De-icing and maintenance of wind turbines with drones

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Participants:
Cristian Petrica Gidinceanu

Supervisors
Anders Schmidt Kristensen
Saqib Mehmood

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Abstract

The purpose of this project is to analyze a new concept that uses a drone to perform de-icing and maintenance operations on wind turbines.
First an introduction to the wind energy sectors is made to understand the effects that ice have on wind turbines and energy production and why there is a need for a cost effective system to perform de-icing and other maintenance operations.
The drone concept is analyzed alongside with the maturity of the system to understand the capabilities and the opportunities that a concept like that creates for the wind energy sector.

The research concluded that using a drone system for de-icing and maintenance on wind turbines has a lot of potential. It has the potential of performing operation and decrease the downtime due to icing but the technology seems to be not quite mature enough to handle day to day operations although successful tests have been made.

Preface

This report contain the author's research work, study and analysis of the possibilities of implementing a new concept that uses a drone to perform de-icing and maintenance operations on wind turbines. This is a relative new domain, in continuous development that brings new opportunities for wind energy sector. It is taken in consideration that this new technology can create new ways to minimize maintenance costs, increasing profits and reducing the downtime.

This report is directing towards students, professors and professionals interested in the wind energy sector, drone technology, thus the targeted individuals are supposed to understand the concepts and terminology used in the report.

This project is part of the Msc. Risk and Safety Management, master program at Aalborg University Esbjerg, Denmark. The project starts with an introduction to the wind sector and issues regarding icing on wind turbines, followed by analyzing the drone concept, and a risk assessment of the system. The report ends by discussing the benefits of the drone concept in the wind industry.

The author would like to thank for the supervision and support to Anders Schmidt Kristensen and Saqib Mehmood and to Martins Ummers from Aerones for the information provided in the interview.

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Cristian Petrica Gidinceanu

Contents

Chapter 1

1. Introduction

The energy sector in the past years, has suffered a lot of changes and currently wind energy is one of the principal renewable energy sources. The industry is shifting towards environmentally friendly methods of obtaining clean energy and particularly the wind segment has had a significant increase in the number of installed wind capacity all over the world.

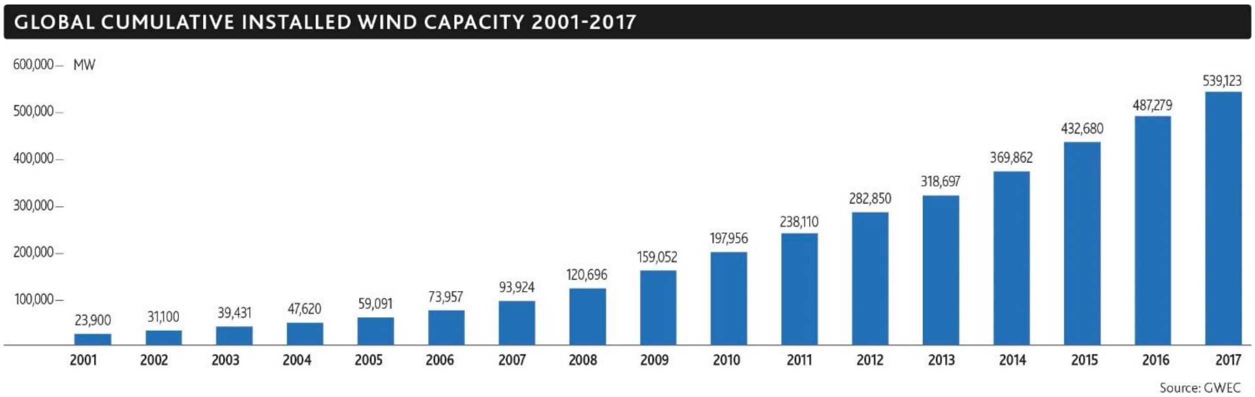

Figure 1. Global cumulative installed wind capacity 2001- 2017 [1]

Every year new technologies are developed alongside with improving the existing ones to increase energy production. Wind turbines are the most conventional way to produce energy and in the past years have been pushed from land to offshore locations, due to the fact that there is an increased potential, stronger and constant winds and the possibility the generate more electricity in better conditions than onshore parks. Wind turbines have gotten bigger and more efficient, new systems have been developed and now wind turbines can be placed even further out offshore.

Ice accretion

A part of the wind turbines installed worldwide that offer high potential for energy production are exposed to low temperature. Icing is significantly influencing the performance of the wind turbine blade when harvesting wind energy. One of the major problem that ice accretion on a turbine blade present is the change in the aerodynamic shape of the blade reducing the efficiency of the wind turbine [2]. Another effect of ice accretion is mass imbalance, which means that the added ice can increase the load on different components and can cause imbalance between bladed which can reduce the lifetime of the whole wind turbine. Ice presence on turbine blades increases the safety risks. Large pieces of ice from a rotating blade can pose serious safety issues to the system itself or to the surrounding areas and humans [2] [3]. There are also various effects on the instruments and controls, where the sensors can be affected by ice and provide wind speed errors. When operating in cold weather the wind turbines face other problems related to maintenance for example, the lubricants lose their viscosity and it might not be possible for the turbine to start [3].

Figure 2. Icing effects on wind turbine [4]

Structures that are exposed to the cold atmosphere can form ice on the surface. Atmospheric icing on a wind turbine can be in-cloud icing such as glaze ice, hard or soft rime ice, precipitation icing such as wet snow, freezing rain and frost. The difference between these types of ice accretion can be observed in Figure 3.

Physical data		Type of ice: Glaze	Wet snow	Hard rime	Soft rime
Physical properties	Density (kg/m^3)	900	300–600	600–900	200–600
	Adhesion and cohesion	Strong	Weak (forming) strong (frozen)	Strong	Low to medium
	Color	Transparent	White	Opaque	White
	Shape	Evenly distributed/icicles	Evenly distributed/eccentric	Eccentric, windward	Eccentric, windward
Meteorological data	Droplet size	Medium/large	Flakes	Medium	Small
	LWC	High	Very high	Medium	Low
	Typical storm duration	Hours	Hours	Days	Days

Figure 3. Physical properties of atmospheric icing [3] .

Figure 4 below show the difference between glaze ice, hard and soft rime ice, the temperature at they form and wind speed.

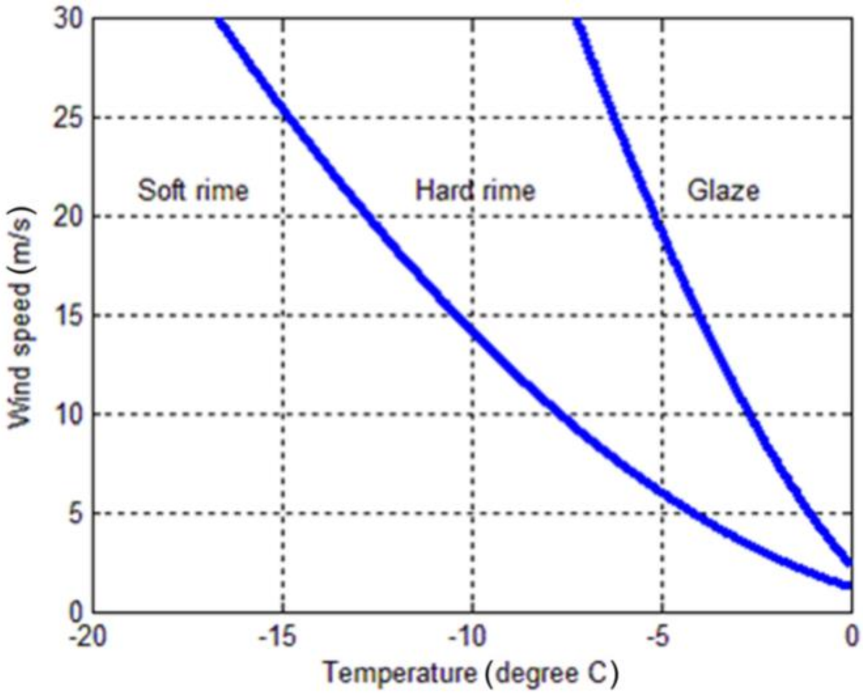

Figure 4. Ice formed at different conditions [3].

