example, alter some parameters, activate an ice protection system, limit production, or shut down the turbine. (Krenn et al. 2016)

The produced power can be optimised by changing parameters such as pitch, tip speed ratio and/or torque as icing of the turbine occurs. This may reduce icing-induced stall and maintain the turbine in the operational state during icing events. Loads can be reduced by possibly limiting the operation of the wind turbine in some situations in order to decrease fatigue on the turbine components caused by icing. (Krenn et al. 2016) A properly designed wind turbine control system should nevertheless manage additional loads regardless of their source (Laakso et al. 2010).

The wind turbine controller can also interact with the possible ice protection system as all active ice protection systems demand a certain amount of control provided by the turbine. Some systems, typically de-icing ones, are only activated when the iced wind turbine is stopped. Anti-icing systems can run relatively independently from the turbine controller, yet they may require the stoppage of turbine operation during severe icing or other specific events. (Krenn et al. 2016)

Certain wind turbines can also shut down in icing conditions simply due to the risk of ice throw from the rotor blades while the turbine is in operation. This procedure can be implemented due to, for example, local regulations or insurance commitments. In such instances, the wind turbine control system may also include a specialised operation mode for mitigating the risk of ice throw. (Krenn et al. 2016)

A preventive stop strategy contains shutting down the wind turbine in the beginning of an icing situation to reduce ice accumulation on rotor blades, which appears to be more severe when the blades are in motion. The operation is restarted when the icing event has passed. The fundamental principle behind these preventive stops is the approximation of overall energy yield being higher compared to operating the wind turbine in icing conditions. This strategy is usually directed manually by wind farm operators. (Krenn et al. 2016)

5.3.3 Other components

Surface heated gearboxes, gearboxes with embedded heaters and constant oil circulation, and generator heaters can be utilised to decrease problems induced by ice and low temperatures. Heating can also be implemented on various other components such as yaw and pitch drive motors, lubrication units, transformers, and batteries. The protection of the controller from moisture and condensation is highly important and can be ensured by installing heaters in the cabins containing control electronics. (Laakso et al. 2010) The nacelle space can also be heated and equipped with additional sealing to prevent snow accumulation inside. Sealing of components can be implemented with low temperature elastomers to maintain flexibility. Additionally, special low temperature materials and welding procedures can be used in the tower and drivetrain components. (Krenn et al.

2016) Using cold resistant steel with welds, for instance, does not increase the installed wind turbine costs notably (Laakso et al. 2010). Special concrete mixtures and grout solutions can be used in the foundations of the turbines (Krenn et al. 2016).

5.3.4 Offshore adaptations

Especially offshore wind turbine components must be resistant to additional vibrations. Offshore turbines should ideally be equipped with sensors monitoring the environmental loads caused by both turbine icing and sea ice, and the condition of the turbine structure. This concept still requires some development by more advanced diagnostic tools. Semi-active methods could be automatically activated based on the information provided by the sensors. One of the mitigation methods could be embedment of damping and smart elements in the support structure of the turbine, which could reduce the dynamic response of the turbine and extend the fatigue life of turbine structure and components. Structural damping has been detected to be an effective solution against additional vibrations. The foundations of the wind turbines can also partially prevent excessive movements of the turbine induced by ice. (Battisti 2015)

5.4 Site access and safety

The risk of ice throw should be considered in the site design phase as well as during turbine operation. The areas possibly exposed to ice throw should be determined and the proximity to roads, buildings, hiking or snowmobile trails, and other infrastructure such as ski slopes and lifts must be noted in locating the wind turbines. Wind turbines are also expected to intrigue visitors if allowed, thus the average number of visitors to the surrounding areas and to the specific site should be evaluated and a risk analysis executed. (Bredesen et al. 2017; Baring-Gould et al. 2009)

Warning signs of falling ice, visual warnings during icing periods, and horns or other attention systems prior to starting the wind turbine should be utilised in order to increase the safety of the area (Baring-Gould et al. 2009). It is also important that the threat of injuries caused by ice throw is understood by the public, ensuring respect for the signs and other warning methods. Information can be distributed through local media, leaflets, QR codes on warning signs and comprehensive information boards at the entrance of the wind power site. The information should be provided before each icing season, and in some areas it can be favourable to use multiple languages. It may also be needed to prevent traffic near the site with temporary barriers during periods of high risks of ice throw. (Bredesen et al. 2017)

Other examples of safety measures can be a reinforced roof on maintenance vehicles and over turbine access doors, parking spaces, and nearby buildings or other structures subject to ice throw in order to reduce the risk of damage on equipment and materials (Bredesen et al. 2017; Krenn et al. 2016). Fitting turbines with ice detection and blade heating also naturally decreases the danger of ice throw as less ice is allowed to accumulate on the blades (Baring-Gould et al. 2009). It may additionally be appropriate to shut down the turbines during significantly high risk of danger from ice throw (Bredesen et al. 2017).

