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Probabilistic Safety Analysis for Small Wind Turbines

Master Thesis

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Declaration of authorship

I hereby declare that the thesis submitted is my own unaided work. All direct or indirect sources used are acknowledged as references. This paper was not previously presented to another examination board and has not been published.

Larissa Jana Zajicek
Vienna, May 31, 2017

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Abstract

Small wind turbines (SWT) enable the use of wind to produce electricity at sites, where large wind turbines are not suitable. SWT provide the possibility of decentralized energy production also in urban areas. Besides photovoltaic systems they are suitable to fulfil the requirements of Directive 2010/31/EU on the energy performance of buildings. Due to missing standardization the market of SWT is highly diverse regarding quality and safety of SWT. Particularly in crowded urban areas, however, improving reliability and safety are essential. The aim of the present study is to create a method for assessing SWT in urban areas to detect weak points and shaping possibilities to minimize the resulting risk. Within the research project the main failures of SWT have been analysed and the Probabilistic Safety Analysis (PSA) was adapted to SWT. The data of 15 SWT (with a nominal capacity between 1 and 10 kW) tested at the energy research site Lichtenegg, Lower Austria between 2011 and 2016, has been used. Three unwanted events within the risk aim "failure of the SWT that potentially harm people" have been identified: burning, falling parts and ice throw. Further five initial hazards were identified to cause the unwanted events. The criteria axial orientation, nominal capacity and certification have been tested whether they significantly influence the occurrence of the initial hazard material failure by using Fisher's exact test of independence. Vertical design as well as nominal capacity < 5 kW are detected to increase material failure frequency. Examining the presently used protection systems by using event-trees, it turned out, that improvements regarding safety of SWT in an urban environment are feasible. It appeared that the occurrence of burning can be reduced successfully. Regarding ice throw and falling parts, in contrast, frequencies of occurrence can be high, since effective protection systems are often missing.

Keywords: PSA, Probabilistic Safety Analysis, Small Wind Turbines, urban windpower

Kurzfassung

Kleinwindkraftanlagen (SWT) ermöglichen die Nutzung von Wind zur Stromproduktion an Standorten die für große Windkraftanlagen nicht geeignet sind. Ergänzend zu PV-Anlagen könnten SWT zur urbanen Stromerzeugung und zur Umsetzung der europäischen Richtlinie 2010/31/EU über die Gesamtenergieeffizienz von Gebäuden beitragen. Auf Grund mangelnder Zertifizierung unterscheiden sich SWT jedoch stark hinsichtlich Qualität und Sicherheit. Die Verbesserung der Zuverlässigkeit der Anlagen sowie deren Sicherheit sind für die urbane Nutzung essentiell. Ziel dieser Arbeit ist es, mit einer angepassten probabilistischen Sicherheitsanalyse (PSA) Verbesserungspotentiale hinsichtlich Sicherheit der SWT zu identifizieren und ein Verfahren zur Abschätzung des Risikos von „Schäden mit Gefährdungspotential für Personen" zu entwickeln. Zur Ermittlung von relevanten Anlageschäden wurden neben bereits publizierten Daten, die Daten von 15 SWT (mit Nennleistungen zwischen 1 und 10 kW) herangezogen, die im Energieforschungspark Lichtenegg innerhalb von fünf Jahren (2011-2016) erhoben wurden. Drei unerwünschte Ereignisse konnten identifiziert werden: Brand, fallende Anlageteile und Eiswurf. Deren auslösende Ereignisse wurden identifiziert sowie der Einfluss der Kriterien Achsenorientierung, Nennleistung und Zertifizierung auf das auslösende Ereignis Materialversagen mittels dem exakten Test nach Fischer untersucht. Nur die Kriterien vertikale Achsenausrichtung sowie Nennleistung < 5 kW zeigten eine signifikante Erhöhung der Auftrittshäufigkeit. Schadenshäufigkeiten sowie die Effizienz von verschiedenen Sicherheitssystemen wurden mittels Ereignisbäumen betrachtet. Es zeigt sich, dass gerade für eine urbane Anwendung von SWT Verbesserungspotentiale hinsichtlich der Sicherheit bestehen. Das Brandrisiko kann zufriedenstellend reduziert werden. Besonders Eiswurf aber auch fallende Anlageteile weisen eine hohe Auftrittshäufigkeit auf, da oft keine geeigneten Sicherheitssysteme Verwendung finden.

Schlagwörter: PSA, Probabilistische Sicherheitsanalyse, Kleinwindkraft, Kleinwindenergieanlagen, urbane Windkraft

Glossary of terms

The following abbreviations are used throughout this study:

SWT	small wind turbines
HAWT	horizontal axis wind turbines
VAWT	vertical axis wind turbines
PV	photovoltaic
ET	event-tree
FT	fault-tree
W	watt (SI unit of power)
kW	kilowatt, equal to 10^3 watts (unit of power)
MW	megawatt, equal to 10^6 watts (unit of power)
GW	gigawatt, equal to 10^9 watts (unit of power)
TW	terawatt, equal to 10^{12} watts (unit of power)
m	meter
km	kilometer
km^2	square kilometers
J	joule
A	ampere
kA	kilo ampere
a	year
€	euro
ct	eurocent
LCOE	levelized cost of electricity

The following terms are often used throughout the safety analysis. They are further explained in chapter 2.4 and 4.1.

failure	nonperformance of a system
harm	physical damage to health or property
hazard	potential source of harm
risk	probability of occurrence and severity of harm
safety	adequate reduction of risk
risk aim	failure of the turbine that can lead to harm
unwanted event	failures within the risk aim: burning, falling parts, ice throw
initial hazard	hazard initiating an unwanted event: high wind, lightning, material failure, fog and freezing rain

Contents

1 Introduction

Energy supply is one of the big challenges at present times. While population is steadily growing, climate is changing and the impact of people on the planet gets more and more serious. That indicates that a dramatic change in energy supply is needed. Worldwide organizations and scientist as well as politics predict that wind energy will play a significant role in future energy supply. The International Energy Agency (IEA) is predicting in their main scenario (New Policy Scenario) of the World Energy Outlook, that wind power will grow from 317 GW (2013) to 1 320 GW in 2040. This implicates that wind power would provide 8 % of the total energy supply. Wind energy is forecast to be the most growing renewable energy source in the next decades (International Energy Agency, 2014). Even though the IEA forecast wind energy to grow, the total amount in the scenario is far away from a total renewable energy systems like it is politically targeted. Davidsson *et al.* (2014) in contrast describe different scenarios fully based on renewable energy technologies, with wind and solar power fulfilling almost the entire energy supply. Kleijn & Van der Voet (2010) for example predict a 24 TW capacity of wind energy installed by 2050. These predictions are based especially on political decisions as well as the growth of the market within the last years.

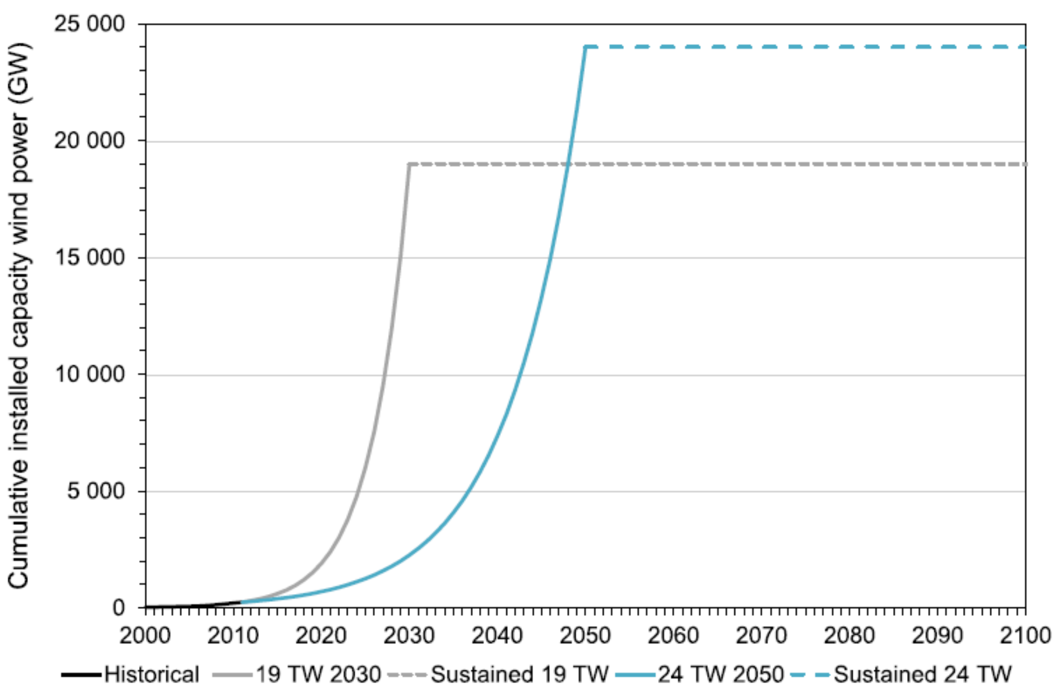

Figure 1.1: Cumulative installed capacity of wind energy described by a logistic curve fitted to historical data reaching 24 TW by 2050 (Davidsson *et al.*, 2014)

Efficient large wind turbines are continuously growing in height and production yield. They are suitable in regions, where free space in combination with high wind speeds and a good grid connection are available. But there are some locations where large wind turbine projects are not viable or cannot be afforded. Considering the vast expansion of the renewable energy system needed, alternative applications have to get developed additionally. Small Wind Turbines (SWT) can be a suitable alternative for isolated rural as well as urban sites. Especially in regions where there is no or only a bad grid connection as well as not much power needed, SWT are already in use. In an isolated system they are also used in combination with PV systems and batteries if enough wind as well as sun is available (Sumanik-Leary, 2013).

Besides the use in rural off-grid areas, the use in urban areas, where no space for larger turbines is given, is possible. The EU Energy Performance of Buildings Directive determines "by 31 December 2020, all new buildings are nearly zero-energy buildings..."(Directive 2010/31/EU, article 9, § 1a). The use of SWT in addition to PV systems can help to reach these goals. Furthermore a hybrid system combining PV and SWT has a considerably lower fluctuation than using one source of energy. That has potential to relieve the grid and be able to produce power locally and decentralized by using renewable energy systems.

Even though at present there are a few companies selling SWT for urban use, they are not very well-established. SWT are only profitable if the electricity is used by the producers themselves, because the grid feed-in tariffs are too low. In some countries, including Austria, even the direct use is not profitable due to the present low electricity tariffs. People with an efficient grid connection are hardly interested in investing in a technology, which is unproved to be profitable in cities. Scientific estimations are diverse and only few work has been done regarding SWT yet. The urban use of SWT is considered to be challenging, because of the high wind turbulences in cities and the impact on the building the SWT is arranged on as well as the safety of the surrounding. The combination of a reliable technology and politically driven economic adaptation can make SWT urban use suitable in the future. Therefore, it is important to find out what risk it may cause to install SWT in urban areas.

At present a huge number of SWT designs are available on the market, because there is not one established technology, but a lot of different techniques and designs. Between 2000 and 2010 over 120 new manufacturers appeared on the worldwide market (Gsänger & Pitteloud, 2016). There is an international certification scheme (IEC, 2006), but most of the turbines are not certified, because the certification is too expensive for small enterprises. Therefore, many of failures occur, for example blades are falling off, turbines burning and towers are cracking. Some serious failures are documented, but a detailed analysis of reasons of failure is missing. Especially in urban areas where many people pass by and buildings are around, it is important to reduce the risk of failure. To ensure safety the main reasons for failure have to get identified so that research and development as well as maintenance can be successful. Moreover an applicable tool for identifying risk in special cases is needed.

1.1 Aim of the study

The aim of the present study is to detect the weak points and shaping possibilities regarding the safety of SWT. Therefore, the method of Probabilistic Safety Analysis (PSA) is adapted to SWT. Using PSA accident sequences are examined. The aim is to identify the initial hazards as well as the most serious consequences and their occurrence frequencies. With a special focus on the presently used protection systems, this Master thesis aims to evaluate how risk can effectively be reduced. The purpose is to provide a tool, which makes it possible to compare different protection systems. It can assist to detect which risk can be effectively eliminated and where more research and development is needed. The adapted PSA can further be used for individual decision making. An analysis of occurred failures is done previously to detect which hazards and what consequences are the most relevant ones. Due to the fact that there is not much experience on SWT used in urban areas, this study uses data of failures in rural areas. Considering the lack of information regarding urban use, it is analyzed which effects these failures would have in an urban environment. The present analysis is also part of the project "Urban Wind Power Vienna", which is focusing on an evaluation on whether the use of SWT in Vienna could be viable and efficient. The present study shall give an overview of the main failures to consider and their occurrences as well as a methodology for analyzing individual cases. The findings will be integrated in the overall evaluation of the possibilities for SWT in Vienna. The following research questions have been formulated:

What are potential failures of SWT, which may physically harm people in urban areas?

Further five subquestions are deduced:

1. What kind of failures were the most frequent ones within the last 10 years?
2. What hazards are mainly causing failure?
3. How can the main risk paths be identified by using Probabilistic Safety Analysis?
4. How often do the failures occur?
5. How can risk be reduced for the use of SWT in urban areas?

Within the present study it will not be evaluated what role SWT can play in future energy supply. The consideration of safety of SWT in urban areas is necessary to make an urban adaption of the technology viable.

1.2 Structure

The study is structured classically in four main parts: A theoretical part – giving all background information necessary, a main part – presenting the method used as well as the findings, a discussion – which relates the findings to the theory and finally the conclusion – shortly presenting the main statements deviated from the present research.

The theoretical and technical background (chapter 2) is presented in four subchapters: 2.1 is giving the basic information on wind power, 2.2 is related to SWT and is separated in the market situation, different designs, Piggott turbines and the use of SWT in urban areas. Chapter 2.3 is giving an overview on recently used protection systems of SWT. 2.4 introduces safety and risk analysis with a special focus on the risk assessment EN 14121 and PSA.
Chapter 3 is presenting the method used. It is explained what data is used and how the research project was conducted. In chapter 4 and 5 the findings are presented. Chapter 4 is arranged in five subchapters and is presenting the findings regarding failure analysis. In 4.1 the terms regarding safety analysis are defined. Chapter 4.2 and 4.3 present what kind of failures could be detected from the current data, expert dialogues and literature. In chapter 4.4 and 4.5 the unwanted events as well as the initial hazards necessary for the conduction of the PSA are derived from the failures observed. In chapter 5 the PSA is conducted. It is started by presenting the occurrence frequencies of the initial hazards, followed by the test of independence regarding the influencing criteria on material failure. In chapter 5.3 the event-trees for the consideration of the protection systems are shown. Chapter 5.4 and 5.5 present the quantitative results for the two examples: Ecovent 10 and Amperius VK-250.
In chapter 6 the findings are discussed in relation to the given background information. 6.1 and 6.2 focus on general SWT safety, discussing material failure and the shaping possibilities regarding the protection systems. Chapter 6.3 focuses on the relevance of the findings in relation to urban use. Chapter 6.4 discusses whether the findings regarding physical safety also have an influence on economic safety. In chapter 6.5 evaluation of the method is made, also considering how PSA could be used further. In chapter 7 a short conclusion is made.

2 Theoretical and technical background

Before presenting the failure analysis of SWT, some definitions and background information are needed. The first part of this chapter is focusing on the technical basics of wind turbines and will regard SWT profoundly: Their definition, the market situation, their different designs and their use in urban areas. The second part will focus on different protection systems of large wind turbines as well as SWT. The last part of this chapter will introduce the basics of safety assessment in general and specifically PSA. It is explained where it is originally used and what differs it to other types of safety analysis.

2.1 Wind to electricity

Wind turbines can be used for different purposes. The two main applications are generating mechanical energy, for example for pumping water, and generating electrical energy. In this chapter the physics behind using wind for generating electricity are presented. Generally electricity (or electrical energy) is not *produced*, but *converted* from other forms of energy into electrical energy. In case of wind turbines the rotor converts the kinetic energy of a stream of air into mechanical energy and the generator further converts the mechanical energy into electrical energy (Hau, 2014). Due to these transformations, the basic structure of every wind turbine to generate electricity has to be:

Rotor → Drive train → Generator → Wire

The kinetic energy of wind can be defined as a stream of air by the mass (m) and the velocity (v) as presented in equation 1.

$$E = \frac{1}{2} m \, v^2 \, [J] \tag{1}$$

To illustrate the conversion of energy, figure 2.1 shows an air parcel moving towards the wind turbine. The mass flow of the air parcel is defined by the swept area of the rotor and the velocity of the wind. The mass of an air stream $(\dot{m})$ for a specific area (A) can be calculated as shown in equation 2.

$$\dot{m} = \varrho \, v \, A \, [kg/s] \tag{2}$$

By replacing the mass (m) in equation 1 by the mass flow at the rotor by unit and time (equation 2) the energy of the air parcel can be expressed as shown in equation 3. Thereby the power available in the wind stream is calculated. It depends on the air density, the rotors diameter and the velocity of the wind. Whereas the velocity is having the greatest impact owing to its cubic relationship.

$$P = \frac{1}{2} \varrho \, v^3 \, A \, [W] \tag{3}$$

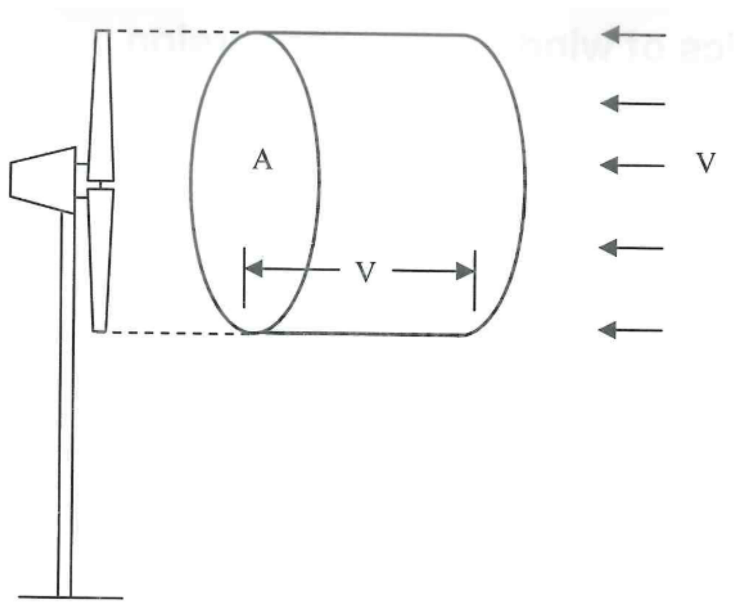

Figure 2.1: Air parcel moving towards a wind turbine (Mathew, 2006)

After calculating the theoretical power of the wind stream, it has to be considered what power can be converted into mechanical energy by the wind turbine. It is assumed that the mass flow is the same in front of and behind the turbine, that means if energy is taken out at the turbine, the velocity has to be lower behind the turbine and therefore is having a greater area than in front of the turbine (see figure 2.2). So for calculating the power possible to generate, the mass flow in front of the turbine, at the turbine and behind the turbine has to be considered.