Ice accretion mitigation techniques

Based on the research [3] [5], there are more than 20 direct or indirect methods of ice detection available. The direct methods include mass changes, reflective properties, and electrical conductivity. The indirect methods to weather condition monitoring that leads to ice formation and measuring the icing effects on wind turbine such as production loss.

There are 2 types of icing mitigation techniques and these include anti-icing and de-icing procedures. Anti-icing techniques refers to preventing the ice to accrete to the blade and de-icing refers to step taken to remove the ice after it was formed on the surface of the blade. These mitigation techniques can be passive or active. Passive procedures include chemicals, black paint, surface coating with ice-phobic or hydrophobic coatings, flexible blades that can crack the crack the ice when in motion and active pitching. All of these mitigation techniques take advantage of the physical property and the design of the blade to prevent ice formation and have advantages and disadvantages for example painting black the wind turbine blades is cheap and easy to apply but is ineffective for moderate to heavy icing and during night time. Active procedures include an air layer, microwave, electro thermal, flexible pneumatic boots which require external energy to eliminate or prevent ice formation [3].

Techniques	Protection type	Retrofitting	Lightning protection	Control issues	Stage	Effectiveness	Roughness increase	Cost	Energy Consumption
Hydrophobic coatings	Anti-icing	Yes	No	N/A	Prototype	Limited	Medium	Low	N/A
Icephobic coatings	Anti-icing	Yes	No	N/A	Prototype	Limited	Medium	Low	N/A
Biscous coatings (non-water soluble)	Anti-icing	Yes	No	N/A	Prototype	Momentaneous and degrading	Medium	Low	N/A
Biochemicals	Anti-icing	Yes	No	N/A	Experimental	Momentaneous and degrading	Medium	Low	Medium
Black paint	Anti-icing	Yes	No	N/A	Prototype	Very limited	Very Low	Very Low	N/A
Pneumatic	De-icing	No	No	Medium	Operational(1)	Very effective	Very High	High	Very Low
Expulsive	De-icing	No	No	Medium	Operational(1)	Effective	High	High	Very Low
Hot air	Both	No	No	High	Operational	Effective	N/A	Very High	Medium-High
Outside resistive heaters	Both	Yes	Yes	Medium	Operational	Effective	Medium	Very high(3)	Low-Medium
Inside resistive heaters – In the resin	Both	No	Yes	Medium	Experimental	Very effective	N/A	High	Low-Medium
Inside resistive heaters – Outside the resin	Both	No	Yes	Medium	Experimental	Effective	N/A	Medium	Low-Medium
Microwave	De-icing	Yes	Yes	Very High	Experimental	(2)	N/A	Medium	Low
Infared	De-icing	Yes	Yes	Very High	Experimental	–	N/A	Medium	–
Ultrasonic waves	De-icing	Yes	No	Low	Experimental	Very effective	Very low	Medium	Low
Active pitch control	None	Yes	No	High	Experimental	Effective	N/A	N/A	Low
Operational stop	Anti-icing	Yes	No	High	Prototype	Limited	N/A	N/A	N/A

Figure 5. Comparison of ice mitigation techniques.

(1) In aeronautics. (2) Concerns with high intensity microwave. (3) Low durability. [6]

Icing effects

In average a wind turbine is expected to operate around 20 years. Turbine blades affected by icing become unbalanced and they increase the load on the other components increasing fatigue and reduce the overall life expectance of the part.

Effects of iced blades are:

- Additional weight of the ice can cause higher deterministic loads
- Asymmetric mass cause unbalance
- Increased vibration
- Change in natural frequencies causes resonance predominantly for smaller turbines.

Ice accretion has a very big impact on the air foils leading to important performance loss. Production losses due to air foils shapes changed by ice are between 0.005 - 50%. A light icing event can reduce the energy production by 15-30%

Downtime due to a severe icing event can last from several days to weeks especially in the absence of mitigation techniques. Wind turbines have to be stopped to prevent any damage to mechanical components and the result is colossal power losses. [6]

Other secondary effects of ice accretion are overload due to delayed stall which can create a peek in the energy production that can affect the electrical components and can increase the stress on other mechanical parts such as gearboxes and blades.

There are major safety risks regarding ice falling from the rotating blades which can be projected over large areas. This is a main concern when the wind turbine is near private houses, nearby structures or there is maintenance personnel working at the base of the wind turbine [6] [7].

Other contamination sources

Dirt and other sources of contamination such as ageing, sand impact and rain contaminants occur on the wind turbine blade during operations in the wind field. Wind turbines parks are installed in open, agricultural areas thus contamination with insects is very probable especially during turbine operations. Contamination usually occurs at temperatures above 10 ℃ when the weather is warm, wind speeds are small and there is no rain. When this type of contamination occurs the power out may drop with up to 40% from normal values [8].

Summary

Ice accretion and other contamination sources on a wind turbine blade rises different issues related to the functionality of the turbine, production of energy and maintenance, especially de-icing of the blade. As mentioned above icing mitigation techniques have advantages and disadvantages, most of them increasing maintenance costs and are not very effective. They also have increased risks and difficulties involved so implementation of a new de-icing methods is necessary. Several methods for de-icing exist and are already used and proven effective but with high maintenance costs. Still there is the need for another de-icing technique that can be performed in case of emergency that can offer a cost effective method.

A study done in California shows that washing the blades regularly performance dips are avoided. It have been noticed also that although the wind turbines with contaminated blades performed good at low wind speeds, with each return of a higher wind speed the production loss would be worse [9].

1.1 Problem description

Considering the icing effects and the other contamination sources of a wind turbine blade especially the downtime of the system and production losses, a new de-icing and maintenance equipment is examined. To implement a new de-icing and maintenance equipment brings several uncertainties thus a risk analysis of such system before hand is suitable. This concept has already started tests and is under future development and improvements therefore the following question is posed:

What are the risks of using a drone system to perform maintenance and de-icing of wind turbine blades?

A drone de-icing system is a new technology that has some specific advantages and stands out due to its operating costs, efficiency and safety risks comparing to the other icing mitigation techniques.

This concept has been under development for over 3 years. It features a heavy lifting drone system that can lift around 280 kg of weight. The drone is connected to the ground with a power cable and a hose. The electricity cable is used to power the drone thus the system can be operational as long as needed. The hose is connected to a pump system that can use water, hot water or distilled water. The pump system can use also other antifreeze liquids such as hydrophobic coatings or other bio-degradable and non- hazardous liquids. The system has also a trailer with a landing and take-off platform and has the necessary equipment to safely operate the drone, such as electricity generator. The system has also grid connection which means that the drone can be plugged into the wind turbine therefore it is not only cost effective but also is better from the environmental point of view. Whenever there is downtime due to icing, the production losses of the wind turbine has to be replaced with other methods of producing energy such as a has plant, which is more harmful for the environment.

