EXPERT GROUP STUDY
ON

WIND ENERGY PROJECTS IN COLD CLIMATES

1. EDITION 2005

Submitted to the Executive Committee
of the International Energy Agency Programme
for
Research and Development
on Wind Energy Conversion Systems

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FOREWORD

Mountainous and elevated areas around the world offer great wind energy potential in demanding winter climates. Activities have been conducted in a number of countries to master the difficulties that atmospheric icing and low temperatures pose for wind technology. The current wind capacity in cold climates (defined as those that experience either icing events or temperatures lower than the operational limits of standard wind turbines) in Scandinavia, North America, Europe, and Asia, is about 500 MW. Increased experience, knowledge, and improvements in cold climate technology have enabled the economics of such projects to become more competitive in relation to coastal and lowland projects. The internationally accepted procedures for testing and evaluating wind turbines or wind energy conversion systems encompass a variety of aspects. Though there is vast wind energy potential in cold climates, little attention has been paid to the environmental impacts of wind projects in these areas.

The large-scale exploitation of cold climate sites has been limited by our lack of knowledge about their special issues and the lack of proven and economical technological solutions.

The purpose of this report is to provide the best available recommendations on this topic, reduce the risks involved in undertaking projects in cold climates, and accelerate the growth of wind energy production in areas that have been overlooked. This document addresses many special issues that must be considered over the lifetime of a cold climate wind energy project. The importance of site measurements, project design, and system operation is emphasised.

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March 2005

CONTENTS

1. INTRODUCTION

Wind turbines in some climates are exposed to icing or temperatures that are lower than the design limits of standard wind turbines. Standard turbines in extreme environments can have considerable production losses and higher than normal loads, which will cause financial losses and risk premature mechanical failure. Some 500 MW of installed capacity is located in cold climate (CC) sites in Scandinavia, North America, Europe, and Asia. These are typically in northern latitudes or at elevations higher than the surrounding landscape, such as on mountain ridges that provide favourable wind conditions.

CC sites have vast energy production potential, so wind energy projects will probably be implemented increasingly in these areas. Our increased experience, knowledge, and improvements in CC technology have enabled the economics of such projects to become more competitive in relation to coastal and lowland projects.

The purpose of this report is to provide developers, owners, and operators of CC wind projects the best available information on this topic and thus reduce the risks and accelerate the growth of wind energy production in areas that have been overlooked This document also provides preparatory information that should benefit manufacturers, banks, and insurance companies.

The document includes sections on site considerations, measurement programs, project design, installation, operations and maintenance (O&M), and decommissioning. Each section addresses issues that are unique to wind energy in CCs.

These recommendations aim to provide solutions for the CC-specific challenges and reduce the cost of wind energy by lowering the social, technological, and economic risks.

2. GLOSSARY

Cold climate (CC)	Sites that have either icing events or temperatures that are lower than the operational limits of standard wind turbines.
Ice accumulation	The amount and speed at which ice accumulates on structures, specifically on turbine blades, towers, and guy wires. It depends on many factors and affects turbine performance and safety. Ice accumulation must be measured to understand the need for deicing and anti-icing equipment.
Icing event	The length of time weather conditions that cause icing last. This needs to be measured to assess the amount of time that anti-icing equipment will need to operate. It reflects a specific storm or weather system.
Duration of icing	The amount of time ice stays on a turbine, structure, or instrument. It differs from an icing event in that once a structure is covered with ice it may remain for a considerable time before it melts or is removed. This information is important to assess the need for and impact of anti-icing or deicing equipment.

3. WIND POTENTIAL IN COLD CLIMATES

The governing conditions in CCs are not necessarily included in the design limits presently covered by national and international standards for wind turbine design and implementation. Additionally, microclimates with these same conditions are found in more temperate areas such as southern Europe, China, Japan, many parts of the United States, and locations in the southern hemisphere such as Australia, New Zealand, and southern South America.

The recent interest in offshore wind development increases the applicability of these issues as turbines installed in the shallow waters off northern Europe and off the coast of New England in the United States also face severe icing conditions.

Currently more than 500 MW of wind capacity has been installed in CCs. Many more projects have been installed in areas that are less severely influenced by extreme temperatures and icing, although the research on the impacts of turbine downtime and maintenance is limited.

Limited efforts have been made to assess the potential of wind development in arctic and arctic-like microclimates, but papers by Tammelin et al. [1,2] report potential markets of 20% of the installed capacity by 2010. This estimate would correspond to some 8000 MW annually if combined with the forecast for 2010 presented in “Wind Force 12” [3].

4. SITE CONSIDERATIONS

The first step in developing any wind project is to select potential sites. A huge number of factors must be addressed as part of this process; these are all applicable to cold and arctic climates. This section addresses some additional considerations that become important during this initial stage, and provides an overview of some key elements to development in CCs, such as the impact of extreme temperatures and icing.

4.1 Use available best practises

Best practise guidelines for implementing wind energy projects are available from many national, international, professional, and industrial organisations. These should be used as far as possible, even though they do not generally consider CC. An example is the “Best practise guidelines for wind energy development” presented in [4]. However, CC-specific issues such as accessibility, temperature, ice, snow, energy potential, technology, economic risk, public safety, infrastructure, and labour safety will require additional thought.

The best practises guidelines, even without CC-specific topics, provide relevant information regarding CCs as wind energy in CCs will presumably benefit from the rapid development of offshore wind energy technology, an application that, like CC, requires high technical availability with limited O&M.

4.2 Accessibility

Icing and snow drifts can make vehicle access difficult or impossible without snowmobiles or other over snow transport. Access roads are likely to face seasonal restrictions because of ice, snow drifts, and even avalanches during the winter and possibly swampy conditions or flooding during the spring and summer. Storm frequency and avalanche dangers should be assessed, to plan for possible use of snowploughs or specialised equipment such as skidoos, tracked snow vehicles, and possibly even helicopters. Roads need to be marked with poles that will protrude above snowdrifts for snowploughs and other vehicles. Flood frequencies and high stream levels caused by snow melt and soil type must also be studied to design adequate road surfaces, culverts, fords, and bridges that will keep the site accessible during the spring and summer.

A power supply will be required during the assessment phase of a project to heat the measuring instruments, as access will be required to fuel the generators. Turbines should be selected according to site accessibility, taking into account road and bridge limitations for heavy cranes and trucks. The logistics of turbine installation must be planned according to seasonal and climatic limitations, and special care may be required to avoid damage to equipment during transportation.

4.3 Temperature

Temperature consideration is critical to project development, construction, operation, and decommissioning. A wind turbine has components that can often be adapted to CC. The lowest operational temperature limit for the turbine is usually governed by qualities of steel and welding. The wind resource below the operational temperature limit of the turbine design cannot be harvested. Consequently, the local temperature distribution must be measured along with the wind speed and icing events during site investigation to enable a turbine to be selected with the correct CC modifications. This is discussed in greater depth in chapter 5, Site Measurements.

Air density variations affect the power output of wind turbines. Based on the equation of state for an ideal gas, air at –30°C is 26.7% denser than at 35°C. Since power is proportional to air density, power output increases at low temperatures. This may cause the generator to operate above its rated power, which could damage it, and may even require the turbine to be shut down.