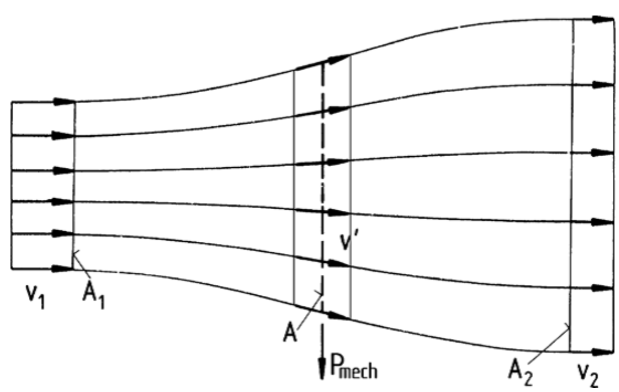

Figure 2.2: Relation of velocity and area of wind in front of, at and behind the turbine (Hau, 2014)

V1 is the wind speed in front of the turbine, v2 after slowing down the mass flow by taking energy out throughout the turbine. A1 is the area of the mass flow before taking the energy out, A2 the area after passing the turbine. The difference of power between situation 1 and 2 equates the mechanical power detracted from the wind. Regarding to the law of conservation of mass flow, by looking at the two situations, the mechanical power can be calculated by adding the difference

of velocity to the equation (Hau, 2014).
By looking at the power and energy differences before and after the turbine and applying axial momentum theory to wind turbines, in 1962 Albert Betz calculated the maximum theoretical power coefficient of a wind turbine to be 59.3 %. This is known as the Betz Limit. The Betz limit is the maximal power coefficient (c_P) of a wind turbine. For further information about the derivation of the Betz limit see for example Mathew (2006). The power coefficient is the ratio of mechanical power of the turbine (P) to the power of the wind stream (P_0), like shown in equation 4. The c_P shows the share of convertible power without relation to the design of the turbine.

$$c_P = \frac{P}{P_0} \tag{4}$$

However the design of a turbine is crucial regarding the possible power output. There are two different air forces, which are used to convert the kinetic energy of the wind into mechanical energy: the drag and the lift force. The easiest way to use power from the wind is using the drag force. This is done for example by old danish windmills or sailing boats. The power is resulting from the drag force of the air and the velocity the air is floating with.
To reach higher efficiency most electricity generating wind turbines use lift force as well. Therefore, airfoil blades are used. Airfoil is an aerodynamic form of a wing, originally used in aviation. The cross section of an airfoil is explained in figure 2.3. The wind is attacking on the leading edge. Airfoil blades use both: The force in the direction of flow, known as the drag force (like described above) and the lift force, which is perpendicular to the direction of flow (Mathew, 2006).

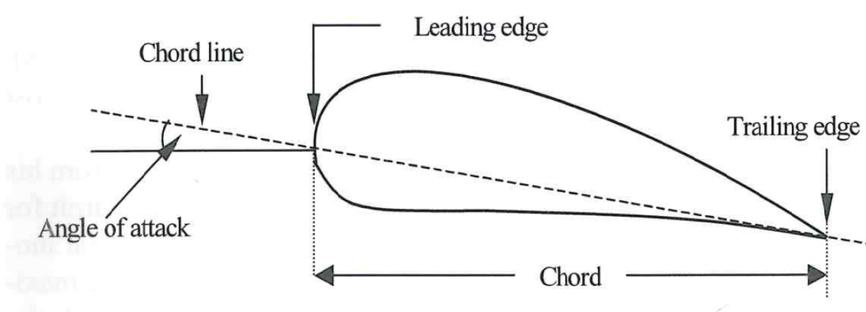

Figure 2.3: Airfoil blades (Mathew, 2006)

The most common design to use the airfoil blades is the three bladed horizontal axis wind turbine. Large wind turbines with nominal capacity from 1 to 5 MW are exclusively using this design. SWT in contrast can have several different designs depending on the environment they are designed for. The different designs and their use are further explained in the next chapter.

2.2 Small Wind Turbines

The International Electrotechnical Commission (IEC) defines SWT in its standard IEC 61400-2 (2006) as wind turbines with a rotor swept area of less than 200 m^2 and a rated power up to 50 kW. There are a number of other definitions varying in the different countries and even within countries in different organizations. Because of the growing market of turbines between 15 and 100 kW, it is discussed to establish a worldwide definition of SWT as wind turbines with a rated power up to 100 kW. Generally there are huge differences regarding size and design between the SWT on the market. From futuristic looking roof-top turbines with a nominal capacity of 100 W to three bladed 100 kW SWT, which look quite similar to large wind turbines. Therefore, it is heavily discussed whether there should be more defined classes of SWT. An approach often used is to class the turbines in "small wind turbines" and "middle wind turbines", like Kühn (2007), who uses the definition of category "S" for SWT with a rotor swept area from 40 to 200 m^2 and a nominal capacity up to 75 kW and category "XS" for SWT with a rotor swept area up to 40 m^2 and a nominal capacity up to 10 kW. Whereas turbines bigger 10 kW are almost entirely classical three bladed horizontal turbines, within the "XS" category there are huge variations not only within the capacity, but also regarding the design of the turbines (Jüttemann, 2016). The main differences will be explained after having a short look at the market situation.

2.2.1 SWT market

The worldwide installation of SWT is estimated to be around one million units with a cumulative installed capacity of 830 MW. Considering Europe the UK, Germany and Spain are the leading markets in terms of installed units. In the UK there are approximately 28 640 units installed, in Germany around 16 000 and in Spain 7 250. The huge increase of installed turbines with a capacity over 20 kW in the UK and Italy is quite surprising. In Italy the installed capacity grew 85 % in 2014 to 32 733 kW, which is the second largest in Europe after the UK. Worldwide the market growth in 2014 was 8.3 % (Gsänger & Pitteloud, 2016). The average capacity of installed SWT was not more than 0.87 kW in 2014. While within Europe SWT with a nominal capacity around 5 kW are preferred, the world's biggest market China shows an average capacity of only 0.5 kW. These differences also get quite visible by looking at the total market share (see fig. 2.4) : While China's share of the total installed units is 72 %, its share on the installed capacity is only 41 %. The USA has a share of 30 % of the installed capacity and the UK, the leading market within Europe, has a share of 15 % .

In Austria SWT are not very well established yet. Until 2015 327 SWT with a total capacity of 1 530 kW have been installed in Austria. The average capacity of 4.7 kW is considerably higher than the global mean (Leonhartsberger & Renz, 2016).

The economic efficiency of SWT in Germany and Austria is very sensitive. SWT show fairly high levelized costs of electricity (LCOE) varying between 12 and 32 ct/kWh depending on the

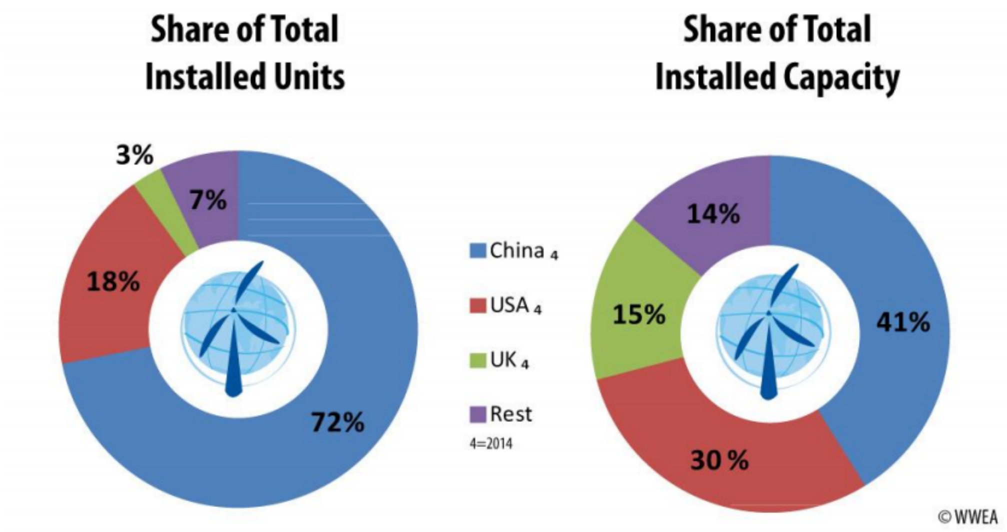

Figure 2.4: Share of total Units and Capacity of world market of SWT. (Gsänger & Pitteloud, 2016)

average wind speed of the site and the performance of the turbine (Liersch, 2010). The feed-in tariffs in Germany and Austria are generally too low to make SWT cost-efficient by feeding the power into the grid. Due to the high end-consumer electricity tariff in Germany of about 25 ct/kWh, SWT can be cost-efficient if the operator is using most of the produced energy by himself. Leonhartsberger & Renz (2016) conducted a survey asking 22 private SWT operators in Austria about the performance of their turbines. The average LCOE was examined to be 24.8 ct/kWh. The present electricity tariff in Austria is about 20 ct/kWh (EuroStat, 2016). Hence most of the installed SWT are not profitable. Nevertheless three SWT could be identified to show LCOE under 20 ct/kWh. That indicates that the profitable use of a SWT is possible, even though it is not common yet. The fast growth of the market in Italy and the UK can be explained by the feed-in policies of these countries. In Italy a fixed feed-in tariff of 0.3 € for wind turbines with a capacity smaller than 1 MW is present. This is strongly actuating the high capacity turbines within the SWT sector (Gsänger & Pitteloud, 2016). In Germany and Austria no fixed feed-in tariffs for SWT are present.

It can be assumed that the investment costs for a SWT vary between 2.000 and 10.000 Euro per kW. The investment cost per energy output increase with decreasing capacity of the SWT. This financial sensitivity requires a careful site selection and a reliable SWT. Next to the call for reliable analysis, there is a present call for insurance. At the moment there is no insurance for SWT in Austria.

2.2.2 Different designs of SWT

At present there are two basic designs of SWT mainly used: Turbines with a horizontal axis (HAWT) and turbines with a vertical axis (VAWT). In the last 30 years HAWT dominated the market. Nevertheless the market for VAWT began to grow within the last few years. In the end of 2011 the World Wind Energy Association examined 327 manufacturers of SWT. 18 % of them adopted a vertical design. But still the average capacity of the VAWT is much lower. While the installed HAWT are mainly used as off-grid installations, the market leans to SWT with higher capacity and grid tied systems (Gsänger & Pitteloud, 2016). At sites with good topographic conditions, where the wind flow is laminar, the horizontal design is more efficient than VAWT. This is owed to the fact that a part of a VAWT always runs against the wind direction (Jüttemann, 2016). Therefore, the VAWT are mainly designed for an urban use, where difficult wind situations are present. In urban areas turbines that have a low run-up velocity and are able to cope with high turbulences are required. The vertical design tries to address these challenges. While HAWT have to turn with the direction of the wind, VAWT can use wind resources coming from different directions. Nevertheless the vertical design still has its challenges, especially concerning vibrations and stability (Thiemke *et al.*, 1996), but also concerning the performance.
Regarding HAWT, further differences in design are the number of blades. While large wind turbines always have a three bladed rotor, SWT vary between two and up to six or even more blades. The number of blades has no big influence on the performance of the turbines. The less blades the turbine has, the faster it turns (Jüttemann, 2016). Another difference within HAWT is whether the rotor is facing the wind (windward) or turned away from the wind (leeward), so that the tower is inbetween the wind and the turbine. Depending on whether the SWT is orientated windward or leeward, there are different styles of wind tracking systems. This is also having a big influence on the design of the turbine. While sensors are nearly not visible by looking from the ground, a "tail vane" to mechanically place the turbine in (or out of) wind direction has a significant influence on the design of a SWT.
As shown in figure 2.5 there are basically three different designs of VAWT: The Savonius rotor, the Darrieus rotor and the H-Rotor (Hau, 2014). The Savonius rotor developed by Sigmund Savonius in the beginning of the 20th century, is only using drag force and therefore is less efficient in using wind energy than the other two designs, which are using lift force as well. It is mainly used for measuring wind speed and pumping water, but does not play a big role for generating electrical energy. The Darrieus as well as the H-Rotor rotor were both invented only a few years later by Jeans Mary Darrieus in the 1930s. In contrast to the Savonius rotor they are mainly lift force driven and therefore more efficient in producing electrical energy. even though the functionality is quite similar, the design is different. Whereas the blades of a Darrieus are airfoil-shaped and directly attached to the shaft, the blades of the H-Rotor are straight. Due to the design the H-Rotor is also called "egg-beater type"(Islam *et al.*, 2006).

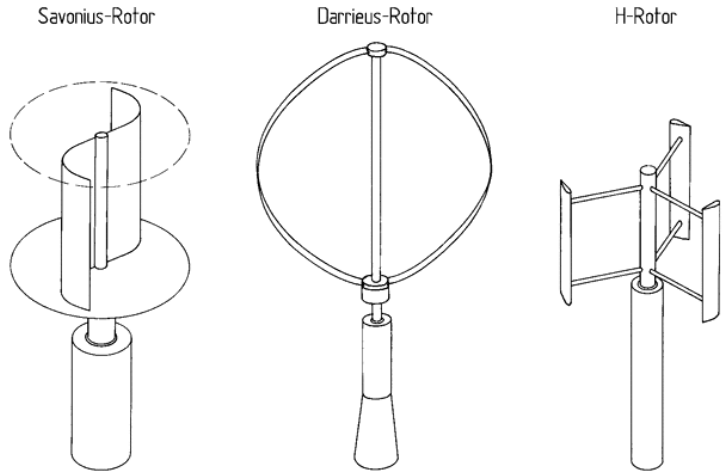

Figure 2.5: Different Designs of VAWT (Hau, 2014)

$$\lambda = \frac{tip\,speed\,blade}{wind\,speed} \tag{5}$$

In figure 2.6 the tip-speed ratio (λ) as well as the power coefficient (c_p) of different designs are shown. The tip speed ratio is defined by the tangential speed of the rotor's tip and the speed of the wind as shown in equation 5. It can be seen that the less blades a turbine has, the faster it turns. Even more interesting is the c_p of the different designs, shown on the y-axis. Three bladed horizontal turbines (3-Blatt-Rotor) have the highest power coefficient of up to 50 %. Modern large wind turbines even show power coefficients above 50 %, which is quite close to the Betz limit (Idealer Leistungsbeiwert nach Betz) of 59,3 %. Old dutch windmills (Holländer Windmühle) and American turbines (Amerikanische Windturbine) as well as the Savonius rotor show lower power coefficients. The Darrieus rotor is having airfoil blades, but due to the vertical design, part of the rotor is moving against the wind and therefore slowing down the turbine. Nevertheless they also reach power coefficients of up to 40 %.

