INVESTIGATING DIMMING OF OBSTRUCTION LIGHTS
IN A SWEDISH WIND FARM

Dissertation in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE WITH A MAJOR IN ENERGY TECHNOLOGY WITH
FOCUS ON WIND POWER

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ABSTRACT

The demand and need for alternative obstruction marking has become a significant challenge for the wind power development in Sweden. While the development of wind turbines pushes for higher heights, the need to denote them as possible obstacles for aviation increase. To reduce undesired effects of the aviation warning lights in the landscape, various technologies for reducing the light emitted have been developed. One of these technologies control the lights’ output by dimming them based on measurements of the prevailing visibility in the vicinity of the wind farm.

Visibility controlled obstruction lighting has not yet been used in Swedish wind farms. This thesis will investigate how a system can be applied from different viewpoints and what would be gained in a wind farm in northern Sweden.

By reviewing literature, interviewing key-persons, studying a case with application of Finnish regulations and estimating the performance during different conditions, and discussing the results, conclusions could be drawn. The findings are general recommendations for acceptance, an aviation risk that need to be considered, indications of preferable regulation applications and approximations of the performance and possible gain.
ACKNOWLEDGEMENTS

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A big thank you to everyone who has helped me out in one way or another.

Finally, a big thank you to my parents and sister for their support and understanding.
NOMENCLATURE

Light intensity  the light emitted by a light source in a given angle, unit candela (cd)

Illuminance  the light hitting a surface, unit lux (lx)
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CHAPTER 1. INTRODUCTION

The demand and need for alternative obstruction marking has become a significant challenge for the wind power development in Sweden. While the development of wind turbines pushes for higher heights, the need to denote them as possible obstacles for aviation increase. To aware pilots and other aviators, the wind turbines have to be equipped with blinking lights, that on turbines above 150 m is to be white and of high-intensity. The lights have arguable effects in the landscape, which has led to local municipalities stipulating use of aviation light technology not in line with prevailing regulations.

On-demand solutions, lighting the obstruction warning lights only when an aviator comes present, have been developed but has not recently been allowed to apply. Meanwhile, as municipalities, county administration boards and environmental courts have been introduced to the on-demand lighting systems as possibilities to reduce occurrences of local disturbances, these permit issuing authorities often condition that an exemption shall be tried to be obtained and, in a few cases, have put the use of on-demand systems as a pure requirement in the wind farm environmental permits. Either way, this has serious consequences for the wind power industry when the aviation obstruction regulating authorities cannot easily allow the technology to be used.

With the purpose of identifying other solutions, this thesis primarily looks in other directions, to a solution not on-demand based, yet might have the desired effect of reducing light emitted to the surroundings. The use of visibility sensors for controlling obstruction lighting is the topic of investigation. The intention of such systems is to adapt the intensity of the obstruction marking lights to the prevailing visibility conditions around wind turbines to maintain the same warning function, however reducing the intensity flashing light to a sufficient level during good weather conditions. The technology is allowed in Germany and in Finland, and visibility sensors in general have a long track record of being used at airports, in offshore and marine applications in harsh, ruff climate, leading to a highly developed state of technology.

Without further ado;
How can a system dimming the obstruction lights be applied, both regulatory and technically and what could be gained and saved by using such a system?

By conducting a literature review of the Swedish regulations concerning obstruction marking, their statutory background, international conventions, foreign regulations, research literature, recommendations, standards and reports, the answer to how visibility systems would fit in the Swedish circumstances is searched.
The complex situation involving many stakeholder interests affected by aircraft obstruction lighting will be considered, including interests of aviators depending on the lighting, authorities requiring and regulating it, some neighbors annoyed by it, municipalities and county administration boards wanting alternative solutions and companies selling them and authorities investigating them. The main focus will be from a wind farm development perspective, having to consider all the above opinions to find a suitable approach.

While conducting a walkthrough of foreign regulations, more basic alternative means of coping with social acceptance (hence, permitting) issues will be highlighted in an attempt to provide material useful for positive future developments in the obstruction lighting scene of the Swedish wind power industry.

Further a case-study will be performed to see how visibility controlled obstruction lighting would operate with Finnish regulations, full or partly applied, in a Swedish wind farm. Key-persons will be interviewed to find additional answers and information necessary. The results of the methods applied will be discussed and conclusions drawn.
CHAPTER 2. PREVIOUS WORK ON MARKING OF WIND TURBINES

2.1 General about aircraft obstruction marking

Aircraft, or aviation, obstruction marking is a rather self-explanatory term; warning denotation of objects that may endanger the safety of airborne vehicles in order to allure attention and aware the aviators of an obstruction. The marking is often made with specific colorations, lighting or fitting of flags or spherical balls (on wires etc.). The objects to be marked as obstructions are typically tall or serving a function at a higher height, both at land and sea. Some examples of obstructions are permanently or temporarily installed masts, guy wires, buildings, wind turbines and weather balloons (Transportstyrelsen, 2013). Their height may restrict the flight paths for low altitude aviation operations such as police or rescue missions and other helicopter operations, aircraft emergency landings, fertilizing, instrumental flights and soaring (Trafikverket, 2010) or in a military context; combat aircraft training and operations or cargo transportation (Försvarsmakten, 2015).

Before any object or construction with a height of 20 m above ground level (agl) is erected outside coherent settled areas, a notification shall be submitted in order to register the obstruction. When the height of the object reach above 45 m agl it has to be fitted with marking, and as further explained in chapter 3, wind turbines shall be fitted with lights and marked with paint (Transportstyrelsen, 2013). In the following, studies concerning the effects of these lights will be reviewed.

2.2 Effects of wind power obstruction lights on the local environment

These subchapters will explore the effects imposed in the local environment by the lights and try to identify the critical light factors found annoying.
Swedish findings of aircraft obstruction marking affecting the local environment

The synthesis report *The Effects of Wind Power on Human Interests, Vindval Report 6545* from 2013 briefly mentions how aviation obstruction warning light can be perceived as “a disruptive element in the landscape”. The context implies that when a high intensity light keeps flashing around the clock this can be expected (SEPA, 2013).

The report also raises a question that, at least in 2013, had not been covered in research: “Is the value ‘free view” a national economic resource that can be utilized by everyone?” The question come from discussions on “the value of everyday landscape” and “free starry sky”, somewhat philosophical and very subjective topics but far from irrelevant when it comes to wind power development. “Views over marshes are part of the wilderness and its natural values where influence from urbanization is minimal and ‘free skies” therefore become important.”. The synthesis also describe the visual impact and industrialization effects wind turbines may infuse in untouched landscapes (SEPA, 2013).

A study of sound crossing light

In 2013, Kajsa Olsson made a study with six in-depth interviews on wind turbine sounds in the wilderness (*Vindkraftsljud i vildmarken*). One finding in the results was that the participants annoyed by wind turbine noise, also felt an intrusion in the private sphere by the obstruction marking lights. The high intensity white blinks were subjectively described as particularly annoying during darkness and a big contrast to the landscape, spared of city lights. Two subjects had to deploy blinds to keep the light out of their bedroom. However, most of the interviewees indicated they accepted the lights since they were a temporary disturbance as the wind farm developers had informed they were to install an on-demand radar system, i.e. only lighting the obstruction lights when aircraft approach the wind farm (Olsson, 2013).

Other theses

Further Swedish social acceptance questions related to obstruction lighting are raised or touched upon by some other studies. *Nimby eller Yimby* is the name of a thesis (Sörensen, 2014) investigating the local opinions of an established windfarm and the reasons for another wind power project being stopped. Positive opinions shown in some interview-results indicate that local benefits and the environmental value wind power stand for seem to outweigh possible annoyance factors as blinking light or sound emission (Sörensen, 2014). *Olika faktorers inverkan på Vindkraftsetableringar* by Matilda Pettersson, 2013, studies the influence of various factors on wind power developments. The focus of this thesis lies on investigating the impact of media, municipal approval and overview-plans as well as communication between the developers and the public. The lighting from wind turbines was categorized under visual impacts, and the findings in media statements showed the category mainly represented by neutral or negative public statements (Pettersson, 2014).
International manual highlighting environmental concerns
Considering a broader perspective, at obstruction lighting in general, more material can be found. Section 14.4.9 of the ICAO document Aerodrome Design Manual Part 4 – Visual Aids, 2004, explains environmental problems found with obstruction lighting in general and their dependency on location. Some of the areas more sensitive are “suburbs, national parks, valleys and locations where lights are placed on buildings of historic or architectural significance.”, and further, the light characteristics influencing the subjective environmental acceptance is listed as “color; intensity in the direction for the viewer; flash characteristics; and lighting configuration on the structure”. Further, it is mentioned that it is generally agreed that regarding the color of the lights, red are “less objectionable” than white. The following section of the manual explain that the acceptability of white flashing lights at night is to a great extent depending on the light intensity in the direction of the viewer, a phenomena influenced by meteorological visibility conditions among others (ICAO, 2004).

2.3 International studies and recommendations on the use of alternative obstruction marking

A German acceptance study
In Germany, Pohl, Hübner and Mohs investigated the Acceptance and stress effects of aircraft obstruction markings of wind turbines in their 2012 surveys with 420 participating residents living in the vicinity of 13 wind farms (Pohl, et al., 2012). In contrast to the effects of noise emission, the possible effects of obstruction lighting on local habitants was a rather unexplored area in academia. Looking to answer “whether obstruction markings cause stress or even substantial annoyance to residents living in the vicinity of wind farms” and how it affected social acceptance, they set out to carry out the first systematic research in the area. A questionnaire was handed out to the residents, the questions according to the following categorization. Five different obstruction marking scenarios were compared:

- Different marking technologies used,
- placement in simple (rural area) or complex (suburban area) landscape scenery,
- day and night lights,
- lights with synchronized blinking or not and
- markings adapting the light intensity after the visibility (lower light intensity in case of clear sky) vs. regular, constant intensity lights.

The well-reasoned indicators of stress and acceptance gave a lot of results. One eye-catching result was the indication of annoyance which, both day- and night time, where lower in wind farms without light intensity adjustment. Though, as explained in the text, this can be the outcome of wind developers frequently providing other compensatory initiatives (e.g. blinds) to manage the annoyance wind farms without light intensity adjustments, as wind farms using adjusting lights did not trigger such “protective actions”.
Some other of the presented results were: xenon lights indicated more unpleasant than LED lights; the level of annoyance being strongest at night; clear evidence that synchronized lights reduced annoyance compared to non-synchronized; in 35 relevant stress indicators no stress effects could be proven; the general wind power acceptance was moderate with LED installations, whereas xenon and color markings produced less positive evaluations (Pohl, et al., 2012).

Further, the residents were to rate which function characteristics they would prefer. On-demand-lit warning lights (only lit when aircraft approach) was most desired, although no such systems were installed in the surveyed wind farms. Longer flash intervals, lower light intensity and synchronized flashing were “clearly preferred”. Remarkably, the option “no marking” had the lowest overall score, hinting that the residences understood the necessity of marking the wind turbines (Pohl, et al., 2012).

Looking into stress factors from wind farms in general, Pohl et al. found their results pointing in the same directions as earlier studies; the highest annoyance was due to changes of landscape scenery, ensued by noise emissions. In comparison, obstruction markings (in the existing wind farms) generated “considerably lower” annoyance, and daytime lights were “significantly” less annoying than shadowing and the sight of blades rotating on the horizon. Although, daytime markings created annoyance comparable to light reflections from the rotor blades, and night time lights was found more annoying, at a similar level as shadow casting. Summarizing, obstruction markings could not be blamed for any “substantial or harmful annoyance”, as no proof could be found among the results of the observed stress effects. Comparing the findings of obstruction markings with other impact factors, annoyance by shadowing were stronger, and changes to the landscape and wind turbine noise were even stronger, in resemblance to other impact studies (Pohl, et al., 2012).

Even if the annoyance of obstruction markings were not found substantial, xenon caused the strongest stress effects. Weather conditions played an important role and obstruction lights in clear nights were most annoying, regardless of synchronization or intensity adjustment. This was explained by the visibility of wind farms being higher, which also in other studies have triggered negative evaluations (Pohl, et al., 2012). Consequently, Pohl et al recommended to reduce the brightness of the obstruction markings in order to lessen the overall visibility of the wind farm, reasoning even though the fairly neutral stress indications for light intensity adjustment. Continuing with the favorable characteristics, “the light signals should be less bright, less frequent, and synchronized”, and the top solution would be to install on-demand warning lights (Pohl, et al., 2012).

Pohl et al. (2012) also recommended that the German General Administrative Regulation for Marking of Aviation Obstructions, 2007, already regulating a reduction of light intensity should require a minimum reduction requirement during certain weather conditions. Penultimate, the authors reflect; the acceptance of wind farms is influenced by many aspects, and the recommendation to install intensity adjusting equipment constitute
“a small building block” as it will not solve the bigger impacts of noise, though slightly improve the landscape impacts.

Finally, the summarized recommended practice for obstruction marking, by Pohl et al.: “abandon Xenon, permit block signaling systems, pre-scribe intensity adjustment and synchronization, and test the possibilities of demand-oriented navigation lights. In sum: from the perspectives of resident protection and the general acceptance of wind energy, light emissions should be reduced as much as possible. Moreover, a positive and fair planning process is crucial to reduce opposition as well as annoyance.” (Pohl et al).

Note
To be kept in mind are that the German wind turbine obstruction lighting regulations have different definitions of high and medium intensities than Sweden, and that no white flashing lights cannot be used night time (Die Bundesregierung, 2007)(Transportstyrelsen, 2013).

Recommended use of visibility systems for wind turbines
Re-focusing research efforts on the public acceptance of energy infrastructure: A critical review by Cohen et al. (2013) analyses the best practices for social acceptance of renewable energy projects meeting local resistance. In a table, the best practices with supporting evidence for reducing local opposition are presented. For wind power, the first concrete measure is to “Use less intense synchronized lights” (Cohen, et al., 2014), based on the above cited study by (Pohl, et al., 2012).

Visibility controlled obstruction lighting - internationally recommended practice
The recommendations in Pohl et al.’s study also appear in international recommended practices – published by the International Energy Agency. The International Energy Agency (IEA) has a corporation agreement with the member countries within the IEA Wind, with the purpose of exchanging information about research, development and deployment of wind energy systems. The IEA Wind – Expert Group Summary on Recommended Practices – 14. Social Acceptance of Wind Energy Project, 2013, is the project report carried out by experts from ten countries worldwide. The report contains recommended practices in five main categories with the aiming to achieve “societal consensus on the planning, construction, and operation of wind power projects”. It is clarified that there is no general recipe for social acceptance, as the local conditions are individual for each project. With that said, what is presented in the report is based on what has been working in the past and can be expected to accommodate greater wind power support (IEA Wind, 2013).

Under the category of “Well-being and Quality of Life”, concerns of health, annoyance and stress are found together with some factors possibly appearing in a wind energy
project. It is declared that empirical material allows for recommending practices for some of the influencing factors, and among them obstruction marking. As a general recommendation it is explained how care should be taken to consider the concerns together with the population and have an open dialogue about solutions.

The recommendations concerning obstruction lighting, based on the minimization of luminous intensity are: “

- Abandoning xenon-markings
- Synchronising navigation lights
- Applying light intensity adjustment
- Creating less-stressful planning and construction periods
- Allowing and using demand-oriented navigation lights”

Where navigation lights are obstruction lights, and planning and construction are not strictly related to obstruction lights, the concerns were raised in that context, why they are listed. These recommendations are justified by the findings and recommendations of Pohl et al. 2012, but in this setting, they are coming forth as recommended practices by an international agency (IEA Wind, 2013).