The low temperature effects on humans are addressed in section 4.8

4.4 Ice

Icing on any exposed part of the turbine can occur in the form of wet snow, super-cooled rain or drizzle, or in-cloud icing. Deicing equipment allows an object to ice up before the ice is removed; anti-icing effectively prohibits ice from building up. Designers of offshore wind turbine foundations in CCs must considered the effects of sea ice. The national meteorological services regularly predict icing at low altitudes for the aviation industry. The relevance of such ice prognosis for wind energy is still unknown, as no regular icing measurements are carried out.

Icing is a key parameter for CC in project development, construction, operation, and decommissioning. The performance of an iced-up wind turbine will normally degrade rapidly as the ice accumulates. If the icing continues without proper anti-icing, the turbine will either stop because of excess vibrations or disconnect from the grid because of increased aerodynamic drag that slows the rotor down. The wind resource outside the operational icing limit of a wind turbine design cannot be harvested. Consequently, the local icing distribution must be measured along with the wind speed and temperature during the site investigation so a turbine can be selected with CC modifications. This is discussed in greater depth in chapter 5, Site Measurements. Heavily iced meteorological measurement masts and power lines may also break with or without exposure to wind.

Deicing equipment might suffice to avoid long downtimes or to fulfil possible future power performance requirements set by the licensing authorities. Atmospheric icing of offshore structures should be considered if in-cloud icing can occur at subzero temperatures.

Recent research indicates that an imbalance in power, i.e. torque, once per revolution is characteristic even for a lightly iced-up wind turbine because ice formations on the blades will vary and change blade aerodynamics. As light icing is presumably more frequent than the other natural conditions that may trigger the vibration alarms, the designer should consider the influence of fatigue caused by icing. Icing might also cause surfaces to be unserviceable, which would prevent access, and ice thrown from blade or that falls from the tower or nacelle may pose a significant safety hazard.

4.5 Snow

Snow is quite easily suspended and transported by wind [5]; it forms drifts wherever there is an interruption or discontinuity in the airflow [5]. Wind turbine nacelles are generally not airtight compartments, and in fact usually incorporate many openings to provide cooling. Snow can accumulate inside the nacelle, damage equipment, and prove detrimental to the electrical machinery. It can also obstruct openings and prevent normal air circulation.

4.6 Technology for cold climates

Air density variations affect the power output of wind turbines. Based on the equation of state for an ideal gas, air at –30°C is 26.7% denser than at 35°C. Since power is proportional to air density, the available power in the wind will increase similarly and require a well-adapted power control system.

4.7 Framework for economic risk

Many economic risks are associated with the use of wind power in any climate; operating in arctic and arctic-like climates adds costs and performance variability that must be assessed when any wind turbine site or project is considered. A framework for assessing this risk must be developed as part of the project development process.

Examples of these risks are:

- Increased initial costs of the turbine project because of limited installation schedules and higher equipment and installation costs.
- Increased downtime or power reduction caused by icing events.
- Turbine downtime and liability because of concerns for public safety from turbine blades and tower ice throw.
- Long exposure of rime ice, which may increase fatigue loading and cause premature failures.
- Increased downtime caused by extreme low temperatures in combination with any potential increase in power from higher density air flows. Unlike icing, in many areas extreme low temperatures are caused by high pressure, which coincides with still air and thus low wind turbine production.
- Increased maintenance costs because of cold temperatures and the likely higher average downtime between repairs because of turbine inaccessibility.
- Assessment of the economic impact of potential deicing and cold temperature operation equipment.

Risk mitigation strategies such as blade deicing equipment, increased preventive maintenance, and prestocking replacement parts are available, but these increase the operational costs of the turbine and of the overall project. Any economic risk assessment should assess and weigh such strategies. Detailed site and meteorological information will be crucial to any risk mitigation calculation.

4.8 Public safety

Special technical solutions will have to be implemented to prevent accidents associated with the use of turbines in CCs in addition to legal protection to limit the risks associated with these new applications.

Turbine operation with iced blades might not be permitted in certain countries or permitted only in the case of rime ice, as glaze ice is considered more dangerous. However, rime ice can be almost as dense as glaze ice, so there is no obvious reason to make such an exception. A setback of 1.5 times the sum of the turbine’s hub height and its rotor diameter is proposed in [6]. The fact that no serious accidents caused by ice throw have been reported is no reason to avoid the subject. As the visibility is poor (as low as 20 m) under active icing conditions, warning signs must be placed quite close together unless the area is accessible only via entry points.

The areas of potential ice throw should be calculated and the proximity of developed areas, roads, and tourist infrastructure such as ski slopes and ski lifts must be taken into account in siting the turbines. The turbines are likely to attract visitors, if the site is not too inaccessible. Visitor numbers to surrounding areas and to the site in question should be analysed and a risk assessment made. Local authorities may already have issued ordinances that restrict the siting of wind turbines.

4.9 Labour safety

Outdoor activities should generally be avoided when temperatures are very low. Humans' capability to focus on safety and problem solving quickly decreases at low temperatures and high wind speeds, and during precipitation. Thus, apart from being more costly by requiring extra time and equipment, low temperatures may pose significant safety hazards. Wind chill is based on the rate of heat loss from exposed skin caused by wind and cold. Recent research has produced an updated wind chill factor [7]. More information is provided in [8].

Logistics for the comfort and safety of O&M staff should be planned. Heated accommodations and an emergency evacuation plan are necessary.

4.10 Offshore

Sufficient knowledge of the wind resource and icing conditions is required to minimize the risk associated with offshore wind farms in cold climates. Developers can rely on hydrological and climatological data, although these generally do not provide enough detail for full-scale development. Erecting meteorological platforms is a more common option, although in areas where sea ice is likely, towers must be designed with this in mind. For tower and turbine installation, over-the-ice transport may be more cost effective.

Various cost-effective ways to access wind turbines in a frozen or semifrozen sea need to be considered. Hovercraft, helicopters, and ice breakers are options. Ice roads can be built to enable access by ordinary land vehicles. Such roads are reinforced by removing the snow and if needed, by sluicing, and need to be clearly marked to enable driving in low visibility conditions. Turbine access in rough seas must also be addressed.

Icing and rough seas increase the risks for service craft. The icing of boats that weigh less than 500 tons and move faster than 15 knots is not well studied or understood. Many factors, including salinity, humidity, wave height, temperature, wind speed, and boat size, contribute to the icing process, which can cause vehicles to flounder. Using sheltered locations, travelling with the wind and waves, and reducing speed to avoid breaking waves decrease the risk of icing.

The ice breaking capability of the foundation will influence the loading. Winters with difficult icing conditions will determine the dimensioning maximum ice thickness. The possibility of ice drift needs to be considered, as it might trigger structural vibrations.

Even located offshore, ice from the rotor blades may pose a safety hazard. Ice must be detected and other precautions taken.

5. SITE MEASUREMENTS

Monitoring the wind resource at a potential site is usually one of the first steps of any proposed development. The complexity of a measurement program will vary greatly depending on the location and the parameters that need to be measured. The CC and icing complicate matters further.

Many issues associated with the implementation of monitoring programs in CCs, including accessibility and measurements, are addressed in this section.

5.1 Guiding principles and design

Monitoring systems need power, so the use of heated sensors and the additional installation requirements in cold and arctic locations is usually more complex than in most temperate climates. Difficult weather can also be an obstacle for site visits, so more effort should be put into the measurement campaign. Details like the quality and strength of all equipment, lightning spikes, mounting booms, cable straps, wind vanes, and anemometers must be considered. In addition equipment covers and locks should be selected so that those can be used with winter cloves on. Since conditions will likely be quite harsh, redundant measurements to ensure a high percentage of data capture are also recommended.