2.2.3 Piggott turbines

Besides the commercial market, there are also self-constructed SWT existing. In the 1990's Hugh Piggott started to teach and write about how to build SWT. In his book "A wind turbine Recipe Book" he is sharing his knowledge on how to build a SWT. The book is regularly updated and used by several organizations for teaching courses. Figure 2.7 shows a Piggott turbine constructed in a weekly workshop in Germany in 2016. Even though there are many different ways and instructions on how to built a wind turbine, the Piggott turbine is the most widely-used design of self-constructed turbines. The SWT design is monitored and improved over decades by several organizations. On his homepage Hugh Piggott declares: "My main focus is to make the designs easy to build, reliable, and efficient in low wind speeds" (Piggott, 2017). The Piggott turbine is

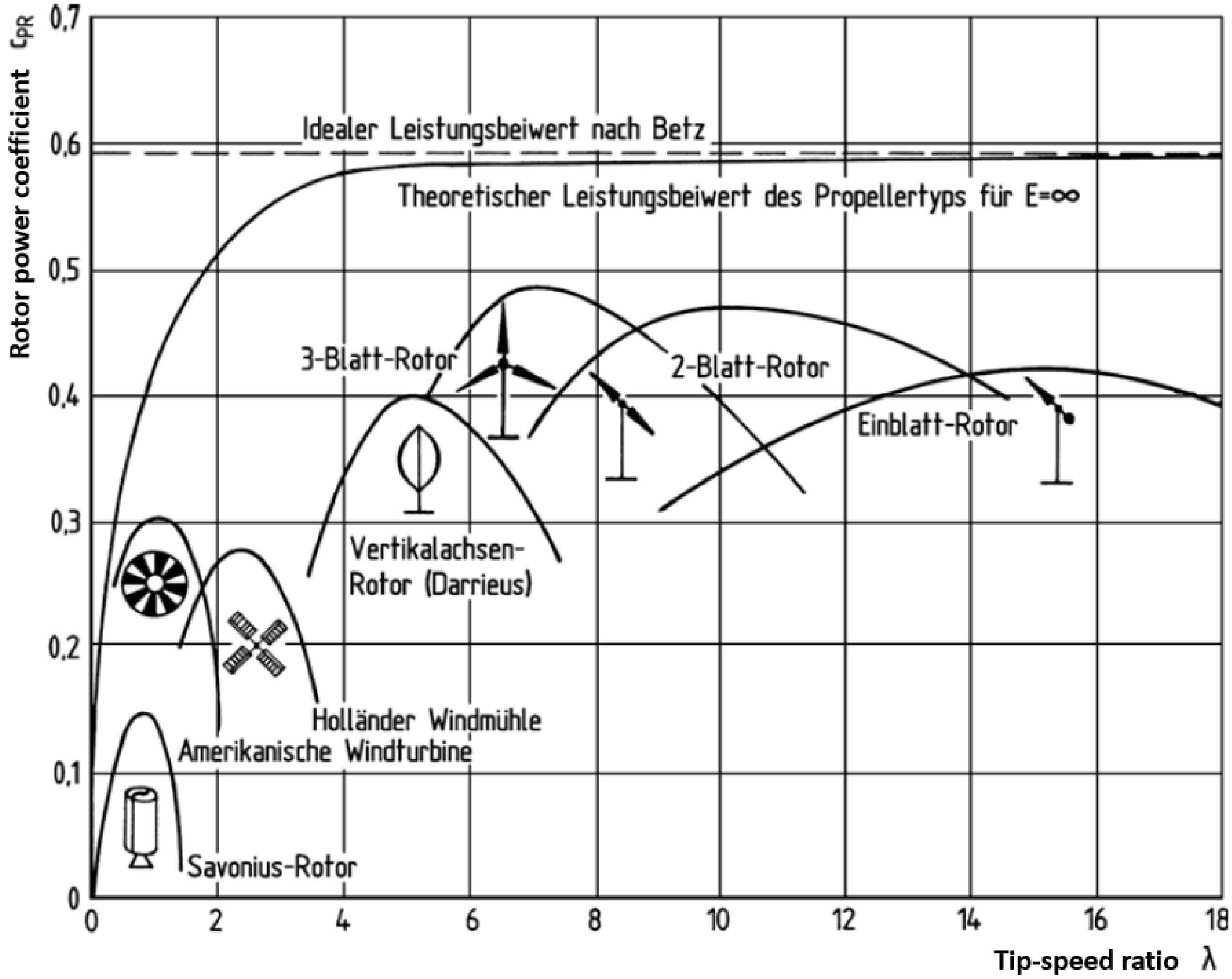

Figure 2.6: Tip-speed ratio and power coefficient of different turbine designs (Hau, 2014)

a three bladed HAWT, build mainly out of wood and recycled steel. The generator is a magnetic inducted asynchronous generator using neodymium or ferrite magnets. Rotor and stator are connected by a hub, using a wheel hub of a car. The Piggott turbines have capacities between 0.2 and 2.5 kW. They are mainly used for decentralized energy solutions in rural areas to supply single buildings. Often they are used in combination with PV systems. They are operated in gridless areas within Central Europe, but also in developing countries. The association "Wind Empowerment" (2017) brings together several organizations, enterprises and researchers working on rural electrification using Piggott turbines. Besides the technical functionality, members are focused on primary using renewable resources, sharing knowledge, development cooperation and raising awareness of energy production.

Some scientific work exists on using self-constructed SWT for electrification in rural areas. In 2013 Jon Sumanik-Leary wrote his thesis on rural electrification using Piggott turbines (Sumanik-Leary, 2013). Further at a testing site in the Netherlands several SWT have been tested. The normalized production yield (production in kWh by the rotor swept area in m²) was compared. The Piggott turbine with a nominal capacity of 700 W showed a normalized yield of 38 kWh/m², the 350 W Piggott turbine 61 kWh/m². Only two out of five other tested SWT showed higher values (Bosman, 2014). Hence the efficiency of Piggott turbines is comparable to commercial well functioning HAWT.

Figure 2.7: Self-constructed SWT referring to Piggott's design built in Germany, 2016 (picture by KanTe)

2.2.4 SWT in urban areas

The major field of application of SWT is the use in rural areas. Especially in gridless areas, like Mongolia, some areas in South America or Scottish islands, SWT are a common technology for supplying single households or community buildings with electrical energy. As Sumanik-Leary (2013) shows SWT can provide a suitable energy supply, especially in combination with PV systems. In middle Europe, above all in Italy and Germany, SWT are often used by farmers as a grid connected system. These turbines often have capacities up to 10 kW and are used for the energy supply of the farm. Energy surplus can be fed into the grid and if there is less wind the farmers can use electricity from the grid. At sites with good wind resources as well as high electricity tariffs, like for example coastal areas in Germany, this kind of application is profitable and therefore well-established.
Nevertheless 51 % of population is presently living in cities and it is forecast that by 2050 two-thirds of the population will be living in cities (Niesing, 2012). Cities play a huge part in energy

consumption. While discussing how to get a more decentralized, locally produced energy supply, the focus shifts increasingly onto urban energy supply. PV systems are one possibility, which is already well-established and is growing steadily. In new buildings, which have to fulfill the 2010 Energy Performance of Buildings Directive, some kind of energy production system has to be integrated. Starting 2020 all new buildings within the EU have to fulfill the criteria of a "nearly zero-energy building", which is defined by the Directive:

> "'nearly zero-energy building' means a building that has a very high energy performance, as determined in accordance with Annex I. The nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby" (2010, article 2, §2).
>
> "'energy from renewable sources' means energy from renewable non-fossil sources, namely wind, solar, aerothermal, geothermal, hydrothermal and ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas and biogases" (2010, article 2, §6)

So according to the EU, new buildings irrespective whether they are built in the city or in rural areas, should not only have a small amount of energy use, but shall also produce energy themselves. Wind is directly mentioned as one of the renewable energy sources, which can be used to meet the targets of the Directive 2010/31/EU. Using urban buildings for energy production can help to discharge the grids as well as reduce the required amount of rural balance energy. Furthermore it can increase the autonomy and security of energy supply for cities. This leads to big interest in adapting the technology of SWT to be suitable for urban applications.

Nevertheless the conditions for SWT installations in urban areas are very different compared to rural areas. Besides having less wind in urban than in rural areas, wind flow is not laminar in cities, but has high turbulences due to the great amount of obstacles (e.g. buildings). This makes the choice of a good SWT location very difficult. The wind speed as well as the turbulences can have a huge variability within meters (Auer *et al.*, 2016). Further the requirements concerning safety, acoustic noise and appearance have to be more demanding. It becomes clear, that it is not possible to use the same technologies as in rural areas. The SWT themselves, the procedure of site selection as well as the safety evaluation have to get adapted to the needs of urban use.

A lot of research is already conducted addressing these needs. For example Drew *et al.* (2013) and Auer *et al.* (2016), concerning the site selection in urban areas or Peppoloni (2016) concerning the vibrations of rooftop installations. By looking at the amount of publications illustrated in figure 2.8 it becomes visible that it is a relevant issue currently: Querying publications in ScienceDirect containing "small wind turbines" or "small wind power" the number of publications has risen since 2008 with a peak in 2014. While there have already been some publications about SWT in the 1990's, the first publication for the query "urban wind power" or "urban wind energy" is found in 2004. 2013 followed by 2016 have been the years with the highest numbers of publications concerning urban wind power. The main focus in publications lay in site evaluation and models on wind speeds in cities.

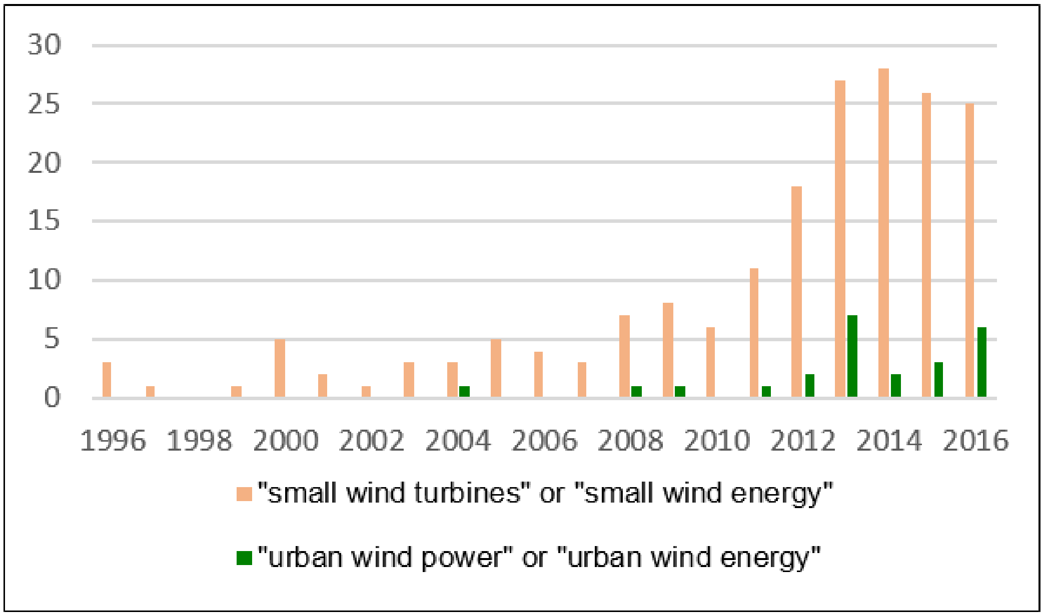

Figure 2.8: Amount of publications in ScienceDirect by year using two different queries (data from 16.11.2016, own figure)

Besides the research on SWT, manufacturers are trying to build turbines that fulfill the advanced criteria for urban use, mostly with a reduced performance as negative side effect. Further regulations have to get adjusted. Clear permission procedure as well as a general certification is still missing. While the research and development concerning SWT in urban areas is slowly starting, already the first projects are realized. In 2013 three VAWT were installed on the roof of the Greenpeace office at the riverside in Hamburg. Thirteen Years earlier in 2000 the University Melbourne had installed a SWT on their roof. The first skyscraper with integrated wind power is the Bahrain World Trade Center. The two buildings are connected with three bridges, each holding a 225 kW HAWT. Furthermore there are plans to install wind turbines on top of the Freedom Tower replacing the World Trade Center in New York (Ragheb, 2014).

2.3 Protection systems of wind turbines

Wind turbines are exposed to all kinds of weather conditions. There are some weather conditions the turbines have to be protected of. All of the large wind turbines and some of the SWT possess protection systems considering the three events: High winds, lightning and ice accumulation. Hereafter the main designs of protection systems will be described, starting with the protection systems for high winds, followed by lightning protection and finally protection systems to prevent ice-throw.

2.3.1 Power regulation in high wind speeds

Rising wind speeds do not lead to a higher power output of a wind turbine unlimited. The transmission and the generator are designed for a specific nominal capacity. If wind speeds rise over nominal capacity the turbine will not produce more energy, but stay at that limit. Higher wind velocity generally means increasing rotor speed. Rotor speed higher than the dimension of the generator can lead to severe accidents, like burning of the turbine due to thermal run-away or cracking parts, which will be discussed later. To protect the system from over-speeding there are two main protection systems, shown in figure 2.9: Aerodynamic power regulation and braking systems.

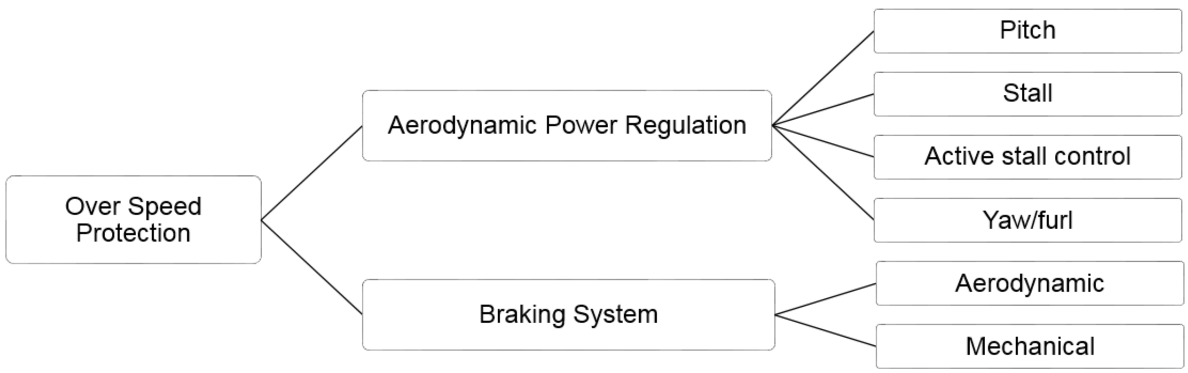

Figure 2.9: Most common overspeed protection systems of wind turbines (own figure)

Aerodynamic power regulation systems adjust the power input without stopping the turbine. There are four main control systems for power regulation by blade adjustment (figure 2.9): Pitch control, stall control, active stall control and yaw or furling control. Nowadays pitch control is the mostly used method, especially considering large wind turbines. Sensors are constantly checking the output power of the turbine. If the power output exceeds the nominal capacity of the turbine, the control mechanism changes the angle of attack of the turbine's blades. Therefore, the blades are turnable in their longitudinal axis. The control system is a combination of hydraulic and mechanical devices. Changing the angle of attack only 10 degrees, lowers the power coefficient by more than half. Stall control in contrast, increases the angle of attack. That forces the air on the top of the blade into whirling motion. This is heavily reducing the lift force of the blades and therefore regulates power in high winds. Stall control is not as accurate as pitch control. It does not require any control systems, but the blades have to be aerodynamically twistable along their longitudinal axis. Active stall control is a combination using the advantages of both, pitch and stall regulation. In lower winds the blades are pitched like described above, but at a certain velocity of the wind, the blades are suddenly turned in the other direction and put into stall position. The last mechanism described here is called the yaw regulation, often also called furling system. It differs from the other two aerodynamic power regulations, because it is not the

blades' angle which is changed, but the whole rotor is turned out of main wind direction. It can be done mechanically, without the need of sensors. It is often used by small, low budget wind turbines.The yaw regulation is not suitable for big turbines, because if the rotor is partly yawed, the turbine experiences cyclic stress (Mathew, 2006). The active yaw control, often used by large wind turbines, is no yaw regulation, but a system to place the rotor in wind direction. It is often used in combination with an active pitch system. There are also some SWT which do not have any active system to reduce bearing pressure in high wind speeds.
Brakes are the second safety mechanism related to high wind speeds. In very high winds as well as emergency conditions, e.g. a disconnected generator, the turbine should be stopped instantly and completely. There are two different braking systems (figure 2.9): Aerodynamic brakes and mechanical brakes. Large wind turbines normally use both systems. Most of them have an aerodynamic brake as a primary system and a mechanical brake as a back up system, in case the primary system fails. Aerodynamic brakes change the blade position for braking. Which part of the blade is turned, depends on the power regulation system of the turbine. Pitch controlled, as well as active stall controlled blades, also use the longitudinal twist for braking. To brake the turbine the blades are turned 90 degrees around the axis. Therefore, the lifting force is killed and the turbine stops turning after a few more rounds. At stall controlled turbines the tip of the blades are turned. While the blades are not changing position, the tip will be turned 90 degrees. This is not stopping the turbine completely, but heavily reducing the rotating speed. Mechanical brakes are "full stop" brakes. They are similar to brakes of a car, using a braking disk with braking blocks on the high speed shaft coming from the gear box. Most brakes are hydraulically controlled, which means that in normal conditions the brake is held apart using hydraulic pressure. To brake the pressure is released and the brake spring presses the blocks against the disk. Furthermore there are also some wind turbines using electro-dynamic braking systems working on the principle of self excitation (Mathew, 2006).

2.3.2 Lightning protection

Lightning strikes on a wind turbine can have severe effects. Besides destroying the electrical components, blades crack or the whole turbine can start burning. To prevent big accidents most turbines have a grounding conductor leading through the tower. However this basic protection system is not always preventing serious damages. Asakawa *et al.* (2010) observed 125 lightning strikes on wind turbines and concluded that only 10 % of the peak current value flow into the grounding conductor. Most of the current flows through the tower. They also identified the blades to be damaged by lightning often. Therefore, metal parts are included in the blades to lead the current to the grounding conductor throughout the tower, to prevent blades from cracking (Heier, 2003). Surveillance show that lightning accidents primarily happen to large wind turbines in coastal areas, producing several MW of electricity. Therefore, Yokoyama (2013) examined different unconventional types of lightning protection systems. Nevertheless efficient lightning protection systems, like a lightning tower within a wind park or long lightning rods on the turbine, are not cost-efficient. The International Electrotechnical Commission standard on wind turbines IEC 61400 includes in part 24 (lightning protection, 2010-6) lightning protection requirements for wind turbines. This contains an earthing, protection systems for all subcomponents as well as evaluation and documentation of lightning protection (Teoels & Sørensen, 2008). SWT are excluded from that standard. Concerning SWT generally not much effort is put on specific lightning protection systems. Most SWT possess an earthing, but there is no standard demanding it, except for roof-top installations. If the turbine is installed directly on a building the general building requirements have to be fulfilled, which include a lightning protection. There are also some turbines without any lightning protection system. Other protection systems for SWT next to earthing are not known by the author.