2.4 Complex Swedish situation

In January 2016 the CEO of the Swedish Wind Energy Association, Charlotte Unger sent a letter on behalf of the association to the Swedish Minister of Energy, Ibrahim Baylan, addressing the need for a solution to the multifaceted issues concerning the use of on-demand obstruction lighting for wind turbines (Behov av lösning på frågan om behovsstyrd hinderbelysning på vindkraftverk) (Unger, 2016). The letter emphasizes the deep concern of the Swedish Wind Energy Association, representing all wind power developers directly affected by the situation and the problematics arisen due to the Swedish Armed Forces’ ongoing investigations of on-demand obstruction lighting systems (Unger, 2016).
CHAPTER 3. REGULATIONS AND STANDARDS CONCERNING OBSTRUCTION MARKING

In the following subchapters the legislation concerning obstruction lighting will be described, from higher level law down to specific requirements, starting nationally in Sweden and continuing with international standards and regulations.

3.1 Laws, ordinances and bodies for wind power development and obstruction lighting

The Environmental Code
The Swedish Environmental Code (miljöbalk, SFS:1998:808) is the overhead legislation concerning all environmental and sustainability matters. The second chapter of the Environmental Code contain the general rules of consideration, and in relation to obstruction marking of wind power, the third and seventh section are important when describing the development. The third section is called the “precautionary principle” (försiktighetsprincipen), and describe how available precautions necessary shall be implemented to prevent any harm to human health or the environment. To achieve this, “the best possible technology” shall be applied for commercial activities. The seventh section then explain how the sections 2-6 apply. It states “compliance cannot be deemed unreasonable” and refer to a cost-benefit analysis to complement the reasoning (SFS:1998:808).

Wind farm permits
The Ordinance on Environmental Permitting (miljöprövningsförordning, SFS:2013:251) appoint the governance and categorize various activities, where wind parks fall under either the B- or C-category. The vast majority of commercial wind farms in Sweden fall under category B, defined by (among other things) a group of at least 7 wind turbines at least 120 m agl (above ground level) high including the rotor, or two or more wind turbines with a height of 150 m. All B-category activities are required to apply for environmental permits at the county administration board, and any such application shall include an environmental impact assessment according to chapter six, section 3-10. The B-category wind farms must also receive municipal approval (chapter 16, section 4). Wind farms falling under the C-category will not be required to apply for an environmental permit, but shall notify and consult the municipality board of environmental- and health-matters according to the ordinance and obtain a building permit according to the Planning and Building Act (plan- och bygglag, SFS:2010:900).

A B-category permit has “legal force” (rättskraft) meaning that no new demands can be made concerning previously un-addressed matters in the permit procedure (e.g. a late conditional reduction of disturbance from aviation lights). However, that is not the case for municipality decisions concerning C-category wind farms where the municipality can make a new decision with new demands at any time. Further, a full permit procedure can
be required at any time after the first notification is made, e.g. after the wind farm is built. To reduce risks of additional demands, wind power developers can choose to voluntarily apply for a permit in the same way as for a B-category wind farm at the county administrative board in the first place.

Further, depending on their configuration, wind farms may also need other permits and notifications for example according to the Planning and Building Act (plan och bygglagen), the Electricity Act (ellagen), the Ordinance on Seafaring (sjötrafikförordningen) or the Aviation Ordinance (luftfartsförordningen).

The Aviation Act and obstacle notification
The Aviation Act 2010:500 chapter 6 requires a “flight obstacle report” on any works that may constitute a hazard to be issued and submitted, and allows the Government to further regulate this (SFS:2010:500). The Government then issued the Aviation Ordinance (2010), containing supplementing provisions to the Aviation Act. In the sixth chapter of the ordinance the Swedish Transport Agency is appointed to “issue regulations on, or in individual cases decide on, the marking of the flight obstacle”, where the obstacles may constitute “buildings, masts, natural features and similar objects”. In addition, the ordinance state “Such marking may not lead to any significant detriment for those who own or hold a special right to the land in question.”. Further, the Agency shall consult the landowners, the possible affected ones in previous quotation with the addition of “representatives of other interests affected”. The sixth chapter also appoint the Transport agency to regulate the obstacle notification reports if necessary, a right currently (2016) being applied, see subchapter in 2.3 below. Also, the Aviation Ordinance appoints the Armed Forces to be the main body to be notified regarding new obstacles (SFS:2010:770).

3.2 Swedish regulations concerning obstruction marking and obstacle notification

Marking of objects that may pose a threat to the aviation safety
All object or constructions reaching 45 m agl will be in scope of the Swedish Transport Agency’s regulations TSFS 2010:155K – The Transport Agency’s regulations and recommendations concerning marking of objects that may pose a threat to the aviation safety, as amended in 2013 with TSFS 2013:9 – Concerning changes in TSFS 2010:155 (Transportstyrelsen, 2013). These regulations set requirements for the marking of obstructions that may affect civil aviation, which for wind turbines mainly involve marking by coloring the turbines according to specific paint schemes and installing obstruction lighting (Transportstyrelsen, 2013). In the following some definitions are presented and followed by and the requirements concerning wind turbine obstruction marking will be described in the order of section wise appearance.
Walkthrough of *TSFS 2010:155K* with focus on wind power

The regulations concerning obstruction markings are generally categorized by type of object and further divided with respect to the object’s total height. The twelfth section covers general marking of wind turbines and specifies that a turbine with a total height (height with rotor at its highest point) above 45 m agl (above ground or water level) shall be colored white according to section 19 and be marked with lights. The lighting for a turbine between 45-150 m agl shall be red medium-intensity flashing during dusk, dawn and darkness. A wind turbine above 150 m agl shall be fitted with white high-intensity flashing light. *TSFS 2013:9* introduced the alternative to substitute the red medium-intensity flashing light with white high-intensity flashing light for a wind turbine with a total height between 110-150 meters. Further, if a wind turbine is not protruding enough in its surroundings it may be required to be fitted with additional marking.

Section 13 set the specific rules for wind farms, defined as four or more wind turbines where the distance between two neighboring turbines does not exceed 900 m. The rules modify the previous paragraph by requiring low intensity lights for the wind turbines not making the outer border of the wind farm, with some exceptions explained in attachment 2. The wind turbines making the outer border are to be marked according to section 12 and attachment 2 and 3 (next page). Section 18 then tells that the highest points and corners of a group of objects (e.g. wind farm) shall be marked to show the contour for the group. Further, the horizontal distance between any of these lights shall not be greater than 900 m.

In section 25 the placement of lights is described. The lights shall be fitted so that the highest point of any object is marked. In the case of a wind turbine with a highest fixed point at maximum 150 m agl, it is sufficient to fit lights at this highest point. If this point however, is located above 150 m agl, the placement will be decided in a case-by-case evaluation by the Transport Agency. Section 27 states that the marking light or lights shall be visible 360° around the horizontal plane.

The sections 29 to 31 defines the characteristics for the low-, medium- and high-intensity lighting categories. Low-intensity lights shall be constantly shining red while medium-intensity lights shall be flashing red and high-intensity lights shall be flashing white. All intensity levels shall follow their respective specific requirements in attachment 9, where also possible reductions are presented. It is advised to synchronize flashing lights with nearby flashing lights to reduce annoyance in the surroundings.

Section 32 was introduced in *TSFS 2013:9* and requires high-intensity lights to be pointed upward to reduce annoyance in nearby settlements. The required angles of lights are presented in a table and the main philosophy is increased angles with decreased installation height.

Section 33 is the last paragraph and also the exemption paragraph, stating that the Transport Agency may grant exemptions from these provisions.
Attachments to the regulations
The first attachment to the TSFS 2010:155K is not wind power related, but it allows the use of meteorological visibility measurements as a mean to determine when obstruction lighting shall be used for wires on heights up till and above 150 m.

Attachment 2 show, as seen below, the methodology to apply from section 13 above when obstruction marking a wind farm with turbines with a total height of 150 m or less agl. The methodology is described below the picture.

The purpose of having a safety zone surrounding a wind farm is to provide a safe space for aircraft to evade the wind turbines. To determine which turbines are making the safety zone border, and thus making the outer border of the wind farm with turbines max. 150 m agl and to be marked with medium-intensity lights, the safety zone can be graphically established by the proposed method. Centered at suitably selected turbines along the outline of the wind farm, 450 m radii shall be drawn and connected to make a closed outer border of the safety zone. The safety zone shall be at least 450 m wide, and no turbines shall be within 450 m of the outer border. If the alternative lighting is used, with white high-intensity lights as suggested in section 12, the outer 450 m radii shall be replaced with 2000 m radii, making a closed safety zone around the wind farm.

Figure 2. Explanation of safety zone. Source: Transportstyrelsen, 2013 (attachment 2)
Attachment 3 provides a similar way of finding the borders of the safety zone for wind turbines with a total height higher than 150 m agl. The turbines making the basis for the safety zone of the wind farm shall be equipped with high-intensity lights. The safety zone is calculated by the same principle as in attachment 2, with the differences of radii being 2000 m, the width being minimum 1600 m and the distance between any turbine and the outer borderer being 1600 m. Also here, the wind turbines located in the parts of the wind farm shall be fitted with low-intensity lights.

Attachment 9 specifies the operational requirements for the categories of light intensities. Presented in the form of a table (cited below) and explanation, the following categories are regulated:

- Intensity class of lights and color, where the intensities vary with the position of the sun and background luminance.
- Signal type (flash interval or steady)
- Maximum point light intensity (effective intensity for flashing lights) in candela
- Vertical distribution of light beam and intensity at given angles of elevation when the illuminating unit is adjusted from the horizontal plane

Table 1. Intensity descriptions. Source: Transportstyrelsen, 2013 (attachment 9)

<table>
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<tr>
<th>Ljusstyrk</th>
<th>Färger</th>
<th>Signaltyper</th>
<th>Dager (cd)</th>
<th>Skymsning/Greyning (cd)</th>
<th>Mörker alternativt där baktlands- lumenan vore underlaget 50 cd/m² (cd)</th>
<th>Stryks (cd) vid givna elevationsvinklar när ljusenselen är justerad utifrån horizontalplanet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lågintensiv</td>
<td>Röd</td>
<td>Fast</td>
<td>min 32 (d)</td>
<td>min 32</td>
<td>10°</td>
<td>min 32 (e)</td>
</tr>
<tr>
<td>Medelintensiv</td>
<td>Röd</td>
<td>Blinkande</td>
<td>(20–60 bpm)</td>
<td>2000 (d)</td>
<td>2000</td>
<td>min 300</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>± 25 %</td>
<td>± 25 %</td>
<td>max 50 %</td>
</tr>
<tr>
<td></td>
<td>Högintensiv</td>
<td>Vit</td>
<td>Blinkande</td>
<td>(40–60 bpm)</td>
<td>100 000</td>
<td>10 000</td>
</tr>
</tbody>
</table>

The explanations on the following page, a) to e), further define the requirements. a) to c) define the light spread and specify their respective values. d) provides a condition which
say the intensity only needs to be attained when the background luminance is below 500 cd/m\(^2\) and that the lighting can be omitted in daylight, however it is implicit that this only apply for low and medium intensity marked wind turbines. The letter e) gives the general requirement that the lights shall have sufficient intensity beside the already specified values.

From the requirements, table and explanations it can be extracted that red medium intensity lights (turbines up to 150 m) only need to be lit daytime when the background luminance is lower than 500 cd/m\(^2\), and so with 20-60 beats per minute (bpm) and an effective intensity of 2000 cd ±25 %. During dusk and dawn they shall flash with 2000 cd, and in darkness or when the background luminance is below 50 cd/m\(^2\) a light intensity of minimum 200 cd is required. The vertical angle of spread shall be minimum 3°.

Meanwhile, the high intensity lights for turbines above 150 m (or using the option for wind turbines 110-150 m in § 12) shall be white and flash 40-60 bpm at an intensity of 100 000 cd ±25 % in daylight, 20 000-100 000 cd ±25 % during dawn/dusk and 2000 cd ±25 % in darkness or when the background luminance is below 50 cd/m\(^2\). The angle of vertical spread shall be 3°-7° with maximum 3% of the intensity at a 10° angle below the horizontal plane (Transportstyrelsen, 2013).

**Notification of aviation obstruction**

When planning any construction higher than 20 m agl (or 45 m in deployed areas), including wind turbines and MET-masts, the Armed Forces shall always be notified with an obstacle notification report and the aeronautical information service LFV consulted as a stakeholder. The Swedish Armed Forces owns the database for national aviation obstacles (Vindlov, 2015), which is governed by LFV. LFV is both a commercial provider of navigational and traffic management services, and a public enterprise acting under instructions from the Ministry of Enterprise and Innovation (Näringsdepartementet). The main public tasks are to provide safe, efficient and environmentally sound air navigation services for civil and military aviation.

LFV also manages the obstacle database and make sure planned constructions are in line with flight procedures and landing surfaces and areas according to national regulations and adopted international standards such as *ICAO Annex 14*, with minimum sector altitude (MSA) surfaces and other obstruction sensitive areas (LFV, 2016). More about ICAO and international standards in chapter 2.4.

As mentioned in previous subchapter, the obstacle notification report is obliged under the *Aviation Ordinance* (2010:770). In wind power projects, the contents shall include the coordinates of each turbine, their rotor diameter, turbine hub- and total heights together with ground elevation and other specifics (Försvarsmakten, 2012). The notification shall be submitted at least 4 weeks in advance of planned construction and for big wind farms built in stages multiple reports can be submitted as positions are decided. The obstacle information is registered in the national database and is used for both civil and military flight maps and in various publications for pilots (LFV, 2016).
2016 Revision of TSFS2010:155K
There is currently (spring 2016) an ongoing revision of the regulations on obstruction markings TSFS 2010:155K where the Transport Agency propose to start regulating the notification process of aviation obstruction in more detail (as promoted in the Aviation Ordinance), to increase the accuracy and precision of the obstacle position. It is motivated by the recent years’ heavy expansions of obstacle amount, a major part being communication masts and wind turbines. The inaccuracies occur partly due to the early notification, where the location in the report is not used and also the obstacle height differs, and the suggested measure to cope with these offset placements is to measure and confirm or update the position of newly raised or moved obstacles. Another proposed addition to the regulations are infra-red (IR) obstruction lights in addition to the more common light emitting diode (LED) lights used today. This to aid aviators using night vision goggles during night time flights (Transportstyrelsen, 2016).

3.3 International regulations, guidelines and standard practices
This chapter goes through the international basis of regulations, with focus on obstruction lighting. The literature of interest is summed, described or compared.

ICAO and the Chicago Convention
The United Nations agency ICAO - International Civil Aviation Organization, was founded in 1944 by a group of states drawing up the lines for the Convention on International Civil Aviation, aka “the Chicago Convention” (ICAO, 2016). Sweden was one of the 52 initial states and ratified the convention in 1946 (Transportstyrelsen, 2016). Today, the 191 member states are maintaining the convention together with industry groups to manage a “safe, efficient, secure, economically sustainable and environmentally responsible civil aviation sector”. To achieve those aims, the member states and working groups are collaborating to reach agreement on standards and recommended practices, to be leading policies for the individual states to accommodate and establish the international aviation standards in their own countries (ICAO, 2016). This has led to an extensive set of regulations, standard practices and guidelines, covering most (if not all) aspects of aviation matters that may be scope of standardizing.