5.2 Accessibility

Meteorological towers in CCs can usually be accessed with snowmobiles or other over snow transport during winter. Rapid weather changes can pose safety risks that require emergency shelter at the maintenance site. To provide safe travel to and from the site when visibility is poor, reflective route markers (long poles) with short separation distances should be installed in early winter. Limited site accessibility also justifies multiple sensors for high-priority signals such as wind speed and temperature.

5.2.1 Installation

Meteorological monitoring installations should be set up during warmer weather to improve safety and increase the quality of measurements. In remote areas planning must begin in midwinter so the measurement program can start during the summer.

5.2.2 Site power

Power for heated sensors can often be a problem when grid power is not available. Small wind chargers, diesel engines, and hybrid power systems are options. A diesel engine should be combined with a battery bank to decrease engine run time and reduce the use of diesel fuel. Diesel engine air intake must be kept open; a chimney with a U bend on top protects against drifting snow. Care must also be taken with engine cooling, as radiator fans tend to stick if they are not operated continuously. Large radiators without fans should be used.

A heated sensor installed as close as possible to the site where power is available can be used if the winds at the two locations are expected to be similar. The sensor can then be redundant to the unheated ones at the site. The relationship between the site and the heated sensor must then be established during nonicing periods to allow the heated sensor to be used when the regular sensor is not operating.

5.2.3 Site communication

Site communication at remote CC sites can be challenging. Consequently, the simplest communication will be regular visits by the staff who conduct measurements. Reliability is more important than cost. Measurement data should be checked regularly, as the quality of data depends on the reliability of subsystems and ultimately how well supervision can be arranged.

5.3 Towers

Ice buildups should be recognised as a selection criterion in the tower selection phase if icing is likely at the installation site, as towers have to be designed to support heavy ice loads [9]. The lower ends of guys (where they are attached to anchors) need to be protected in severe icing climates, as large ice masses may slide down along the guy wires.

The standard steel structures become brittle in low temperatures, so some caution is necessary when tubular steel towers are erected during winter. The tubular tower may buckle, so these should not be erected in extreme low temperatures.

5.4 Wind measurements

Wind measurements in CCs can be challenging. Many factors can reduce their quality and availability. Anemometers might stop or slow down, wind vanes might stop, iced-up booms or lightning spikes might affect the measurements.

As a rule, heated sensors are recommended at sites with frequent icing. Because most heated sensors have disadvantages like high mass and sensitivity to vertical wind, conventional cup anemometers should also be used. A significant difference in measured average wind speed will indicate the time during which the unheated sensor is iced up.

Various types of heated sensors—shaft heated, completely heated, heated ultrasonic, and others—are available. The completely heated sensors have varying amounts of power output that will dictate the conditions under which they will remain ice free. Some sensors cannot stay ice free under all conditions. A shaft heated sensor is not ice free, but is suitable to keep the bearing at constant temperature in cold climates. In an ice environment, ice will build up on mounting booms, guy wires, lightning spikes, tower, and other components. The dimensions of these iced-up structures and their influence on the measurements must be considered. More information on the operation of ice-free wind sensors can be found in [10,11].

At sites where icing occurs more infrequently, filtering techniques can be used to remove samples that are affected by icing. A significantly lower standard deviation of wind direction occurs when sensors are iced up. A filter that combines the standard deviation of wind direction and temperature will remove most of the ice-affected samples [12]. Because the icing process is slow, samples should be removed some hours before and after a suspected icing event to ensure quality. This technique might not work in all climatic conditions.

A heated sensor should be installed as close as possible to the site where power is available. The readings can be considered redundant. The relationship between the site and the heated sensor should be established during nonicing periods.

5.5 Temperature

Radiation shields around temperature sensors need ventilation to work properly. The ventilation in conventional small shields with lids may become filled with ice or incased in snow, and provide false readings. Large housings such as those used on meteorological stations might be necessary.

5.6 Ice detection

Various types of ice detectors are available, but their purpose is the same: to indicate or measure the assumed accumulation of ice. Some detect the frequency variation in a sonic or vibratory wave; others monitor the capacitance between metal strips. An ice detector is recommended in connection with site measurements.

Different ice detecting methods are suitable to different climates and for different purposes. Different devices are needed to detect the persistency of icing and the actual icing time. Both icing time and persistency are needed to estimate ice climate. The time ice accumulates needs to be estimated when the necessary heating energy and the persistency of ice needs to be calculated to determine ice-induced production losses.

Equipping the measurement mast with one properly heated and one unheated anemometer to estimate wind resource measurements is cheap and advisable. This arrangement gives an overall picture of ice climate. Acquiring information such as time series of cloud base height from the nearest airport and comparing that with the measured data is also advisable. These two methods are likely to give a fairly good idea of the time that ice is likely to affect the operation of the wind turbines.

A dew point detector that has been designed for subzero operation could also provide valuable information, because in practice air temperature is at frost point nearly all the time when in-cloud icing occurs.

5.7 Atmospheric pressure

Measuring pressure in an icing environment is similar to measuring pressure at a conventional site. Care should be taken to ensure that the surrounding pressure can be felt on the pressure gauge, without being obstructed by ice.

5.8 Offshore

Erecting a meteorological platform or mast to measure the wind resource and icing conditions offshore should be considered well in advance of installing an offshore wind farm. Offshore meteorological platforms are expensive, and may require different environmental and regulatory assessments than onshore measurement programs. It might be worth considering whether winter access over ice is more cost effective than by sea. The tower should be equipped with strain gauges to measure the force created by the breaking ice, as this will be required for the proper design of the turbine tower.

6. PROJECT DESIGN, PLANNING, AND ECONOMICS

An investor generally intends to maximize the profit of a project. The cost of energy affects the total project economics and may vary over time and season on the open market. This implies that maximum profit is not, in generally liberalized electricity markets, equivalent to always maximizing the difference between energy production and energy consumption.

As with any project, there are always trade-offs between engineering designs and the economic impact of those designs. Installing anti-icing equipment on a turbine will improve energy production during some periods but will come at an additional expense and will consume more power and accrue extra maintenance costs. These trade-offs will have to be assessed to determine the most cost-effective approach that meets legal or legislative requirements.

Although the costs of power generation in CCs are generally higher than in more temperate areas, many factors may add to the value of that power. Compared to other power generation options, wind may still provide the lowest cost of energy. In this section we will address additional design issues that should be considered in the early stages of project development.

6.1 Accessibility

Given the likely problems of seasonal and climatic restrictions on site access, the issues of transportation and the logistics of installation and construction need to be considered early in the design stage. The weight of tower and turbine components may be limited by the upper weight limits of access roads and bridges for cranes and heavy trucks. Turbines with separate components that can be assembled on site with a smaller crane, tower-mounted cranes, and tilt-up towers can all be advantageously used in such circumstances. Seasonal limitations on accessibility may cause project construction to be implemented over more than one season. This will raise mobilization costs for cranes and installation crews. Similar considerations apply to the construction of transmission lines to grid connections.

The issue of accessibility and the likely additional costs of transportation and installation in cold climates, including the possible need for helicopters, can have important impacts on the overall economic viability of a project. They must be carefully analyzed in the early stages.