2.3.3 Ice throw prevention

Prevention of ice throw clearly depends on the site SWT is placed on. There are SWT placed in cold climate areas, like mountain areas in Canada, Northern Europe or parts of China. "Cold climate (CC) are regions where atmospheric icing or periods with temperatures below the operational limits of standard wind turbines occur" (Cattin & Heikkilä, 2016). Regarding large wind turbines there are several de- and anti-icing techniques, whereas for SWT there are nearly no protection systems applied. The general standard on atmospheric icing of structures ISO-12494 (2001) is valid for large wind turbines, but not for SWT. The standard proposes an ice mass measurement, but no de- or anti-icing mechanism. Nevertheless due to several observations of heavy ice loads fallen or thrown from the turbines, different prevention methods are in development. They can be grouped in:

1. Accretion Measurement (detecting sensors) and stopping the turbine when ice accreted
2. Passive anti-icing systems: coatings that prevent ice accretion on the blades
3. Active anti-icing: heating mechanisms that prevent ice accretion on the blades
4. Passive de-icing systems: flexible blades or active pitching to remove ice from the blades
5. Active de-icing systems: heating, electromagnetically induced vibrations or other mechanisms to remove ice from the blades

Method two to five are mainly used for large wind turbines and will therefore not be discussed in depth. There are some ongoing studies, especially on using passive anti-icing mechanisms, but they do not play a significant role in SWT industry yet. For more information on mechanisms of anti- and de-icing mechanisms see Parent & Ilinca (2011). Most SWT operate without any ice

throw prevention, also in cold climates, where ice accumulation occurs regularly. Some possess an accretion measurement to stop the turbine if ice is accumulated on the blades. Hence the accumulated ice will not get thrown away by the turning turbine, but will fall down at a certain point. Clearly it can still be transported quite far, depending on the wind speed. There are different sensors used concerning SWT including optic sensors, vibration probes or synoptic sensors. Synoptic sensors get information out of the weather data. By considering temperature, humidity and dew point it can be calculated if ice accumulation is probable (Pospichal & Formayer, 2011). This can also be done without any sensor by using the data from a weather station nearby. Synoptic sensors are often combined with sending an alert signal to the operator. Optic sensors as well as vibration probes detect ice directly if it reaches a certain amount. Mostly they are combined with a direct shut down mechanism.
Anti- and de-icing is not common on SWT market. Nevertheless some manufacturers recommend manual active de-icing if the turbine stops due to ice accumulation. Therefore, the operator has to climb the tower to remove the ice by using deicer sprays or chipping down the ice.

2.4 Safety and risk analysis

To ensure safety and to be aware of the residual risk of a technology, it is crucial to conduct a safety assessment for every kind of machinery or technology. This chapter shall give a short introduction on safety analysis. First of all the basic definitions related to Risk Assessment are given. Further it is summarized what kind of assessment is required by the European Directive of Machinery (2006). In 2.4.2 the concept of Probabilistic Safety Analysis (PSA) is described. In the last part of that chapter it is presented how PSA was used considering wind turbines in the past.

2.4.1 Risk Assessment ISO 14121

The terms *harm, hazard, risk* and *safety* are crucial for safety assessments. In the present study these terms will be used like defined in ISO 14121-1: International Norm for Risk Assessment for Safety of machinery (2007):

harm physical injury and/or damage to health or property

hazard potential source of harm

risk combination of the probability of occurrence of harm and the severity of that harm

safety ability of a machine to perform its intended function(s) during its life cycle where risk has been adequately reduced.

In article 2a of the European Directive on Machinery Directive 2006/42/EC *machinery* is defined as:

"an assembly, fitted with or intended to be fitted with a drive system other than directly applied human or animal effort, consisting of linked parts or components, at least one of which moves, and which are joined together for a specific application,..."

Wind turbines of any kind clearly fall within that definition. Therefore, the following requirement, according to Annex 1 of the directive, has to be fulfilled:

"The manufacturer of machinery or his authorized representative must ensure that a risk assessment is carried out in order to determine the health and safety requirements which apply to the machinery."

In which way the risk assessment has to be conducted is defined in two equalized standards: EN 14121 and ISO 14121. The approach of a risk assessment according to the international standard is shown in figure 2.10. The risk assessment is organized in three main steps:

- risk estimation
- risk evaluation
- risk reduction

The risk estimation is done through a risk analysis, which includes the first three steps shown in figure 2.10. First of all the limits of the machinery are determined. All phases of the machinery's life have to be taken into account, including people, environment and products related to it. Limits of use, space and time have to get defined. In a second step all foreseeable hazards have to get identified. This has to be done for all phases of the life of the machinery. The third step of risk analysis according to the EN 14121 is risk estimation. Here not only the probability of the occurrence is taken into account. According to risk being a function of probability of occurrence of the harm and the severity of harm, the latter is also taken into account. The probability of occurrence of harm is defined by the occurrence of the initial hazard, the exposure of people to the hazard and the possibility to avoid the harm. After the phase of risk analysis all foreseeable risks should be estimated.
The second step of the risk assessment is the risk evaluation. In the evaluation the results of the risk analysis are rated. It is considered whether a risk reduction is necessary. If further risk reduction is necessary an appropriate protection system has to be added and a new risk analysis has to be executed. Adequate risk reduction includes three steps: Firstly the requirements for inherently safe design are fulfilled and risk related to the machinery itself is eliminated or most suitable reduced. Secondly the risk of foreseeable external harms is reduced by adapted safety measures. Thirdly the residual risk is included in the users information.
The risk estimation does not necessarily need actual probabilities. Annex A of the standard provides an example of a method to conduct a risk assessment. Some SWT manufacturers

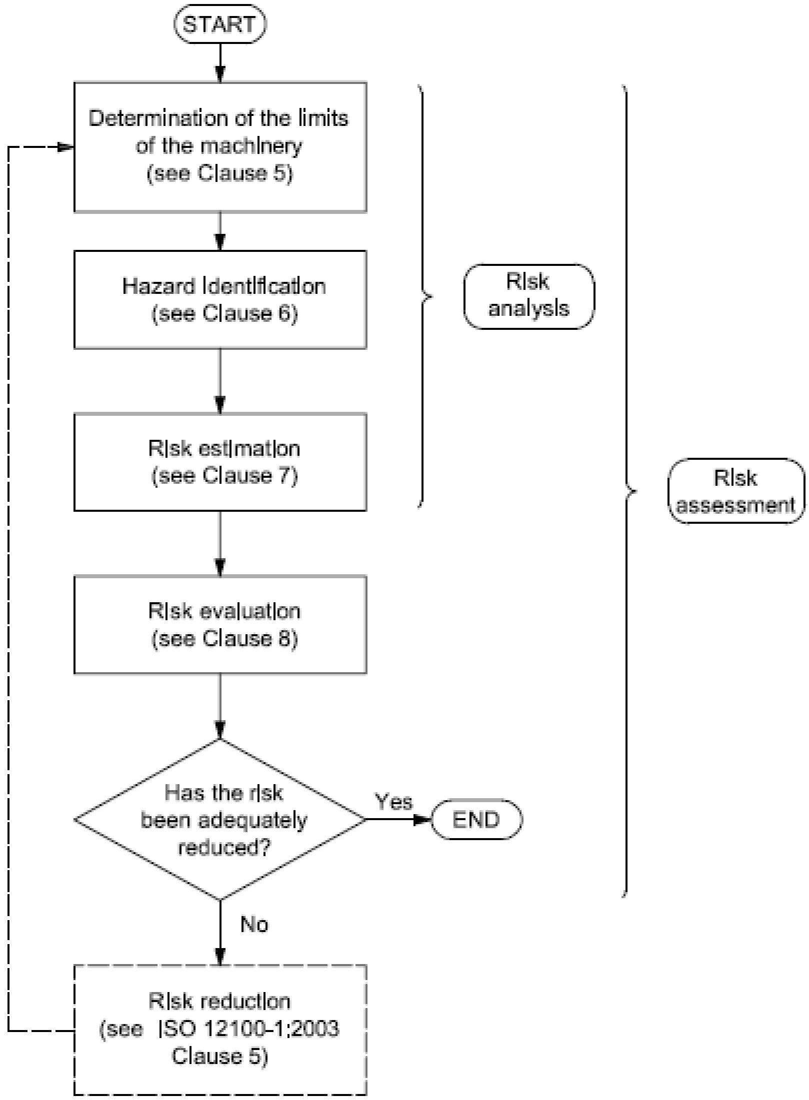

Figure 2.10: ISO 14121 Risk Assessment Scheme (ISO, 2007)

conducted a risk assessment according to the method submitted by the standard. The approach is deterministic, using the values 0 and 1 for the frequency of a hazard. Whereas 0 means seldom occurrence and 1 means frequent occurrence.

2.4.2 Probabilistic Safety Analysis

Probabilistic Safety Analysis was first used in the 1970s. Its original application was to quantitatively analyze the risk of a core melt in a nuclear power plant. By linking event trees (ET) and fault trees (FT) and considering the probabilities of the different safety mechanisms failing, the risk of failure can be calculated (Nusbaumer, 2009). It soon became an established tool for analyzing safety of power plants because, by quantifying the risk for every little step, weak points of the system can be identified. Even though the main field of application lies within the nuclear power technology, it can be used for identifying weak points and shaping possibilities for every

kind of technology. It is already used in several industries like wind power, chemical plants or waste water management.
A PSA gives answers to the following three questions:

- What can happen?
- What are the probabilities of these scenarios?
- What are the consequences?

Within PSA it is crucial to be aware of the difference between frequency and probability. Frequency is the likelihood of an event occurring per unit time (for example per year). Probability in contrast is dimensionless. It is always conditional and given in percentage (Sholly, 2014).
Figure 2.11 presents a schematic overview of the process of conducting a PSA. Before starting the PSA, the risk aim has to be defined. The risk aim is the accident, the failure of the system, the unwanted condition, which is tried to prevent. The next step, like shown in the upper box of the scheme, is to identify the initial hazards for the risk aim. What are the initiating hazards, which could lead to the unwanted event? The initial hazards are often weather conditions or other parameters beyond the system's boundaries. For every detected initial hazard the annual frequency of occurrence has to be determined. The next step, shown in the second box "Success Criteria and Accident Sequences" is to analyze every sequence within the safety system, step by step, and define their probability to fail. In case of nuclear power plant analysis there is a fault tree made for every safety system. The probabilities of these faults are later connected by event-trees (ETs). Step one and two are the fundation of the analysis. The necessary information about the failure frequencies and probabilities are estimated related to data analysis of accidents that happened in the past (the box on the left). Especially in evaluating nuclear power plants analyzing human reliability (box on the right) is a crucial part of a PSA. The "System Analysis" (central box) is the combination of actual data from past observations with the mathematical system connecting all parts. Finally quantitative statements of the frequency of occurrence of an accident can be given and the weakest branches of the tree get identified. Nevertheless it is important to mention that no matter how detailed a PSA is carried out, it is impossible to include all influencing factors in a frequency of occurrence. There are always initial hazards, which are very unlikely, but still there is a possibility for them to occur. For example an asteroid hitting the plant.
Within the last decades PSA was also conducted for other technologies than nuclear power plants. Pressl *et al.* (2015) for example conducted a PSA to analyze failure of wastewater pipelines in Austrian lakes. Next to the classical evaluation of the protection systems, they additionally considered influencing factors on the failure rates. Therefore, they defined several influencing factors and conducted a test of independence for each. The study was commissioned by the Austrian ministry for environment (Ministerium für ein lebenswertes Österreich) and three Austrian

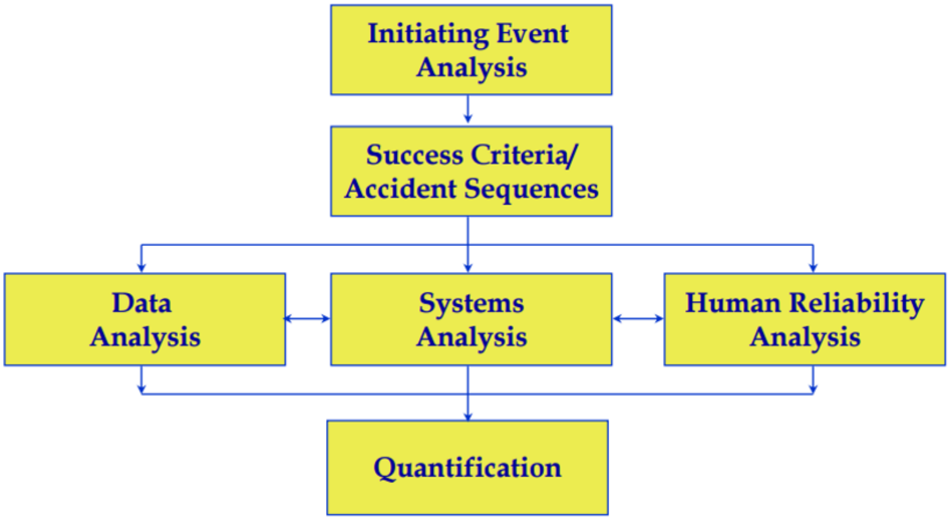

Figure 2.11: Systematic of PSA (Khatib-Rahbar, 2011)

federal states. Hence it was not for scientific purpose only, but also presented recommendations for the Austrian authorities.

2.4.3 PSA for wind turbines

The use of PSA in association with the technology of wind turbines is not totally new, still it is not very established. There has already been some scientific effort on adopting PSA to the technology of wind turbines. In 1993 Rademakers *et al.* published a study on adapting PSA to wind turbines. They described a 6-Task PSA-Methodology for analyzing safety issues of a wind turbine. The six tasks are:

1. Thorough System Description: Getting familiar with the turbine and the functioning of all parts
2. Failure Mode, Effects and Criticality Analysis (FMECA): Identifying the failure possibilities. The result of the task should be a list with all initiating events
3. Event Sequence Analysis and System Modeling: Event tree analysis for every initial hazard as well as fault-tree modeling for the control and safety systems
4. Data collection and Parameter Estimation: Collect data of operation, failure and maintenance
5. System Reliability Quantification: Quantifying of the trees developed in Task 3 and identifying weak points

6. Structural Reliability Analysis: Analyzing failure of structural parts like blades, tower and hub, parts where failure rates can not be analyzed from operational experience; using Mean Value Approach (MVA) to take into account different failure mechanisms

Rademakers *et al.* (1993) applied the methodology within two projects. The first one was Lagerwey, LW15/75, a wind turbine which was already operating a few years and therefore had a lot of data available. All 6 Tasks have been applied. The second one, Atlantic Orient Corporation, AOC 15/50, was a turbine still in development, so only task 1 to 3 have been applied. As a result they published a table with the methods that can be used for the different tasks, depending of the stage of the turbine. The operation stages are classified in: Design and Development, Burn-in, Useful Life, Wearout. They recommend the use of PSA in all three of these stages.
Nearly ten years followed without any publications about PSA and wind turbines. In 2002 Michos *et al.* published a paper on using an event-tree approach on wind turbines. The scientists from the Technical University of Athens combined the classical PSA fault-tree approach with Markov's procedure for modeling all failure modes of the control and protection systems of wind turbines. They developed a computational method for reliability and safety analysis to identify all unsafe events of a wind turbine. The three steps they use are:

- Identification of all possible initiating events
- Development of event sequences
- Selection and grouping of end states

They applied the method to the overspeed protection system of a wind turbine at the Center for Renewable Energy Sources at the island of Agios Efstratios. They recommend their method to improve wind turbines by designers or manufacturers and especially for the conduction of the certification procedure. After seven years without publications on this topic, in 2009 a paper by danish scientist Sørensen was published. He did not conduct a classical PSA, but instead used Bayesian Decision Theory on optimal planning of operation and maintenance of offshore wind turbines. Even though he focused on maintenance planning and cost efficiency and did not calculate actual risk probabilities, he used a PSA related approach. In his second publication on that topic he concludes that:

> "Probabilistic methods can be used as a decision tool for design of structural wind turbine components, thereby ensuring a more uniform and economic design than obtained by traditional design using standards such as IEC series" (Sørensen & Toft, 2010).

The most recent study on fault tree analysis of wind turbines was conducted by a Spanish research group. Marquez *et al.* (2016) did not use event-trees, but only fault-trees (FTs) to identify the critical wind turbine's components to optimize reliability, availability, maintainability and safety.

They conducted FT analysis for four different parts of the turbine:

- the foundation and the tower
- the blades system
- the electrical components (including generator, electrical and electronic components)
- the power train (including speed shafts, bearings and a gearbox)

By the FT analysis they detected the most important failure events. They approved the FT approach for analyzing either a whole turbine or specific components. The work was financially supported by the European FP7 OPTIMUS project. This is illustrating the current great interest in the topic and is ending up the present brief summary of the development of PSA and ET/FT analysis within the last 25 years. The summary displays that the topic arose a few times, but never played a big part in wind turbine research, even though all scientists working on it heavily recommend using the approach for safety and maintenance issues.
Regarding SWT, there are some publications on fault analysis of SWT, but none adapting PSA or FT analysis in general on the technology. Especially Kühn (2007) and Arifujjaman *et al.* (2009) give a good overview of what failures happen most and what components are the most critical ones. The accident sequences as well as probabilities of occurrence are not considered.
The adaption of PSA to SWT could provide the possibility to conduct a risk assessment according to the standard ISO 14121 using actual probabilities instead of deterministic values and therefore could be better suitable to identify weak points.

3 Methodical Approach

In this chapter it will be described how the present study was conducted. Basically the study can be divided into two parts: The first one, presented in chapter 4, is a data analysis of failures of SWT. Therefore, the data described below has been analyzed to detect the main failures, as well as the initial hazards causing them. This is also the preliminary work needed to conduct the PSA. In the first section of this chapter it is be described what data was used. Afterwards, in section 3.2 it is explained how the first part of the study was conducted. In section 3.3 it is finally described how the adaption of PSA to the technology of SWT was done.

3.1 Data acquisition

Collection of data regarding SWT quickly turned out to be quite challenging. The basic idea was to get in contact with people operating SWT and ask them about their experiences concerning failures of turbines. But in contrast to large wind turbines, for SWT there are no big companies operating a great amount of turbines. Most of the SWT are operated by single households, often farmers. Additionally there is no official register where operators of SWT are listed. Due to these two circumstances it would have been very time consuming to get a solid amount of data using that strategy. To stay within the time frame of a master thesis, it was decided to not contact the operators of single turbines directly. Instead, people working within the industry of SWT and researchers that had already collected some data about failures of SWT were contacted.
The author came into dialogues with several experts from industry as well as researchers working in that field. One face to face interview with a manufacturer was conducted. Walter Hoffmann is the head of the company "Mischtechnik Hoffmann & Partner GmbH", which stands behind the SWT Ecovent 10. The interview was conducted on January the 17th 2017 at the companies office in St. Andrä-Wördern, Lower Austria. Within the last eight years, they set up 18 SWT of the Ecovent 10 and supervise all of them until today (Hoffmann, 2017). More information was provided by the "Arbeitsgruppe Kleinwindkraft Wien". This working group brings together people from research and industry working within the field of SWT in and around Vienna. A feedback meeting within that group took place in June 2016 to use the joint knowledge and the experiences of the members. The aim was to validate and improve failure estimations and to get an understanding of the accidents sequences. In addition, five telephone interviews have been conducted: three with engineers from industry and two with employees from insurance companies. In addition the author has been in continuous contact with the operators of the energy research site Lichtenegg. The energy research site is further described in chapter 3.1.1.