The analysis has been conducted under the PBL dynamics, the project is dedicated to find solutions for the aforementioned problem. Using a drone for de-icing a wind turbine is a huge opportunity for the wind industry that can be exploited and in order to do this the analysis has been made following the ISO 31000:2009 the Risk Management Standard framework which lead to the following process:

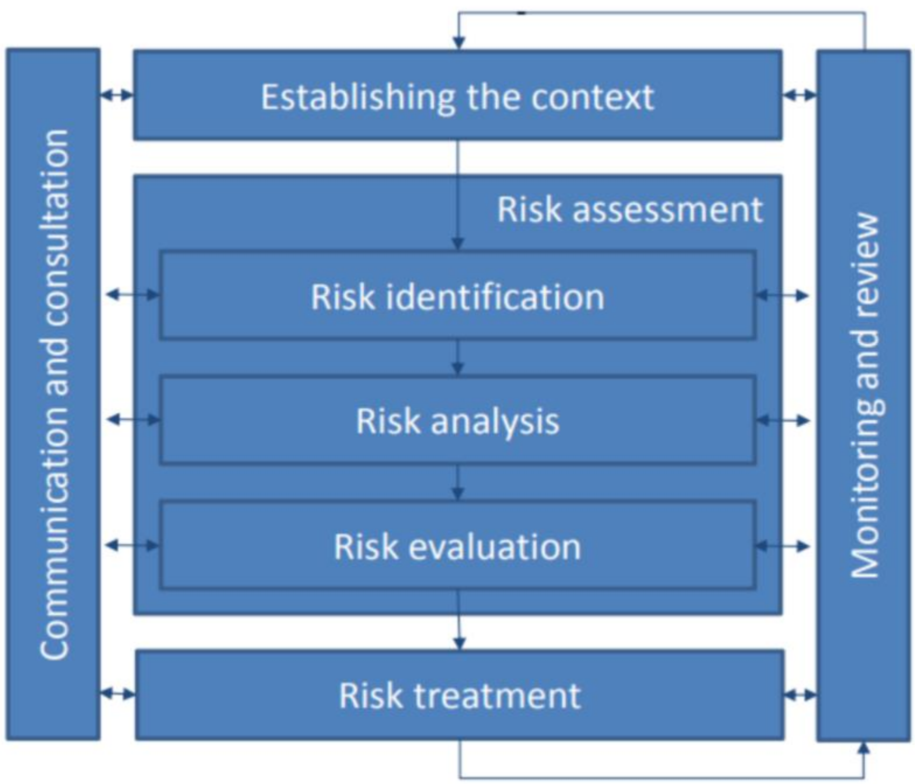

Figure 6. ISO 31000:2009 Risk Management – Principles and Guidelines.

For this project, there will be an inductive approach which means that the theory is generated as a result of conducting research. After the research is done it will be possible to draw a conclusion if drones for de-icing and maintenance are able to perform maintenance operations on a wind turbine taking into account current legislation and the maturity of the technology.

1.2 Problem analysis

From the problem description, there are many operational issues which a drone de-icing system therefore there are risks involved with using such method for de-icing of a wind turbine. The project focuses on the capability of the drone and the pump system. Is the drone able to fly and perform maintenance operation safely? Is the technology ready for repetitive operations? What is the status of the legislation, are there limitations that could hinder the possibilities of the drone to perform tasks around a wind turbine? From the outline of the risks involved several categories can be generated:

Drone

There are operational risks using a drone especially for a system that needs to get close to the wind turbine blade. Drone handling poses risk for maintenance personnel that works under the wind turbine thus a handling procedure must be developed. Also flying with a drone has to conform to Denmark legislation.

Equipment

The pump system presents safety risks to the unit itself and to the workers, especially when using hot liquids. A maintenance plan for the tools is required to ensure functionality on site.

Maintenance personnel.

The operator must be certificated in order to use a drone and specific safety training courses must be followed.

The problem analysis identifies different operational hazards. These hazards increases the risks of injuries, damage to the drone system or the wind turbine and environmental damages.

1.3 Problem formulation

The central question revolves around the implementation of a new method to do de-icing and maintenance on wind turbines. From the main question related to the initiating problem the following sub questions have emerged:

How can a drone de-icing system can improve maintenance costs due to icing effects?

What are the risks of using such systems?

Under which conditions can a company invest in a drone de-icing and maintenance system?

1.4 Problem delimitation

The scope of this project is limited therefore certain aspects of the industry are not covered or analysed in this thesis.

The offshore wind industry is not analysed although it seems that a drone system might be suitable for operations.

There were significant obstacles met in the risk analysis given the fact that the field is quite new and there are no studies about drone de-icing techniques therefore some data had to be estimated or assumed.

Chapter 2

The Aerones drone concept

Aerones is a Latvian company that develops and builds drones and equipment for wind turbine de-icing and maintenance, firefighting and building cleaning solutions. The company aims to develop safer and faster methods that the alternative de-icing solutions available therefore a tethered drone was the preferred design.

The main component of the system is a square shaped frame that is equipped with up to 36 propellers. The maximum payload is 280 kg at 100 meters. The maximum height that it can fly tethered is between 350 and 400 meters. When it’s connected with the pump system and under load the maximum height is 200 meters [10].

Figure 7. Aerones drone [10].

2.1 Operating principle

A multi rotor drone is a complicated system that uses multiple propellers to gain altitude. This system is aerodynamically unstable and requires an on-board computer to control the flight and making the system stable. The flight controller uses and combine data from other systems installed on board to maintain an accurate positioning and orientation [11].

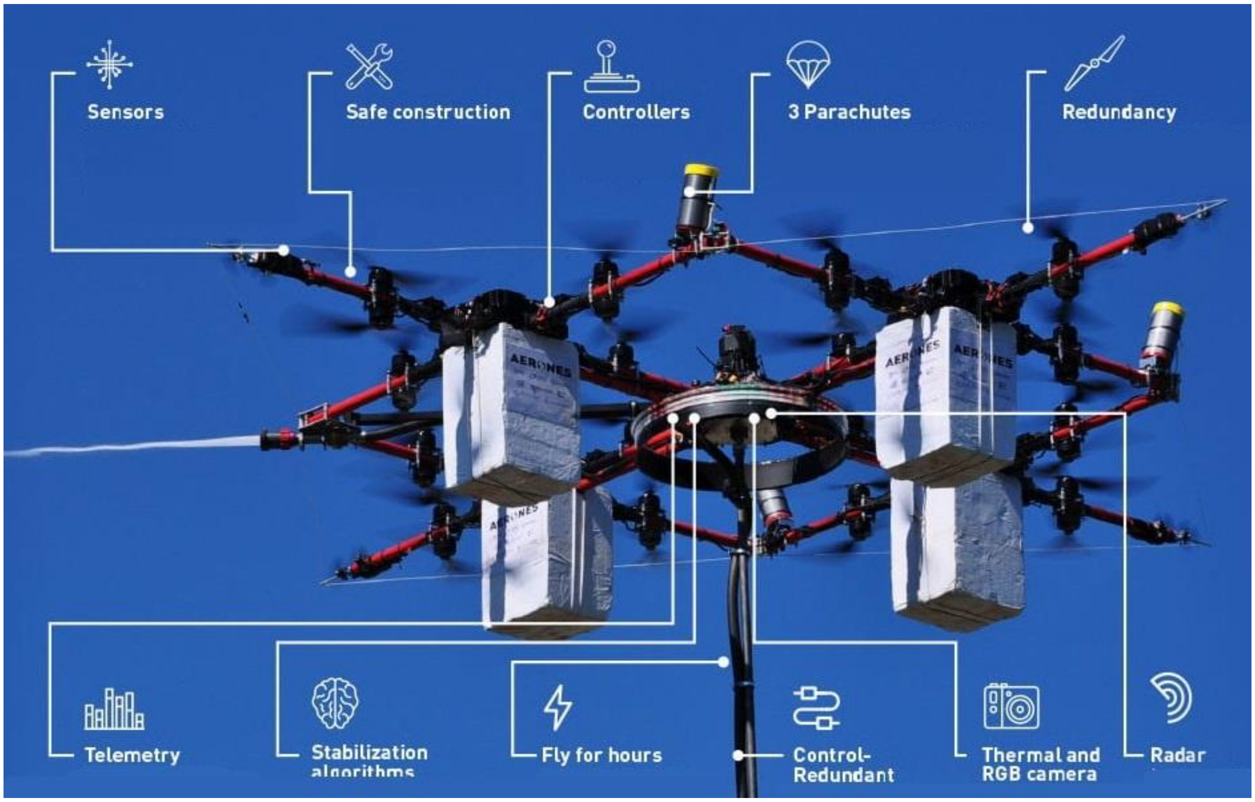

Figure 7. Aerones Drone system breakdown [10]

Drone components are vital for the functionality and a safe flight. Aerones drone is designed with the following systems:

The frame is build up with aerospace grade materials, making it very strong, safe and rigid.