6.2 Technical solutions

Many problems caused by cold temperatures and icing environments can be addressed by selecting wind turbines and adapted features that are designed for arctic climates. Examples of some adapted technology are heating elements, CC hydraulic oil and grease, anti-icing or deicing equipment for blades, heated sensors, and sealing specific turbine components.

Current wind turbine standards do not address CC conditions, so specific technology has to be adopted outside the scope of most national and international standards. The current standards state only that any turbine installed at locations outside of “normal” atmospheric conditions should have the class S rating, a requirement that, at no fault to the standards authors, is woefully inadequate. Wolff [13] and Ganander [14] discuss icing impacts in current and proposed standards in greater detail**.**

The following section addresses many of the impacts of installing wind turbines in cold and arctic microclimates.

6.2.1 Communications and turbine control

Whether a project includes many turbines or only one, communication is essential to successful operation. For example, a wind turbine with iced-up blades may not be operated in certain regions; in some countries alarms cannot legally be reset without a visit to the site. Communication, including a web camera and other relevant sensors, can be used to enable a legal remote startup. For maintenance purposes a more advanced level of self-diagnosis is usually beneficial because most CC turbine installations are remote. Many communication methods are available, each with a specific cost. An assessment of the local conditions will likely indicate which specific method is most appropriate; however, erring on the conservative side will likely pay off greatly over the life of the project.

CC adapted sensors need to be weather and ultraviolet (UV) resistant and must specify low temperature use. Modern sensors such as ultrasonic anemometers and data acquisition networks can be connected via fibre optical cables. However, fibre cables for CC operation need to be adapted for such use by, for example, using nonfreezing gel that is pumped into conduits that surround the interior cables to prevent water ingress and subsequent ice formation. One such example is shown in [15]. The gel will also protect a cable against breaking too easily if exposed to a) unforeseen external loads by a maintenance crew and b) movements when cable attachments are deteriorating. Cable attachments and connectors will occasionally break, and weather-resistant cable ties are not sufficient in cold climates. Weather-resistant nylon 6.6 [16] has greater resistance to UV, but weather-resistant nylon 12 is needed in CCs and under high moisture conditions.

6.2.2 Power control

The choice of power control technology will influence the energy production and loads expected by a wind turbine and its subcomponents. Special attention should be paid to loading the gear box, generator, and transformers. These should never be operated below rated temperature or above rated power or wind speed. A wind turbine generally requires a reliable wind speed signal from an anemometer mounted on the nacelle, as an iced-up anemometer will prevent the turbine from operating. For this reason, heated control anemometers should be specified. Heavy icing will usually cause a wind turbine to vibrate heavily and stop or set off alarms. On the other hand, frequent operation in light icing conditions might cause a low level, once per revolution variation in torque and power which, if not properly detected, may cause unexpectedly high loads.

Passive stall wind turbine blades will usually experience iced-up leading and trailing edges at a standstill and if icing occurs at low wind speeds. Icing at high wind speeds will cause an upwind, parked passive stall wind turbine to be iced up on the pressure side of the airfoil. Grid synchronization might not even possible as the aerodynamic drag caused by ice accretion will prevent the turbine/generator from reaching the RPM needed. Anti-icing systems intended for use on operating wind turbines are generally more expensive than deicing at a standstill. If wind energy in CCs is to be implemented on a large scale, wind turbine investors and licensing authorities will presumably require power production independent of icing. Downtime caused icing that lasts longer than a few hours may be unacceptable.

6.2.2.1 Passive stall

Passive stall combined with constant speed can be a cost-effective solution only if the air density at a site does not vary too much or icing is infrequent or, if frequent, relevant countermeasures are implemented. Although simple to implement, the drawbacks of passive stall during nonoptimal conditions are under- and overproduction, which result in energy losses and overloading. The reason for this is that a turbine, which uses passive stall and constant speed, is controlled indirectly via the fixed blade pitch setting and ultimately by the local aerodynamic angle of attack on the blade. Consequently, each turbine blade (there may be many in a wind farm) initially has to be mounted at a fixed pitch angle that assumes an “optimal” air density at the site. The initial blade pitch setting might later have to be changed to increase energy capture or reduce maximum power.

Constant speed combined with passive stall is not recommended unless a) the pitch angle can be easily adjusted to significant shifts in air density, b) a lower maximum power can be accepted during low air density conditions, or c) passive stall is combined with variable speed. The advantages of simplicity in the passive stall control strategy should not be underestimated in CCs.

6.2.2.2 Active pitch

Controlling the power by pitching, by active stall, or by variable RPM will enable the maximum power to be independent of air density variations. Icing will usually reduce the efficiency of an airfoil [20]. The consequences will depend on the implementation of the control system. For example, a pitch-controlled wind turbine with blades iced and operating above rated wind speed, might try to increase the aerodynamic angle of attack (increase the rotating torque) by decreasing the blade pitch angle and vice versa for the active stall turbine. Eventually, if the difference between nominal power—based on the measured wind speed and actual power—is too large, the wind turbine is either shut down or anti-icing countermeasures are activated.

6.2.3 Deicing/anti-icing

The methods currently used to prevent and remove ice from wind turbine rotors can be divided into two main categories: active and passive. Anti-icing prevents the formation of ice; deicing removes the ice when a predetermined amount has accumulated.

6.2.3.1 Passive ice protection methods

The passive methods take advantage of the physical properties of the blade surface to eliminate or prevent ice. Black blades and stick-free surface coatings are passive methods. Some European operators have coated blades with different materials and special paint. They concluded quite early that these methods are not sufficient to prevent icing [17]. Flexible blades may passively hinder and remove ice, but there is no published information on the subject.

Many semipassive methods such as active pitching of the blades, start stop cycles, and facing the blades into the sun are used to remove ice from turbine blades. Although these methods may work in light icing environments, their use has not been scientifically verified and may damage the turbine.

6.2.3.2 Active ice protection methods

Active methods that have been developed at least to a prototype stage are based on thermal systems that remove the ice by applying heat to the blade. The inherent difficulties of chemical or pneumatic impulse-based-systems, which are familiar to the aircraft industry, have prevented these methods from being developed for wind turbine purposes. The electrical ice protection system, which is based on electrical heating elements, and a heating system that is based on hot air circulation inside the blade structure, are commercial ways to protect the blades against ice.

The electrical ice protection system consists of a heating membrane or element that is applied on the blade surface. The heat is obtained from electrical heating elements embedded inside the membrane or from the heating element that has been laminated into the blade structure. Such thermal ice prevention systems are simple and have been used in the aerospace industry for many years. In wind energy applications such heating systems were developed in mid 1990s and those systems have now been tested some 10 years. The technology is still at the prototype level because of limited markets [18,19].

The other thermal method is to circulate hot air inside the blade shell with a hot air blower. This kind of system works well in milder climates where icing occurs mainly at temperatures close to 0°C. However, as the turbines become bigger and the blades longer, shell structures become thicker and thermal resistance becomes higher. In practice this means that very high temperatures are needed inside the blades to keep the outer surfaces free of ice even in mild conditions. Considering the maximum operating temperatures of thermoset composites that are being applied wind turbine blades, in the future using such temperatures inside the blade structure to keep the blades free of ice will be challenging.

The current anti-icing technology calls for power requirements at 6%–12% of the capacity for turbines that ranging from 1000 to 220 kW. The power that is required to remove accretions already formed (deicing) by rapid heating far exceeds this capacity. The heating demand also varies according to the airflow condition on the blade.