Annex 14
The 14th annex to the convention, Aerodromes — Volume I, Aerodrome Design and Operations, 2013, brings forth the international standards and recommended practices for marking of obstacles in aviation environments, especially in aerodromes, but also in their vicinity and generally elsewhere. In the sixth chapter “Visual aids for denoting obstacles” wind turbines have a separate set of requirements and recommendations in subchapter 6.2.4. The requirements are general, saying that wind turbines shall be marked and/or lighted if considered an obstacle, and recommends that they are painted white. The lighting recommendations say that medium intensity lighting shall be used if necessary and wind farms (“a group of two or more turbines”) shall be marked as an extensive object where the perimeter is marked, together with recommendations to the spacing between
marking and simultaneous flashing lights. Further, it is recommended that “The obstacle lights should be installed on the nacelle in such a manner as to provide an unobstructed view for aircraft approaching from any direction.” (ICAO, 2013).

*Aerodrome Design Manual Part 4*

The sixth chapter of the 14th annex also contain more specific requirements for obstacles and refers to the *Aerodrome Design Manual Part 4 – Visual Aids*, 2004 Doc 9157. This manual goes into details about obstruction lighting in general, starting with intentions and human reactions to color and light, translating terms such as pilot’s “reaction time” to “acquisition distance” depending on airspeed and as an example, explains why runway lights must be dimmed not to dazzle pilots during different atmospheric visibility conditions (1.2.23). The manual further explains the regulations (detection ranges at certain airspeeds) and implications (“negative visual impact on the local environment” in 14.1.7) and reasons with the matters. However, the main focus of the manual lies with the requirements in annex 14 and their basis. Section 14.4.5 explains that the intensities in Annex 14 are chosen to give a sufficient range of visibility during the “most demanding situations”, referring to table 14-1 below. 14.4.7 tells that “lights must produce a visual range in excess” of the visual range at the site of the unlit obstruction to be of “operational benefit”. The visual range of the unlit obstruction is at best synonymous with the meteorological visibility, however often less (ICAO, 2004). Thus, the practical interpretation of the light intensity requirements should be that the light’s range have to be greater than the visible range of the unlit obstruction.
Further describing the regulations in annex 14, section 14.4.19 in the 2004 manual explain the medium intensity ‘Type A’ lights, white 20 000 cd, and its applications. This type of lights can be used in “many applications where an environmental study can show that it is not necessary to install the high-intensity equipment and that the range performance of the medium-intensity lighting is adequate”. In 14.4.20 the benefits of using a ‘Type B’ medium intensity light for use in dual lighting systems (white light daytime, red light nighttime) are described: “it overcomes the objection to the use of flashing-white lights at night which occurs with other systems. Because it is medium power and requires no intensity control, the cost of the Type B light makes the use of dual lighting systems economically viable.” (ICAO, 2004).

Section 18.3 in the manual provide the method to calculate the effective intensity of flashing lights. The effective intensity of lights with flashing characteristics is defined as “the intensity equivalent to that of a steady burning light to produce the same visual range for the eye”, which imply that they are not the same. It is explained that the maximum intensity during the flashes cannot be used to estimate the range, as an abrupt flash has another illumination threshold (for the observer) (ICAO, 2004).

**EASA**

The European Aviation Safety Agency, EASA, was established in 2002 to be the authority for aviation safety within the European Union (Transportstyrelsen, 2016). With the
Certification Specifications and Guidance Material for Aerodromes Design, Issue 2, 2015 (updated according to ICAO changes or proposals), the Aerodromes Design from the ICAO annex 14 is taken into EU legislation - with some alterations - by a number of regulations. The remarkable difference concerning obstacle marking is the explicit regulation of obstruction marking in or in the vicinity of aerodromes, areas “under control of the aerodrome operator”. Further, it refers to ICAO documents as well, e.g. Doc 9157 Aerodrome Design Manual, Part 4, Visual Aids in multiple places. The light intensity table is also remarkably similar to ICAO annex 14 (EASA, 2015).

3.4 Regulations in other countries

National regulations
With the Swedish regulations cited above in chapter 3.2, and the international standards and regulations laying the basis for the national provisions described above, Finnish and German regulations will here be described with the Swedish TSFS 2010:155K as a reference point.

Finnish regulations
The Finnish provisions on Obstacle Restrictions and Aviation Obstruction Markings, Luftfartsbestämmelse AGA M3-6 – Hinderbegränsningar och Markering av Flyghinder, 2000 is “based on the Standards and Recommendations in the Chapters 4, 6 and 8 in Annex 14, Volume 1 to the Convention on International Civil Aviation” (Ilmailuhallinto, 2000). Obstruction lighting is found in the seventh chapter (Aviation obstruction marking) of these provisions and though the wording of requirements is different than the Swedish TSFS 2010:155K, their practical meaning seems reasonably familiar being based on height and dimension of the objects and marking using corresponding intensities and colors. Although the overhead picture seems similar, it is clear these requirements are founded upon the international convention as the structure of requirements are the same, the intensities and characteristics of the required light-types too and references are made to the Annexes of the aforementioned convention and to other complementing documents where further explanation and definition might be needed. An example of this is the expression “effective intensity”, mentioned in the light characteristics-table, similar to the one for the intensity requirements in TSFS 2010:155K, but followed with a reference to Aerodome Design Manual Pt. 4 in which how to find the effective intensity is explained. Another difference worth noting is the application of expert statements (sakkunnigutlåtande), for instance in Reg. 7.3.10 where the essence is: if an expert judgement indicates high- or medium intensity lighting causing a danger of pilots being blinded or causing considerable inconveniences in the vicinity, a double system can be required where the night lighting shall be red color with the choice of steady light or bigger blinking intervals (Ilmailuhallinto, 2000).

Finnish instructions on wind turbine marking
The Finnish Transport Safety Agency (Trafi) in 2013 published further instructions specific for obstruction marking of wind turbines, Anvisning för dagmarkering av
vindkraftverk, för flyghinderljus och för gruppering av ljusen (TraFi, 2013). This set of requirements is also similar to the Swedish regulations for wind turbines when total height above 100 m agl., though yet again with some exceptions. Firstly, it is clarified that the high intensity requirement of 100 000 cd can be achieved with two 50 000 cd lights (something that is unclear in Swedish regulations and developers often use two 100 000 cd). Secondly, for wind turbines total height above 150 m, the night-condition high intensity marking can be chosen between three alternatives, all with 2 000 cd intensity: blinking white, blinking red or fixed red. Another addition is extra lights on the tower when its height exceeds 105 m. These lights are to be installed with maximum 52 m height intervals and must be placed above the tree line. Also, the lights of a wind farm are required to be synchronized, something only recommended in the Swedish regulations. Further, when the obstruction lighting consist of LED-lights it must be ensured that infra-red (IR) light within a wavelength span of 800-940 nanometers (nm) is also emitted with specified intensities, depending on the light intensity requirements at hand. The IR requirements are there for the same reason as for the currently ongoing (2016) revising of the Swedish TSFS 2010:155: all LED-lights are not visible with the night vision goggles used by pilots, primarily military (TraFi, 2013).

Weather dependent light intensity reductions in Finland

The final difference compared to the Swedish regulations, (and most important difference for this thesis,) is the additional requirements opening for a reduction of light intensity during good visibility conditions. When the meteorological visibility exceeds 5 000 m the light intensity can be reduced to 30% of its nominal requirement and further, when the visibility is over 10 000 m the light intensity can be reduced to 10% of its value. That is a 70% respective a 90% reduction of the nominal intensity.

It is then described that visibility measuring instruments shall be used, mounted on nacelles and in a wind farm with a maximum distance of 1500 m between each unit. The instruments shall filter out light emissions from the obstruction lights during measurements and detect any disturbances or defects to their function automatically and in case of any interference or when the output is deemed unreliable, no reduction of the light intensity shall be made. The weakest visibility value from all units in a wind farm shall be applied as visibility of the wind farm, and thus determine the maximum light intensity reduction. The equipment shall be calibrated once a year or when in offshore use twice a year. The wind power developer shall submit a declaration of the visibility measuring system attached to the aircraft obstruction notification report. In case of a wind farm, a plan over the instruments placement shall be submitted. Before the visibility instruments are put into service, the operational functionality shall be inspected by an independent institute or organization and the test protocol submitted to the Finnish Transport Safety Agency. During operational state, the measuring equipment shall be calibrated once a year (twice when used offshore) (Ilmailuhallinto, 2000).
German regulations introducing more alternatives to marking

The German regulations *Allgemeine Verwaltungsvorschrift zur Kennzeichnung von Luftfahrthindernissen*, 2007 amended 2013 (Die Bundesregierung, 2007) may very well have constituted the foundation for the Finnish instructions, as they also allow for intensity reductions in addition to being based on the ICAO recommendations. Yet, in the third part regulating wind turbines, the major differences compared to the Swedish regulations are the addition of alternative ways of marking with combinations of color marking stripes on the blades and tower, blade tip lighting, tower lights, dual light systems, another type of obstruction lights called “w, red”, and intensity reduction. Blade tip lighting was discussed in 2005 along with other potential solutions at the IEA meeting in Sweden (IEA, 2005). However, at the time it was considered unreliable due to lack of lights surviving the forces, complicated maintenance and also considered more annoying to look at. The dual light systems, also described in *Aerodrome Design Manual Part 4*, 14.4.20, is basically the use of white flashing medium intensity lights (Type A according to ICAO annex 14, 20 000 cd) daytime and red lights night time, which is also allowed in Finland. The “w, red” lights are specially designed for wind turbine use and reduction of public disturbance. These “w, red” lights operate with low red light intensity and a wider vertical light spread and a special rhythmic blinking. Both the dual lights and the “w, red” seem to come as optional lighting to the “standard” ICAO red types of lighting. Namely, white flashing lighting is only for daytime and twilight use in Germany (Die Bundesregierung, 2007).

Intensity reductions in Germany

Reduction of the light intensity is allowed both day- and night time in the regulations, provided the instructions in the fourth annex to the regulations are followed. “If the visibility exceeds 5 000 m, the initial luminous intensity can be reduced to 30%, and if the visibility exceeds 10 000 m, it can be reduced to 10 %”. Annex 4 instruct that visibility measurements shall be done according to German standards and with equipment approved by the German Meteorological Service DWD. The measuring unit shall be installed near the nacelle and one measuring unit can maximum cover wind turbines within 1 500 m in case of a wind farm, and if multiple sensors are installed the worst value shall be used for all turbines. If any device is malfunctioning, all lighting shall operate at 100 % intensity. Data of the operation and measurements shall be recorded and stored for a minimum of 4 weeks. Before the light control is allowed for operation, the function and operation shall be tested and approved by an independent institution and the protocol submitted to the approving authority (Die Bundesregierung, 2007).
CHAPTER 4. LIGHT CONTROLLING TECHNOLOGIES

4.1 The available alternative light controlling technologies: on-demand- and visibility controlled obstruction lights

Need for alternatives
The above mentioned studies and documents, indicating that characteristics of the lighting might be a concern for some local inhabitants and environment, and also a possible concern that has triggered a demand for alternative solutions with both the wind power developers and local authorities to enable better co-existence between wind power and society. The wind power industry’s responding measures to cope with municipal concern and local annoyance is described in the following subchapters.

A brief introduction of the technologies
Technologies available from other industries and concepts have been adapted and further developed to be applicable for coping with the above mentioned concerns with obstruction lighting. In the following, a brief conceptual description of the technologies appearing in the subsequent subchapters will be provided.

Radar based solutions
This concept is based on installing radar units in wind farms or on wind turbines for surveilling the airspace and detecting approaching aircraft. It is an on-demand solution, meaning the obstruction lights will only be lit, steady or flashing, as an airborne object is detected in the surrounding airspace, and when the aviator is out of the danger zone the lights are switched off (Bergström, 2014).

Transponder based solutions
Another concept is transponder controlled obstruction lighting. This solution is also on-demand oriented, only lighting up the obstruction lights when aircrafts are detected. An anti-collision system will be installed in one wind turbine and recon the transponders of approaching the aircraft. These systems also open the opportunity for communicating, letting the pilots know there is a wind farm ahead with a certain number of turbines with a certain height (Bergström, 2014).

Visibility sensors
The third technology solution is using another principle for reducing light emitted. By using visibility sensors to measure the prevailing visibility conditions, this concept reduces the light intensity (dim the lights) to the intensity sufficient for pilots to identify the wind turbines in the present ocular circumstances in the surroundings of the farm (Bergström, 2014). This is the mentioned technology in both German and Finnish regulations (Die Bundesregierung, 2007) (TraFi, 2013), and is further described in chapter 4.2 and 4.3.
The alternatives need a decision on exemption from the Swedish regulations
However, neither of the above mentioned technologies are in line with the operational requirements for obstruction lights in Sweden today. As described in the TSFS 2010:155K, obstruction lighting shall be continuously lit or flashing with given intensities. This mean that in order to use any of the technological solutions above in Sweden, an exemption must be obtained from the Transport Agency. Unlike the first two on-demand solutions, the visibility controlled obstruction lighting had in 2014 not been tried for exemption (Bergström, 2014).

A Swedish project to increase the knowledge on how to reduce light emissions from obstruction lighting
In 2013 the trade association Swedish Wind Energy, in joint consultation with the Swedish Transport Agency and the Swedish Energy Agency started the project Exemption procedures for on-demand systems (Dispensförfarande för tänd- och släcksystem) to get an overview over the possibilities and conditions for reducing the light emission from aircraft obstruction lighting. The purpose was to map an unclear situation rising in the Swedish wind power industry and identify less complicated and time-consuming ways of future wind power development. The project outcomes were the two reports Specification of requirements (Kravsbeskrivning), 2014, and Market description (Marknadsbeskrivning), 2014, by Daniel Bergström, Rejlers AB. Both reports are focused on the concepts to solve the researched problematics around aircraft obstruction lighting. The focus lies on four possibilities; radar controlled systems, visibility adapting systems, transponder controlled systems and changed regulations (Bergström, 2014).

The reports of the project, intended to be living documents continuously updated with new decisions and experiences, will be further reviewed in the following paragraphs.

Specification of requirements
The Specification of requirements report is a synthesis of the use and research regarding on-demand and intensity reducing systems available in first half of 2014, regulations in some countries, information about air craft obstruction marking in general and some abstracts and brief reviews of literature. The aim of the report was to find an exemption procedure for controllable obstruction lighting-systems, usable for both the authorities and developers. Estimations for processing time together with a generic exemption application was proposed based on previous radar-system exemption applications. Also an overhead issue analysis concerning the current regulatory requirements and authorities involved was discussed in an exemption context. Regulatory safety thresholds and some foreign experiences are also presented and discussed (Bergström, 2014).

Market description
The second report of the project, Market description takes a market approach to the situation. It presents the on-demand- and visibility-based systems commercially available in 2014, list the suppliers of the systems and present a table with the system technical
specifications in an attachment document. Also a future market prediction with new market entrants in the radar-section is presented.