Access to wind power sites during snow conditions can be ensured with specialised vehicles or snow removal. A cost-benefit analysis should be executed to evaluate whether it is more preferable to supply maintenance personnel with vehicles suitable for such conditions, or to implement a snow removal strategy. The analysis should consider parametres such as the expenses of possible solutions, the distance to the site, yearly snowfall, and safety, for instance. Snow removal can allow regular vehicles with winter tires to access wind power sites, but in some areas snow removal actions can be overly expensive. In such cases it can be favourable to use specialised vehicles including snow mobiles, snow cats and service vehicles equipped with special tracks. Most wind power operators utilise a combination of a partial snow removal strategy and snow vehicles. (Krenn et al. 2016) Regular maintenance visits should be executed during periods when accessibility is the best. If the site must be visited during more severe climatic conditions, the actual and forecasted weather and meteorological conditions should be observed. (Baring-Gould et al. 2009)

To increase the safety of travelling to and from the site when visibility is decreased, road markers with reflective surfaces can be installed along the route in the beginning of winter. Poor weather conditions may also complicate evacuation actions for emergencies, and planning for such incidences should be executed in the beginning of the wind power project design process. Evacuation operations must be tested regularly. Maintenance personnel should be adequately trained and provided with extreme winter clothing and survival kits, containing emergency food, medical supplies, and special tools. Sufficient shelter and heating need to be accessible for personnel. (Baring-Gould et al. 2009)

Turbine access and maintenance in offshore environments can require travel in a frozen or a semi-frozen sea. Helicopters, hovercraft and ice breakers are examples of possible transport solutions. Ice roads can be opened in some areas to allow access by normal land-use vehicles. Considering turbine installation, transport over the ice can be financially more feasible compared to sea vessels. (Baring-Gould et al. 2009)

Turbines constructed in environments with heavy snowing should contain several doors or entries fairly high above the ground plane to allow access despite snow accumulation around the turbine. All exterior doors and locks should be protected from water to prevent freezing. Doors should also open inside the turbine to enable access after severe snowfall. Storage spaces and tool sheds can be integrated, and they should preferably be accessible from inside of the turbine. Access to the nacelle of a turbine can typically be secured by tubular towers equipped with enclosed ladders or elevators. Tubular towers do not protect maintenance staff from extremely low temperatures, and climbing ladders can be quite dangerous under icing conditions. There are rubber coatings available which are designed for arctic climates, increasing the safety of possibly slippery metal ladders and stairs. (Baring-Gould et al. 2009)

Meteorological monitoring structures can be installed during warmer weathers to increase safety and the quality of measurements. Installation during wintertime is achievable, but it should be discouraged. Meteorological measurement towers should be oversized to account for the ice accretion on guy wires and towers. Prior to installing a meteorological mast to an environment with possible icing occurrences, a calculation of the highest ice load and highest speed of wind should be executed. (Baring-Gould et al. 2009)

Utilising stable ice-rich permafrost can decrease the costs and complexness of foundation structure of a wind turbine. Ice-rich permafrost ground can be protected from heat by keeping the foundation raised above the ground level to allow free air flow on the ground surface, and by installing thermo siphons to the ground. Thermal ground cover application can also help to preserve a strong layer of permafrost. Power cables can commonly be placed on the ground attached to concrete elements or other types of ground ties. The cables can be protected from animals and other threats with wood structures or steel conduits. (Baring-Gould et al. 2009)