6.2.4 Cold climate kit

The definition of a CC site calls for adapted technology. CC kits and even adapted wind turbine designs are available from manufacturers engaged in delivering wind turbines in CCs. CC kits (apart from anti-icing systems) are readily available, reasonably priced, and generally include heating and material selection. The following modifications are usually included in a wind turbine CC kit:

- Control system
- Selected sensors, particularly wind speed and wind direction
- Yaw system
- Gear box
- Nacelle to allow a reasonably comfortable work environment for turbine maintenance.

The selection incorporates materials and techniques such as steel quality and welding that are suitable for use in CCs. Special lubricants (oils, greases, and hydraulics) are used.

Special CC turbine modifications such as avoiding LCD displays that can freeze or encapsulating circuit boards to protect from condensation may also be incorporated. It is also good to determine as part of the turbine selection process the level of experience the specific manufacturer has in installing turbines in CCs. Black blades or leading edges might be profitable where there is enough solar radiation to deice the structure.

6.2.5 Environmental impacts

Many projects are implemented in microclimates that, because of their short growing seasons, fragile ecosystems, and limited animal habitats, require special consideration. Additionally, flora and fauna in these extreme climates have generally been studied less than those in other climates. However, the limited number of affected specimens and the remoteness of most sites may allow for a simpler environmental impact assessment.

A critical aspect of environmental impact is the length of time flora will need to regenerate after it has been disrupted. There are many ways to reduce this impact; for example, heavy construction can be completed during the winter when snow or ice roads can be used instead of more permanent ones. Wood planking-based corduroy roads that are removed after summer maintenance can reduce local impact, as can boardwalks instead of trails or paved roads.

Any organisation that conducts an environmental impact assessment in an arctic or mountain climate needs to have specific experience in these areas, as the specific microclimates can be very different from normal wind development projects.

6.2.6 Impact of arctic climate on project design

In addition to the clear turbine needs addressed earlier, a number of environmental impacts must be assessed during the project design and turbine selection process. As we have seen, most issues relate to cold temperatures or to ice and snow.

6.2.6.1 Cold temperatures

Cold temperatures affect several other turbine selection decisions. Access to the turbine nacelle should be protected, usually by tubular towers with enclosed ladders or elevators. Tubular towers will not protect service personnel from the extreme temperatures, and climbing lattice towers under these conditions is very dangerous. Staff need a nacelle that offers some protection to perform winter maintenance. Also, adverse conditions may prevent evacuation.

6.2.6.2 Ice and snow

Snow buildup around the turbine can bury doorways and make tool sheds inaccessible. Turbines installed in climates with large amounts of snow should include multiple entry points or doors high above the ground plane (Figure 1).

Figure 1. Turbine in Gütsch in Switzerland. Photo by Markus Russi.

Tool sheds and storage rooms should be integrated and accessible from the inside of the tower or designed to allow access during the winter. Ice and snow commonly freeze doors and hatchways closed, especially those, such as hatches in the turbine nacelle, that are exposed to the freeze-thaw cycles. Care should be taken to protect all external doors and locks from water, which can freeze and make entry impossible. Finally, all external doors should open inward to allow egress even after heavy snowfall.

Blowing snow can also be problematic and will enter most vents or openings. All doors and hatches should be sealed and the venting designed to limit the access of blowing snow. All areas around venting should be equipped with drains to remove water from melting snow and all electronic equipment should be sealed. Moving parts such as yaw drives and hydraulic cylinders should be protected to prevent ice accumulation that can inhibit movement. A chimney with an inverted U-bend on top of a container can supply air for proper ventilation.

6.3 Climatic impacts on power production

The important parameters in estimating energy production losses caused by ice are the number of hours ice affects the turbine and the performance of a wind turbine when the blades are covered with ice. Atmospheric icing reduces the aerodynamic performance of a wind turbine rotor significantly, as the blade aerodynamics are very sensitive to extra surface roughness caused by ice [20]. Significant decrease in production power with stall-regulated wind turbines is to be expected even after short icing periods.

Extreme temperatures below the operational limits of standard turbines cause downtime, but their high air density can also increase production. Leclerc and Masson [21] report cases with stall-controlled turbines where, at low temperatures, unexpected high power outputs were observed. For instance, 5-minute averaged power outputs of 89 kW were recorded for a 65-kW turbine. A 220-kW turbine produced peaks of 360 kW that led to excessive loading and generator failure [21]. These cases all occurred in very cold weather. Such a phenomenon cannot be expected to increase the annual production significantly, but it should be considered as an extra loading to the generator and therefore as a source of increased risk.

6.3.1 Quantifying and estimating direct and indirect energy losses

6.3.1.1 Low temperature

The effect of extreme low temperatures on energy production may be estimated with

$$E_T = EO(1 - \int_{-\infty}^{T} f(t)dt)$$

where E_T is energy output in low temperature, EO Energy output, T low temperature limit of a turbine and f(t) probability density function of air temperature.

Normal distribution may be assumed if there is no f. In calculating energy output, one should notice the correlation between wind speed and temperature. In many areas very low temperatures are tied to high-pressure systems during which winds are often weak.

6.3.1.2 Ice

Ice buildup on the blades usually reduces lift and increases drag, which results in reduced power output. The amount of reduced power depends on the amount of ice. Detailed information about wind speed, duration of ice accumulation, duration and amounts of ice, temperature, and how the turbine is affected by ice are needed to calculate the reduced power output. It is also necessary to know how these parameters correlate in time. A time domain calculation is usually recommended.

Many parameters can be difficult to obtain, so rules of thumb can be used for the initial calculations. Some rules of thumb can be found in [22] and are reproduced in Table 1.

Table 1 Approximations for energy loss caused by icing [22]

Frequency of icing [days/year]	Annual energy loss
< 1	Insignificant
1-10	Small
10-30	5-15%
30-60	15-25%
>60	>25%

More detailed estimates can be made based on the results of thorough site measurements. Parameters that need to be at hand include:

- Duration of ice accumulation
- Duration of ice
- Frequency distribution

- Temperature
- Wind speed and direction
- Simultaneous (ice–wind)

Statistical analysis based on these parameters and estimated production losses that are based on local ice climate and turbine technology give the most accurate estimates. However, no method has been verified.

The difficulty of estimating ice-induced production losses relates to the aerodynamics and control system of a wind turbine. More work is needed in this area before a reliable production estimate method or tool can be presented. Theoretical and measured performance of an iced-up wind turbine is presented in [23].

6.3.2 Estimating financial losses

Financial losses result from lost energy production caused by ice and low temperatures and the costs of more demanding maintenance. If the site is remote, malfunctions that require site visits extend downtime. Financial losses should be estimated so that the effects of ice and low temperature on energy production are taken into account according to 6.3.1. Energy consumption of adapted technology should be included in the energy production estimate according to the best information from the manufacturer. The effect on the duration of stoppages caused by the site location and access should be determined during the project planning phase. Clearly, the economical uncertainty associated with cold climate projects is higher than at conventional sites.

6.4 Balance of system

Cold temperatures and ice affect the choice and design of the specific wind turbine and many aspects of the project balance of system components. This section provides a brief examination of some key aspects.

6.4.1 Permafrost

Permafrost can be divided in two categories: ice-poor and ice-rich. Construction techniques must be adapted to the type of permafrost. If construction can be founded on clean, non-frost-susceptible sand or gravel or on rock that is free of ice, the design of the foundation can be undertaken as if no permafrost were present [5].