Propellers: most propellers are made out of plastic or carbon fibre. The design of the propellers will influence the smoothness of the flight and increase the fly time.

Sensor: on board there are 2 accelerometers, 5 gyroscopes for precise angle determination. There are no magnetometer or GPS installed due to the fact that these sensors can be jammed making the system hackable and unstable.

Controllers: There are 2 redundant controllers installed, one being a back up to the main controller. The flight controller gets input from all the other components and on board sensors. It is in charge of regulating motor speeds, provide steering, and controls cameras, autopilot, waypoints failsafe and other autonomous parameters [12].

Parachutes: there are 3 parachutes installed on board which are activated immediately in case the drone freefalls. It takes only 5 meters to deploy the parachute, thus there is the possibility to save the system in case of emergency.

Redundancy: There are 28/36 motors and 16 hot plug batteries thus the system tends to be without a single point of failure. Control redundant signal is provided via a cable which is not jammable. If the signal is lost the drone is controlled with a Radio Frequency remote control unit.

Telemetry. There is a low latency protocol. Motor temperatures and battery health status is continuously monitored for autopilot to react in case of emergency.

Stabilization algorithms: Aerones has developed unique stabilization system for easier auto piloting in case there is harsh weather conditions and the system is “rock-steady” in strong winds.

Tethered system: the drone is connected to the ground with an electricity cable that provides power for as much as needed. In case there is a connection problem to the power unit, the drone can fly with the on board batteries for up to 20 minutes. The tether affects the thrust capability. Flight height is also affected by the cable weight and resistance [13].

Cameras: there are thermal and RGB cameras installed for hotspot identification and to facilitate the operator’s vision to aid piloting.

Radar: increases the awareness of surroundings and ability to avoid obstacles even in thick smoke or fog [10] [14].

In the operation mode the drone is connected to a trailer on the ground that has a take-off and landing platform. At the base there is also the pumping equipment that includes the pump, diesel generator and a grid connection. The Aerones drone can be connected directly to the wind turbine for electricity needs therefore making it very efficient and able to have very low CO_2 footprint. [14]

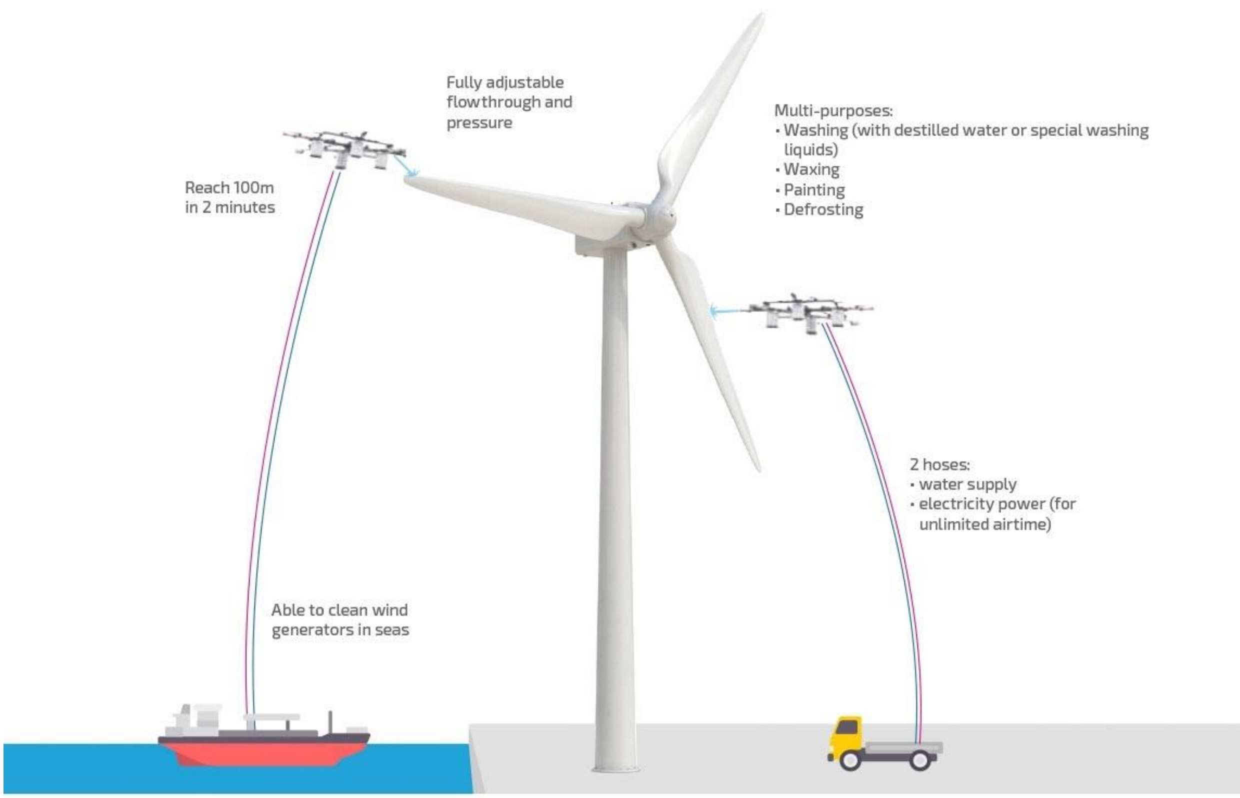

Figure 8. Drone operations [15]

The system has a pump equipment that can work with different types of water and other cleaning and de-icing liquid chemicals, the company is providing all the necessary parts to successfully de-icing multiple wind turbines a day.

The operating distance is quite small. The drone is capable to do coating with various paints or chemicals thus the distance that can approach the wind turbine blade is under 1 meter. For de-icing the drone can get up to 1-1.5m meter thus ensuring that the de-icing liquid is spread and used efficiently. Based on the information available from tests done, the drone can completely de-ice a wind turbine with blades up to 35 meter long between 1-2.5 hours, depending on the ice thickness and working conditions such as outside temperature [14].

2.2 Comparison with the other de-icing methods

Aerones claim that their system is 5 times faster than rope access method to de-ice a wind turbine, and it is 5 times cheaper that de-icing with a system that uses a helicopter, or with the icing mitigation techniques presented in Chapter 1 such as heating up the blade. They also claim they reduce the risks by using the drone and one operator, instead of the other methods that requires more man power to operate [14].

Figure 9. Rope access workers [16]

Rope access operations have multiple liability and insurance issues. The safety of the workers is very important and the job presents multiple risks. Training is necessary to complete the maintenance operations and the workers needs to use high quality ropes, climbing equipment which must be approved by the International Rope Access Technicians Association.

Comprehensive safety check is required before each operation, specific wind speeds are required and brakes applied to the rotors [17].

Based on research a helicopter de-icing system in Sweden managed to de-ice 10 wind turbines with an overall energy consumption of 41.9 MW. In this particularly case the personnel and equipment used had to travel to a site situated 500 km away so the calculations include the transport of the equipment to the working site [18].