Next to the information coming directly from the dialogues, three sets of data have been identified to be the most suitable ones regarding the research approach of the present study:

1. Primary data of different commercial SWT collected at the energy research site Lichtenegg, Austria between 2011 and 2016
2. Secondary data of Piggott turbines collected in Peru by Jon Sumanik-Leary between 2008 and 2010
3. Results of data analysis of 235 SWT published by Kühn in 2007

Following the three different sets of data are described and it is emphasized, why they are the most suitable ones regarding the research approach.

3.1.1 Research site Lichtenegg, Lower Austria

The *Energieforschungspark Lichtenegg,* further shortly called Lichtenegg, is an energy research site for SWT located in Lower Austria, approximately 90 km south of Vienna. Since 2011, different SWT are tested here. It is operated by four project partners: Technikum Wien GmbH, Institute for Renewable Energy, Energie Versorgung Niederösterreich AG (EVN), Solvento energy consulting GmbH and energiewerkstatt eV. Between April 2011 and April 2016, 15 different turbines with a total amount of 364 turbine operation months (30.3 turbine operation years) have been tested. As shown in table 1, turbines of four different basic construction types were tested: VAWT, HAWT with a tail vane, HAWT without a tail vane and ducted HAWT. The nominal capacities of the turbines varied between 1 and 10 kW. All of them have been installed on towers between 12 and 15 meters high. The time of operation differed significantly between the turbines. The shortest testing period was four months, the longest 60 months.

Table 1: SWT at the energy research site Lichtenegg between April 2011 and April 2016 by type of construction

Type of construction	**Number of turbines**	**Total operation months**	**Example**
VAWT	3	44	Amperius VK-250
HAWT with tail vane	7	162	Windspot 1,5
HAWT without tail vane	2	117	Ecovent 10
ducted HAWT	3	41	Windtronics BTPS 6500
total	*15*	*364*	

Lichtenegg is the only SWT testing site in Austria. There is no other testing site in middle Europe having that much data collected and still being operated. Performance and failure data

of the turbines themselves have been collected by Solvento and Technikum Wien. Additionally there are huge amounts of weather data available, collected and provided by energiewerkstatt eV. Furthermore by working together with the research park Lichtenegg, the author came into dialogue with different experts. In Lichtenegg engineers from industry, SWT specialized scientists as well as meteorologists work together.
The data from Lichtenegg is used within both parts of analysis of the present study: The data as well as the expertise collected from the dialogues provided helpful information to identify the main failures and initial hazards. Additionally, due to the detailed information about the weather conditions in Lichtenegg as well as the protection systems of two specific turbines tested at the site, it was possible to conduct the PSA for two example turbines in Lichtenegg. To conduct the PSA the author exclusively used data from Lichtenegg. The preliminary work concerning the identification of failures in contrast, was also related to the two other sets of data.

3.1.2 Piggott SWT in Peru

To get a better understanding of what kind of failures occurred within in the last 15 years by using SWT, two other secondary sets of data are examined in chapter 4. Jon Sumanik-Leary analyzed the use of Piggott SWT in Cajamarca region, Peru between 2008 and 2010. The collection of data was part of his PhD work, concerning the use of SWT in rural areas for decentralized electrification (Sumanik-Leary, 2013). Within two years he collected data of 35 turbines. The turbines are placed at different sites within the area of Cajamarca, always next to a household providing local electrification. Cajamarca region is a state region in the north of Peru being part of the Andes Mountain Range. The location at the border of rainforest and one of the world's highest mountain regions makes the climate different to the the climate of northeast Austria, which is examined in the present study. This has to be taken into account when comparing failure frequencies.
The data provides an overview about failures of self-constructed SWT installed in rural mountain areas. It has to be taken into account that these are completely self-built turbines and that it is recommended by the organizations building them, to only use them in rural areas. Nevertheless, there is no other recent source providing that detailed data about failures of one specific design of SWT. Even though Piggott turbines are a low-tech technology, they have a production yield which can be compared to other turbines (see chapter 2.2.3). Due to the fact that the Piggott design is open source, the turbine and its protection system can nicely be evaluated.

3.1.3 SWT in Germany

In 2007 Kühn published a study examining 235 SWT representing 16 different manufacturers in Germany in between 1989 and 2007. Each turbine has been monitored at least ten years. The monitoring was part of the Scientific Monitoring and Evaluation Program (WMEP) within the

"250 MW Wind" funding program, accompanied the development of wind energy use in Germany since 1989 (Kühn, 2007). In contrast to the other two sets of data the author has no access to the raw data of the monitoring program, but can only use the published results for the present analysis. Therefore, even though Kühn's study is based on a great amount of data, it plays a minor role in the present analysis. Nevertheless the published results provide a helpful overview about the main failures of SWT in continental climate.

3.2 Empirical identification of Small Wind Turbines' failures

As a preliminary study, before adopting PSA to SWT, it had to be figured out what kind of failures generally occur, what failures are in scope of research and what events lead to that failures. Therefore, four steps of analysis have been conducted:

1. Definition of failure and risk aim
2. Detection of failures in Lichtenegg
3. Comparison to other failure studies
4. Identification of initial hazards

To detect the considerable events for the present analysis, it was crucial to first of all define the *risk aim*. The risk aim is the unwanted event, whose occurrence is calculated within the PSA. It is crucial for risk analysis in general to specify what specific definition of failure and risk shall be used.

To get a picture of what kind of failures occur, failures that occurred in the past had to be examined. This step was necessary to find out about what actually can happen. Therefore, the failure data of the three different sets were considered. Firstly the data of Lichtenegg has been analyzed. The author spoke to the different people involved in the testing of SWT in Lichtenegg and generated a table with all failures happened there. These failures have been compared to failures which occurred within the two other datasets. After considering what is actually happening and what other experts define as failures, the failures where sorted whether they are within the risk aim definition, or not. By looking at all failures within the risk aim, failure groups were built by taking the risk associated with the failures into account.

In the last step of data analysis, the initial hazards leading to the unwanted events were detected. This was done by examining the origin of the failures occurred in Lichtenegg and the failures occurred in Peru. By listing all initial hazards leading to these failures, only five different hazards were detected to cause the different types of failures. The output of the failure analysis are three types of failure and five initial hazards.

3.3 Adapting Probabilistic Safety Analysis to Small Wind Turbines

After reading several PSA studies considering large wind turbines, nuclear power plants as well as other technologies, it became clear that there are several ways to adapt PSA to SWT. There are some obvious differences to the original use of PSA for assessing nuclear power plants. A SWT is a much smaller technology and therefore also has less protection systems. It also became clear, that most of the protection systems of SWT are not protecting from rarely occurring severe accidents. As seen in chapter 2.3, most of the protection systems come into action regularly. This is depending on the occurrence frequency of the initial hazards leading to the necessity of the protection system. Most of them also appear regularly, some even more than once a year. This is an important difference to other assessed technologies like nuclear power plants or wastewater pipelines (Pressl *et al.*, 2015): In contrast to the present study, the methodology as well as the mathematical assumptions are designed for very low occurrence frequencies of the initial hazards. Calculations with annual probabilities used for these approaches showed to be unsuitable for assessing SWT. Frequencies per year turned out to be more suitable for the technology of SWT protection systems and will therefore be directly used.
The PSA was be conducted by four steps:

1. Determine frequencies of initial hazards in Lichtenegg
2. Calculate influencing factors
3. Create event-trees
4. Consider protection systems

Compared to the classical approach of PSA shown in figure 2.11 there are some differences. Human Reliability Analysis will not be taken into account. Even though human reliability plays a significant role in installation a maintenance of SWT, while operating there are normally no humans involved and therefore no risk of human failure is present. Nevertheless human reliability has to be integrated if a full risk assessment for a turbine is conducted. The present PSA exclusively deals with the risk resulting directly from the turbine while operation. Although the initial hazard *material failure*, which is considered within the analysis, can be a result of human failure.

3.3.1 Frequencies of initial hazards in Lichtenegg

In the first step the frequencies of the initial hazards have been calculated for the specific site, the testing site Lichtenegg. Due to the fact that most of the initial hazards are weather related, a short topographic analysis of the site was done first. Further the frequencies of the five initial hazards: *high wind speeds, lightning, material failure, fog* and *icy rain* have been determined.

High wind speeds were analyzed by using the weather data generated by energiewerkstatt eV at a measuring tower directly at the research site Lichtenegg. Information of lightning frequencies have been provided by the Austrian Lightning Detection and Information System, which according to ÖNORM EN 62305.2 shall be used for risk assessments concerning lightning. The initial hazard *lightning* describes the specific frequency of a lightning strike hitting a SWT. To evaluate this frequency the Geometrical Method according to Cooray (2015) was used. *Material failure* was calculated by using the amount of failures happened as well as the full-load-hours observed in Lichtenegg. The frequencies of *fog* and *icy rain* have been determined by the topography of the site, using the assumptions of Pospichal & Formayer (2011).

3.3.2 Event-trees and frequency calculation

The frequencies of the unwanted events (h_j) have been calculated as shown in equation 6. The calculation of the frequencies of the initiating hazards (f_i) are already described above. Next to the initiating event, the protection systems of the SWT are crucial for the annual frequencies of the unwanted events. The probability of failure of the protection systems was taken into account by the second part of the equation (P_i). Table 2 is giving an overview of the used operators. Further equations 7 are the basis for the calculations for every of the three unwanted events: Burning, falling parts and ice throw, shown in chapter 5. Note, that in the context of *burning* other probabilities for failure of the protection systems have to be considered as in the context of *falling parts*. That is also explained in more detail in chapter 5. The basis of the influencing factors F_k are explained in the following subsection.

Table 2: Operators used in the calculations for the frequencies of the three unwanted events

Operator	Description
h_j	frequency of the unwanted event
f_i	frequency of the initial hazard
P_i	probability of failure of the protection system
F_k	influencing factor on material failure (see chapter 3.3.3)

$$Frequency\,of\,unwanted\,event\,(h_j) = \sum [frequencies\,of\,the\,initiatin\,hazards\,(fi) \times probabilities\,of\,failure\,of\,the\,protection\,system\,(Pi)] \quad (6)$$

$$\begin{aligned} h_{burning} &= f_1 \cdot P_1 \quad + f_2 \cdot P_2 \\ h_{falling\,parts} &= f_1 \cdot P_1{}' \quad + f_2 \cdot P_2{}' \quad + f_3 \cdot P_3 \cdot F_1 \cdot F_2 \\ h_{ice\,throw} &= f_4 \cdot P_4 \quad + f_5 \cdot P_5 \end{aligned} \quad (7)$$

Within the present study ETs for every combination of initial hazard and unwanted event have been created. For every protection system the ETs branch vertically. The top branch represents success and the bottom branch failure of the protection system. These ETs show the general protection mechanisms of SWT. Therefore, they are suitable for any SWT. The same ETs can be used for evaluating different SWT.

3.3.3 Influencing factors

Influencing criteria on the initial hazard *material failure* have been tested on their independence. This method has firstly been used by Pressl *et al.* (2015) and is extending the classical PSA approach. The occurrence frequency of the initial hazard *material failure* was calculated by taking the material failure frequencies of all SWT tested in Lichtenegg into account and calculating a mean annual frequency from it. Using the annual mean over all turbines assumes that all SWT have the same frequency of failure, whatever materials and design are used. But, whereas all other initial hazards are site related, *material failure* is depending on the turbine itself. By testing different criteria on their influence of *material failure*, it can be detected if some criteria have a significant influence on *material failure*. Pressl *et al.* (2015) used the χ^2-test to test the influence of different criteria on failure frequency. To use χ^2-test the data has to fulfill two basic assumptions: Values have to be absolute, data is randomized collected and for every criteria at least five values exist. Whereas the first assumption can be taken to be fulfilled, the second one is not fulfilled within the data of Lichtenegg. Only seven failures related to *material failure* occurred within the testing period. The seven failures were grouped for every criteria in failed SWT fulfilling the criteria (*yes*) and failed SWT not fulfilling the criteria (*no*). So at least one group of the criteria (*yes* or *no*) contains less than five values. Therefore, in the present study *Fisher's exact test of independence* was used instead. Fisher's exact test is especially designed for a small number of samples. For more information on Fisher's exact test see McDonald (2014). The calculations of Fisher's exact test of independence were conducted using R-Statistical Software.

The failures have been grouped in *yes*- and *no-groups* per criteria and were compared by referring to the accumulated full load hours SWT. Full load hours are the hours the turbine has to run on nominal capacity to produce the same amount of energy, which it actually has produced within a specific time (Twele, 2013). It was decided to use full load hours instead of installation time (in months) to consider failure rates with regard to production-time, not to installation-time. The decision was based on the assumption that productivity is a basic prerequisite for the use of a SWT. Since the full load hours differed a lot between the tested SWT, this has to be taken into account while discussing the results. In this study the full load hours from five years of testing have been used.

Three criteria have been tested:

Axial-orientation In Lichtenegg VAWT and HAWT have been tested. The design of the two approaches are entirely different from each other.

Certification Even though there is no well established international certification scheme, a few turbines of the ones tested in Lichtenegg passed a certification orientated on IEC 61400-2. No difference was made concerning the international or national certification. All established national certifications are orientated on the IEC 61400-2.

Nominal Capacity the turbines in Lichtenegg are notable different in size and rated power. The nominal capacity differs between 1 and 10 kW. Therefore, they have been grouped in *size A* and *size B* by using nominal capacity as criteria of size. *Size A SWT* are turbines with a nominal capacity smaller than 5 kW, *size B SWT* are turbines with a nominal capacity from 5 to 10 kW.

The null hypothesis always assumes that the criteria is not having an effect on fault frequency. If a criteria was tested to have an influence on fault frequency, an influencing factor (F_k) was added to the calculation of *material failure* frequency. Equation 8 shows how the influencing factors (F_k) were calculated. The failures observed at the testing site have been divided by the expected failures calculated by Fisher's exact test. Expected failures is the number of failures calculated by using an equal distribution of failures related to the full load hours by the two characteristics of the criteria. Equation 9 shows how the influencing factors were integrated in the calculation of material failure frequency. The frequency of *material failure* was multiplied with the probability of not preventing *material failure* (P_3) and the influencing factors (F_k) for the design of the specific turbine. The occurrence frequency (f_3) is similar for every turbine, whereas the prevention probability (P_i) as well as the influencing factors (F_k) added are turbine specific.

$$F_k = \frac{failures\,observed}{failures\,expected} \tag{8}$$

$$h_{material\,failure} = f_3 \cdot P_3 \cdot F_1 \cdots F_n \tag{9}$$

3.3.4 Calculations for Ecovent 10 and Amperius VK-250

To illustrate the failure bandwidth in Lichtenegg the PSA was conducted for two different SWT tested in Lichtenegg. To fill the ETs with actual probabilities, the protection systems of the turbines have been taken into account. This was done by examining at the technical menu of the turbines and speaking to the manufacturers as well as engineers, who are installing the turbines. The two turbines examined are the Ecovent 10, a HAWT without a tail vane, with a nominal capacity of 10 kW and the Amperius VK-250, a VAWT with a nominal capacity of 5 kW. These two SWT are entirely different designed, protection systems and failure rates. Therefore, they are suitable to show the whole bandwidth of failure frequency in Lichtenegg.

Figure 3.1: SWT Ecovent 10 (EcoVent, 2014) and Amperius VK-250 (own figure) at energy research site Lichtenegg

4 Empirical failure identification

In this chapter the findings of the empirical failure analysis are presented. After some basic definitions necessary for the analysis, the failures from the three datasets have been examined. Following the identification of the unwanted events as well as the initial hazards with regard to the research question is described.

4.1 Definition of the risk aim and related terms

Before having a deeper look into what kind of failures occurred in the past, the *risk aim* of the present study and the related terms *initial hazard* and *unwanted event* are defined. Therefore, the term *failure* has to be defined. According to the dictionary *failure* is principally the "nonperformance of something required or expected" (HarperCollins, 2014). The system is not working the way it is supposed to do. Looking at wind turbines, the performance should be "producing electrical energy by using the kinetic energy of the wind". So the estate of a turbine not producing energy while there is a certain amount of wind blowing can be defined as a failure. Failures can differ in many criteria: origin, consequences, turbine parts and the time needed to repair it. So the question arises, what kind of failure should be addressed in the present study.
The leading aim of the analysis is to detect, what kind of risk the use of SWT in urban areas can have. Therefore, the differences of the use of SWT in urban areas compared to the use in rural areas have to be considered. A great difference is that there are more people crossing just next to the turbine. While installations in rural areas are at least 30 m away from housings, the center of living, the urban turbines are positioned directly on the houses. Hence it has to be ensured that there is minimal risk occurrence in the urban use of SWT. This especially concerns people next to the SWT but also materials nearby, for example cars standing next to housings or the housing itself.
One way to separate between different failures of a technology is to consider the consequences of the failures. A failure, no matter if it is an electronic or mechanical failure of the machine, can have effects on:

1. The turbine itself
2. Economics of the owner
3. Other electronics connected to it
4. The surrounding: buildings or people close to the turbine

Consequences 1 to 3 are technical and economical, consequence 4 in contrast is having a physical impact on third parties. Regarding people it has the potential to physical harm people. In the present study failures which can lead to physical harm of people are defined as the *risk aim* . The *risk aim* comprises all *unwanted events*. Therefore, in the present study, the term *unwanted event* is always related to failure with consequences which might physically harm people. The term *failure within the risk aim* is used equally. So the *risk aim* is defined as *failure of the turbine that can lead to harm*, whereas the term *failure* is also used more generally for every non-performance of the system.