Ice-rich permafrost is usually composed of fine grain soils that contain a significant amount of frozen water. Then thawing must be prevented to retain good load-bearing capability and avoid volume change [5]. For a heavy structure like a wind turbine foundation, the design should be extended beyond the annual frost zone and well into the permafrost. The frozen soil maintains its strength and keeps the foundation stable [5]. In that case, the permafrost must remain frozen and protected from heat that may come from the heaters inside the towers.

6.4.2 Foundation design

The optimal design of a wind turbine foundation for use in CCs might be influenced by, for example, a lack of soil and an increase in price for transporting materials including concrete. Rock anchors or large diameter gravity foundations can be used. During construction in a CC, a concrete foundation might, depending on the additives and reinforcement used, need a relatively long time to cure. Outdoor construction, maintenance, and repairs are generally more difficult to carry out in low temperatures.

Installing a wind turbine foundation in permafrost may require substantial changes in its design; freezeback pylons (Figure 2) or other proven construction techniques may be necessary.

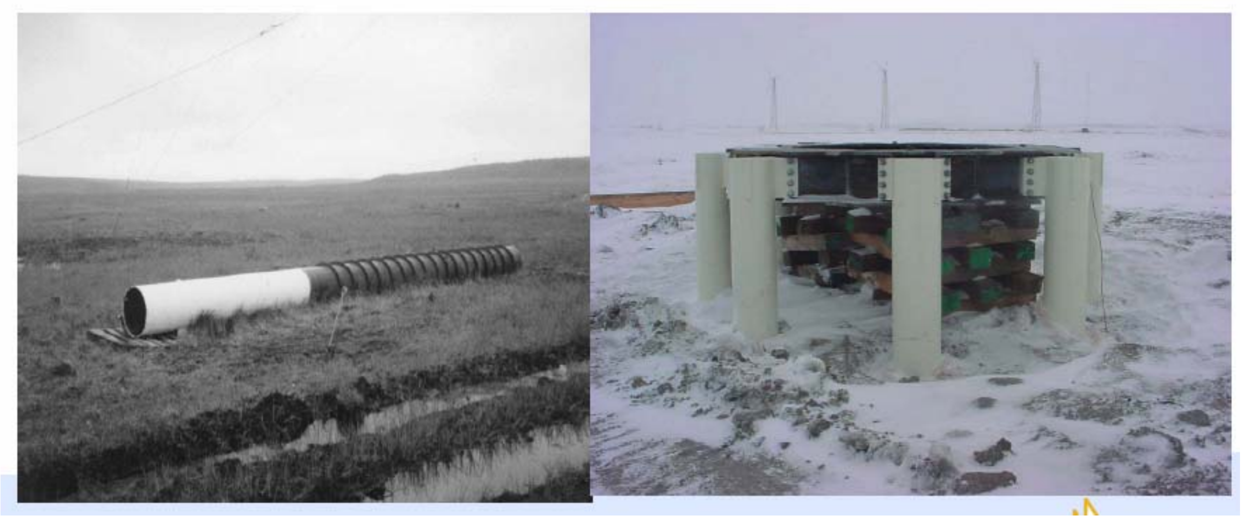

Figure 2. Freezeback pylon. Foundation for permafrost areas based on pylons.

6.4.3 Grid connection

Generally permafrost or solid rock limits the use of buried cable, both because of the expense of trenching and because the dynamic behaviour of the frozen soil can rupture conduits and damage cables. Overhead cable could be damaged by the ice. Cable can usually be laid on the ground surface, tied to concrete blocks, and protected by simple wooden structures or steel conduits. In many cases armoured cable is used to protect against animals or other hazards.

Sealing of transformers and seasonal ventilation may also pose problems for CC installations. Transformers designed for remote or arctic climates should be specified and used. As with other cooling devices, fans and other active cooling techniques should be avoided. Because of blowing and drifting snow, only sealed transformers should be used. Connections to the grid or other distribution systems must be made in a sealed container where there blowing or drifting snow cannot enter.

6.4.4 Special vehicles and tools

The need of special vehicles and tools need to be identified before construction work begins. The ability of large cranes to ascend and descend steep roads must be defined. If heaters are needed to tighten bolts at low temperatures, this must be assessed before construction begins.

6.5 Maintenance

Heated work premises should be available for the convenience and safety of maintenance staff. Basic tools should be available at sites with difficult access. Accessibility depends on local conditions, which may result in downtime or force staff to remain at the site for long periods. Annual maintenance visits should be scheduled for the best possible climatic conditions and the easiest possible access to the site. Special transportation such as skidoos and bulldozers will be required. Repairing unexpected faults in a CC is usually more time consuming than in more temperate climates.

6.6 Decommissioning

Site decommissioning includes its own challenges in the climates covered by this text. Many have limited growing seasons and very slow plant growth, so reconditioning can be costly and time consuming. Efforts can be made at the start of the project and during project development to expedite this process. Project installation and decommissioning can be concentrated during the winter when snow or ice roads can be used to protect sensitive vegetation. Wood planking-based corduroy roads that are removed after summer maintenance can reduce local impact, as can boardwalks instead of trails or paved roads.

Environmental preparation and assessment after decommissioning can also take longer than normal projects and are usually more costly. Funds should be set aside during the project to cover these costs.

Most damage occurs during site construction and decommissioning. Careful planning can reduce the impacts and prevent costly environmental reconditioning.

6.7 Public safety

Ice that is thrown from turbine blades or that falls from the tower can be quite dangerous and cause serious damage. Any structure close to turbines should be designed to withstand the impact of ice thrown from the turbine blades and overhangs installed above doors Signs that warn of falling ice and oral warnings after icing events and before turbine startup should be incorporated to help ensure public safety.

Figure 3. Warning signs for falling ice. Photos by Lars Tallhaug.

A simple formula for calculating the zone of likely ice throw is presented in [1]. For an operating turbine the following has been suggested:

$$d = (D + H)x1.5$$

and for a turbine still standing:

$$d = v\frac{(D/2 + H)}{15}$$

where

d = maximum falling distance of ice (in m)

D = rotor diameter (in m)

H = hub height (in m)

v = wind speed at hub height (in m/s)

Seifert et al. [24] suggest that the formulas should be used only as a rough estimate and recommend more detailed calculations, including risk assessment.

In many cases the area around the turbine will be accessible to the public either intentionally or because fencing is buried under snow. Alarm and security measures need to be incorporated into the project design.

In addition, turbines can be chosen with ice detection and blade heating to minimize the dangers of ice throw occurrences. Insurance coverage should be planned for, and the necessary analyses done to estimate visitor frequency and plan mitigation measures.

6.8 Risk management and assessment

Planners, operators, authorities, insurers, and investors should use a risk evaluation to determine the kinds of risks a wind turbine installation in a CC will face and measures to avoid or decrease these risks. Although projects in CCs will have additional risks (most of which have been addressed in this document), their assessment will be no different than other wind farm development projects.

General considerations include an assessment of:

- Quality and standard of turbine under consideration
- Experience and references of installation company, contractors, and operator.

Based on these considerations, the following recommendations are provided:

- Assess the complexity of the site and assess risk accordingly.
- Include results of the risk assessment as part of specifications for turbine and equipment manufacture, installation, and operation.