The Aerones drone system has the capability of using the existing grid connection. The drone uses 30-35 kw/h which means the overall energy consumption is far less than what the helicopter example above used [14].

Chapter 3

Risk assessment

3.1 Stakeholder analysis

Stakeholder analysis is used to identify and estimate the key players and their knowledge, position, interest and importance regarding de-icing and maintenance of a wind turbine using a drone system. The stakeholder analysis is directed by following the cycle engagement process which can be observed below in Figure 9.

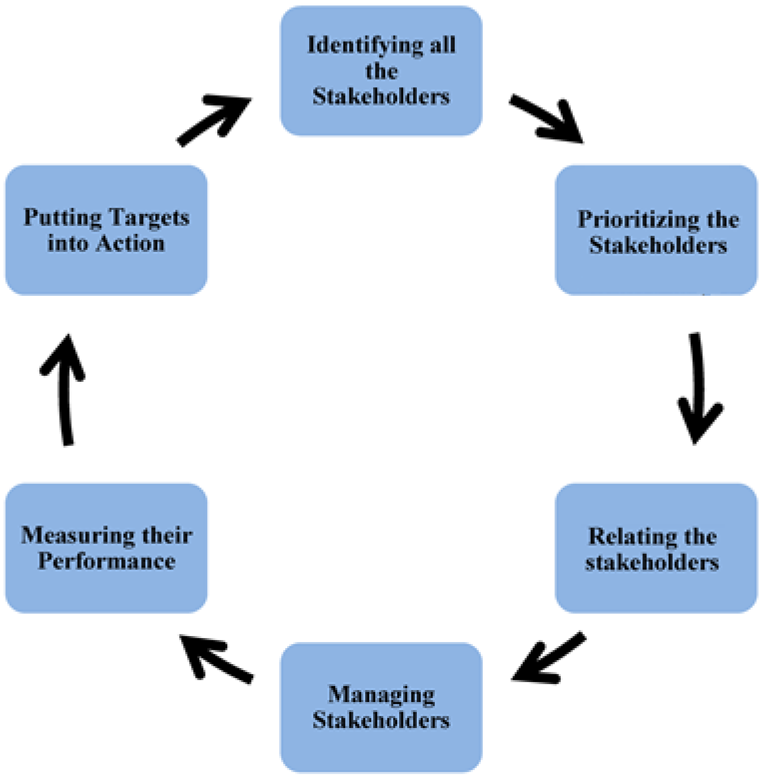

Figure 10. Stakeholder engagement process source

Identifying all the stakeholders

Attention to stakeholder management is crucial for private and public organizations success. The success of this project depends on the satisfaction of the key stakeholders, therefore the identification of the stakeholders is one of the important part of the analysis. In order to include all potential risks even the minor stakeholders have to be taken in consideration.

Some questions arise to facilitate stakeholder identification:

Which are the interested parties in implementing a drone de-icing and maintenance system for the wind industry?

Who are the beneficiary of such system and what are their interest?

How does the system affect each stakeholder?

The identified stakeholder are listed below and list can be bigger by further brainstorming and analysis. For management and analysis purpose the stakeholders are split in 2 sections.

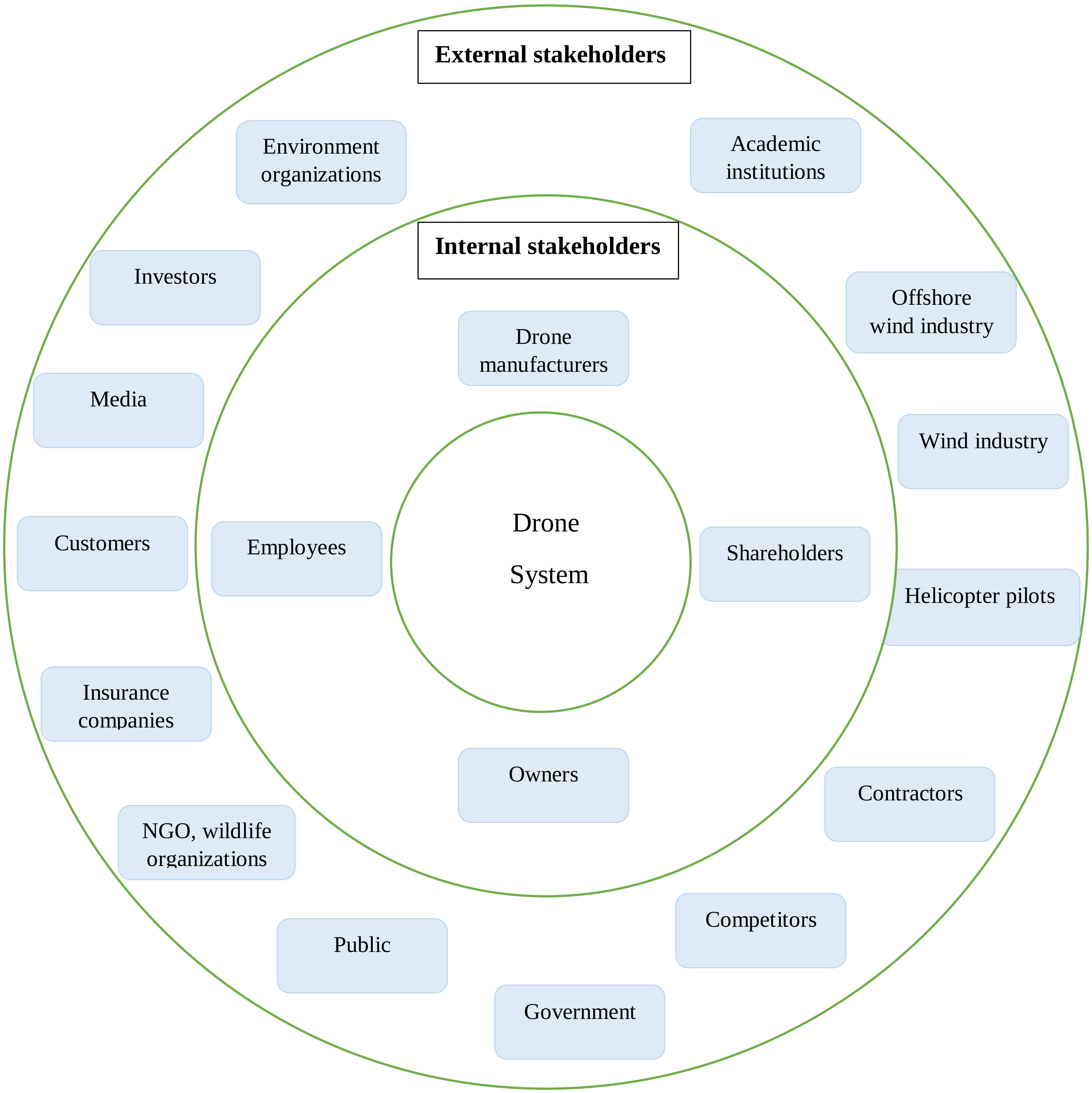

Figure 11. Internal and External stakeholder for the Drone system

Internal stakeholders

Employees

The employees can affect the performance of the project. They possess the skills that are needed for the project to be successful. This is a new concept for the wind industry and there are a lot of procedures that needs to be carried out to make the implementation of the drone de-icing method succeed.

Owners

The owners want to cut maintenance costs therefore they have to find the best solutions and manage all the risks involved with this project.

Shareholders

The shareholders are connected with the owners and they are involved in this project because the success can increase profits while fail can increase potential losses for the company.

Drone manufactures

Drone manufacturer companies are important for the project because they are the one providing the technology and concept. Others in the industry can learn from the success of this particular project and develop or improve new techniques, components and other parts that can improve current designs.