4.2 Failures in Lichtenegg

Within five years of testing, seven failures of SWT occurred. All of these failures are unwanted events. The age of the turbines in operating months at failure time, as well as the construction types of the SWT are shown in table 3. All failures were mechanical failures in terms of breakdown of the material. Three times a rotor blade broke, two times the connection to the tower broke, one time the tower broke and one time the windings in the generator broke.

Table 3: Failures at energy research site Lichtenegg between April 2011 and April 2016

number of failure	failure	type of turbine	age of turbine [operating months]
1	connection to tower broke	VAWT	21
2	windings in generator broke	ducted HAWT	18
3	rotor blade broke	VAWT	4
4	rotor blade broke	VAWT	4
5	connection to tower broke	HAWT with tail vane	30
6	tower broke	HAWT without tail vane	57
7	rotor blade broke	VAWT	11

Related to the risk-aim *failure of the turbine that can affect people nearby* it was discussed whether other failures occurred that were no turbine failures within the general definition of failure, but failures within the risk aim. This includes all events, which do not impair the SWT from its origin purpose of producing energy from the wind, but nevertheless may harm people. While often discussed problems like noise or shadowing could not be identified to fit into the risk-aim, ice falling from the turbine was detected to fulfill the criteria. Ice throw or fall is much harder to detect than failures of the turbine itself. This is related to the fact that the turbine itself is normally neither detecting the ice nor taking damage from it. A study of the manufacturer of Ecovent 10, who tested his SWT in Lichtenegg between December 2012 and march 2014, detected four days within the two winters where ice accumulated on the turbine (EcoVent, 2014). In January 2016 the occurrence of ice throw could be detected once in Lichtenegg and was sampled by the Institute of Safety and Risk Science. Related to the observations and literature about ice throw of large wind turbines, it can be assumed that next to the seven failures listed in table 3, within the five years of testing in Lichtenegg at least five times ice throw or fall occurred.

4.3 Failures described in literature

To get a better understanding concerning the types of failures that occurred within in the last 15 years by using SWT, two further datasets, already described above, are examined in this section. In Jon Sumanik-Learys data of two years of evaluating 35 turbines, 70 failures occurred. Figure 4.1 shows the failures separated by failed component. The two different colored columns show two different organizations building SWT for rural decentralized electrification in Peru. According to this data, similar to Lichtenegg, blades showed to fail regularly. The tower in contrast does not seem to be a major component of failure. The electronic system, including a generator, a rectifier and an inverter, showed a high amount of failures.

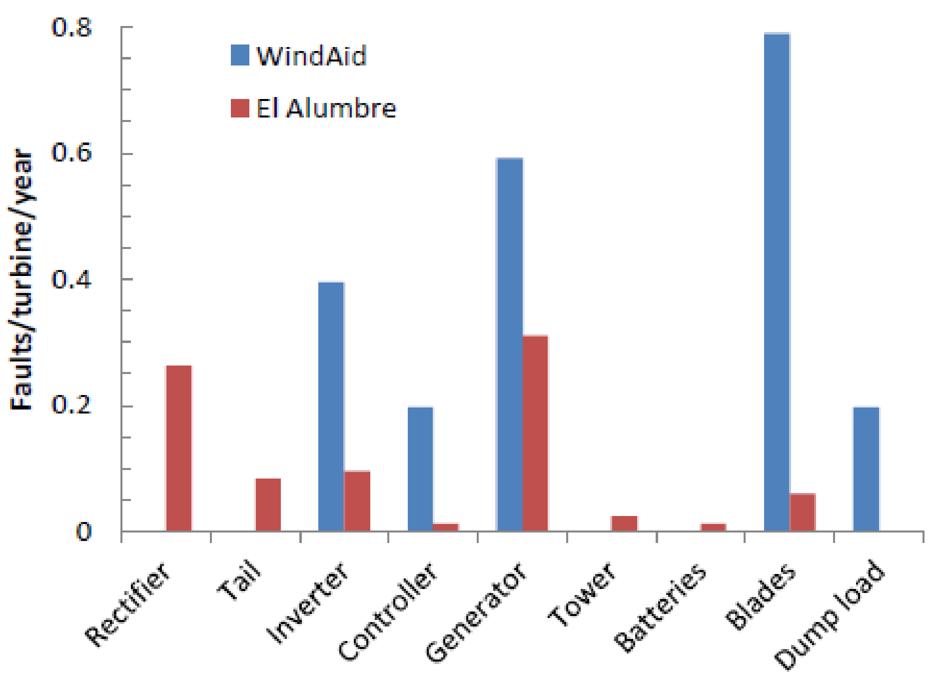

Figure 4.1: Normalized comparison of the breakdown of faults per component of Piggott SWT experienced by the development organizations WindAid and Soluciones Prácticas in Peru (Sumanik-Leary, 2013).

By having a closer look at the 70 occurred failures, only 45 of them were identified as failures within the risk aim. Especially the failures of blades and the tail vane showed potential to physically harm people. The failures of the generator, which resulted in a burning turbine, also lead to harmful situations for people. The 25 failures, not considered, did not directly lead to harmful situations.

Most of them have were electro-technical failures within the turbine itself. Therefore, only 45 failures are considered as unwanted events in the further analysis.
The study of Sumanik-Leary (2013) also provides a detailed insight in SWT in Scotland. In the Thesis Sumanik-Leary points out that several SWT have problems in coping with the high wind speeds on Scoraig Peninsula, Scotland. It is reported that blades were flying off in high wind speed and other parts of the turbines, including the tower, were breaking apart.
The data of Kühn (2007) does not provide much information on the effects of failure. Nevertheless figure 4.2 shows what components failed. That can be related to the described risks the components caused in the two other sets of data. The components with the highest failure rate were the electrical system, the electronic control and the sensors. These failures do not lead to physical harm. In contrast, failures of the rotor hub, the yaw system or the rotor blades can lead to physical harm by parts flying off the turbine. Failures of the mechanical brake and the generator can lead to an overspeed situation resulting in a burning generator.

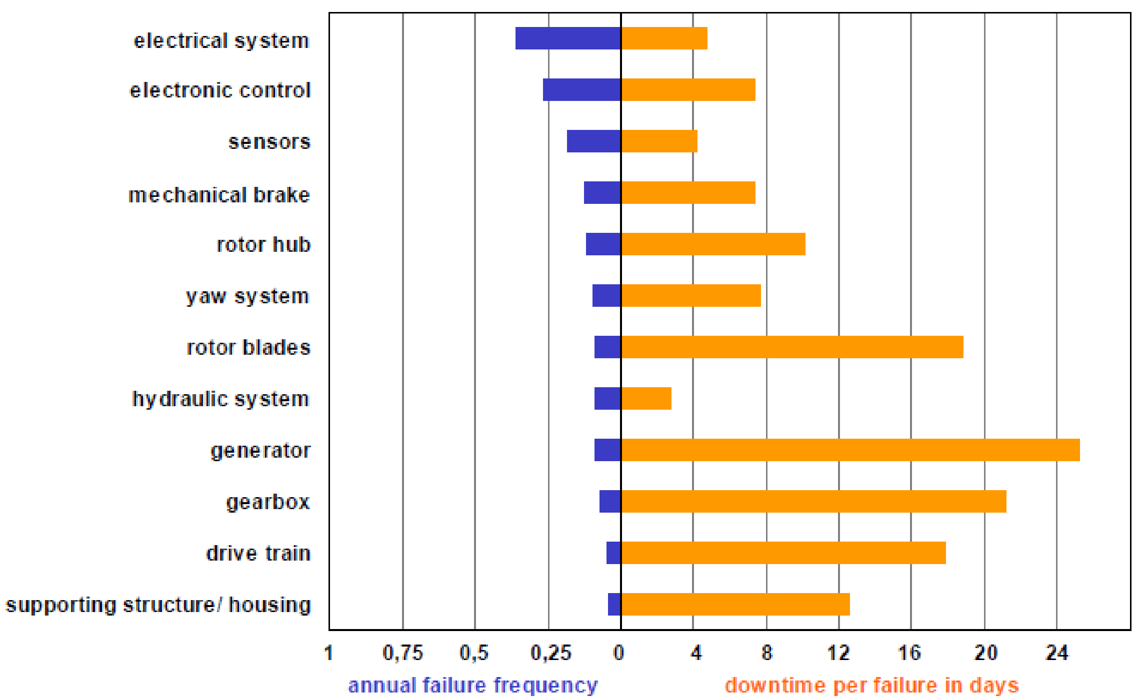

Figure 4.2: Frequency of failure by main components and related downtime for 235 SWT in the WMEP 1990 to 2007 (Kühn, 2007)

Kühn (2007) is further giving a helpful overview on hazards causing failure. The causes for failure, illustrated in figure 4.3, are a basis for identifying the initial hazards, even though Kühn did not publish the connection between the failure occurring and the hazard causing it. The 22 % control system malfunction will be covered by the event-trees in the present analysis. All other causes presented by the figure are crucial for the identification of initial hazards in chapter 4.5.

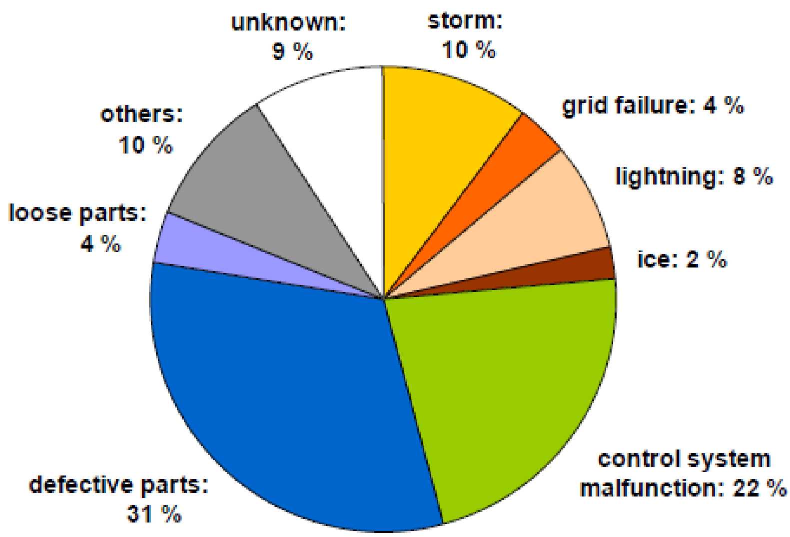

Figure 4.3: Causes for failure of 235 SWT in the WMEP 1990 to 2007 (Kühn, 2007)

4.4 Identification of unwanted events

By considering the failures referring to the risk aim of the three datasets, three types of unwanted events could be identified: *burning, falling parts* and *ice-throw*. These unwanted events will further be characterized in detail.

4.4.1 Characterization of the unwanted event burning

A burning turbine can have several severe impacts on people next to the SWT: Fire can ignite other objects and may cause for example a burning house. It may also burn other parts of the turbine and effect them to fall down, which can directly harm people. Smoke inhalation is another resulting harm. Toxic gases can directly cause health problems for peoples. In the 45 failures referring the risk-aim of Sumanik-Leary data, 31 failures with the code *burn* occurred. A occurrence frequency of 0.37 can be calculated, considering the event burning due to high wind speeds and the total operating years. In most cases the rectifier was burning, in eight cases the generator was burning. Even though *burning* did not occur in Lichtenegg, experts pointed out that a burning generator is a risk which can occur but is eliminated well by the protection systems.

4.4.2 Characterization of the unwanted event falling parts

Falling parts comprises all events where an object falls down from the turbine without a connection to either burning or ice accumulation. Falling parts due to fire is an unwanted event in terms of *burn*, falling ice due to ice accumulation is an unwanted event in terms of *ice throw*. The unwanted event *falling parts* therefore mainly covers components of the turbine itself falling due to any form of breaking within the system. This kind of failure occurred in all three sets of data. All of the seven unwanted events, which occurred in Lichtenegg had *falling parts* as the resulting unwanted event. 14 failures in Peru can be related to *falling parts* and also the failures of rotor blades in the graph of Kühn can be related to *falling parts*. An occurrence frequency of 0.17 times per year can be calculated from Sumanik-Learys data by dividing the 14 failures within the risk aim by the total operating years.

4.4.3 Characterization of the unwanted event ice throw

Even though all unwanted events which occurred within the three datasets are included in the two other types of unwanted events, *ice throw* was detected as a third event which can lead to a dangerous situation for people next to a SWT. Unfortunately, ice is not considered in the studies of Sumanik-Leary and Kühn. Nevertheless ice throw could be observed in Lichtenegg to be a dangerous event. Regarding the observations in Lichtenegg it is very important to differentiate between *ice throw* and *ice fall*. In both events ice is accumulated on the turbine. The difference is, whether the turbine is in operation during the time the ice loosens. When the ice falls down from a SWT, which is standing still, the ice will fall down near the turbine. In contrast, if the turbine is turning, the ice can get thrown over huge distances and lead to severe accidents. Facility operating personnel as well as third parties can get hit by the thrown ice. A risk due to ice throw could be identified for people walking nearby as well as vehicle passengers (Bredesen & Refsum, 2015). Regarding large wind turbines there are some studies on ice related risk, risk zones and actual killing probabilities due to ice throw of wind turbines (e.g. TNO 1992; Bredesen & Refsum 2015). So in the present study *ice throw* is defined as an unwanted event, whereas *ice fall* is excluded, because it is not assumed that people stand directly under the turbine. A specific area around the turbine should always be blocked, at least an area with the radius of the height of the tower. For roof-based turbines it is assumed that the ice will fall on the roof. *Ice fall* can lead to harmful events, but does not differ from ice falling from other objects and is therefore not further examined within the present study.

Due to the difficulties in observing the accumulation of ice, the observed events are assumed to not be complete. Therefore, the calculation of the occurrence frequency of ice accumulation is done by considering the local weather conditions. The calculation is considered in depth in chapter 5.1.4.

4.5 Identification of initial hazards

After the identification of the three unwanted events, it was analyzed which initial hazards lead to them. Initial hazards are defined as hazards that can lead to an unwanted event if the protection systems are not well performing or if no protection system is installed. The initial hazards have been identified by considering the accident sequences of the observed failures as well as the common protection systems. Regarding protection systems it was examined at what conditions the system starts intervening. It is assumed, that conditions where the protection systems should intervene, always lead to a failure if the protection system is failing. Figure 4.4 shows unwanted events and their initial hazards: *high wind speeds, lightning, material failure, fog* and *freezing rain*. In the following part it will be explained how the author examined these initial hazards for the three unwanted events.

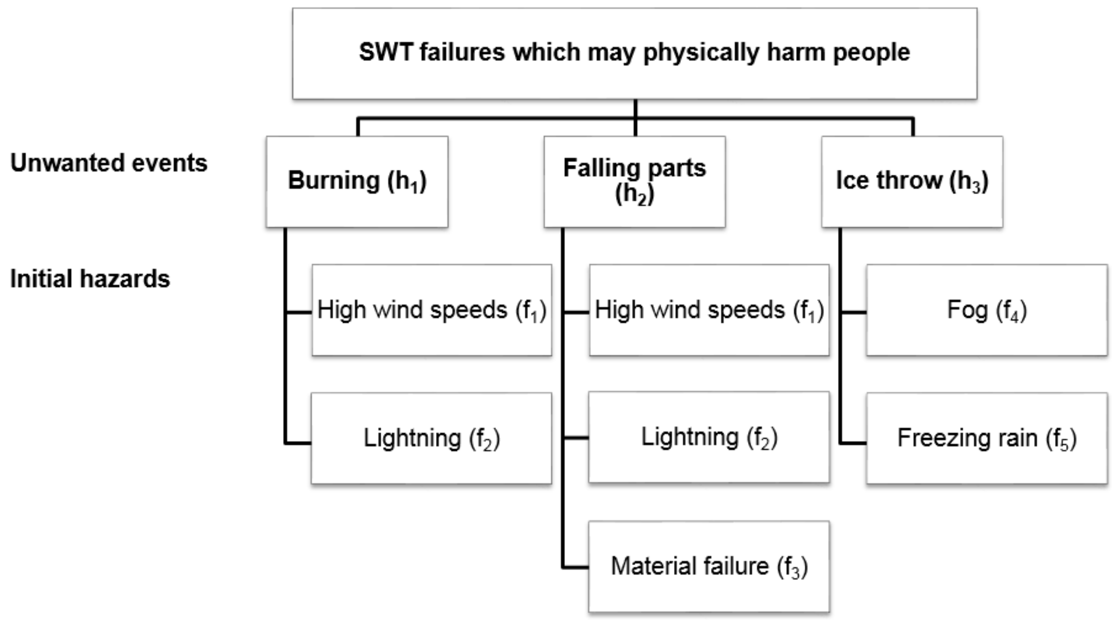

Figure 4.4: SWT failures which may physically harm people with their occurrence frequencies h_j and the initial hazards causing them with their occurrence frequency f_i (own figure)

4.5.1 Initial hazards of burning

By looking at the data of Sumanik-Leary it was found that high wind speeds were the main cause for burning of Piggott turbines. All of the 31 events of *burning* that occurred have been a result of high wind speeds. The study of Kühn (2007) is not presenting the relation of initial hazards and unwanted events. No information about the accident sequences of the 235 turbines analyzed is given. Nevertheless it provides a good overview of initial hazards for failures in general. As shown in figure 4.3 within Kühn's data, 10 % of failure were caused by *storm*. Even though this value relates to failures in general, it shows that storm has to be taken into account. In Lichtenegg no burning occurred within the five years of data collection. Nevertheless in dialogue with experts from industry, it was mentioned that burning could occur, either when the protection systems fail or the turbine gets struck by a lightning. Failures of the protection systems, which represent a crucial part in failure analysis, is no initial hazard, but is considered separately in event-trees. Lightning strike is also mentioned by Kühn to be responsible for 8 % of failures (see figure 4.3).

Within Sumanik-Leary's data no lightning strike occurred. Nevertheless it can be assumed that lighting can lead to burning and was therefore taken into account as an initial hazard. Hence the initial hazards considered in relation to *burning* in the analysis are *high wind speeds* and *lightning*.