6.9 Summary of economic impacts

Clearly the application of wind energy in cold and adverse climates requires special consideration of many factors. Although these considerations affect the project design and system economics, the potentially higher costs can be more than offset by the increased energy production available at high altitudes, in coastal areas, and in the extreme latitudes where these conditions persist.

The additional complications of harnessing the energy in these climates must be weighed against the positive impacts of developing these projects. High wind potential, the availability of land for project installation, the generally reduced impact, and the need for clean and renewable energy sources all lead to a market that will increasingly favour wind projects in these areas.

Although there are no specific guidelines for assessing the economic impacts and risks associated with projects in extreme and arctic climates, this understanding will increase as more projects are developed.

6.10 Offshore

See chapters 4.10 and 5.8.

7. PROJECT CONSTRUCTION

The construction of a CC site requires more planning for time of the year, vehicles, tools, and labour safety. This is especially true if construction work is planned for the cold season.

7.1 Time of year

Construction should be scheduled so climatic conditions during the construction phase are as favourable as possible. In a permafrost area this usually means winter or spring.

7.2 Labour safety

CCs pose particular problems for labour safety. Power supplies will be needed for electrical equipment, for heating and working, and for temporary living quarters. Extended ice and snow storms deteriorate access roads and can isolate construction sites. Adequate shelter, food, and fuel supplies must be on hand to cover such eventualities. Trained paramedics and medical equipment should also be kept on site. Powerful torches, lamps, and even guns (in case of encounters with wild animals) should also be part of a construction crew's basic equipment.

Alternative transportation solutions for entire crews should be planned in case of extreme conditions, access road deterioration, and emergency evacuation. Insurance should be purchased to cover the additional risks associated with CC sites, and supporting mitigation data should be supplied to the insurer. This will likely include details on emergency response procedures in addition to basic safety procedures and equipment.

7.3 Public safety

Efforts should be made to minimize the number of nonessential visitors and spectators on the construction site, especially if tourism infrastructure is nearby. Standard public safety techniques may be inadequate in extreme climates. Dangers of accidents on icy public access roads should also be considered. Additional insurance coverage should be purchased if the risk exposure is not covered by standard insurance policies.

7.4 Offshore

The preferred construction time of a CC offshore wind farm is likely during the warm season. However, access over ice may be more cost-effective than by sea. Keeping up and adapting to changes in weather conditions will be more important far offshore than on land.

8. SYSTEM OPERATION

8.1 Operation

Modern utility-scale wind farms require automatic operations. The cost of labour prohibits operators, especially for small wind farms. However, wind turbines still require monitoring and maintenance [25]. They are usually monitored via a *Supervisory Control and Data Acquisition* (SCADA) system [26]. SCADA systems communicate with the controller of each turbine and can start and shut down turbines. A SCADA can report turbine status during operation on a remote computer screen.

In the context of CC operations, a SCADA can be fitted with ice detection, moisture, temperature, and vibration sensors. It can also monitor the temperatures of components like the gearbox, generator, and electrical panels. By comparing readings from sensors and preprogrammed values, the SCADA system can control the turbine and ensure safe operations. For instance, if atmospheric icing is detected, a SCADA can activate the turbine ice protection system. It can even stop the turbine if icing becomes severe and is accompanied by unusual nacelle vibrations.

Sensors should be redundant when parameters are critical to turbine operation and integrity. For example, the control anemometer that is used to monitor power output and wind speed and whose signal triggers the turbine may shut down in high winds. A heated anemometer could be installed in case the control anemometer ices up.

8.2 Overhaul and maintenance

If wind turbines are to reach their rated life expectancy (usually 20 years for a utility-scale machine), they must be maintained according to the specifications in the manufacturer's operating manual. Turbine maintenance must also address environmental conditions.

Operating conditions for wind turbines are unusually tough [25], especially in CCs. Lubricants, rubber seals, and mechanical properties of materials are all affected by cold air temperatures [26]. Of all the turbine components, the gearbox is probably most affected by CC operations. It must support the large torque caused by the combined effect of gusty winds and higher air density conditions. Low temperatures call for low-viscosity lubricants. However, those offer less protection at normal operational temperatures. A synthetic lubricant may be required.

Recently, some gearboxes (which should last 20 years) have failed. This demonstrates that, in addition to maintenance, gearboxes need to be carefully designed and selected.

Special care must also be given to the blade pitch change mechanisms in variable pitch turbines and to the yaw drive mechanisms. Cold weather conditions impose supplemental stresses to these mechanisms.

The maintenance procedures outlined in the wind turbine operation manual should always be followed. An oil analysis should also be performed periodically on the gearbox. A great deal can be learned about its condition from this simple check.

8.3 Environmental impact

The environmental impacts of a CC wind farm differ in principle only slightly from those of other wind projects implemented in sensitive areas. Recovery from oil spills and vehicle tracks is likely to take longer in CC environments where flora is typically scant. The environmental impact that should be considered is increased noise from ice on the blades. The increased surface roughness multiplies the noise levels compared to clean blades.

8.4 Labour safety

Labour safety during operation is less of a potential problem than during construction, when far greater numbers of people are involved. Nonetheless, ice throw and the danger of maintenance crews being cut off during visits must be taken into account. Maintenance crews should be properly trained and equipped with extreme winter clothing, survival equipment, and possibly special tools. Accidents can also occur because of icy roads, avalanches, or blizzards.

As previously discussed, cold temperatures cause concern for turbine maintenance staff, as even limited exposure can lead to frostbite and other injuries. Ice can also form inside turbine structures and make movement inside the turbine more dangerous.

Routine maintenance visits should be scheduled during periods of best accessibility, but if they must be made during more unstable climatic conditions, actual and predicted weather and meteorological conditions must be monitored.

Emergency response and evacuation procedures need to be planned for, and adequate shelter and heating must be available on site for possible extended periods of isolation. Maintenance crews should carry sufficient emergency food and medical supplies. A 24-hour emergency response capability should be in place and additional insurance coverage should be considered.

8.5 Public safety

Labour safety is less of a problem during operation than construction, but public safety is likely to be a greater concern, especially if the site is near tourism infrastructure or the turbines become tourist attractions. Visitors could be injured by ice throw from turning turbines, or have accidents on icy access roads owned by the project.

8.6 Offshore

See chapters 4.11 and 5.7.

Access to offshore platforms when ladders are iced up can be quite dangerous, especially during adverse weather. In high ice environments other methods of turbine access will have to be determined.

9. DECOMMISSIONING

9.1 Turbine-specific issues

Check local building codes to determine whether any CC-adapted technology, such as special insulation of a low-temperature gearbox lubricant, requires specific handling or recycling.

9.2 Site-specific issues

The specific site decommissioning process will depend on the requirements set forth with the landowner or regulating body at the start of the project. In most cases the site should be returned to its predeveloped state with all structures, roads, and wind turbine foundations removed.

All specific issues for decommissioning have been covered in previous sections; however, two notes of caution are appropriate. Permafrost acts very differently than regular soil, in regards to both its movability and its fill ratio. Secondly, the slow growth of native plants may indicate that the plants and the ground covers need to be greenhoused several years before the site is decommissioned.

9.3 Environmental issues

Simple plant growth in these extreme microclimates is very slow, sometimes on the order of 20 years. For this reason extreme measures should be taken to reduce impact throughout the life of the project, and plans for site decommissioning should start very early. Environmental monitoring of the site after it is decommissioned will likely require more time than with wind turbine installations in more temperate climates.