External stakeholders

Academic institutions

Local academic institutions can get involved in developing current techniques for drone de-icing and maintenance. They can work closely with the companies and it would be benefic for both parties.

Offshore wind industry

The success of this project onshore can influence how de-icing and maintenance offshore will be done. The drone system might be suitable for offshore use decreasing risks and cut down costs.

Wind industry

In general the entire industry might benefit from this project. Energy production might increase, there will be less downtime in good wind situations which means that the power demand might be covered by the wind turbines.

Helicopter pilots

The pilots are affected by the project success. With an increase usage of the drone system their job might suffer.

Contractors

Contractors can affect and be affected by this project. If successful the some contractors might gain new opportunities while other lose jobs. They have a lot of knowledge about de-icing, maintenance, methods and techniques which can be useful therefore business relations should be kept in good conditions.

Competitors

In this case the competitors are other companies offering the same service. This concept can get popular in the future and other companies might invest in development and research.

Government

Like in any industry the government provides legislation, guidelines and they are in charge of health and safety issues regarding the project.

Public

The public is an import stakeholder. Multiple complaints about noise, pollution or damage to the environment can bring changes to the project or increase the operation costs. A communication channel should be kept open for information about the system and operations.

NGO and wildlife preservations

Some of the wind turbines are placed near or in natural parks. The drone and equipment might have a bad influence for wildlife and threaten the species that are living nearby.

Insurance companies

The drone system and equipment is expensive. The equipment operates next to other expensive parts which might bring objections regarding certain aspects of the project.

Customers

The customers are the consumers of the energy produced by the wind turbines.

Media

Can play a big role in influencing the customers, investors or other stakeholders. Media is interested in new concepts and technologies but also looks for the bad parts of the project.

Investors

Investors are very important for the project. They are bringing capital to the company and thy can gain interest depending on media publicity, the results of the system or they might lose interest if the company is not producing the expected target.

Environment organizations

The environmentalists can influence a project negatively or positively. The drone can use hot water or distilled water to do the job but it can also use a combination of chemicals that might have an impact on the environment.

Prioritizing stakeholders

For the purpose of this project a qualitative analysis has been completed and the values acquired are based on the knowledge of the author.

	Stakeholder	**Level of importance 1-5**	**Level of influence 1-5**	**Total score**
Internal stakeholders	Drone manufactures	5	5	25
	Employees	5	2	10
	Shareholders	5	5	25
	Owners	5	5	25
External stakeholders	Academic institutions	2	1	2
	Offshore wind industry	2	2	4
	Wind industry	3	2	6
	Helicopter pilots	2	2	4
	Contractors	2	2	4
	Competitors	3	3	9
	Government	5	5	25
	Public	1	1	1
	NGO’s	1	3	3
	Insurance companies	2	2	4
	Customers	5	4	20
	Media	5	5	25
	Investors	5	5	25
	Environment org.	1	4	4

Table 1. Stakeholder power matrix

Based on the results from the table 1 the stakeholders can be further prioritized according to their power. For the project to be successful is it important to understand the stakeholder requirements.

Drone manufacturers	25
Shareholders	25
Owners	25
Government	25
Media	25
Investors	25
Customers	20
Employees	10

Stakeholder risks

Risk management requires to prioritize the risks according to the probability and impact. A table with the primary stakeholders

3.2 Risk analysis

Assumptions and estimations

For this project some assumptions are made. The calculations are completed using information from research and the interview with Aerones official. The wind turbines are on land at different distances away from the maintenance workshop. The drone and de-icing and maintenance equipment is considered to be an investment made by a company that is in charge of the maintenance done to the wind turbine.

Another assumption is that the drone and equipment is used every working day in the year for cleaning, coating and other maintenance issues that appear from day to day operations.

The expenses with the personnel are not included in the calculations.

Downtime cost due to icing

From the research [18] downtime costs of a wind turbine in normal wind conditions is approximately 15 000 DKK/day. The drone can de-ice up to 3 wind turbines a day.

There are no guidelines or protocol under which conditions de-icing should be made therefore the decision belongs solely to the company.

Based on the research done in Sweden [18], at 16° C a wind turbine was delivering 460-500 kW at a wind speed on 9-11 meter/second. According to the manufacturer specification the turbine at 9.11 m/s should deliver around 2.5MW of power. After de-icing was complete the wind turbine produced 550-600 kW at 6-7m/s which was an improvement in production at a lower wind speed. When the wind speed increased to 10-11m/s the wind turbine increased the production to 1.5MW.

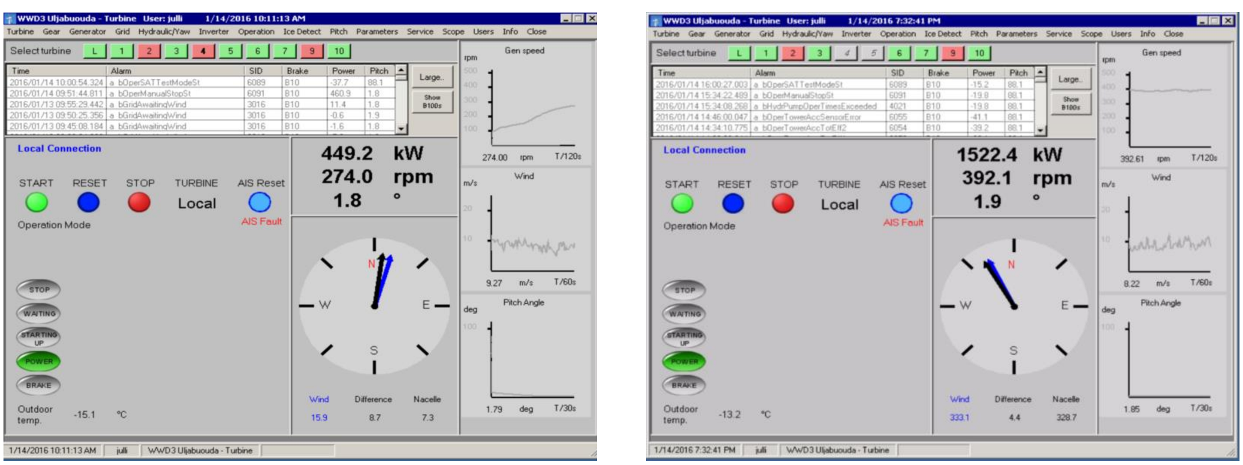

Figure 12. Turbine 1 before and after de-icing [18]

It is know that a wind turbine with a total capacity of 3MW in a year the average production is around 33%, which means that on average the production is approximately 1MW/hour. In the study case [18] a helicopter was used to de-ice 10 wind turbines with a total energy consumption of 41.9 MW/hour. In the calculations was included the fuel consumption for a truck and a van with equipment, helicopter fuel consumption and the fuel used for heating up the water. If the drone would replace only the helicopter, which had the largest fuel consumer, the total energy consumption would have been 17.5 MW/h. This means that 10 wind turbines with an average energy production of 1MW/h would have delivered the energy required for de-icing in approximately 1.8 hours. This means that de-icing wind turbines with a drone system is benefice and it should be implemented if the wind forecast for next days is good.

Investment

The project lifetime for this example is set to be 5 years. Technology changes all the time, the equipment is continuously improved and at this point there is no information that the equipment purchased will be updated with new and more efficient parts or components.

Expected lifetime = 5 years

Drone + all equipment = 200 000 EURO

Installation and other costs (includes training personnel, coordination system, power generator, pump system) = 0

Total Drone cost = 200 000 Euro

The payment is used to calculate the net present value and the rate of return for 5 years. Other taxes and payments are not included for this analysis because it is considered that the funds were available for investment.