The frequency of floods and higher stream levels due to melting snow should also be examined to design sufficient roads, bridges, culverts and fords to ensure site accessibility during spring and summer months. The logistics of turbine installation should be arranged conforming to seasonal and climatic limits, and special protection may be needed to avoid damaging of equipment while transport. Wind turbines can be selected in accordance with the accessibility of the site, considering road and bridge limitations for heavy vehicles and cranes. For instance, turbines consisting of reasonably sized separate components can be used, allowing lighter transport and installation with smaller cranes, tower-mounted cranes and tilt-up towers. (Baring-Gould et al. 2009)

6 CONCLUSIONS AND DISCUSSION

This chapter includes conclusions based on different issues addressed on this thesis. Each section of this chapter answers to a research question posed in the introduction chapter of the thesis. The answer to the research question on icing solutions has been presented according to the state of a wind power project – design phase or operation and maintenance. Lastly, a discussion section is included, presenting personal thoughts on the topic.

Wind power is utilising the kinetic energy of wind by converting it into electricity with a rotational axis and an electric generator of a wind turbine. Wind turbines comprise multiple different components, most importantly a rotor, a drive train containing the generator and a gearbox, a nacelle, a control system and a tower and its foundation. The gearbox is an important part of wind turbine machinery as it controls the rotational energy provided to the generator. The axis of a wind turbine can be horizontal or vertical, and the rotor of a wind turbine is either fixed-speed or variable-speed. Fixed-speed rotor implies that the rotor speed is defined by turbine design, whereas variable-speed rotors allow the rotational speed to be adapted to the speed of wind. Wind turbines typically contain a yaw, pitch or stall system, by which the produced power can be controlled aerodynamically.

The wind power in capacity in Finland has increased in recent years, and there are currently multiple projects under development and construction. The amount of wind power capacity in Finland and Scandinavian countries is expected to continue rising in the next decade due to national objectives and climate targets of the EU. The Nordic wind power capacity in the end of 2019 is presented in Figure 2. The largest share of wind power is located in Sweden, being over 45 % of the combined capacity of the countries.

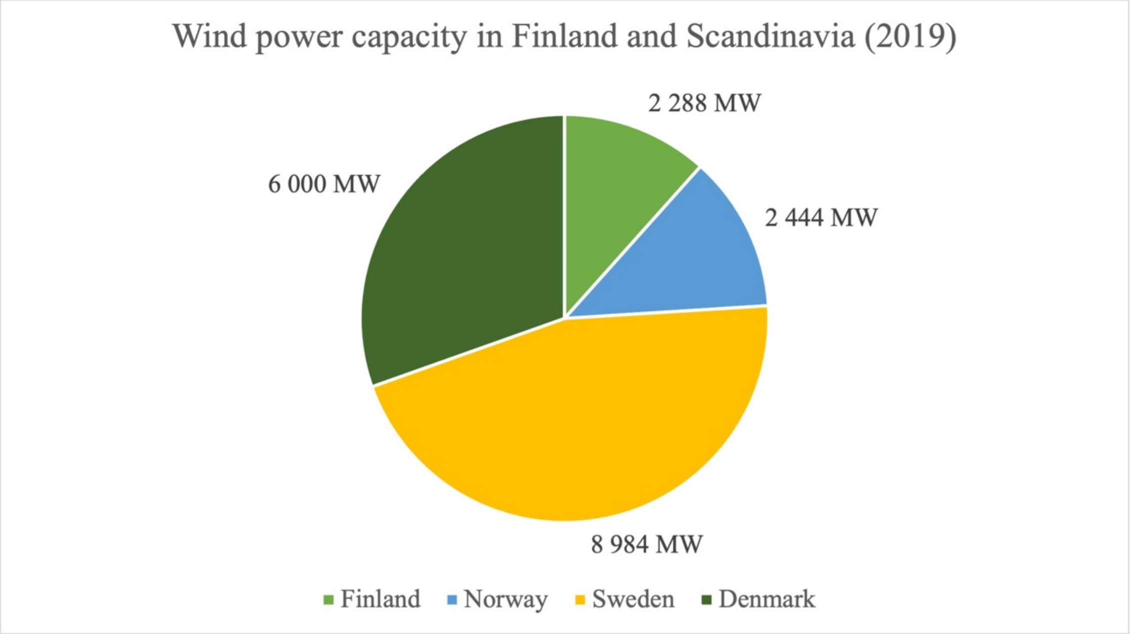

Figure 2. The wind power capacity of the Nordic countries in the year 2019 (Finnish Wind Power Association 2020a; Gustafsson & Rigole 2020; Remler et al. 2020; Østenby 2020).