In the Market description it is stated (2014) that although the use of systems applying light intensity adjustments according to visibility measurements have not been tested with the Swedish Transport Agency, the agency takes a positive position to the use of the systems. However, the knowledge to what would be required as well as the official praxis of the authorities were and remain unknown (2016). Yet, there is a statement in Market description saying an exemption case shall fulfill the requirements in TSFS 2013:9 to visibility at the outskirts of the safety zone at 2000 meter. Further, it is indicated that the Transport Agency expects the exemption application to be built on the same methodology as for the radar-systems. It was also explained that visibility adjusting systems for wind turbines are used in Germany and Finland. The intensity reductions for both countries are described as a 90% reduction during 10 km visibility, and 70% reduction during 5 km visibility. They are further used for similar purposes but in other applications, e.g. airports, oilrigs, helipads etc. (Bergström, 2014).

Criticism to the TSFS 2010:155
Both Specification of requirements and Market description take a critical stand to the Swedish regulations. Below, two quotes pointing out the standpoint for the discussions:


- «The Swedish regulations for aviation obstacles have to a certain extent created the need for mentioned technological solutions, when e.g. the light intensity requirements for wind turbines higher than 150 m are the strictest in Europe. » – Market description.

4.2 What is visibility and how is it measured?

This chapter will describe visibility, ways of measuring and the technology applicable.

Definitions
The U.S. Department of Commerce’s 2005 Federal Meteorological Handbook explains visibility as a measure of the opacity of the atmosphere, either achieved by converting a visibility sensor value using algorithms or by manual observation (U.S. Department of Commerce, 2005). Visibility for aeronautical purposes is defined in the 18th edition of the Meteorological Service for International Air Navigation, Annex 3 (2013) to the ICAO Convention on International Civil Aviation, as “the greater of:

a) the greatest distance at which a black object of suitable dimensions, situated near the ground, can be seen and recognized when observed against a bright background;
b) the greatest distance at which lights in the vicinity of 1 000 candelas can be seen and identified against an unlit background.”

Visibility is measured in meters or kilometers (ICAO, 2013) and can be said to be the distance a prominent object or light can be seen, and so independent of day or night. When manually observing the prevailing visibility, reference points at known distances are compared to determine the visibility (U.S. Department of Commerce, 2005). If visibility sensors are used, the extinction coefficient, telling the degradation of vision (ICAO, 2005), of the atmosphere is determined locally and calculated according to standardized algorithms to give the final output in form of prevailing visibility with high accuracy (U.S. Department of Commerce, 2005).

Manual determination of visibility
Manual observations of the prevailing visibility determine the greatest representative visibility distance that can be seen throughout at least half the horizon circle, though not necessarily continuous (U.S. Department of Commerce, 2005). All available reference points shall be used, in all directions around the horizon. Daytime, dark or almost dark objects shall be used as reference points against the brighter background horizon, and during night the points shall constitute of unfocused lights of low intensity. If a reference point is visible with sharp contours and without significant color blurring the visibility distance is much greater than to the object. If the object can barely be seen or identified, the visibility is about the same distance as to the object. When all values around the horizon circle are obtained, the prevailing visibility is determined, for reporting purposes, by finding the greatest distance visible in at least half of the horizon. If the distances are varying a lot during observations, the average of all values shall be used as “variable prevailing visibility” (U.S. Department of Commerce, 2005). Complementary visibility sensors can aid the final evaluations when determining the prevailing visibility.

Instrumental determination of visibility
When measuring visibility with sensors there are two main measurement principles: using forward scatter meters or transmissometers. The forward scatter meters can be said to measure and calculate the extinction coefficient in a portion of the atmosphere (U.S. Department of Commerce, 2005), which tells how fast light radiation is extinct. The transmissometer on the other hand is more direct as it measures the capacity to transport light, the transmittance, in a portion of the atmosphere. There are also other techniques for measuring visibility, but currently ICAO recommend using forward scatter meters or transmissometers for visibility measurements at airports (ICAO, 2005).

The forward scatter meter
The forward scatter meter measures the amount of light that scatters back from particles, both small and suspended in, and larger travelling through, a portion of the air. The sensors are equipped with a transmitter and receiver of light radiation placed at an angle, not directly facing each other, in order to measure the light scatter at angles less than 90 degrees, see figure below showing the principle (ICAO, 2005). The angles used between
the transmitters and receivers differ with models and manufacturers. Further, the most common light to use is infra-red (IR) light (U.S. Department of Commerce, 2005).

![Figure 3. Illustration forward scatter measurements. Source: ICAO, 2005 (Fig 8-1).](image)

In figure 3 above, the atmosphere sample volume is represented by the intersecting fields of the transmitted light beam and the field of reception of the forward scatter receiver. The particles in this volume may be suspended in the air e.g. fog, haze and aerosols, or be precipitating particles such as rain, snow ice pellets, drizzle and mist. In a horizontal optical visual range up to 100 km, the aforementioned particles are the main reasons for atmospheric light extinction, and quantitative measurements in the sample volume will provide the basis for determining the visibility (ICAO, 2005).

The measurement of the scattered signal can then be assumed to be proportional to the atmospheric extinction coefficient (ICAO, 2005), the relationship between them depend on the scattering particles physical properties.

**The transmissometer**

The transmissiometer on the other hand measure the atmospheric transmittance, directly related to the extinction coefficient, by sending light radiation between two points in a space of known length (ICAO 9328). It can be said that a mean extinction coefficient with the impacts of scattering and absorption is assessed, meaning a good determination of the extinction is achieved regardless of the air conditions lowering visibility e.g. fog, snow, dust etc. (ICAO 9328).

**Calculating visual range**

When the extinction coefficient or the transmittance is determined, the visual range can be computed. This is done with Koschmieder’s Law (daytime) and Allard’s Law (night-time) or variations of each of them. Daytime, when the luminance contrast is above 0.05 (during conditions where manual observations would include black objects) the visual
range can be determined Koschminder’s Law. When the contrast is lower Allard’s law is applied. Other factors than extinction or transmittance considered in these laws would be light characteristics and the assumed sensitivity of an observer’s eye in the current luminance conditions (ICAO, 2005).

The final visibility output can be in various formats depending on what is of use in the context. Meteorological optical range (MOR) and Runway visual range (RVR) are commonly used, but there are also other formats, which considers additional factors and in similarity to RVR calculations interpret the data according to standardizations (ICAO, 2005). MOR data, in units of km or m will be used in the case study.

**Development of the technology**

The past decades have driven the design development of forward scatter meters with focus on reliability and accuracy. Various designs have been tested and many problems experienced with early models been coped with by current models. Some early models experienced interference from sunlight, but that was coped with using flash light or infra-red light emitting diodes, which also has given improved maintenance intervals. Window contamination has been heavily reduced by using “look-down” scattering geometry and sensor covers (ICAO, 2005).

**Pro’s and con’s with the forward scatter sensors**

Advantages and disadvantages of using a forward scatter sensors are also listed in the *Manual of Runway Visual Range Observing and Reporting Practices*.

Some of the advantages are the small size and low weight enabling pole installation as well as the ability to withstand unstable ground conditions. Further, a single unit can cover a full runway range. The instrument is not very sensitive to window contamination and the “look-down” geometry makes the cleaning intervals less frequent. It can also be put back to service (repaired, recalibrated or restored) in most weather conditions, except in high winds and blowing precipitation (ICAO, 2005).

Listing disadvantages, the same manual firstly mentions the need to use a transmissometer for exact calibration, typically done in the production process. Next in the list: if an absorption-phenomenon (e.g. aerosols) is reducing visibility, the measurement and extinction factor relationship can be influenced, though if the sensor identifies the phenomenon type this variation can be automatically corrected. However, inaccuracies may appear with mixtures of for instance fog and snow or rain and snow. Continuing on disadvantages, narrow tolerances must be kept on the scattering geometry during manufacturing to avoid variations in calibration in between units. Lastly, the sensor lenses may be obstructed by blocking snow, leading to better visibility values than present, however the “look-down scattering geometry significantly reduces the chances of snow clogging.” (ICAO, 2005).
4.3 Visibility sensor applications and comparison

The visibility sensors are used in an array of applications where visibility is a weather parameter of importance. In the following examples of the practical uses today and their environments are given.

**General applications**

At runways the visible range (RVR) is crucial to determine if aircraft can perform instrumental landing and if taxing is safe. Both transmissiometers and forward scatter meteres are common practice to use as RVR sensors at airports (U.S. Department of Commerce, 2005) and in a page note under the definition of prevailing visibility in the (ICAO, 2013), mentioned that the best estimate of prevailing visibility will be obtained by using visibility sensors. Visibility is also part of the obligatory METAR-reports as well as playing a role when adjusting intensity of the runway lights to avoid dazzling of pilots (although in addition to radio communication with the pilots) (ICAO, 2004).

At roadsides, visibility sensors as part of instruments called present weather sensors are used with the purpose of determining the weather conditions, precipitation, temperature, humidity etc. and thus predict road conditions (snow, ice, fog, heavy rain etc.). This information can then be used for sending out plowing machinery, predict congestions, issue warnings, reduce speeds limits or close the roads (Biral, 2016).

Visibility sensors are also used for controlling guidance, aiding and obstruction denoting lights in a number applications and countries. The sensors functions help determining the light intensity required for pilots to land on oilrigs, helipads (Bergström, 2014) and as mentioned above runways (ICAO, 2004). Further, and more importantly, they are used in obstruction lighting settings for wind turbines. In Finland and Germany among other countries visibility sensors are used to a great extent to optimize the light intensity of the obstruction marking to the prevailing conditions (Bergström, 2014).

**Visibility sensors controlling obstruction lighting on wind turbines**

In this subchapter the examples of three visibility sensors and their application are described.

The sensors, whose functions described and are looked into based on product sheets and official webpages, are:

- Vaisala PWD20W,
- Campbell Science CS120A and
- Biral SWS-200

The three are all well suited and adopted for wind power use and are certified according to CE-standards and importantly, by the Deutscher Wetterdienst to fulfill the requirements of visibility sensors in the service of controlling light intensity of the obstruction lights of wind turbines in Germany (Vaisala, 2010), (Biral, 2016), (Campbell Scientific, 2015).
General principle
All three sensors operate from the same principle: forward scatter metering, meaning they use the particles in the air to bounce light from the transmitter to the receiver. Their design allows for undisrupted airflow in the field of measurement and the meteorological optical range reported differs a bit, however for obstruction light controlling purposes all three is well sufficient to provide the 10 000 m visibility range stipulated in existing regulations.

Mounting and physical installation
For how long visibility technology has been used for dimming obstruction lighting of wind turbines is hard to find out, however some clues are the German regulations (Die Bundesregierung, 2007) allowing the use and Vaisala live-testing their current model solution prior to the product launching in 2006. The testing at the time was of the algorithms for identifying and eliminating possible light-interference from the obstruction light flashes, which showed to be successful – results according to the meteorological observations and the advanced algorithms and filters detecting the polluting light. Different mounting arrangements were also tested, where the best results (with least interference) showed installation high enough above the nacelle to avoid direct transmitter reflections of lights via the nacelle surface, yet still below the obstruction lighting (Vaisala, u.d.).

Continuing on mounting, the sensors shall be mounted facing away from the rotor blades (Campbell Scientific, 2015) and are suited for mounting on masts and poles. The installation can be carried out by a single person (Biral, 2016) (Vaisala, 2010) with their light weight of 3-4.9 kg and small size well within a meter between the transmitters and recievers.

Weather proof
All three sensors are made for the harsh weather conditions on top of the nacelle of a wind turbine, meaning they are robust and withstanding vibrations. They have all proven records in use at airports as well as in other harsh environments e.g. offshore. All three have heated lenses to prevent dew, and automated hood heaters can be installed, preventing snow build up and ice accumulation from being issues. The hoods also protect the sensor lenses from window contamination in form of perspiration, spray and dust (all three). They facilitate functions for automatic window contamination detection and reporting. At least the SWS-200 continues operating while compensating for the dirt on the lens, the PWD20W has a fault alarm relay and the CS120A can be upgraded with dirty window compensation function. Regarding operational temperatures, the CS120A manage -25°C while the others an entire manage -40°C and the common upper limit for all is +60°C (Biral, 2016), (Campbell Scientific, 2015), (Vaisala, 2010).

Connections
Common for the three is also the programmable visibility alarm threshold ready for coupling with relays to control the obstruction lighting. Other connections necessary is of course power supply, which can be done by both AC and DC. They consume about 3-3.5 W during normal operation, and an additional 36-65 W with the heating of hoods. (Biral,
The sensors come calibrated from factory and are recommended an annual check, however a needed recalibration is rare.

Clouds
In Part 1 of the 1975 revision of International Cloud Atlas, clouds are explained to consist of very small particles of water, both liquid and frozen, hanging in the free air (WMO, 1975). Sometimes also bigger particles and foreign substances, from “fumes, smoke or dust”, are part of the mix. The luminance of clouds follow a luminary (light source) shining on the clouds’ constituent particles, scattering, reflecting and transmitting the light to the observer. The clouds are mostly direct lit from a light source or the sky, but also from sun- or moon-reflections in snow or ice of our planet. Haze between the cloud and the observer may cause the luminance to be increased or lowered, depending on factors such as density and angles of light (WMO, 1975). Nighttime, the clouds are mostly lit by artificial light, from cities hereunder also wind turbines and their obstruction warning lights. The luminance of a dense cloud will be highest close to the luminary, though clouds with even higher optical thickness will show a more even luminance distribution throughout. As the clouds’ internal compositions vary a lot, some more homogenous, others very mixed and giving interesting light phenomena.

The visibility is always reduced within a cloud, also in very thin ones, and some very dense clouds may limit the visibility to almost zero (WMO, 1975, p. 55).
CHAPTER 5. SUMMARY OF PREVIOUS WORK, REGULATIONS AND TECHNOLOGIES

Increasing local acceptance
Some local acceptance measures that can be done today, even without using additional technology. Supported means in existing literature are:
- xenon-lights abandonment,
- synchronizing lights and
- reducing the light intensities to the minimums allowed.
These can be done without any regulation impairment speaking against it. They are strengthened by international recommendations and synchronizing the lights also nationally.

Visibility sensors
Reliability
The wide spread use on airports speaks for reliability of visibility instruments. The note to the definition of prevailing visibility in the third annex of the ICAO convention, saying the best estimate of prevailing visibility is achieved by using sensors, something also encountered in one of the interviews. This argues for the use of visibility sensors in an aviation safety perspective.

Visibility controlling wind turbines
By using reductions of light intensities, as recommended by IEA, Cohen et al. (2013) and Pohl et al. (2012), the annoyance of local inhabitants would likely be decreased in Sweden as well. This is further strengthened by ICAO Aerodrome Design Manual Part 4, telling light-intensity is a characteristic in the subjective environmental objections and meteorological visibility an influencing factor in the subjective observer’s determination of opinion (14.4.9, 14.4.10). With those facts, it seem a favorable solution to a complex problem to employ visibility sensor technology to reduce light intensities during high visibility conditions, and thus reduce local annoyance.

Adding the current situation in Sweden, a test of using visibility controlled obstruction lighting could be motivated. At least as an intermediate measure until other solutions can be approved.
CHAPTER 6. METHODOLOGY

Research Question
The question of investigation, also in the introduction:

- How can a system dimming the obstruction lights be applied, both regulatory and technically and what could be gained and saved by using such a system?