9.4 Offshore

See chapter 7.5.

10. SUMMARY OF KEY RECOMMENDATIONS

This chapter lists the key issues that should be considered in CC wind energy projects.

- Be aware of the extra risks involved in CC wind energy production at early stages of the project.
- Employ available best practises as far as possible, even though they generally do not consider CC issues.
- Instrument and turbine manufacturers have CC solutions available. Conduct a survey to find solutions for each project, because CC circumstances vary greatly.
- Perform a thorough site assessment measurement of at least one year with measurement devices, including ice measurements. This phase provides valuable information on site access and working conditions.
- There is no standard method for estimating ice-induced production losses. Make the best estimate based on the results of site measurements.
- Notice the CC-related safety aspects, low-temperature working conditions, and risk of ice throw in the project planning phase.
- Carry out a risk assessment that includes assessment of the quality of the selected turbine and experience and references of the installation company, contractors, and operator.
- Include the results of the risk assessment as part of the specifications for turbine, equipment, manufacture, installation, and operation.

11. CONCLUSIONS

Mountainous and elevated areas around the world offer large wind energy potential in demanding winter climates. Various national activities have been conducted in a number of countries to master the difficulties that atmospheric icing and low temperatures pose for wind technology. Our lack of knowledge of special CC issues and the lack of proven and economic technological solutions have limited the large-scale exploitation of these sites.

The best practises provide a good starting point for developing a CC site. Those practices should be used as far as possible, even though they do not normally consider CC issues. The additional risks that are involved in CC wind energy projects must be assessed in detail. CC conditions directly affect site access, working conditions, technology selection, safety, and energy production.

The importance of thorough site assessment is emphasised in CC and icing conditions, which can complicate the measurements. It is the most important phase, however, as project decisions are based on the results. A thorough site measurement, including ice measurements for at least one year with the correct measurement devices is recommended. The complexity of a measurement program will vary greatly, depending on location and parameters. A proper measurement campaign also provides valuable information on site access and working conditions.

Instrument and turbine manufacturers have CC solutions available. Potential solutions for each project need to be surveyed because CC circumstances vary greatly. This is partly because commercial and prototype level anti-icing and deicing devices and other solutions for low operational temperatures have been presented, but only limited published information is available. Solutions for low temperatures are generally more mature, because most of that technology has been introduced in other fields of engineering. A distinctive feature is the lack of proven anti-icing and deicing technology for different icing climates.

Icing may significantly influence energy production. There is no verified method for estimating ice-induced production losses, but simple approaches have been presented that can reasonably evaluate the effects of extreme low temperatures. Additional costs that are related to working conditions, construction, and site access, can be limited with careful planning. CC wind energy projects can maintain high safety standards.

CC wind projects involve higher risks than normal lowland undertakings. Planners, operators, authorities, insurers, and investors should use a risk evaluation to determine the kinds of risks a CC wind turbine installation will face and the measures that have to be taken to avoid or decrease these risks. Although CC projects will have additional risks, their assessments will be no different than that of other wind farm development projects.

More work is needed, especially in estimating ice-induced production losses and in developing countermeasures against ice. The climatic circumstances at CC sites demand high reliability of adapted technology.

REFERENCES

[1] Tammelin, B. and H. Seifert (2000), The EU WECO-project Wind Energy Production in Cold Climate, Proceedings of an International conference BOREAS V, Levi, Finland. CD-ROM. Finnish Meteorological Institute.

[2] Tammelin, B., M. Cavaliere, H. Holttinen, C. Morgan, H. Seifert, and K. Säntti (2000), Wind Energy Production in Cold Climate, Meteorological Publications No. 41, Finnish Meteorological Institute, Helsinki. 41 pp..

[3] Wind Force 12, http://www.ewea.org, date of reference 12.4.2004.

[4] http://www.bwea.com/ref/bpg.html, date of reference 10.11.2004.

[5] Freitag, D.R. and T. McFadden (1997), Introduction to Cold Regions Engineering. New York: ASCE Press, 738 pp.

[6] http://www.vtt.fi/virtual/arcticwind/boreasiv/assessment_of_safety.pdf, date of reference 19.11.2004.

[7] http://www.wrh.noaa.gov/slc/projects/wxcalc/windChill.php, date of reference 19.11.2004.

[8] http://www.nws.noaa.gov/om/windchill/windchillglossary.shtml, date of reference 19.11.2004.

[9] Atmospheric Icing of Structures, International Standard, ISO 12494.

[10] Tammelin, B. et al. (2001), Meteorological measurements under icing conditions – EUMETNET SWS II project, FMI reports 2001:6.

[11] Tammelin, B. et al. (2004), Improvements of severe weather measurements and sensors - EUMETNET SWS II project, FMI reports 2004:3.

[12] Tallhaug L. (2003), Calculation of potential ice risk in Norway, Boreas VI, Pyhätunturi, Finland.

[13] Wolff J., (2000), “Icing in standards”, Boreas V, Levi, Finland.

[14] Ganander, H. (2004), “Evaluation of Suorva measurements 030121-030219. Frequency contents compared to 10-minute conditions,”, TG-R-04-03, Stockholm, November.

[15] http://www.polywater.com/icefree.html, date of reference 15.1.2005.

[16] http://www.banduit.com, date of reference 15.1.2005.

[17] Tammelin, B., H. Holttinen, C. Morgan, F. Richert, H. Seifert, K. Säntti, and P. Vølund (1998), Wind Energy Production in Cold Climates. Proceedings of Boreas IV Conference 1998: 23-38.

[18] Laakso, T. and G. Ronsten (2004), Operation of Blade Heating System in Different Icing Conditions, Internal project report, New Icetools NNE5/2001/259, VTT PRO2/P5163/04.

[19] Laakso, T., H. Holttinen, G. Ronsten, L.Tallhaug, R.Horbaty, I. Baring-Gould, A. Lacroix, E. Peltola, and B. Tammelin, State-of-the-art of wind energy in cold climate, IEA Wind Annex XIX, 53 pp. http:\arcticwind.vtt.fi.

[20] Lynch, F.T. and A. Khodadoust (2001), Effects of ice accretions on aircraft aerodynamics, Progress in Aerospace Sciences 37:669-767.

[21] Leclerc, C. and C. Masson (1999), Abnormal High Power Output of Wind Turbine in Cold Weather: A Preliminary Study. The 15th CanWea Conference and Exhibition and the CanWea Seminar Proceedings: 190-199.

[22] Tammelin, B. et al. (1997), Wind Energy Production in Cold Climate, European Wind Energy Conference, October, Dublin Castle, Ireland, pp. 347-353.

[23] Laakso, T., E. Peltola, and S. Rissanen (2004), Tool to Calculate Power Production in Various Types of Icing Climate, Public project report, New Icetools NNE5/2001/259, VTT PRO2/P5164/04.

[24] Seifert, H., A. Westerhellweg, and J. Kröning (2003), Risk analysis of ice throw from wind turbines, Boreas VI, Pyhätunturi, Finland.

[25] Hau, E. (2000), Windturbines: Fundamentals, Technologies, Application and Economics. Berlin: Springer, 624 pp.

[26] Manwell, J.F., J.G. McGowan, and A.L. Rogers (2002), Wind Energy Explained. West Susses: John Wiley & Sons, 590 pp.