4.5.2 Initial hazards of falling parts

All of the seven unwanted events that occurred in Lichtenegg were somehow related to *falling parts*. Different parts were breaking always resulting in falling parts, or even the whole turbine falling. It is difficult to bring these events in relation with a specific initial hazard, because of their different nature. Nevertheless, taking into account that at least in six of seven failures the protection system was well functioning and five of the seven failures occurred in the first two years of operation, the failures can not be related to external conditions, but to the turbine itself. The material fails to withstand standard operation conditions. This is defined as *material failure*. In Kühn's study also 31 % of the turbines failed because of *defective parts* (figure 4.3). In conclusion, *defective parts* are also integrated in the initial hazard *material failure*. Looking at the data of Sumanik-Leary, 14 of the 45 unwanted events were categorized as either *snapped*, *fall* or *loose*. The three categories are covered by the unwanted event *falling parts*. One of this failures was caused by loose guy wires, two by bad weldings. These three events also fit to the characteristics of the initial hazard *material failure*. Eleven other unwanted events in Sumanik-Leary's data was caused by high wind speeds. Therefore, this is taken into account as a second initial hazard for the unwanted event *falling parts*. As a third one, *lightning* is also detected as a hazard leading to *falling parts*. Two manufacturers reported about a SWT struck by a lightning without having burning as a consequence, but damage of the electric parts. By studying lightning literature, it could be determined that *falling parts* can be another possible consequence of a lightning stroke in a SWT (Cooray, 2015).

4.5.3 Initial hazards of ice throw

Ice throw is no failure of the turbine itself. Hence it is not included in most failure studies. In the study of Sumanik-Leary it is not included at all. The cause might be that snow is not occurring often in Cajamarca Region in Peru where the data was collected. Figure 4.3 shows ice to be the reason for 2 % of the failures. In the graph's data only failures of the turbines itself are included, therefore it can be assumed that there have been more events of *ice throw*, which are not mentioned in the study, because they did not damage the turbine itself. Nevertheless *ice throw* without damaging the turbine can have serious consequences for people. In Lichtenegg one occurrence of *ice throw* was detected in January 2016 by the Institute of Safety and Risk Science. A manufacture detected four events between December 2012 and March 2014 (EcoVent, 2014). Due to the fact that it is hardly possible to detect every event of *ice throw* without having a full time observation, it is hard to quantify the occurrence of the unwanted event *ice throw*. However even from the present small amount of data, it can be derived that ice throw is occurring regularly. Quantitative assumptions can be made by looking at the weather conditions, which lead to the accumulation of ice on the blades. Pospichal & Formayer (2011) conducted a study about the climate conditions which lead to ice accumulation on large wind turbines. It is assumed that these conditions are comparable for SWT. In conclusion the two initial hazards for the unwanted event *ice throw* are *freezing rain* and *fog*. They are further examined in chapter 5.1.4.

5 Probabilistic Safety Analysis for Small Wind Turbines in Lichtenegg

In this chapter it is shown how PSA was adapted to SWT. After detecting the main aforementioned hazards causing failure as well as the three unwanted events, the safety analysis was conducted for the energy research site in Lichtenegg . ETs regarding the safety mechanisms have been constructed. The PSA was adapted in regard to the use of PSA for large wind turbines as well as to the study by Pressl *et al.* (2015), concerning wastewater pipelines in Austrian lakes. Equal to Pressl *et al.* (2015), *influencing factors* were tested by using a test of independence. However, while Pressl *et al.* (2015) used *chi*^{2}*-test*, in the present study *Fisher's exact test of independence* was used.
In chapter 5.4 and 5.5 the results of the two exemplary SWT: Ecovent 10 and Amperius VK-250 are shown.

5.1 Occurrence frequency of initial hazards

As a first step, the frequencies of occurrence for the initial hazards, which have been detected in 4.5 have been determined. Therefore, a short topographic analysis of the site was necessary.
Lichtenegg is located in the province Lower Austria in the East of Austria, approximately 90 km south of Vienna. The region is called *Bucklige Welt.* It is a hilly landscape, which is part of the eastern foothills of the Alps. The geodetic coordinates are 47.608668 north and 16.203555 east. The testing site is 800 m above sea level on a knoll. In the present analysis Lichtenegg will be used as an example site for calculating the frequencies of the occurrences of the five different initial hazards (f_{1-5}). The initial hazardsf_1,f_2,$f_4$and f_5 are exclusively depending on the climatic conditions of the specific site. Material failure (f_3) in contrast is not depending on the site, but was calculated by taking the occurrences within the five years of testing in Lichtenegg into account.

5.1.1 High wind speeds (f1)

High wind speeds are defined as wind speeds of over 12 m/s. This threshold was chosen due to the fact that at this wind speed, overspeed protection systems cut in. It is assumed that wind speeds lower than 12 m/s can not lead to *burning* or *falling parts*. This does not mean that these unwanted events do not occur at those conditions, but if the wind speed does not exceed 12 m/s, they must have a different initial cause. Furthermore, it is not assumed that if wind speeds over 12 m/s occur, the turbines will directly start burning or braking if the protection system fails or if the turbines are not having a protection system. It is assumed that if the turbine is running at wind speeds over 12 m/s for a certain amount of time without a protection system, the unwanted

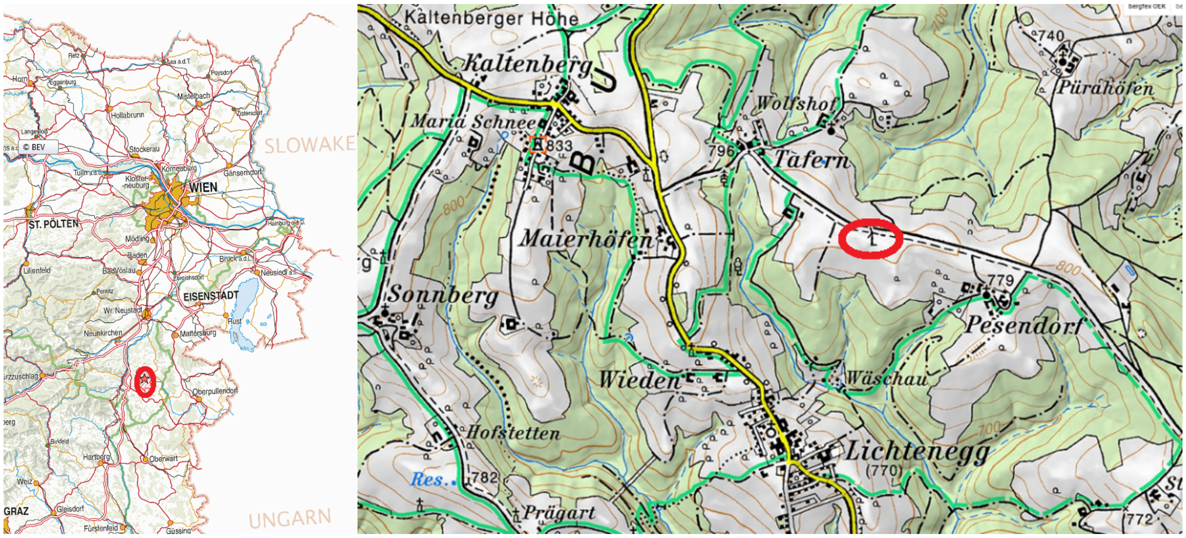

Figure 5.1: Topography of the energy research site Lichtenegg, Lower Austria (BEV, 2016)

events *burning* and *falling parts* can occur. The different protection systems preventing *burning* were already presented in chapter 2.3.

In Lichtenegg the energiewerkstatt eV collects data about the weather, including wind speeds, since January 2012. The wind data is measured in two heights: 10 and 19 meter above ground. For this analysis the data of the anemometer in 19 m height was used, because this height fits the height of the nacelle of the tested SWT the best. The tower heights vary between 12 and 19 m. The data is measured in one minute interval. Between January 2012 and April 2016 wind speeds over 12 m/s occurred in 2 % of the measured minutes. Wind speeds of over 12 m/s occur 10 589 minutes per year in average (figure 5.2). Wind speeds of over 14 m/s occur 4 680 minutes per year in average.

Table 4: Frequencies of wind speeds higher than 12 m/s at the energy research site Lichtenegg in 19 m height

year	total minutes	minutes wind speed above 12 m/s	percentage wind speed greater than 12 m/s
2012	475 049	8 887	1.87
2013	525 088	9 841	1.87
2014	500 649	11 614	2.32
2015	513 500	9 123	1.78
2016	172 795	4 598	2.66
sum	2 187 081	44 063	2.01
average year	*525 600*	*10 589*	*2.01*

5.1.2 Lightning (f2)

The Austrian Lightning Detection and Information System provides information regarding lightning density per km^2 for Austria. According to ÖNORM EN 62305-2 this data shall be used for risk analysis concerning lightning. The stroke density for Lichtenegg is 2.39 strokes per km^{2}and year. The stroke density for a specific object is always depending on the surroundings due to the fact that the lightning always hits the highest object within a specific area. Therefore, it has to be considered if there are any other high buildings around the SWT. Furthermore, the stroke density is directly related to the peak current of the stroke (I_p). The striking distance, which defines the area within which the lightning will strike the highest object, is directly related to the peak current of a lightning strike. Whereas a stroke with a peak current of 30 kA hits objects within a distance of 57 m, a lightning stroke of 3 kA will not strike further than 20 m.
To calculate the hazardous zone of a wind turbine at the site Lichtenegg, the Electro Geometrical Method according to Cooray (2015) was used. By using this method, the radius of stroke can be calculated. As mentioned before, the radius of stroke depends on the current of the stroke and the height of the object. According to Cooray (2015) I = 30 kA is a typical mean current of a lightning strike with a negative polarity and often used as a calculation parameter. Therefore, this current is used for the present calculations. Additionally, a height of 20 m was assumed for the SWT. This is the total height from bottom to nacelle. The third assumption is that the turbine is the highest object within a radius of 60 m. This range is called the radius of stroke. Using the Electro Geometrical Method, the striking distance (S) was calculated. S is the average electric field between the stepped leader and the ground. It is calculated by dividing the potential of the tip of the stepped leader by the distance between the structure and the stepped leader (Cooray, 2015). As seen in Equation 10, S is directly related to the prospective peak return stroke current (I_p) in kA. After calculating the striking distance, it is directly possible to calculate the attractive radius. The attractive radius (R) predicts whether the strike will hit the object or the ground. For a striking distance smaller than the height of the object, the attractive radius is equal to the striking distance. If the striking distance is higher than the object's height, the attractive radius depends on the striking distance and the height of the object (see equation 11). Therefore, with the assumption of a stroke current $I_p = 30\,kA$ and a nacelle height of h = 20 m, the attractive radius is 57 m (see equation 12).

$$\begin{aligned} S &= 10 I_P^{0.65} \\ S\,(30\,kA) &= 91.228\,m \end{aligned} \tag{10}$$

$$R = \begin{Bmatrix} \sqrt{S^2 - (S-h)^2} & for\, S > h \\ S & for\, S \leq h \end{Bmatrix} \tag{11}$$

$$since\, S = 91.228\, m > h = 20\, m:$$

$$\begin{aligned} R\,(91.228\, m; 20\, m) &= \sqrt{(91.228\, m)^2 - (91.228\, m - 20\, m)^2} \\ &= 57\, m \end{aligned} \tag{12}$$

$$\begin{aligned} A &= \pi * R^2 \\ A\,(57\, m) &= 10207.43\, m^2 \end{aligned} \tag{13}$$

$$\begin{aligned} N &= \tfrac{2.39*10^{-6}}{a*m} * A \\ N(10207.43\, m^2) &= 0.024\, a^{-1} \end{aligned} \tag{14}$$

The area of a circle with the radius R can now be calculated as seen in equation 13. The resulting attractive area (A) is 10207 m^2. Considering the striking density of 2.39 strokes per km^2 in Lichtenegg, a stroke frequency (N) of *0.024 per year* can be assumed within the attractive area (see equation 14). This is calculated very conservative. According to Asakawa *et al.* (2010) 50 % of lightning strikes do not have a current peak greater than 3.1 kA. Using this value for the calculations would lead to a much lower stroke density of $3 \cdot 10^{-6}$ strokes per year.
In addition to the stroke density, the duration of a stroke is influencing the occurrence of the unwanted events, because it is determining the failure resulting from a lightning strike. Generally, it can be differentiated between two types of lightning current waveform: *Pulse type current* with a duration of tens of microseconds to hundreds of microseconds and *continuing type current* with a longer duration of tens of milliseconds to hundreds of milliseconds. The pulse type strokes are mainly destroying electronics and can lead to spark-over, they are short and multiple. The probability of this stroke leading to fire is very small. Continuing type current strokes cause wire melting and can lead to *burning*. There is also a third type of current, which is a combination of both types and can lead to all failures mentioned above. According to studies about large wind turbines, strokes mainly damage the blades of the wind turbines. Therefore, large wind turbines normally have a blade protection system, which is a metal wire leading the current through the blade and the tower, into the ground (Asakawa *et al.*, 2010). SWT normally do not have a protection system within the blades. According to Cooray (2015) blades are most probable to get hit, because they are the highest point of the turbines.
Due to the fact that there is no present data about lightnings on SWT, the probabilities of lightning strikes causing *burning* and *falling parts* of a SWT have been determined related to the given information. It can be assumed that *burning* is only possible if it is a continuing type current stroke. In the study of Asakawa *et al.* (2010) 67 out of 85 observed lightnings had a continuing current. So the value 0.8 was added for the probability of the lightning strike leading to the unwanted event *burning*. Therefore, the frequency of a stroke, which can lead to burning

of a turbine was assumed to be 0.019 times per year. Every type of lightning can lead to *falling parts*. Due to the fact that lightning most probable hits the unprotected blades of the SWT the occurrence frequency regarding *falling parts* could not be reduced. The value remains *0.024 strikes per year* for the frequency of a lightning strike leading to *falling parts*.
It should be mentioned that one lightning strike is often simultaneously hitting two or more turbines if they are standing close to each other. So SWT standing side by side are not protecting each other.

5.1.3 Material failure (f3)

Material failure is the only initial hazard which is not depending on the topography of the site. It has nothing to do with the surroundings, but with the turbines themselves. SWT are made out of different materials and built in various ways. This is why it is impossible to conduct a material analysis that is suitable for an overall approach for SWT. In Lichtenegg *material failure* occurred six times. Three times a blade broke, one time the connecting part between the turbine and the tower broke, once the tower itself broke and one time the winding in the generator fell down. The overall operation time in Lichtenegg was 30 turbine operation years. This suggests a frequency of *0.2 events per year*. This value neither takes the material into consideration nor which component failed.

5.1.4 Fog (f4) and freezing rain (f5)

The occurrences of *fog* and *freezing rain* can be derived from the weather data: Ice can accumulate at two different weather conditions. Either by fog freezing on the blades or by freezing rain. The frequencies of occurrence can be determined by the topography of Lichtenegg and the weather data measured from energiewerkstatt eV. For the analysis the criteria for ice accumulation on wind turbines published by Pospichal & Formayer (2011) was used.
Regarding *fog*, the site itself has to be taken into account. The site is exposed on a knoll, so it can be assumed that fog is occurring regularly. The upper limit for the occurrence of fog in the northeast of Austria is 600 to 1 000 m over sea level. The testing site is located 800 m over sea level, so it is within the limit of fog. Pospichal & Formayer (2011) present example sites for the east of Austria. One of them is *Bernstein*. This site is representative for elevated sites in the center of the province *Burgenland* and specifically the *Bucklige Welt*. Lichtenegg fits this description rather well. At those sites ice accumulation occurs 9.9 times per year.
Freezing rain is "Rain that falls in liquid form but freezes upon impact to form a coating of glaze upon the ground and on exposed objects" (AMS, 2012). The glaze can accumulate on the ground as well as on objects like trees, power lines or wind turbines. This mostly happens when a high-pressure area follows a low-pressure area. So if very low temperatures are followed by a swift change to temperatures over 0°C snow is melting in the warm air near the ground and

freezing again on the cold surfaces. Freezing rain generally is a dangerous weather condition. In all the eastern parts of Austria the occurrence of *freezing rain* can be assumed to be similar without considering the micro-climate. According to Pospichal & Formayer (2011) it happens once every two to three years. This occurrence frequency was calculated from the weather data at Airport Schwechat, which is around 80 km away from Lichtenegg. Therefore, also regarding the testing site Lichtenegg the frequency of *0.4 times per year* can be assumed. Although *freezing rain* occurs more seldom than *fog*, it can not be neglected, because it is often followed by high wind speeds, which can lead to *ice throw* Pospichal & Formayer (2011). The total frequency of ice accumulation due to the mentioned weather conditions is shown in equation 15. It is 10.26 per year for Lichtenegg.

$$f_{ice\,accumulation} = f_{fog} + f_{freezing\,rain} \tag{15}$$

$$f_{relevant\,ice\,accumulation} = (f_{fog} + f_{freezing\,rain}) \cdot p_{relevant\,size} \cdot p_{turbine\,running} \tag{16}$$

Compared to observed ice accumulation in Lichtenegg, ten occurrences per year seem to be a rather high frequency. It is assumed that the difference is related to the mass of the accumulated ice load. In most of the ten events per year, ice accumulates as a relatively thin layer, not resulting in heavy parts falling from the turbine, but in small pieces or dropping down. The Netherlands Organization of Applied Scientific Research (TNO, 1992) defines ice pieces starting with a size of 200 g as relevant for falling ice. This is related to the kinetic impact energy of 40 J and a velocity of 20 m/s. In consideration of the observations in Lichtenegg, it is assumed that in 20 % of the occurrences of ice accumulation the mass of the accumulated pieces of ice is greater than 200 g. This probability is added to the calculation of the frequency of relevant ice accumulation, shown in equation 16.