6.1 Framework

Aiming to identify technical, regulatory, performance, and feasibility preconditions and limitations with visibility controlled obstruction lighting, the methodological framework is based on conducting a literature review and a case study with complementing interviews. Firstly, a literature review is required to obtain the basic knowledge, a complex mixture of interests of the stakeholders involved as well as the state of art. To achieve this, the literature review has to touch upon many topics. The findings of the literature review will be applied to a case study to identify the possible framing legislative and technical conditions of a real life scenario. Based on an assumption that reduced light intensities would reduce annoyance from the lights, a performance study is conducted to visualize how often an intensity reduction can be made in Juktan, and to what degree. During this process, additional questions will likely arise, requiring the expertise of key stakeholders. To answer some of these additional questions, together with loose ends found in the literature reviewed, interviews with key stakeholders will be conducted. The results from each sub-method will be discussed, where synergies and contradictions between results will be highlighted. Finally, conclusions drawn and future research will be suggested.

6.2 Case Study – Visibility controlled obstruction lighting system in Juktan Vindkraftpark

To explore the prerequisites of applying visibility controlled obstruction lighting a case study on a real wind park, Juktan Vindkraftpark will be conducted. Aiming to identify how the systems can be applied technically, regulatory, and how they would perform, and identify feasibility preconditions and general limitations, different sub-studies will be made. The overhead two will be: a study of regulation application frames and scenarios for visibility systems, and a study of how the lights would be able to operate in the local weather conditions, by using real measurements and mesoscale analysis data from SMHI.

6.3 Juktan Vindkraftpark

(See map in appendix A)

Juktan Vindkraftpark is a wind farm situated next to the lake Blaiksjön in Sorsele municipality, Västerbotten county, Sweden. The wind park commenced production in the
last quarter of 2015 and was developed by Vattenfall Wind Development and the wind turbines are owned by Vattenfall Juktan Vind AB.

Juktan Vindkraftpark constitute of nine Siemens 3.2 MW SWT-113 wind turbines, making a total installed capacity of about 29 MW with an estimated production of 82 GWh electricity annually, enough to power 16 000 homes (Vattenfall, 2016).

The wind turbines are equipped with deicing technology, factory-installed heating mats within the blades, to enable more operating hours in the generally cold climate with temperatures peaking around -30°C in the winter.

In an obstruction lighting perspective
The wind turbines of Juktan are 149 meters high and are painted white and equipped with medium intensity blinking red aviation obstacle warning lights. The height to the rotor hub is 92.5 m and the rotor radius of 56.5 m. The wind farm layout does not allow the application of the park-regulations with steady red lights, as a minimum safety zone of 450 m has to be marked with blinking medium intensity lights around the perimeter.

The surrounding areas are forested and are sparsely inhabited with no permanent residents. Vattenfall has from before hydro power generation in the area and there are neighboring wind farms. Blaiken Vind, owned by Skellefteå Kraft and Fortum is currently building a large wind farm with 99 wind turbines, equipped with both medium and high intensity obstruction lighting. This would make Juktan a good test subject for a future live test to visualize the effects of reducing light intensities.

6.4 Regulation scenarios and cases

As a granted exemption is a necessity for reducing light intensities further than the prevailing provisions, and an exemption naturally comes with terms and conditions in respect to how the lights would be operated (minimum intensities etc.), two scenarios including two subcases are looked into, and a special case found in literature will be examined. Firstly, a zero case in which Juktan will remain the same and will constitute the basis for comparisons. To not fully invent the wheel anew, a case where foreign regulations will be applied to identify the outcomes. Further, a scenario where the turbines in Juktan wind farm would be higher than 150 meter will be studied. This scenario is of particular interest, as the most difficult and concerning industry struggle lies with the high intensity lighting. Finally, the solution presented in literature (Bergström, 2014) as required by the Transport Agency will be examined. The findings of operational functions of all cases and markings required will be presented and discussed.

Scenarios
To assess what frames would be suitable for operating and using visibility based obstruction lighting, scenarios based on reviewed literature is set up. Two scenarios of applying different application schemes to Juktan Vindkraftpark will be looked at:
• Scenario 1. 149-meter-high wind turbines
  Case A. Application of reduction rules only
  Case B. Application of full Finnish instructions
• Scenario 2. Above 150-meter-high wind turbines
  Case A. Application of reduction rules only
  Case B. Application of full Finnish instructions

The reasons for using Finnish instructions is a combination of similarities between Finland and Sweden. In addition to also being a Nordic country, Finnish climate is very similar to the climate in Sweden, especially when looking to interesting sites for wind turbine development. The climate should be considered as visibility is a meteorological measurement, and the differing regulations between the countries make the comparison relevant. Further, the overhead legal structure is very similar between the countries. Finally, both the Finnish regulations and instructions for wind turbine marking are available in Swedish, reducing the risk of misinterpretations.

Case A - Application of reduction rules only
In the first case, only selected parts of the regulations will be used, the reduction of intensity during good visibility, as often mentioned in literature. The current Swedish regulations TSFS 2010:155K will lay the basis regarding requirements to the color, function and nominal luminous intensity of the lighting in the wind farm.

Case B - Application of full Finnish instructions
The second case will be adopting the full Finnish instructions on the marking of wind turbines. This case will incorporate changes to the obstacle marking colors, function and nominal luminous intensity of the lighting in the wind farm.

The solution found in literature
In the Market Description report by Bergström, it is foretold an exemption case shall fulfill the requirements in TSFS 2013:9 to visibility at the outskirts of the safety zone of a wind farm, at 2000 meter. This is not straight applicable to a wind farm and require some elaboration and clarification. The solution will be examined and elaborated in an attempt to understand its practical meaning.

General starting ground
Some basic assumptions have to be made to limit the cases. The wind turbines in Juktan are 149 meters high in scenario one, and in the second the turbines are about 200 meters high with a hub-height at 150 m, as the Swedish regulations open for additional marking when the highest fixed point exceed 150m. Both will follow the TSFS 2010:155K as a starting reference point.

In the cases, it is assumed that all obstruction lights still are installed at the nacelle of the respective wind turbines and that the lights can be dimmed to the intensities calculated. Further, a visibility sensor also installed on the nacelle of a wind turbine, and is assumed
sufficient to control the lighting of all turbines within 1 500 m as stipulated in both the Finnish instructions (TraFi, 2013) and the German regulations. Finally, all countries’ studied have some provision saying the wind turbines may have to be further marked if not protruding enough. This will not be considered in the cases.

**Evaluation factors**

To choose a suitable regulatory framework, two critical stakeholder interests will be used. The first will be the maximum reduction of light intensity, likely desireable by local inhabitants and by municipalities. The second interest is to upkeep a minimum level of aviation safety by either intensity of the lights or by other means of making the turbine visible.

### 6.5 Performance study

The performance study of using a visibility controlled lighting system will try to answer to how big portion of the time the light intensity can be reduced, and how much the light can be reduced. As visibility data is normally not measured at hub-height, estimations have to be done. Visibility data from three SMHI (Swedish Meteorological and Hydrological Institute) weather stations nearby Juktan Vindkraftpark will be analyzed. Further, a set of MESAN-data (mesoscale analysis) is ordered from SHMI for a more detailed analysis also considering the occurrence of clouds.

As the literature review indicated more annoyance occur nighttime and turbines mainly operate their lights in darker hours, a case between 18:00 and 06:00 is looked into, in addition to the overall data and hourly spread.

**Three sets of visibility measurements over the past 5 years**

Three data sets with visibility measurement data over the past five years from SMHI weather stations of SMHI will be studied.

The SMHI-weather stations data was downloaded online (SMHI, 2016), and come from Målö-Brännan 65.5 km, Gunnarn 38.6 km, Buresjön 40.5 km from Juktan. The measurements were made at two meters above ground level, the normal visibility measuring height. The instant hour visibility values measured over a 5-year period (2011-01-01 – 2015-12-31) is used. The visibility data are presented in steps of 100 m and the maximum values reported are 50 000 m. Only values controlled and approved are used, suspect and aggregated values were deleted. After cleansing, the respective data collections constituted 43043, 43536 and 42472 hours. These will be counted after visibility under 5 km, between 5 km to 10 km and above 10 km.

Special case 18-06 is looked into, where the time-stamp is used to identify the same visibility intervals as above for the hours 19:00-05:00 UTC+1. As the data is given in UTC+0, time-compensation is made.
Mesoscale analysis data over the past 15 years at a central location in Juktan Vindkraftpark

From SMHI the mesoscale analysis (MESAN) data was ordered for the coordinates latitude 65.30 N, longitude 17.25 E, a central point in Juktan Vindkraftpark, by the road and close to turbine SJTA01. MESAN is based on meteorological models considering the physics and methods of interpolating input from observations, measurements and data into a grid of points. The detailed mapping of the weather contain parameters as temperatures, persipitation, clouds, wind, visibility, humidity and snow (SMHI, 2014). Visibility data in MESAN is as standard projected at 10 meters height. By using this set of mesoscale data, cloud base can also be taken into consideration. The cloud base, the bottom height of clouds, will be used to project when clouds would interfere with visibility measurements. This, due to clouds having a very close relationship with the prevailing visibility (WMO, 1975).

This data set is also containing hourly data based in UTC, but the duration is over 15 years, 2001-01-01 to 2015-12-31. To make a comparison with the measured weather station data all valid visibility data was counted, 131246 occurrences. Identifying the useable cloud base values 120542 occurrences were counted. When identifying data useful for combined visibility and cloud base the number of occurrences were 120542.

6.6 Interviews

Key-persons
The main aim with the key-person interviews is to gain a better understanding of how the use of visibility measurement for obstruction lighting will be perceived by stakeholders with aviation safety interests, as this was not very elaborated in the literature studied. Further, experiences with the technology and limitations are sought, as well as general thoughts and expectations to a testing and possible exemption situation. Also the necessary equipment and price will be inquired.

Semi-structured
Semi-structured interviews are prepared, with a mix of open-ended and yes/no-questions. Recording methods for the key-person interviews are mainly notes. After the interviews summaries will be compiled over the main coverage and sent to the interviewees for approval and additional information.

Retrieving general information
Additional information on specifics, for instance the sensor prices will be asked on a more spontaneous basis, as their contribution are suspected to be more to the point, qualitative, and presented as numbers. However, the questions to ask will be planned ahead of the inquiries.
CHAPTER 7. APPLICATION OF THE METHODOLOGY AND RESULTS

7.1 Interview results

The interviews showed to be necessary to start the case study, and thus is presented first. The key-person interviews started with introductions of the thesis project collaboration and of the participants. A situation and topic description was discussed to reach a common starting ground. The questions were asked and answered in a discussion manner, with follow up questions both ways etc. The main points were recorded and the summaries attached in Appendix B contain the main questions and findings. The exact formulation of the questions and answers differ slightly to better represent the main topics, follow up questions and shortened discussing answers.

Two key-person interviews were conducted. One in person with the Swedish Transport Agency (Transportstyrelsen) and one over phone over two occasions with Swedish Lapland Airport (Lycksele Flygplats).

The Transport Agency
Andreas Holmgren, head of the section for marine traffic and airports, was interviewed. The full summary can be found in appendix B (in Swedish).
The findings in the interview were;

- There have been no exemption applications for using visibility controlled obstruction lighting on wind turbines previously. However, it has been discussed.
- There have been no exemption applications for applying the ICAO Annex 14 “type A” medium intensity lights due to local annoyance, as described in Aerodrome Design Manual Pt.4 14.4.19 (i.e. 20 000 cd instead of 100 000 cd daytime).
- Discussing an exemption scenario for visibility application, it was highlighted that:
  - from a starting point the regulations shall be followed,
  - reductions can be made to a certain degree today,
  - the aviation safety must be maintained or increased,
  - “How would flight safety be affected?”, “Obstacle protruding enough in its environment?” must be answered,
  - Case-by-case evaluations; size, number, contrast to surrounding (turbines in a field or at sea), and any extra safety barriers like color stripes play in.
- If it can be shown to upkeep the level of flight safety, another country’s regulations may be used as inspiration in an exemption case, if the reasoning behind ensure the aviation safety. The owner of the obstacle will be responsible for following the conditions.
- On the topic of Swedish high intensity lighting:
  - The requirement daytime is that a light intensity of 100 000 cd shall be visible around the horizon. If it can be shown (by calculations) that 100 000 cd can be achieved with two (50 000 cd) lights and fulfill the angular requirements to high intensity lighting, two lights may be used.
- ‘Effective intensity’ shall be interpreted as the maximum intensity, regardless of steady of flashing lights.
- The Transport Agency takes a positive stand to new solutions and technical development, though have to ensure safety and availability.

The Swedish Lapland Airport
Lennart Näslund, airport manager, examiner for pilot-licensing and licensed pilot, was interviewed. The full summary can be found in Appendix B (in Swedish). The findings in the interview were;
- Visibility measurements are necessary for assessing if the weather conditions allow for certain types of flying, and is used as standard at all airports.
- Lycksele airport has two visibility sensors,
- Experiences with the sensors:
  - Represents the conditions well, more accurate than manual observations, partly due to the limited number of reference points,
  - Maintenance mainly consist of cleaning lenses a couple of times a year,
- Remarks on how to apply them for reducing obstruction lighting on wind turbines;
  - May be a good solution if the sensors are given the best conditions to do their job.
  - If one sensor shall be used for a more wind turbines local conditions have to be considered, for example if some turbines are located in a valley the sensor should be on a mountain.
  - Risk for low clouds down to 150 meters’ height, maybe not in the vicinity of the sensor, but in another part of the park.
  - Well proven technology-basis gives a higher level of trust for using this technology rather than on-demand solutions.
  - Perceived as a safer solution, as there will always be some light even if it is dimmed.
  - He would like to see for instance one light fully lit to call for attention.
- The high importance of the function of any alternative technological solution is underlined by a high-stress example; critical ambulance helicopter operations where patients require low-altitude flights due to air, regardless of weather conditions.

On the go interviews
The prices for the three sensors looked into were obtained by phone contact with the manufacturers and a Swedish distributor. The prices, presented as a range below, are including differing additional equipment, e.g. heating hoods and controlling units, and the highest price is including everything, which might be excessive. The prices range between € 4500 - € 6000, excluding taxes, and some manufacturers could provide a volume discount.
Cloud base heights
When ordering the data, the required cloud base for having a representative visibility value at the higher altitude (10 m to 100 m and 150 m respectively) was discussed with a meteorologist (Hans Bengtsson) at SMHI. A cloud base approximately 200-300 meters was guessed to be enough to ensure minimal interference with the visibility as lower clouds often are less compact with diffuse contours and thus reducing visibility by its nature.

7.2 Case study – Visibility application in Juktan Vindkraftpark

Visibility sensor installation
As a visibility sensor is beneficially installed avoiding surface reflections from the nacelle roof and rotor, and also below the lights, the better location solutions are possibly of installing it on the back side of the cooler. This placement would avoid unnecessary interferences that would otherwise have to be detected by the software and in worst case trigger an internal alarm of invalid measurements of the visibility, meaning no light reduction would be made.

Further, a placement below the rear access hatch facing away from the turbine would enable good access for cleaning the sensor lenses. However careful considerations have to be made to follow the model specific installation guidelines as well as to not affect warranty agreements or interfere with turbine functions when operations such as drilling might be required.
Regarding maintenance, it would typically consist of periodical cleaning of the lenses a couple of times a year and an annual check of calibration. Recalibration is rare and the (by the manufacturers) estimated mean time between failure generally exceed the life-time of wind turbines.