Icing affects wind power operation in multiple ways. Ice accumulating on wind turbine blades can decrease the aerodynamic performance of a rotor significantly, possibly causing notable power losses. Ice accretion on blades can also induce additional vibrations and operational loads on the turbine, which can result in reduced lifetime of the turbine components. Higher noise emissions are also probable with icy blades. Materials used in wind turbines are affected by low temperatures and icing as they can become brittle and suffer from micro-cracking. This can speed up the deterioration process of the turbine structure. Lubricants and hydraulic fluids can become stiff in low temperatures, preventing normal operation or lubrication of turbine components. Ice accretion on wind sensors can result in failed measurements and even shutdown of the turbine. Snow and ice can also complicate or even prevent site and wind turbine access and maintenance without special vehicles or equipment. Safety risks caused by ice throw are also evident. Offshore wind turbines experience additional static and dynamic loads as well as enhanced corrosion induced by sea ice.

Wind turbines should be fitted with ice detection systems to secure efficient control and operation of the turbine. Direct icing sensing techniques include mechatronic systems, electric systems and optical systems, whereas indirect icing sensing techniques are based on monitoring wind turbine-based parameters such as power loss and increased noise. Ice accumulation and its negative consequences can be mitigated with ice protection systems.

Ice protection systems can be categorised into active systems, such as anti- and de-icing systems, and passive systems, typically coatings. Examples of anti- and de-icing systems include electro-thermal heating systems, hot air ice protection systems, microwave ice protection systems, and mechanical removal systems. Cold climate packages consist of low temperature adaptations for different components, materials and fluids for wind turbines, broadening the operational temperature scale and increasing the reliability of wind turbines in cold climates.

Accessibility of a wind power site during snow season can ensured with specialised snow vehicles or snow removal. Snow removal alone may not always be financially attainable and thus most wind power operators practice a combination of these solutions. Travelling to wind sites in offshore environments during icing season may require special vehicles such as hovercraft, helicopters or icebreakers. Wind turbines in areas with particularly heavy snowing should have multiple entries high above the ground to enable access despite of snow accumulation. Possibly slippery surfaces can be treated with coatings designed for cold climates to increase the safety of maintenance personnel. Evacuation practices should be tested frequently, and personnel should be equipped with survival kits and proper winter clothing. The risk of injuries caused by falling ice from the blades should be minimised by installing warning signs or other visual warnings on the site during icing season. Preventive shutdown of the wind turbine may also be needed in such situations.

6.1 Discussion

Wind power projects appear to be highly affected by icing and low temperatures. This requires special consideration particularly in the project design phase, but operation and maintenance procedures are also more complex in cold climates than in conventional wind sites. Wind turbines installed in cold climates such as Finland and Scandinavian countries, which have four seasons, experience large variation of air temperatures. They must function in freezing midwinter conditions, milder weathers of early spring and late autumn, and possibly hot summer weathers as well. The turbines and other site infrastructure must also endure winter phenomena, for instance, hailing and even avalanches if located near fjelds or mountains. Wind power appears to be relatively dependent on weather as it requires wind to produce power and is quite negatively affected by low temperatures and icing conditions. However, since adverse impacts of icing and low temperatures can be mitigated with ice detection and protection tools addressed in this thesis, wind power can be more suitable for varying weather conditions. Solar power, another source of renewable energy, requires sunlight to produce power and can therefore be inefficient in typically dark winter conditions of Nordic countries. Wind turbines do not have such seasonal limitations as they only require some wind to function. The winters in Finland, for example, are also generally windier than summers, which can increase the potential of wind power production during wintertime and thus highlight the importance of ice mitigation solutions.

Some solutions addressed in this thesis seem slightly complex. For example, many ice protection systems, especially mechanical de-icing methods, aim at removing ice accumulation from turbine blades. On the other hand, ice throw can be a significant safety risk for site personnel, public and equipment. One of ice throw prevention methods is stopping the turbine operation, whereas long shutdown periods can naturally have adverse impacts on power production and economic feasibility. Considering these aspects of ice throw, it could be favourable to use anti-icing systems instead of de-icing methods. Consequently, ice structures would not form on the blade surfaces, minimising the risk of ice falling from the blades due to meteorological conditions or the use of ice protection systems. This could increase the safety of the site and ensure efficient power production as additional stoppages would not be necessary. It may, however, be technically challenging or financially unattainable to install anti-icing systems, such as heating elements, inside the blades after the wind turbine has already been built. In these cases, it can be easier to use de-icing systems regardless of ice throw risks.