Operation and maintenance costs = 1000 Euro/ month

Total expenditure: Total drone cost + Operation costs over the expected lifetime

= 200 000 + 60 000 (12 000/year x 5 years)

= 260 000 Euro

Gross income

It is assumed that the drone equipment is used every working day of the year to perform operations on wind turbines. According to the interview [14] the offer to clean (de-ice, cleaning bird droppings, oil, dirt) a wind turbine up to 30 meters = 2000 euro

The drone can perform operation on 3 wind turbines a day = 3 x 2000 Euro = 6000 euro / day

For 2019 it is assumed that there are 250 working days = 250 x 3 wind turbines = 750 wind turbines / year

Thus gross income = 750 x 2000 = 1 500 000 euro / year

Net income = 1 500 000 – 12 000 = 1 488 000 Euro / year

Net present value is the difference between the project initial investment and the present value of the income discounted at a rate equal to the firm's costs of capital.

The discounted rate for this example was set to 10%

Year	Expenditures Euro	Gross Income Euro	Net income Euro	Net present Value
0	-200000	-	-	-
1	-12000	1500000	1488000	1352727.27
2	-12000	1500000	1488000	1229752.07
3	-12000	1500000	1488000	1117956.42
4	-12000	1500000	1488000	1016324.02
5	-12000	1500000	1488000	923930.93
				5440690.71

Table 2. Net present value (own work)

The formula used for calculation was:

$$\text{NPV} = \sum_{t=1}^{n} \frac{CF_t}{(1+r)^t} - CF_0$$

Where

CF is the nomical value of a cash flow amount in future period

r is the discount rate

t is the time in years

From a decission point of view if the NPV is greater than 0 Euro the project should be accepted, the company will earn a return greater than its cost of capital. If the NPV is less than 0 Euro the project should be rejected.

3.3 Risk evaluation

The purpose of this subchapter is to evaluate overall risks of implementing drone de-icing and maintenance project as part of the maintenance operations and discover ways for mitigation.

Fault tree analysis

The fault tree analysis is a logical diagram used to show relations between a top event (for example drone failure) and basic events such as component failure. The analysis is deductive and is carried out by asking "how this can happen" [19] . The basic event can be also a human error or issues that have external load such as wind conditions. The top event "drone crash" is the starting point of the fault tree analysis. Next step was to identify possible events that can be direct cause for the top event.

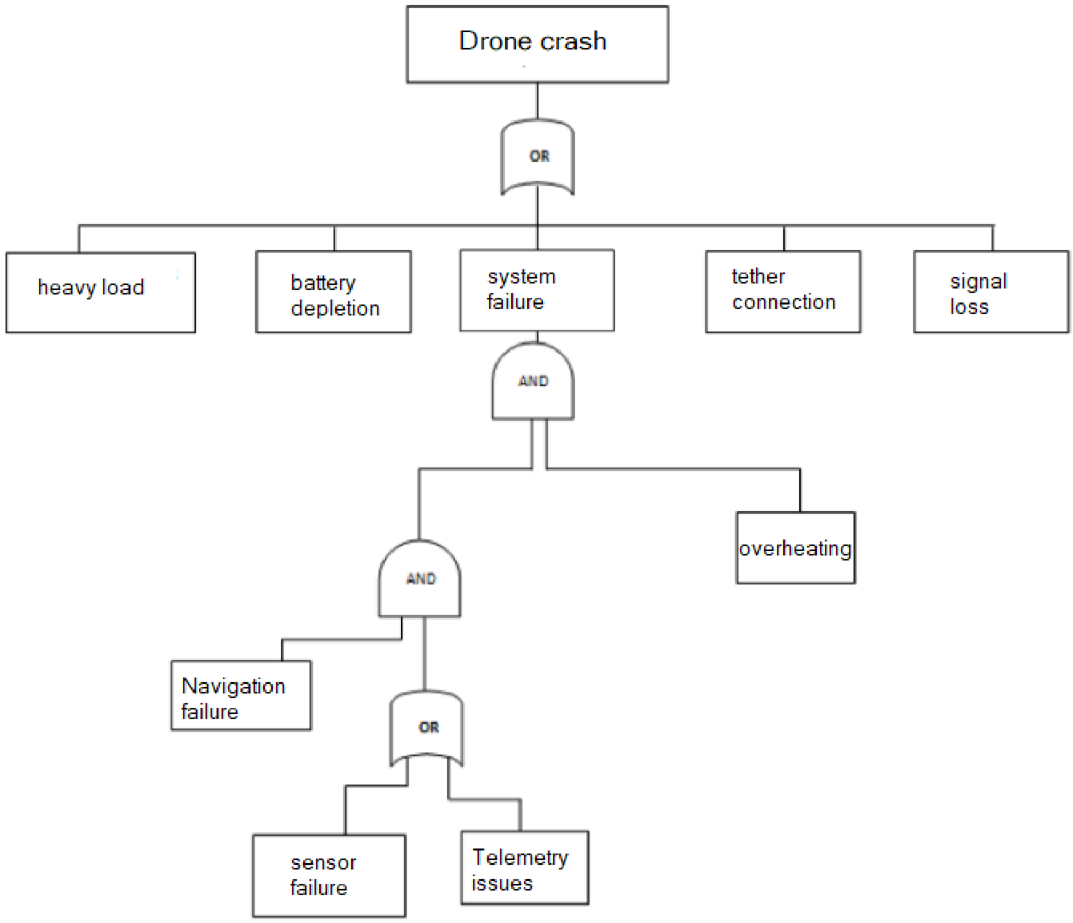

Figure 13. Fault tree Analysis (own work)

In this case the drone crashed due to system failure which was caused by navigation and sensors failure alongside with incorrect telemetry data. The analysis stopped when the desired level of detail was reached.

Swift analysis

The Structured What-If (Swift) analysis is used systematically in order to identify deviations from normal conditions.

ID	What if?	Causes	Consequences	Controls	Treatment
1	Malfunctioning rotors	Bending out of shape; Damage during transport and handling	Injuries to personnel Damaged to other pieces of equipment	Always check each rotor before use	Follow handling guideline from the manufacturer
2	No GPS signal	Drone is out of control	Damage to drone and other equipment Injuries	Check the GPS signal before flight	

3	Compass error	Incorrectly tuned	Drone crash Lose radio frequency connection.	Check equipment	Store drone in safe areas
4	Power failure	Out of battery Cable connection	Drone crash	Check battery levels Check cable before flight	Follow manual from manufacturer
5	Collision with turbine blade	Strong winds	Drone crash Damage to turbine blade	Check weather forecast	Follow manual instruction
6	Tether problems	Tether stuck, mechanic failure	Damage drone components Drone crash	Check equipment before flight	Follow operation manual
7	Telemetry problems	Flight problems	System fail	Maintenance and service	Update software
8	Human error	Negligence	Damage drone	Procedures	Training
9	Weather conditions	Strong winds	Difficulties in handling	Check weather forecast	Training
10	Insufficient power	Faulty connection with grid Grid not capable	Drone loses power	Check grid connection, have backup generator	Check systems before flight

Table 3. Swift analysis for the drone concept

Risk matrix

A risk assessment matrix is a tool used in project management which allows a quick view of the possible risks, the likelihood or the probability and offers an idea about the severity of the consequence.

The likelihood is determining the occurrence probability of a given situation. The most common way to measure is to use a scale from 1 to 5 or to use terms such as “very likely” to “very unlikely”.