Installation location
Some rather quick measurements on the project map (attached in appendix A) indicate that one unit would be sufficient to cover all 9 wind turbines using the 1500 m rule in the Finnish instructions. Further, the sensor can be installed on a wind turbine of choice; an installation at SJTA01, SJTA02, and SJTB04 would all be able to cover the required area.

To fulfill the criteria related to sensor functions in the foreign regulations, the sensors mentioned in the literature review (and others made for wind turbine use), would all be sufficient with the correct installation and setup.

7.3 Application of the regulation and reduction cases

Preconditions for the Case
Today, the wind turbines Juktan operate in accordance with TSFS2010:155K. The light intensity reductions from the Finnish instructions for wind turbine marking are used for the cases below, as motivated in subchapter 6.4. During good visibility conditions when the meteorological visibility exceeds 10 km the light intensity can be reduced to 10% of the nominal light intensity, and with a lower visibility exceeding 5 km, 30% of the nominal intensity is required. When the visibility is below 5 km, no reductions will be made.

Scenario 1. 149-meter-high wind turbines

Case A: Reduction and Swedish lighting requirements
Applying only the reduction this to Juktan will gives the following resulting intensities:

All light intensities below red blinking 20-60 bpm
With a visibility of 5 km or less (no reduction):
- Daytime unlit, unless background luminance is below 500 cd/m², then 2000 ± 25% cd;
- during twilight 2000 ± 25% cd and;
- during night 200 cd.

Visibility exceeding 5 km:
- Daytime unlit, unless background luminance is below 500 cd/m², then 600 ± 25% cd;
- during twilight 600 ± 25% cd and;
- during night 60 cd.
With a meteorological visibility exceeding 10 km:
- Daytime unlit, unless background luminance is below 500 cd/m², then \(200 \pm 25\% \text{ cd}\);
- during twilight \(200 \pm 25\% \text{ cd}\) and;
- during night \(20 \text{ cd}\).

Case B: Full Finnish marking requirements.
The Finnish instructions require the use of medium intensity red “type B” lights night time for wind turbines 100-150 m agl. The “type B” lights blink with an effective intensity of \(2000 \pm 25\% \text{ cd}\) and 20-60 bpm shall be used night time. In addition, infra-red light shall be blinking in the same interval. Daytime, white paint marking of the upper 2/3 of the tower, the rotor and the nacelle is sufficient.

Applying the reductions:

All light intensities red blinking 20-60 bpm
With a visibility of 5 km or less (no reduction):
- Daytime and twilight unlit, unless background luminance is below 500 cd/m², then \(2000 \pm 25\% \text{ cd}\) and;
- during night \(2000 \pm 25\% \text{ cd}\).

Visibility exceeding 5 km:
- Daytime and twilight unlit, unless background luminance is below 500 cd/m², then \(600 \pm 25\% \text{ cd}\) and;
- during night \(600 \pm 25\% \text{ cd}\).

With a meteorological visibility exceeding 10 km:
- Daytime and twilight unlit, unless background luminance is below 500 cd/m², then \(200 \pm 25\% \text{ cd}\) and;
- during night \(200 \pm 25\% \text{ cd}\).

Scenario 2. 200-meter-high wind turbines
Case A: Reduction and Swedish lighting requirements.
Applying the Finnish reductions to the Swedish regulations for wind turbines above 150 m:
All light intensities below white flashing 40-60 bpm
With a visibility of 5 km or less (no reduction):
- Daytime \(100 000 \pm 25\% \text{ cd}\);
- during twilight \(20 000 \pm 25\% \text{ cd}\) and;
- during night \(2 000 \pm 25\% \text{ cd}\).

Visibility exceeding 5 km:
- Daytime \(30 000 \pm 25\% \text{ cd}\);
- during twilight \(6 000 \pm 25\% \text{ cd}\) and;
• during night 600 ± 25% cd.

With a meteorological visibility exceeding 10 km:
• Daytime 10 000 ± 25% cd;
• during twilight 2 000 ± 25% cd and;
• during night 200 ± 25% cd.

Case B: Applying the full Finnish instructions for turbines above 150 m.
High intensity white lights “type B” shall be used, which has the same specification as the Swedish high intensity lights, however without the option to use 100 000 cd during twilight. During twilight 20 000 cd white 40-60 bpm flashing. The candela requirements to the white flashing lights can be fulfilled by using two lights, i.e. 2 x 50 000 cd = 100 000 cd. At night, it can be chosen to use medium intensity red light 2 000 cd, either “type B” blinking 20-60 bpm or “type C” steady lights. Also, if the tower height exceeds 105 meter, steady burning low intensity “type A” lights of 10 cd intensity shall be installed on the tower with a maximum spacing of 52 meter, starting above the tree line. These shall be used during twilight and night and be visible from all horizontal vectors. If LED lights are used, infra-red light shall flash in synchronization with the LEDs.

With a visibility of 5 km or less (no reduction):
• Daytime white flashing 40-60 bpm 100 000 ± 25% cd,
• Twilight, white flashing 40-60 bpm 20 000 ± 25% cd and;
• during night either red steady, red blinking 20-60 or white blinking 40-60 bpm at 2 000 ± 25% cd.

Visibility exceeding 5 km:
• Daytime white flashing 40-60 bpm 30 000 ± 25% cd,
• Twilight, white flashing 40-60 bpm 6 000 ± 25% cd and;
• during night either red steady burning, red blinking 20-60 or white blinking 40-60 bpm at 600 ± 25% cd.

With a meteorological visibility exceeding 10 km:
• Daytime white flashing 40-60 bpm 10 000 ± 25% cd,
• Twilight, white flashing 40-60 bpm 2 000 ± 25% cd and;
• during night either red steady, red blinking 20-60 or white blinking 40-60 bpm at 200 ± 25% cd.

The proposed solution in Market description
The operational requirement in (Bergström, 2014) presented as required by the Transport Agency is looked into. The proposed requirement would be to maintain the same obstacle visibility, here interpreted as the same visible identification cues of the wind turbines, at the outskirts of the safety zone of the wind farm. This statement would need further clarifications to be applied, however a functional suggestion is made.
To determine the luminous intensity of the lights, the illuminance or level of perceptiveness from the obstruction lights to the outskirts of the wind farm may be calculated or measured. Suggestively, the worst visibility conditions lay the basis for the requirement at the safety zone together with using the intensities allowed today. However, thorough thought need to be incorporated into setting representative limits and they probably should vary with the diurnal, and consider both Koschmieder’s Law (daytime) and Allard’s Law (night-time) come with variables. Something that also needs to be minded when calculating is the vertical angle of spread, having an important say to the height at the safety zone boarder from which the wind turbines should be observable. Then, the visibility measurements can be used to reduce the light intensities of the lights to maintain the illuminance or level or perceptiveness at the outskirts. Either continuous light adjustment or in steps.

Possibilities: Approvable. The light intensity would be reduced all time the weather is better than worse case.
Limitations: Complex. Need further elaboration to be useable.

### 7.4 Performance study

In this chapter the methodology described in subchapter 6.5 is applied. By counting various occurrences in the different data sets obtained from the Swedish Meteorology and Hydrology Institute, the performance is estimated. As the purpose of using visibility controlled obstruction lighting would be to reduce the light intensities, the performance spoken of here is a measure of how many hours the light intensities would be reduced.

All calculations are based on number of hourly occurrences of the specified parameters (e.g. visibility, cloud base, time stamps) and are often made in ranges. These counted hours are referred to as ‘no.’, and is not necessarily equal to the number of hours of the years due to invalid data. Compensation for the data sets time zone difference was done computing the values indicating good visibility conditions between UTC+1 (local time) 18:00 and 06:00.

**The visibility in Målö-Brännan, Gunnarn and Buresjön**

The results extracted from the three data sets of measurements are shown in table 3, below. The number visibility values (hours), and their percentage, of occurring in the ranges presented leftmost column, is shown for each station. These station-wise numbers are then summed and averaged in the columns to the right. A special case considering the ‘night time’ was studied between 18:00 and 06:00, as hourly data is used this time-frame mean the hourly values from 19:00 to 05:00 are used. However, the time dependent outcome is very approximate as summer time compensation is not considered.
Table 3. Visibility range occurrence in Målö-Brännan, Gunnarn and Buresjön.

<table>
<thead>
<tr>
<th></th>
<th>Målö-Brännan</th>
<th>Gunnarn</th>
<th>Buresjön</th>
<th>Sum</th>
<th>Avg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of valid values</td>
<td>43043</td>
<td>43536</td>
<td>42472</td>
<td>129051</td>
<td>43017</td>
</tr>
<tr>
<td>Visibility 0-5 km [no.]</td>
<td>5151</td>
<td>4451</td>
<td>5168</td>
<td>14770</td>
<td>4923</td>
</tr>
<tr>
<td>In %</td>
<td>12.0%</td>
<td>10.2%</td>
<td>12.2%</td>
<td>11.5%*</td>
<td>11.5%**</td>
</tr>
<tr>
<td>Visibility &gt;5-10 km [no.]</td>
<td>2393</td>
<td>2309</td>
<td>2702</td>
<td>7404</td>
<td>2468</td>
</tr>
<tr>
<td>In %</td>
<td>6%</td>
<td>5.3%</td>
<td>6.4%</td>
<td>5.7%*</td>
<td>5.7%**</td>
</tr>
<tr>
<td>Visibility &gt;10 km [no.]</td>
<td>35420</td>
<td>36733</td>
<td>34537</td>
<td>106690</td>
<td>35563</td>
</tr>
<tr>
<td>In %</td>
<td>82.3%</td>
<td>84.4%</td>
<td>81.3%</td>
<td>82.7%*</td>
<td>82.7%**</td>
</tr>
<tr>
<td>Total no. of values between 18-06</td>
<td>19725</td>
<td>19950</td>
<td>19478</td>
<td>59153</td>
<td>19718</td>
</tr>
<tr>
<td>Visibility &gt;10 km btwn 18-06 [no.]</td>
<td>15821</td>
<td>16250</td>
<td>15385</td>
<td>47456</td>
<td>15819</td>
</tr>
<tr>
<td>In %</td>
<td>80.2%</td>
<td>81.5%</td>
<td>79.0%</td>
<td>N/A</td>
<td>80.2%**</td>
</tr>
<tr>
<td>Mean visibility*** [m]</td>
<td>36531</td>
<td>36599</td>
<td>34426</td>
<td>35852</td>
<td></td>
</tr>
<tr>
<td>Median*** [m]</td>
<td>48800</td>
<td>47000</td>
<td>43600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Based on the summed values. ** Average of the three percentages presented. *** Maximum visibility is limited to 50 000 m, leading to lower outcome than in reality.

Table 3 shows that the visibility is rather similar on a yearly basis for the three weather stations. The visibility exceeds 10 kilometers in more than 81% (7096 hours yearly) for each individual weather station. Visibility from 5 km to 10 km occur more than 5 % of the time. Approximate night time, the hourly visibility values from UTC+1 19 to 05 averages 80% (7183 hours/year) between the stations.

The relatively high median compared to the mean, may indicate that the visibility is very low during the less occurring periods it is low.

MESAN and performance estimations

Cloud base

The cloud base height values in the mesoscale analysis (MESAN) data for Juktan over 15 years is shown in the two tables below. The first, table 4, show how often the lowest part of clouds occurs at or above the given heights. The second table, table 5, show how often clouds occur below the same heights.

Table 4. Cloud base altitudes.

<table>
<thead>
<tr>
<th>Cloud base(&gt;=):</th>
<th>0m</th>
<th>100m</th>
<th>150m</th>
<th>200m</th>
<th>300m</th>
<th>350m</th>
<th>500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurance</td>
<td>120542</td>
<td>111592</td>
<td>108161</td>
<td>104753</td>
<td>98008</td>
<td>94558</td>
<td>84706</td>
</tr>
<tr>
<td>%</td>
<td>100.0%</td>
<td>92.6%</td>
<td>89.7%</td>
<td>86.9%</td>
<td>81.3%</td>
<td>78.4%</td>
<td>70.3%</td>
</tr>
</tbody>
</table>
Table 4 show the occurrences of cloud base at or higher than the meters in the top row. This gives a reversed cumulative effect (reversed snow-ball-effect), with decreasing values with altitude. From this table it can be seen that in 92.6% of the time the hub-heights below 100 meters are free of clouds.

Table 5. Cloud base altitudes.

<table>
<thead>
<tr>
<th>Cloud base(&lt;):</th>
<th>All</th>
<th>100m</th>
<th>150m</th>
<th>200m</th>
<th>300m</th>
<th>350m</th>
<th>500m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occurance</td>
<td>120542</td>
<td>8950</td>
<td>12381</td>
<td>15789</td>
<td>22534</td>
<td>25984</td>
<td>35836</td>
</tr>
<tr>
<td>%</td>
<td>100.0</td>
<td>7.4%</td>
<td>10.3%</td>
<td>13.1%</td>
<td>18.7%</td>
<td>21.6%</td>
<td>29.7%</td>
</tr>
</tbody>
</table>

Table 5 show the occurrences of cloud base lower than at or higher than the top row. This gives a cumulative effect from the 100m column and forward. Table 5 show that the 150 m blade-tips are in clouds 7.4% of the time, while the hub height of about 100 is only in clouds 7.4% of the time. This mean 2.8% of the time, 245 hours a year the blades are in clouds.

**MESAN and the three stations – comparing the visibility data**
A comparison of the MESAN visibility at 10 meters’ height with the summarized, measured values from the three stations 2 meters’ height is shown in table 6 below.

Table 6. Comparison of visibilities.

<table>
<thead>
<tr>
<th></th>
<th>MESAN</th>
<th>Sum of the 3 stns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of valid values</td>
<td>131246</td>
<td>129051</td>
</tr>
<tr>
<td>Visibility &lt;5 km [no.]</td>
<td>13163</td>
<td>14770</td>
</tr>
<tr>
<td>In %</td>
<td>10.0%</td>
<td>11.5%*</td>
</tr>
<tr>
<td>Visibility between 5 to 10 km [no.]</td>
<td>9866</td>
<td>7404</td>
</tr>
<tr>
<td>In %</td>
<td>7.5%</td>
<td>5.7%*</td>
</tr>
<tr>
<td>Visibility &gt;10 km [no.]</td>
<td>108217</td>
<td>106690</td>
</tr>
<tr>
<td>In %</td>
<td>82.5%</td>
<td>82.7%*</td>
</tr>
<tr>
<td>Sum check</td>
<td>100.00%</td>
<td>99.86%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>MESAN</th>
<th>Sum of the 3 stns</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total no. of values between 18-06</td>
<td>60156</td>
<td>47456</td>
</tr>
<tr>
<td>Visibility &gt;10 km btwn 18-06</td>
<td>47578</td>
<td>N/A</td>
</tr>
<tr>
<td>In %</td>
<td>79.1%</td>
<td>80.2%**</td>
</tr>
<tr>
<td>(18-06: values fr. 19 to 05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean visibility*** [km]</td>
<td>41.72</td>
<td>35.85</td>
</tr>
</tbody>
</table>

*Based on the summed values. ** Average of the three percentages presented. *** Maximum visibility is limited to 50 000 m, leading to lower outcome than in reality.
Table 6 indicate that the MESAN data, generated by SMHI, give similar visibility data as from the weather stations, though the height of the visibility differs slightly (10m and 2m respectively).