The feasibility of wind power projects in cold climates may not possibly be unambiguous. Cold climate sites with good wind resources and high wind speeds can be located in higher elevations and challenging environments such as the fjelds in Finnish Lapland or the mountains in Norway. Low temperature solutions for wind turbines, additional groundwork, and special logistics for construction projects combined could be expensive. Training maintenance and construction crews for challenging conditions could also incur additional costs. Heating systems may cause higher electricity consumption by wind turbines themselves. On the other hand, power production in these locations could possibly be highly profitable due to adequate wind conditions. Considering environmental loads, manufacturing and transporting special gadgets, and operation of snow removal vehicles could produce additional emissions to the atmosphere compared with conventional wind power sites. These emissions, however, can seem negligible and be compensated if cold climate solutions enable adding new wind power to these challenging conditions, advancing the gradual transition from fossil fuels to renewable power production.

7 SUMMARY

The primary aim of this thesis was to examine the effects of icing on wind power production and to introduce solutions preventing or reducing icing risks. Other low temperature impacts and adaptations were also reviewed as ice formation is strongly connected to low air temperatures.

Firstly, the phenomenon of wind and the principles behind wind energy conversion were determined in chapter 2. The main components of wind turbines and their categorisation according to their axis orientation and speed control were introduced. It was stated that most modern wind turbines have a horizontal-axis and fixed-speed rotors. They convert the kinetic energy from wind to rotational energy and further electricity with an induction or a synchronous generator. The chapter also provided an overview of offshore wind power technology and its potential. Offshore wind power has gained increasing interest in recent years due to high offshore wind speeds and the shortage of suitable land. The concept of a wind farm and the siting phase of a wind power project were additionally addressed. Both onshore and offshore wind turbine siting typically requires comprehensive evaluation and investigation of local conditions, the wind resources being the primary focus of interest.

The current and future status of wind power in Finland, Sweden, Norway, and Denmark was overviewed in chapter 3. It was found that there is existing capacity for wind power production, and that the amount of annual wind power generation is expected to increase in the Nordic countries in the next decade.

Chapter 4 focused on the effect of icing and low temperatures on wind turbines and wind power site infrastructure. Firstly, the concept of icing and its possible impacts on the wind turbine structure were determined. Icing of a wind turbine mainly originates from atmospheric icing or sea sprays, and both moving and stationary parts of a wind turbine can experience ice accumulation. It was found that typical consequences of icing and low temperatures are power losses, enhanced vibrations, micro-cracking, stiffness of fluids, and additional noise emissions. The adverse impact of snow and ice throw on other site infrastructure, such as power lines, was also briefly described. The chapter additionally provided an overview on site access, maintenance and construction in cold climates. Safety risks in these conditions include, among others, slippery surfaces, ice throw, extreme temperatures, and snowstorms. It was also stated that sea ice building up on an offshore turbine can result in additional loads on the foundation and enhance the corrosion process of the turbine structure.

Solutions for wind power operation in icing environments and low temperatures were addressed in chapter 5. Icing and low temperatures should be addressed thoroughly in the project design phase, but also in operation and maintenance procedures. Tools for ice detection, divided into indirect and direct techniques, were introduced. It was noted that when using indirect techniques, it is important to read the prevailing temperature to minimise the possibility of false conclusions. The chapter overviewed solutions for reducing and preventing ice accumulation, including active heating systems and passive methods such as coatings. Cold climate packages containing component and material adaptations for low temperatures were also introduced. Examples of safety methods for operation and maintenance include preventive stops, special equipment and warning procedures for ice throw. Offshore systems for cold climates are being developed, and they should address the additional vibrations caused by drifting sea ice.

Lastly, conclusions answering the research questions of the thesis, and personal thoughts on the subject were provided in chapter 6. It was suggested that regardless of possible additional costs and effort that installing wind power in cold climates may cause, it can be profitable considering both its financial and environmental benefits.

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