	Negligible	Minor	Moderate	Significant	Severe
Very likely					
Likely			9		
Possible			10	6	
Unlikely			3; 7		
Very unlikely	2	8		1; 4	5

Table 4. Risk matrix for the drone concept

3.4 Health and safety risks

Wind energy personnel are exposed to multiple hazards that can result in serious injuries and fatalities. Both offshore and onshore workers are exposed to common hazards that includes contamination with harmful substances, lone working, working at great heights and confined spaces, falling objects and moving parts, slips and falls, physical load from climbing blades and towers, musculoskeletal disorders, communication and procedure issues. Furthermore weather conditions bring more and specific hazards [20].

When performing de-icing there are some things that needs to be taken in consideration and needs to be analysed before carrying out the work such as:

- Blade orientation
- Wind speed on the day
- Weather forecast for next 72 hours
- Personnel health and safety around the drone and pumping equipment.
- Handling hot water or the chemicals used for de-icing.
- Safe working procedures

When developing safe working procedures, one must identify elements in each task and the associated risks and hazards. Once identified, the hazards and risks needs to be controlled, documented and implemented through training. This is an ongoing process, after implementation the tasks can be reviewed perhaps some aspects have been omitted, which means to involve the workers, this way it will ensure the fact that the procedures will be accurate, useful and easy to comprehend. When an accident occurs the main target of the investigation is to explain the course of the events, an analysis of how the safety system failed. Often the risks associated with a task are not obvious and safe work procedure briefly documents the risks associated with the work and increase awareness among the workers [21].

When operating a drone close to a wind turbine that has ice on the blades there are risk for personnel injuries due to ice falling down during de-icing or other causes.

Depending on the liquids used for de-icing or cleaning special measures needs to be taken to protect the workers from injuries such as, burns, chemical contamination, fumes inhalation, etc.

Noise pollution

Wind turbines have an environmental impact in Denmark which includes noise and visual effects (lights for warning aircrafts, landscape modifications) and it depends on the proximity to private properties. Wind turbines can produce low and high frequencies noise that is caused by the rotation of the blades [22].

Drones have a certain buzzing sound that accordingly to a recent Aalborg University study [23] stresses the people more than regular street noise of cars or trucks. The public is an important stakeholder for the success of a project like this therefore steps needs to be taken to mitigate the risks involved with this particular issue.

Checklists have to be developed to verify the noise and vibration risks and the levels that the workers are exposed to. Rest periods and appropriate work schedules needs to be designed, safety equipment has to be provided to ensure safe operations [20].

Chapter 4

Discussion

4.1 Legislation

According to the research [24]the legislation is not specific for this type of operations. The field is relative new so many aspects of the current legislation is made for private individuals or companies that uses other types of drones. In the legislation there are special observations marked with "special permission" that concerns other types of operations but is not clear about the drone design used in this project. Also, Aerones is currently developing new ways for the drone to be autonomous which means that the system is not yet part of a certain category of drones. The legislation is not clear about types of accidents and guidelines regarding use of tethered drones.

Section 10 [24] states that flights with increased risks should not be done, unless a special permission has been granted. Those who are of concern in this case of flying the drone out of sight (EVLOS/BVLOS), flying over people that are not part of the drone flight, flying over 100m, autonomous flying and finally flying where pieces might drop or spread out from the drone. However this section might refer only at the drones for private use.

For companies that want to use drones, there is a need to be covered by a liability insurance. In case of an accident or even death, the failure of not having a reliable insurance could lead to large fine. In section 127 in the Air Navigation Act it is stated that the owner of the drone is, by law, obligated to compensate for any damage or injuries caused by the aircraft, no matter the size of the drone. Section 5, in Chapter 3, says that the drone must be covered by a valid insurance [25].

	Permis-sion	ID	GPS logging	Liability insurance	Training requirement	Airworthiness/ technical requirements
Up to 250 g without camera or similar device						
Up to 250 g with camera or similar device		X				
Recreational						
0.250 kg to 1.5 kg		X		X	Drone permit	
1.5 kg to 7 kg		X		X	Drone permit	
7 kg to 25 kg		X		X	Drone permit	
Commercial and emergency response						
Up to 250 g without camera or similar device						
Up to 250 g with camera or similar device	X	X				
0.250 kg to 1.5 kg	X	X	X	X	Drone licence A	
1.5 kg to 7 kg	X	X	X	X	Drone licence B	
7 kg to 25.0 kg	X	X	X	X	Drone licence C	
BVLOS up to 2.5 kg	X	X	X	X	Drone licence D	X
> 25 kg	X	X	X	X	Case-by-case basis	X

Figure 14. Framework for regulation of civil drones [25]

A recommended framework for regulation of civil drones has been developed to create a legal basis that permit requirements to be compulsory to drones. Overall the government recognizes the benefits of using drones for work tasks that usually requires manpower. An area that shows significant potential was identified to be the emergency response context where the drone can be used to provide information about an incident to minimize the risks involved in daily operations. [25]

Chapter 5

Conclusion

How can a drone de-icing system can improve maintenance costs due to icing effects?

From the paper it can be observed that a system that uses a drone can improve maintenance costs due to icing effects. The equipment is easy to transport and can be deployed quite fast. The drone is designed to use the grid available if it can offer the required power consumption or it can be connected to a separate diesel generator. If the wind turbine has a grid connection the diesel generator can be used as a backup or to power the other equipment available. If the drone can de-ice a wind turbine in 2 hours, this means that the energy production can go back to normal thus the overall maintenance costs will be small.

What are the risks of using such systems?

Like with any other de-icing and maintenance operations there are some risks involved with a system like this. The risks were presented in Chapter 3 and it can be observed that some of the risks are related to the equipment itself while other risks are similar to the other types of de-icing and maintenance such as helicopter maneuvers or rope access.

Under which conditions can a company invest in a drone de-icing and maintenance system?

According to the calculations and to the available data it appears that it is a good idea to invest in a system like this. Aerones claim they improve costs, thus increase the profits. Unfortunately due to a lack of data from companies directly involved in de-icing and maintenance operations the answer for this question remains unclear. What is clear is the fact that the mitigation techniques presented in this project are more expensive than using a drone.

Stakeholders are an important part for the success of implementing of a project that uses a drone for operations in the wind industry, therefore is it important that they are closely monitored to ensure their interest and position towards the project remains. All stakeholders needs attention and none of them shouldn't be underestimated because anyone can influence the implementation of the process.

Like any other new concept drone operations present liability issues that needs to be taken in consideration and have a risk management plan.

Training is required by the authorities for the operators to gain the necessary skills to pilot the drones. Upon training a drone license is given which documents the operator's skills, the type of drone and operations category.

However it is not clear that the commercial use refers to a tethered drone working in the wind industry.

	COMMERCIAL AND EMERGENCY RESPONSE		
	SKILL LEVEL	TRAINING	TEST
Up to 1.5 kg	Drone licence A	Theory course	Full Multiple Choice + Practical Test
1.5 kg to 7.0 kg	Drone licence B		
7.0 kg to 25 kg	Drone licence C	Theory course + Practical course	Full Multiple Choice + Practical Test + Model-specific test
Up to 25 kg (BVLOS)	Drone licence D	Individual assessment	Full Multiple Choice + Practical Test + Model-specific test
Over 25 kg	Individual assessment	Individual assessment	Individual assessment

Figure 15. Required skills for professional operators. [25]

Drone operations in industry is a new concept that is under continuous development. Governments are recognizing the capabilities and the benefits that a concept like this brings to the industry therefore a proper legislation is key to maintain a high standard for health and safety and regulations for operations.

According to the interview with Aerones [14] the technology is ready for testing but new improvements are made to the concepts and they expect to be ready for market at the end of 2019.

Source discussion

The materials used for drone research presents some credibility issues due to the fact that the information is obtained directly from stakeholders directly involved in the business and they might have highlighted only good aspects about their equipment and the results of the final product available for public can be different than what is presented in this project.

Front page image source [26]

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