**Combining MESAN visibility and cloud base**

The common occurrences of visibility ranges and cloud heights is identified and presented in the following table 7. The combination of both cloud height and visibility will give an estimate of what conditions a visibility sensor would identify on top of the wind turbines in Juktan Vindkraftpark.

The following is based on assuming that a visibility sensor will not be subject to interference from clouds with a base 200 meter above the point of sensor installation (based on a discussion and recommendation when ordering the data), and further that the visibility at 10 meters’ height can be representative at a 100 and 150 m respective height in the absence of clouds.

Applying this to the case study scenarios, the cloud base for the performance of visibility control at the turbines with a nacelle at 100 meter (scenario 1) will be 300 meter, and for the 150-meter-hub-height turbines (scenario 2) 350 meters.

<table>
<thead>
<tr>
<th>Cloud base (&gt;=)</th>
<th>Visibility</th>
<th>300m</th>
<th>350m</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5km</td>
<td>%</td>
<td>7112</td>
<td>6503</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.9%</td>
<td>5.4%</td>
</tr>
<tr>
<td></td>
<td>hr/yr</td>
<td>517</td>
<td>473</td>
</tr>
<tr>
<td>&gt;5-10km</td>
<td>%</td>
<td>5937</td>
<td>5472</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.9%</td>
<td>4.5%</td>
</tr>
<tr>
<td></td>
<td>hr/yr</td>
<td>431</td>
<td>398</td>
</tr>
<tr>
<td>&gt;10km</td>
<td>%</td>
<td>84959</td>
<td>82583</td>
</tr>
<tr>
<td></td>
<td></td>
<td>70.5%</td>
<td>68.5%</td>
</tr>
<tr>
<td></td>
<td>hr/yr</td>
<td>6174</td>
<td>6001</td>
</tr>
</tbody>
</table>

Table 7 show the occurrences of visibility ranges with cloud bases above or equal to given heights. The percentages are obtained by dividing the number of occurrences (shown in table) for the visibility (left row) at a certain cloud base (upper column), and dividing it with the total number of valid values (containing both visibility and cloud base data) given in the upper left corner. As both cloud base and visibility are presented and calculated in ranges (leading to a reversed cumulative effect) the percentages of each column cannot be summed up to a hundred. The percentages are then multiplied by the number of hours of a normal year, 8760. As an example, visibility above 10 km with a cloud base above 300 meters occur 6174 hours per year.
Reduction possibilities during the diurnal

To visualize how often each hour of the day come with visibility above 10 km, the diagram in figure 5 below is produced. Further, as found desirable in literature, night time reductions possibilities are presented.

![Figure 5. Hourly occurrence of visibility.](chart_image)

Hourly occurrence of visibilities above 10 km at 10 meters’ height with a cloud base at 300 meter and above. The hours are given in UTC+1, with no Swedish summer time compensation. The rates 350 meters’ height is very similar, with high visibility occurring more often during the afternoon than in the early morning.

The night time average visibility between 18 in the evening and 6 in the morning is shown in table 8 below. Total amount of valid values is 54956. The tables show the portion of all night hours when the visibility exceeds 5 and 10 km respectively and the cloud base is above 300m and 350m.

<table>
<thead>
<tr>
<th>Night, cloud base fr. 300m, visibility exceeds 5 km</th>
<th>No.</th>
<th>%</th>
<th>hr/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night, cloud base fr. 300m, visibility exceeds 10 km</td>
<td>39107</td>
<td>71%</td>
<td>2857</td>
</tr>
<tr>
<td>Night, cloud base fr. 350m, visibility exceeds 5 km</td>
<td>37685</td>
<td>69%</td>
<td>2753</td>
</tr>
<tr>
<td>Night, cloud base fr. 300m, visibility exceeds 10 km</td>
<td>35961</td>
<td>65%</td>
<td>2627</td>
</tr>
<tr>
<td>Night, cloud base fr. 350m, visibility exceeds 10 km</td>
<td>34766</td>
<td>63%</td>
<td>2540</td>
</tr>
</tbody>
</table>
The hour-per-year-values for nighttime is based on the annual amount of hours between 18 and 06, which is 4015 hours for 365 days.

**Case study results: Reduction possibilities with the reduction rule in the Finnish instructions**

Based on applying the reduction rules from the Finnish instructions for wind turbine marking and the above estimations using MESAN-data, the following results can be presented:

*Scenario 1 – 149-meter-high turbines*

Combining the performance study estimations with the reductions possible in Finland, it can be seen that at the nacelle of the wind turbines in Juktan, with a cloud base at a minimum height of 300 m, the light intensity could be reduced to at least 30% of nominal intensity in 6570 hours per year, where down to 10% intensity would be 6176 hours yearly.

Further, looking to the night time visibility sensor controlled wind turbines in Juktan could reduce the light intensity to at least 30% of its nominal value in 2857 hours (71%) of yearly nighttime, and all down to 10% in 2627 hours (65%) of yearly nighttime (4015 hrs).

*Scenario 2 – 150-meter hub-height*

Combining the reduction regulations with the performance estimations, a cloud base above 350 meters, the visibility at 150 m high nacelles (of 200+ m turbines) in Juktan would be above 10 km for 6001 hours yearly, above 5 to 10 km in 398 hours per year of the time and a visibility up to 5 km, 473 hours per year.

Night time, with 150 meter-hub-height wind turbines reductions down to 30% for 2753 hours (68.6%) of the nightly hours, and 2540 hours (63.3%) for a reduction down to 10%.

*Price*

An indication of the price for the visibility sensor equipment required to do the reductions above, according to the installation rules in Finland will the price of sensor and direct related equipment. For Juktan would be around € 4500-6000 excluding taxes.
CHAPTER 8. DISCUSSION

This chapter contains discussions of the findings and the results obtained and analytical findings.

8.1 Interviews

General
The thoughts of the Finnish authorities on the topic of aviation safety would have added value. Although, the time limit and the extent of the rest of the study limited a higher number of interviews from being manageable.

Even if the interviewees are key-stakeholders it can be hard to assess if the outcome are facts or personal opinion. Adding to this, the questions were not sent ahead so that the interviewees could prepare their answers. On the other hand, they were given opportunity to comment and add information when the summaries were sent to approval.

Transport Agency
The interview with the Transport Agency made it clear that aviation safety is more important in an exemption case than what nations’ regulations are applied. Also found was the Finnish provision for using other lighting when the lights were judged to be causing local disturbance, was not yet tried for exempting the regulations in Sweden. In addition, the indication of two 50 000 cd lights could be used if proven to do the job required for high intensity lightning, and would probably reduce local annoyance if two 100 000 cd lights are used today.

Further, finding that compensatory marking may strengthen an exemption case was used evaluating the case study results.

Swedish Lapland Airport
From the interview with Lennart Näslund, Swedish Lapland Airport, comes the important insight to use SMHI-data. Another important highlight from this interview is the considering of number and placement of sensors to minimize the risk of clouds being undetected in parts of the wind farm. Further, the positive impression from keeping some light on all the time strengthen the use of visibility sensors rather than on-demand solutions.

8.2 Case study

Starting with the basic assumption of this study: assuming that reducing light intensities are the main mean to better acceptance. Although there are a lot of factors going into how light is perceived, as described by Pohl et al. (2012) and the Aerodrome Design Manual Pt. 4 (2004), the same sources point to light intensity as being a contributing factor, motivating this to be studied.
Regulation application

Scenario 1: Lighting on turbines up to 150m, with reduction
As the intensity requirement to the red nighttime light in Sweden already is 200 cd, a 90% reduction down to 20 cd could be considered unrealistic, minding an exemption is required, whereas the Finnish requirement, with 2000 cd as nominal intensity required it would make sense.

However, looking to the base case, without any visibility reductions, the Swedish light intensities nighttime is already 90% lower than the Finnish. During daytime where it is not necessary to operate the lights in either country unless it is dark, and in twilight, the intensities are the same but the Finnish regulations will allow for intensity reductions and thus enable operation with lower intensities. This finding is speaking against going through the process of getting an exemption to use visibility reductions for turbines up to 150m, as nighttime where the gain would be higher, the Swedish regulations today operate with the lowest intensity reducible to in Finland, and a reduction down to 20 cd when applying the reduction rules to Swedish regulations might be unrealistic in an exemption context.

Yet again, speaking for using visibility measurements and Finnish regulations is if the site is generally dark daytime so that daytime lighting has to be used. Then the Swedish regulations require 2000 cd, while in Finland this could be reduced to 200 cd with good visibility.

Scenario 2: Lighting on turbines above 150m, with reduction
The differences between the Swedish and Finnish way of marking high turbines appear nighttime, where it in Finland is allowed to use red steady or red flashing lights as alternatives to the Swedish white. Using red lighting nighttime may improve acceptability. Though, in addition the Finnish regulations require red steady burning 10 cd lighting of the tower every 52 meters above the tree-line if the tower is above 105 m high. This lighting may be a complimentary measure for reducing the light-intensity, however this is not explicitly stated.

Also, in addition to the above, the reductions speak in favor of applying the Finnish regulations straight off. In this case with higher turbines, it is more interesting to apply Finnish instructions as the visibility controlled obstruction lighting in combination with red lights nighttime appear as a good solution for public acceptance. The addition of tower lighting can be an argument for making the wind turbine more visible in an exemption case.

The visibility controlling solution in Market description
The suggested solution in the Market description (2013), based on that the light provided with today’s regulations is sufficient at the outskirts of the safety zone, need further elaboration to be evaluated.
The weather stations’ visibility
In table 3, for the visibility data for the three weather stations show that the relatively high median compared to the mean, may indicate that the visibility is very low during the time it is relatively low. As this happen for all three stations, it may indicate that this is commonly occurring. This may speak for the sensors installation height, being subject for local fog heavily reducing the visibility at occasions. Or it can indicate the normal visual range often being drastically affected with the weather.

Also looking at the night time was based on literature findings, however they should be combined with the normal hours of high background luminance to be a more accurate reference for how the visibility instruments would operate.

On the other hand, and more important, the output is an indicator that the visibility is not very different during night.

Cloud base – Revealing a risk
The tables 4 and 5 show cloud base occurrence at the blade-tip-heights (150m) 10.3% of the time. Comparing with to the 7.4% for cloud base at 100 meters’ height (about nacelle height), 2.8% of the time the blades are covered to some extent with clouds when the nacelle where a sensor would be installed is clear. This makes a notable aviation risk for 245 hours annual if the sensor does not recognize the clouds above and keep the lights dimmed when the blades are in clouds.

To identify how visibility sensors would operate with clouds, and thus the magnitude of the risk, and also how representative 200 meters above the projected sensor-position is, data from operations in wind farms in Germany or Finland could be analyzed if accessed. Alternatively, a live test can be conducted at the correct height, though it should be done with lights operating in redundancy.

Discussion of the overall results
Scenario 1
Up to 150-meter-high, visibility sensor controlled wind turbines in Juktan could with the Finnish reduction rule, based on the MESAN-data calculations, reduce the intensity by 6570 hours yearly, where down to 10% of nominal intensity during 6176 hours per year. However, as the lights today are rarely required to be lit day time for turbines of these heights, it is more important to look at the night time result. And looking to the night time, visibility sensor controlled wind turbines in Juktan could reduce the light intensity to at least 30% of its nominal value in 2857 hours (71%) of the yearly night time, and all down to 10% in 2627 hours (65%) of the yearly 4015 hours of night time.

Scenario 2
The scenario of wind turbines with 150 meter-hub-height in Juktan, tell of light intensity reductions in 6399 hours (73%) of a year, whereby to a 10% of nominal intensity during
6001 hours. This speak well for this scenario as for clear daytime high intensity lighting, the highest reductions can be made.

Night time, the nominal intensity could be reduced for 2753 hours to at least 30% of the nominal intensity, and 2540 hours 10 % of the nominal intensity during the yearly hours of 19-05. This would be the most interesting gain, as it is for the high intensity lighting and during clear nights seem to be where the main problematics occur (Pohl et al., 2012). As previously mentioned, the Finnish instructions would come with red lights nighttime, which make an application of this very interesting. Further, the additional tower lighting might be seen as an additional safety keeping measure, in line with the interviews as both additional safety measures and a light lit where mentioned.

**Price**

All reductions in the two scenarios above could be made to an equipment price of €4500-6000 excluding taxes. Other, probably a lot higher, costs to assume are production loss during installation, work hours and exemption-related with others, however, these are not further pursued in this thesis. Maintenance costs seem to land rather low as it mainly consists of cleaning of the lenses a couple of times a year.

This price is only a fraction of what would be required of the costs of an on-demand system of radar type, which is said to exceed €1 million, though for bigger wind farms than Juktan and probably including costs that would come with the visibility systems. If a visibility system can be used, even with more units, a substantial amount of money can be saved.
CHAPTER 9. CONCLUSIONS

Improve local wind power acceptance
Firstly, some measures to reduce local annoyance created by the obstruction lighting that can be done today are recommended. International literature backs up xenon-lights abandonment, synchronizing lights and reducing the light intensities to the minimum allowed. These measures can be done without any legal hurdles speaking against them. The abandonment of xenon-lights and synchronizing of lights are recommended in international recommendations and best practices, and synchronizing the lights is recommended in the Swedish regulations.

Visibility sensors controlling obstruction lighting motivated in Sweden
Using visibility sensors to reduce light intensities is recommended internationally, and is strengthened by the literature reviewed, telling light-intensity is a characteristic in the subjective environmental objections, and meteorological visibility an influencing factor in the subjective observer’s determination of opinion.

Case study – Regulation application
The study conducted indicate that for wind turbines up to 150 m, the gain would be low if applying visibility controlled lighting according to Finnish instructions, compared to using the Swedish regulations. The exception is if the site is very dark daytime. Further, only applying the Finnish ‘reduction rules’ combined with the Swedish regulations without any additional marking will probably be have low chances of being accepted by the authorities for an exemption, and will thus not be useable.

For wind turbines above 150 meter, Finnish regulations with visibility control should be the preferred solution over the Swedish regulations. Being a realistic solution for reducing light intensities down to 10% of the nominal value during good visibility, opening for using red light nighttime and at the same time compensate turbine visibility with tower lighting.

Cloud heights – MESAN-data
An important flight risk that need consideration was identified. Cloud base comparisons show that the clouds are below the blade-tip-heights (150m) 10.3% of the time, while below the nacelle height 7.4% of the time. This mean 2.8%, 245 yearly hours, the blades are in the clouds when the nacelle is clear. This makes a flight risk if the lights are dimmed and not visible for an annual 245 hours when the blades touches clouds. This high-lights the importance of the ability of the visibility sensors to recon the weather phenomena also above them. Before live-testing, this need to be sorted out.

Case study – estimations with MESAN-data
In the imaginary scenario of wind turbines with a 150-meter hub-height in Juktan, the estimates based on mesoscale analysis data tell of light intensity reductions according to
Finnish reduction rules in total 6399 hours a year, whereby dimming down to 10% of the nominal intensity during 6001 hours yearly.

Approximated night time, the maximum reduction by 90% could be done 2540 hours (63%) hours of the annual 4015 hours. This would be the most interesting gain, as it is for the white high intensity lighting and during clear nights (good visibility) the main issues of light emission occur. As mentioned above, the Finnish instructions open for the choice of red lights nighttime, which make an application of this very interesting. Further, the additional tower lighting might be seen as an additional safety keeping measure, desired in the interviews.

**Feasible**

The scenarios above, using visibility sensors in Juktan Vindkraftpark, could be made to a feasible equipment price of €4500-6000 excluding taxes. Other, probably higher, costs to assume are production loss during installation, work hours and exemption-related with others, however, these were not further pursued in this thesis.

**Future test**

Combining the points above, a test in redundancy in Juktan is recommended, and recording how well low cloud bases are represented in the visibility measurements could be advised. The outcome would indicate whether the obstruction lights operate desirably from the various stakeholder perspectives, and data of the technology performance can be recorded for a possible future exemption application.
REFERENCES


Ilmailuhallinto, 2000. Luftfartsbestämmelse AGA M3-6, HINDBEGRÄNSNINGAR OCH MARKERING AV FLYGHINDER.


SFS:2013:251. miljöprövningsförordning (2013:251)


Transportstyrelsen, 2013. TSFS 2013:9, Föreskrifter om ändring i Transportstyrelsens föreskrifter och allmänna råd (TSFS 2010:155) om markering av föremål som kan utgöra en fara för luftfarten.


APPENDIX A. JUKTAN VINDKRAFTPARK PROJECT MAP

Available at: https://corporate.vattenfall.se/om-oss/var-verksamhet/var-elproduktion/vindkraft/juktan-vindkraftpark/
APPENDIX B. INTERVIEW SUMMARIES

Intervju med Lennart Näslund, flygplatschef och pilotexaminator, Lycksele Flygplats (Swedish Lapland Airport)


Erfarenheter av siktmätare

Har ni erfarenheter av siktmätare? Används sådan utrustning på Lycksele flygplats?


Hur väl fungerar dem?

Siktmätare representerar sikten väldigt lokalt, är det dimma just där den står rapporterar den dimma. Men han menar att siktmätarna bedömer avståndet bra. Manuella observationer med visuella referenspunkter på kända avstånd i närheten av flygplatsen representerar bara de avstånd det finns fysiska siktmärken till. De autoMETAR-rapporter som utfärdas när flygtrafiktjänsten är stängd (meteorologiska flygdata) har vissa rapporteringsbegränsningar regelmässigt. För att klassas som CAVOK (Ceiling and visibility OK, d.v.s. bra flygväder) måste uppgifterna verifieras av mänsklig observatör. Siktmätaren anger 9999 (meter) när sikten är mer än 10 km när den står i autoläge.

Hur mycket underhåll krävs?

Behovet av underhåll kommer främst av lokala luftföröreningar, som t.ex. snö som blåses upp från marken, något som medför rengöring ett par gånger per år.

Vilka typer av instrument har ni?

Present weather AWOS 7 från Combitech, SAAB som är ett kominationsinstrument för flygplatsanvändning (med siktmätare från Vaisala).

Om att använda siktmätare för att styra hinderbelysning

I Tyskland är det tillåtet att installera en siktmätare på ett maskinhus för att täcka ett område med radie 1500 m i en vindpark, och det räcker att installera ett instrument per park? Vad anser du om en sån lösning i Sverige (ni har ändå två instrument)?

Lennart resonerar att om de är installerade på rätt höjd och ges bästa förutsättningar för att ge representativa mätningar genom att ta hänsyn till lokala förhållanden (exempelvis kan inte hälften av vindkraftverken stå i en dalgång och andra hälften på ett berg) verkar det spontant sett rimligt. På så hög höjd (navhöjd) återspeglas sikten för flygare bättre än vid marken.
Han belyser att ett möjligt problem är att det på 150 meters höjd kan låga lokala moln gå, kanske inte just vid mätaren, men i en annan del av en vindpark.
Annars ser han att siktmätare är väl beprövad teknik och Lennart har högre förtroende för att dimma ljuסטyrkan vid goda siktförhållanden än att släcka ljusen helt och använda radar- eller transpondersystem för att släcka helt periodvis. Han menar att det är mycket bättre och säkrare att alltid ha något ljus.

**Några andra flygsäkerhetsmässiga synpunkter på vid-behov tändning av hinderbelysning och sikttystyrd belysning?**

Lennart menar att radar- och transponderteknik är att det lägger väldigt stort ansvar på avancerad teknik, även om man normalt sett inte ska färdas på sådan höjd.


Vindkraft utgör främst ett hot mot VFR-flygning (flygning med visuell referens), något som också förespråkar att t.ex. hålla en lampa tänd.

Överlag är han positiv till en lösning med sikttbasert reduktion av hinderbelysning, men belyser att det är viktigt att upprätthålla flygsäkerheten. Han poängterar att meteorologiska data från flygplatser publiceras varje halvtimme som offentligt tillgängligt online som kanske kan användas för att estimerar hur sikten kommer att vara i närheten.

**Frågor om ett eventuellt test – ur flygperspektiv**

*Har du några tankar om hur siktmätare bör installeras för bästa mätningar?*

Han föreslår att siktmätare minst bör installeras på minst 50-60 meters höjd (~200 ft) eftersom sikten snabbt kan bli sämre på lägre höjd, med förekomster av dimma och lokala föroreningar. Att installera på navhöjd, 80-120 meter, låter som en bra idé.

*Vilka aspekter anser du är viktiga att ta hänsyn till om ett test ska göras? Vidare, vilka krav borde ställas?*

Effekter av olika höjder. Han tänker att siktmätare bör installeras på fler höjder för att se hur höjden påverkar utfallet, i alla fall i ett ”godkännande av teknologi”-typ av test innan det godkänns i föreskrifter. Därtill borde funktionskontroll utföras vid varje nyinstallation. En riskanalys bör diskutera placering och följderna av den. En spontan tanke är att använda data omgivande flygplatser som mäter sikt som referens för data vid ett test. Detta för att eventuellt kunna kartlägga hur sikten påverkas i närheten och förhåller sig mellan olika platser. Kanske kan man göra siktprognoser. Vidare har SMHI väderstationer som mäter sikt.

Slutligen vill han anmärka att detta är väl beprövad teknik. Flygplatser har lång erfarenhet av dessa instrument och de är mycket mer beprövade än att använda radar för den här funktionen.
**Intervju med Andreas Holmgren, Sektionschef för Sjötrafik och Flygplatser, Transportstyrelsen**


**Erfarenheter av siktmätare**

Inledning med en snabb introduktion om hur tekniken fungerar.

Erfarenheter; Är siktmätare något som Transportstyrelsen ofta kommer i kontakt med, t. ex. på flygplatser för rullbanesikt och dämpning av banbelysning?

Frågan härrör flygtrafikledningen (inte riktigt rätt avdelning) - men flygplatser har procedurer för ”low visibility”, där siktmätare kan tänkas användas som hjälpmedel.

Andreas förklarar att siktmätare används inom sjöfarten, exempelvis för att stänga vissa farleder vid dåliga siktförhållanden.

**Om att använda siktmätare för att styra hinderbelysning**

TSFS 2010:155K: Enligt bilaga 1 till föreskriften kan meteorologisk sikt användas för att avgöra när linor och högsta punkter för vissa objekt ska ljusmarkeras. Är detta något som blir tillämpat, används siktmätare och väl fungerar det?

Det är troligen inte tillämpat i någon större utsträckning, han känner inte till att det är använt.

Har någon sökt om undantag för att installera siktmätare för att styra hinderbelysningen av vindkraftverk i Sverige?

Nej. Men det har pratats om tidigare.

Är det något som på rak arm talar för eller emot att styra hinderljusen med sån teknologi? (Summering av fler frågor)


I detta fall när det gäller att dimma ljusen kan relevanta frågor att svara på vara: ”Vad skulle det innebära (säkerhetsmässigt) att dimma ljusen ytterligare? Skulle hindret eller hindren synas tillräckligt?”

Andreas understryker att undantag ges i enskilda fall där fall-specifika aspekter och egenskaper spelar in. Några exempel som kan spela in vid avväganden är storleken av hindret eller gruppen av hinder, färgkontraster mot omgivningen exempelvis vita turbiner på ett fält jämfört med ute i sjön eller om det finns några extra säkerhetsbarriärer som t. ex. färgmarkeringar på rotorn.

Kan finska instruktioner för markering av vindkraftverk vara smart att lägga till grund vid en eventuell framtida dispensansökan? (Instruktionerna är tillgängliga på svenska, lättförståeliga och ett "fullt set")

Det viktiga är flygsäkerheten (som beskrivet vid frågan ovanför) och det är den svenska föreskriften som undantas. Vid ett undantag tar hinderägaren ansvar för att villkor och
åtaganden följs. Att motivera med resonemang och tankar hos andra stater kanske inte är så dumt, så länge det visar att flygsäkerheten upprätthålls.

Skulle § 3 om Ömsesidigt Erkännande av EES-produkter i TSFS på något vis tillämpas, eller är det fullt ut undantag efter § 33?

§ 3 syftar till produkter, ej regelverk. Det är § 33 som gäller.

Har någon sökt om undantag för att få använda ”typ A” medelintensiva ljus istället för högintensiva på grund av påvisade störningar i omgivningen? (ICAO annex 14 och Finska regler – 20 000 cd istället för 200 000 cd, ett svenskt fall skulle innebära från 100 000 cd. Bakgrunden förklaras i 14.4.19, Aerodrome Design Man. Pt. 4)

Nej.

Generellt om dagens regelverk - konsolerade föreskrift TSFS 2010:155

Några tolkningsfrågor:

Angående högintensiva ljus som ska synas runt horisonten: Är 2 lampor å 50 000 cd tillräckligt för uppfylla kravet dagtid (som i Finland)? 1x100 000? Eller 2x100 000?

Den sammanslagna ljusstyrkan (intensiteten) ska uppfylla regelverket (för högintensiva ljus 100 000 cd) runt horisonten. Om två lampor på 50 000 cd lyser ska ljusstyrkan fortfarande vara 100 000 cd. Om det uppnås med två lampor är jag osäker på om det får man i så fall räknas på. Ljusstyrkan ska vara 100 000 cd i alla lägen och synligt runt horisonten (360 grader).

Kan ’effektiv intensitet’ i TSFS 2010:155 beräknas på samma sätt som i ICAOs Aerodrome Design Pt. 4? (Som säger att blinkande ljus beräknas annorlunda än fast ljus eftersom blinkpulserna (kort sagt) har en uppmärksammande effekt. Därmed bestäms kravet inte bara utifrån maxintensiteten i varje ”blink”.)

Det är fortfarande den maximala ljusstyrkan som avses oavsett om det är ett fast ljus eller ett blinkande ljus. Om kravet är 100 000 cd så ska det blinkande ljuset vara så starkt att det uppnår 100 000 cd.

Följer ni upp och kontrollerar hinderbelysningen (ljusintensiteter, avskärmning etc.) med någon form av inspektion?

Det är krav om att anmäla nya hinder till hinderdatabase som ägs av Försvarsmakten och förvaltas av LFV. Detta görs i dag via en hinderrapport innehållande hinder specifiera data. TSFS 2010:155 innehåller i dag krav om rapportering av brister och tydliggör hinderägarens ansvar för att markeringen är i föreskriftsmässigt skick.

Transportstyrelsen har inget ordnat tillsyn utöver detta men kan agera om information kommer in.


Har ni någon typ av samråd med närboende till hinder? År samrådssplikt något som indirekt läggs på hinderägaren?

Nej, inga specifika samråd i hinderärenden (D.v.s. ärenden om ansökningar om undantag från föreskrifterna), detta är något som eventuellt tas av hinderägare i tillståndssprocesser (ex. miljötillstånd i vindkraftssammanhang). Trafikverket ansvarar för den långsiktiga planeringen av alla trafikslag. Vid miljötillstånden, när vindkraftprojektören eller
fastighetsägaren får miljötillstånd att bygga är det trafikverket som ansvarar för att svara som remissinstans för alla fyra trafikslag.

**Internationella regelverk**

Vid mejlkontakt innan mötet bifogades dokument och hänvisningar som tyder på att länder har olika tolkningar (Sverige, Finland, Tyskland, USA).

**Hur ser ”hierarkin” ut – ICAO, EASA och svenska föreskrifter i ett hinderperspektiv?**

Sverige är förbundet till ICAOs standarder och rekommendationer i annexen (som berör hinderbelysning) via Chicago-konventionen. Standarderna är bindande men rekommendationerna är just rekommendationer och tas eventuellt in i Svenska föreskrifter efter avvägning hos Transportstyrelsen. EASA tas in under EG-förordningen, vilken Sverige förbundit sig till genom och måste införa i nationell lagstiftning. Också här finns både krav och rekommendationer, som baseras sig mycket på ICAO. Vidare är EASA-standarderna begränsade till flygplatser och närliggande områden, vilket i praktiken gör att vindkraft i liten utsträckning inte berörs och behandlas efter dessa.

I amerikanska FAAs cirkulär appendix B förklaras ljusintensiteter och avstånd de syns ifrån (kommer direkt ur ICAO), och det förklaras hur dessa hänger ihop med obelysta hinders avstånd vid olika siktförhållanden.

**Finns det någon minsta distans som hinderljusen ska vara synliga och därmed påverkar ljusintensiteten i svenska föreskrifter? Eller är svenska ljusintensiteter en justering av ICAOs tabell-intensiteter?**

Det är ICAOs krav och rekommendationer som utgör grunden för kraven i föreskriften. Pågår någon regelutveckling för alternativ styrning av hinderljus på internationell basis, exempelvis inom EU?


**Framtidsfrågor**

Önskar TS att vara deltagande vid ett eventuellt projekt med siktstyrning av hinderbelysning, live-test eller vid installation av ett extra, redundant ljus?

Andreas belyser att Transportstyrelsen värnar om ny teknik och lösningar men måste säkerställa säkerhet och tillgänglighet. Att delta i eller sponsra projekt kan bli fel med tanke på Transportstyrelsens roll och position mot ett sånt projekt. I slutändan är de beslutande myndighet i frågan. Så någon direkt involvering kan han inte se. Däremot tar de gärna del av information och bistår med att svara på frågor.

Är det något ni ser att vindkraftsbranschen kan eller borde göra, internationell lobbying eller liknande, som kan ändra dagens halvlåsta situation för vindkraftverk som hinder över 150 meter?

Att utvecklingen för framtida vindkraft finns på högre höjder med bättre vindförhållanden som tillåter effektivare elproduktion leder till komplikationer är Andreas införstådd med. Han förstår de som argumenterar att det finns teknik men att lagstiftning inte riktigt hängt med. Men han vill påpeka att det inte är Transportstyrelsen
som stoppar vindkraftsutvecklingen, utan snarare de olyckligt formulerade villkoren i miljötillstånden som hindrar vindkraftsutvecklingen. Dessa villkor som i vissa tillfällen kräver att ljusen ska tändas och släckas utifrån behov (ex. mha. radar) strider mot Transportstyrelsens föreskrifter. Andreas ser gärna att just ”ska” formuleringen försvinner, och det är något som börjar bli bättre. På senare tid förekommer oftare formuleringar som bygger på ”om”, vilket innebär att ”vid-behov”-belysning skall användas om det är möjligt till att få undantag från Transportstyrelsens föreskrifter. Detta är något som kommer av upplysning och informationsspridning, och att informera involverade instanser och förklara hur vindkraftsutvecklingen påverkas är något han tror är bästa sättet att ta saken vidare.