Next to the ice accumulation, the second requirement for the possibility of *ice throw* is that the turbine is operating. SWT start running at wind speeds of about 2.5 m/s. According to Pospichal & Formayer (2011) 80 to 90 % of ice accumulation on wind turbines happen in December and January, even though ice accumulation is possible between November and March. Due to the high probability of occurrence in January and December the probability of wind speeds of 2.5 m/s or higher at Lichtenegg have been calculated from the weather data of these two months, starting with December 2012 until January 2016. At the site Lichtenegg a probability of 73.5 % for wind speeds higher than 2.5 m/s was calculated (see table 5). This value describes the probability of the turbine operating while ice is accumulated. Adding the probability of the turbine running to the annual frequency of relevant ice accumulation, *ice throw* was calculated to occur *1.51 times per year* (equation 16).

Table 5: Wind speeds of 2.5 m/s or more at 19 meter height measured at testing site Lichtenegg

Month	**Minutes measured total**	**Minutes wind speed $\geq$ 2.5 m/s**	**Wind speed $\geq$ 2.5 m/s [%]**
Dec 12	44 640	36 285	81.28
Jan 13	44 640	32 657	73.16
Dec 13	44 640	33 400	74.82
Jan 14	43 865	31 635	72.12
Dec 14	42 235	29 724	70.38
Jan 15	44 640	37 457	83.91
Dec 15	43 175	26 466	61.30
Jan 16	44 640	31 677	70.96
average	*44 059*	*32 413*	*73.49*

5.2 Statistical testing of influencing criteria on material failure

In this section the results of the tests of independence for the three criteria *certification, axial-orientation* and *nominal capacity* are presented. The failures are brought in relation with the measured full load hours of the SWT.

5.2.1 Test of independence: Certification

Using Fisher's exact test of independence the following null hypothesis was tested:

H_0= *Certification is not having any influence on material failure frequency*

Table 6 shows the data necessary for a test of independence regarding certification. in the first column the criteria parameter-values are listed. The second column displays the number of SWT, which are fulfilling the criteria. This number is not used for the calculation, but is necessary for interpreting the results. The third column shows the accumulated full load hours of all turbines, operating in Lichtenegg and fulfilling the criteria. Column four contains the observed failures in Lichtenegg and the last column contains the expected failures. The expected failures were calculated by distributing the seven failures equivalently to the full load hours among *yes* and *no* of the criteria. They show the average distribution if the criteria has no influence on *material failure*.

Using Fisher's exact test, the observed failures were compared to the expected failures to calculate whether the observed failures fit the distribution. The calculated p-value of Fisher's exact test is p = 0.46. Using a 95 % level of significance, the null hypothesis is accepted due to p-value greater than 0.05. Therefore, no influencing factor was calculated. Certification has no significant influence on material failure frequency. Calculations for the other two criteria were conducted the same way.

Table 6: Test of independence for the criteria certification

Criteria: Certification	Number SWT	Experience [full load hours]	Observed failures	Expected failures
yes	6	172 138	2	3.2
no	9	202 618	5	3.8
total	*15*	*374 756*	*7*	*7*

5.2.2 Test of independence: Axial-orientation

Table 7 shows the values concerning axial-orientation. Three VAWT and 12 HAWT have been tested in Lichtenegg. The null hypothesis for this calculation is:

H_0= *Axial-orientation is not having any influence on material failure frequency*

The p-value calculated for axial-orientation is p=0.000456. The p-value far below 0.05 implicates that the null hypothesis has to be rejected. It can be assumed that the axial-orientation (whether the turbine's rotation axis is vertical or horizontal) is having a significant influence on material failure frequency, so an influencing factor was calculated.

Table 7: Test of independence for the criteria axial-orientation

Criteria: axis orientation	Number SWT	Experience [full load hours]	Observed failures	Expected failures
vertical	3	23 401	4	0.44
horizontal	12	351 355	3	6.56
total	*15*	*374 756*	*7*	*7*

An influencing factor F1 was calculated like shown in equation 8: By dividing the observed failures by the expected failures the values for the influencing factor F1 were calculated. Hence for the calculation of *material failure* the value 0.457 has to get included in the equation regarding HAWT. This design is reducing failure frequency. Whereas for VAWT the value 9.091 has to get included, which is heavily increasing failure frequency (see table 8).

Table 8: Influencing factor F1 for the criteria axial-orientation

Axial-orientation	observed by expected failures	**F1**
vertical	$\frac{4}{0.44}$	*9.091*
horizontal	$\frac{3}{6.56}$	*0.457*

5.2.3 Test of independence: Nominal capacity

Table 9 shows the values determined for the test of independence concerning the criteria nominal capacity. The following null hypothesis has been tested:

H_0= *Nominal capacity is not having any influence on material failure frequency*

Five out of seven occurred failures are related to size A SWT with a nominal capacity smaller than 5 kW. Even though there are more than double full load hours of size B SWT with a capacity $\geq$ 5 kW sampled, only two failures occurred in this category. Comparing observed and expected failures a p-value of p = 0.01961 was calculated. It shows, that nominal capacity has a significant influence on material failure frequency. The null hypothesis had to be rejected and an influencing factor F2 was calculated.

Table 9: Test of independence for the criteria nominal capacity

Criteria: nominal capacity	**Number SWT**	**Experience [full load hours]**	**Observed failures**	**Expected failures**
$\geq$ 5 kW	5	271 782	2	5.08
< 5 kW	10	102 974	5	1.92
total	*15*	*374 756*	*7*	*7*

Equal to the criteria axial-orientation, the influencing factors are calculated. For SWT with a nominal capacity greater than or equal to 5 kW the factor 0.4 is included in the frequency calculation. It is reducing the frequency of *material failure*. For SWT under 5 kW nominal capacity an influencing factor of 2.6 was included in the frequency calculation, as it increases the annual material failure frequency (see table 10).

Table 10: Influencing factor F2 for the criteria nominal capacity

nominal capacity	observed by expected failures	**F2**
$\geq$ 5 kW	$\frac{2}{5.08}$	*0.4*
< 5 kW	$\frac{5}{1.92}$	*2.6*

In conclusion, axial orientation as well as nominal capacity were identified to have a significant influence on *material failure*, whereas certification is not having a significant influence on *material failure*. The influencing factors F1 (regarding axial orientation) and F2 (regarding nominal capacity) were included in equation 9. Hence the adapted equation for the frequency of *material failure* is shown by equation 17.

$$h_{material\,failure} = f_3 \cdot P_3 \cdot F_1 \cdot F_2 \tag{17}$$

5.3 Consideration of protection systems using event-trees

As already mentioned in chapter 3.3 accident sequences can be shown in ET. Therefore, the initial hazard and the possible failure related to it are connected by an ET, having as much branches as the SWT has protection systems.

As described in chapter 2.3, the turbine's protection systems are not primary related to the unwanted event, but to the initial hazard. The initial hazards *high wind speeds* and *lightning* can cause different types of unwanted events. It is difficult to detect if *high wind speeds* cause *burning* or if they cause *falling parts*. Considering a turbine without any protection system it could not be forecast whether the turbine would burn or break first. But there are some protection systems effectively preventing one unwanted event, but not the other. Therefore, the original ET for the unwanted events *burning* and *falling parts* due to high wind speeds will be the same. Depending on the protection systems of the specific SWT, the results of the calculations can be different for the two events, because the probability of successful protection can be different.

For every initial hazard one ET for the general adaptation to SWT is generated. Every branch shows one type of protection system. Upward branches are "yes"-branches, which mean that the protection system is successfully preventing the failure. Along that branch there is definitely no failure occurring. Downward branches are "no"-branches. It can either implicate that there is no protection system, or that the protection system is not preventing the unwanted event. In this case the risk of failure is present. It does not mean that the unwanted event is definitely happening, it only means that the system is not protected from the unwanted event.

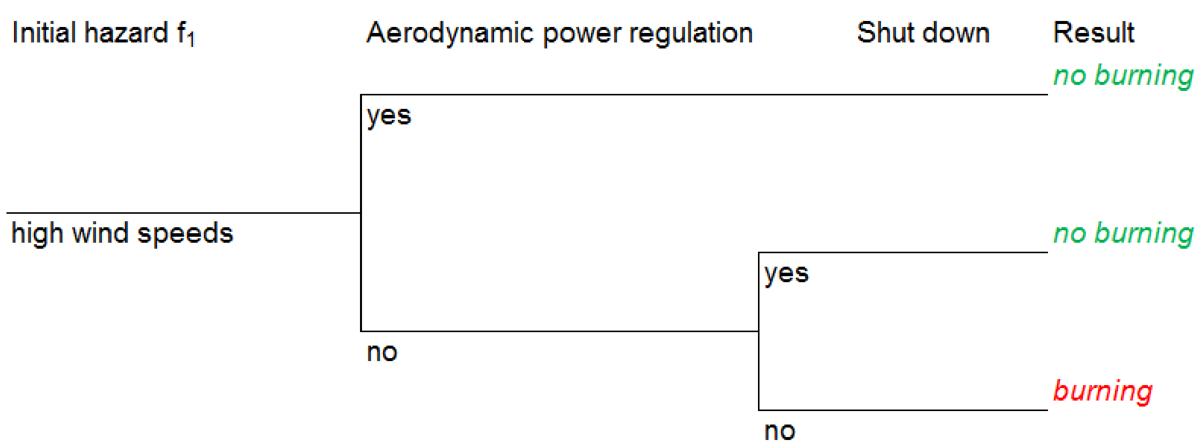

Figure 5.2: Event-tree with the initial hazard high wind speeds (own figure)

The ET concerning *high wind speeds* is shown in figure 5.2. To protect SWT from the consequences of wind speeds higher than the dimensioning of the turbines, two systems are generally used. The first branch of the ET concerns a protection system to reduce the pressure of the wind by adjusting the angle of attack. The different protection system mechanisms are described in chapter 2.3.The vast majority of HAWT have an aerodynamic power regulation, whereas VAWT normally do not have one. When these systems engage, the SWT are still producing, but reduce the angle of attack. Furthermore not all, but most of the SWT use brakes which completely shut down the SWT at even higher wind speeds. Common used SWT possess a redundant braking system, shutting down the turbines for a few minutes, as soon as the wind speed gets higher than the dimensioning for a few seconds. This protection system is considered by the second branch.

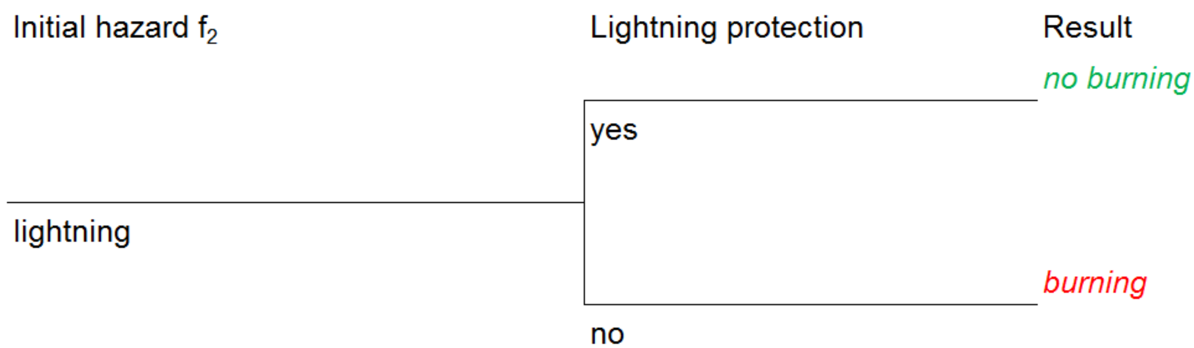

Figure 5.3: Event-tree with the initial hazard lightning (own figure)

Figure 5.3 shows the ET for the initial hazard *lightning*. Again, this one can be used for both unwanted events related to lightning: *Burning* and *falling parts*. In figure 5.3 the ET regarding *burning* is shown. Concerning *lightning* there is only one protection system which can be taken into account. Most SWT possess an earthing within the tower. The earthing makes it possible to conduct the charge down into the ground if the lightning hits the tower or the nacelle. The blades are normally not protected. Nevertheless, the enormous voltage of a lightning destroys most of the electric components, even if a lightning conductor is present.

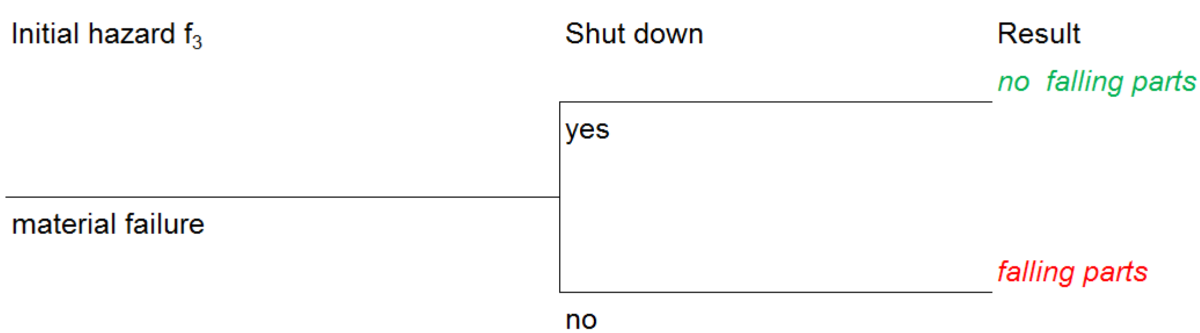

Figure 5.4: Event-tree with the initial hazard material failure (own figure)

Material failure can only lead to the unwanted event *falling parts*. The ET regarding *material failure* is shown in figure 5.4. A successful protection needs a system which is detecting material failure early enough to stop the turbine before parts are falling off. A combination of a sensor and shut down mechanism is needed. *Material failure* can either be detected during maintenance, by optic control of the SWT or by vibration sensors. Not many turbines have an efficient system to detect and prevent *material failure*.

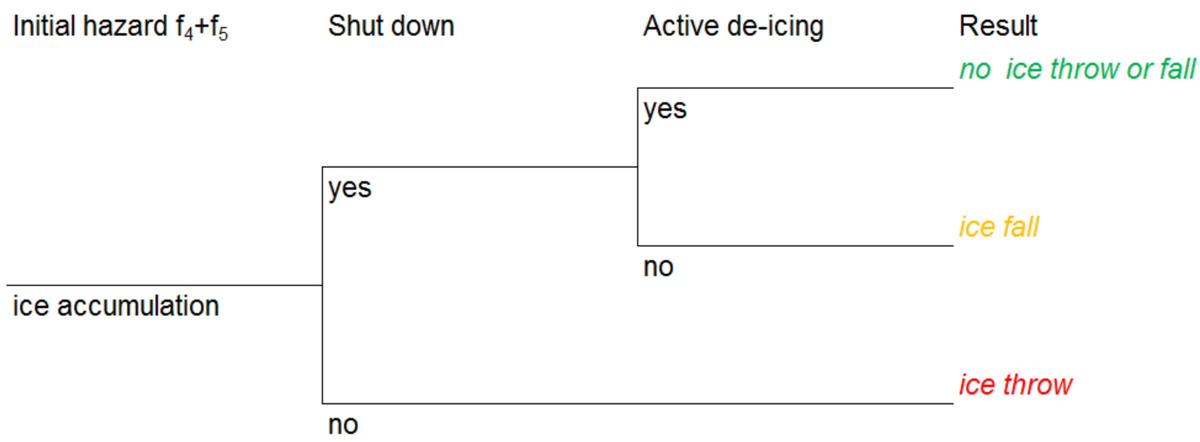

Figure 5.5: Event-tree with the initial hazard ice accumulation (own figure)

The last initial hazard considered is the accumulation of ice due to *freezing rain* or *fog*. The related ET is shown in figure 5.5. Ice accumulation can lead to two hazardous events excluding each other: *ice fall* and *ice throw*. Due to the fact that for ice fall the affected area is more predictable and the risk is similar to ice falling from other objects, only ice throw was considered as an unwanted event. Therefore, especially the first branch of the ET is crucial. The detection of ice on the turbine combined with a shut down system, can prevent *ice throw* and is leading to ice fall. There are optic, synoptic and vibration sensors used in the SWT market. Some are combined with a direct shut down mechanism, some are connected to an alarm informing the operator of the turbine about ice accumulation. The second branch is a further protection against ice fall. Some manufacturers recommend to de-ice the turbine by hand, especially turbines used in urban areas. Automatic de-icing systems like the ones used in large wind turbines are currently not present in the SWT industry.

Using the ETs and filling them with the occurrence frequencies of the site as well as the failure probabilities of the protection systems of specific SWT the frequency of occurrence of the unwanted events can be calculated as shown in equation 6. Following the calculations for the two example turbines Ecovent 10 and Amperius VK-250 are shown.

Using the ETs described above as well as the values from Lichtenegg, in the next two chapters the frequencies of the unwanted events are calculated for two example turbines. The protection systems of these SWT, on which the presumed values for the P_i are based on, are shortly described and the presumed values are presented.

5.4 Results Amperius VK-250

In this chapter the occurrence frequencies of the unwanted events are calculated considering the VAWT Amperius VK-250. Based on the protection systems of the turbine (further described in this chapter), the values for the probability of the protection systems not preventing the unwanted event (P_i) are assumed as shown in table 11. The assumptions are made by taking data from literature, observed accidents in Lichtenegg and the expert interviews into account. The values for the occurrence frequencies of the initial events (f_i) as well as the values for the influencing factors (F_k) were calculated earlier in the present study. Using equation 7 the occurrence frequencies of the three unwanted events are calculated.

Table 11: Presumed operators for the frequency calculation of the three unwanted events for the Amperius VK-250

operator	value	operator	value	operator	value
		P_1	10^{-6}		
f_1	4680	$P_1{}'$	10^{-6}		
f_2	0.019	P_2	0.2	F_1	9.091
f_3	0.2	$P_2{}'$	0.6	F_2	0.4
$f_4 + f_5$	1.508	P_3	1		
		P_{4+5}	1		

$$h_{burning}(Amperius\,VK-250\,in\,Lichtenegg) = 8.48 \cdot 10^{-3} \tag{18}$$

$$h_{falling\,parts}(Amperius\,VK-250\,in\,Lichtenegg) = 7.43 \cdot 10^{-1} \tag{19}$$

$$h_{ice\,throw}(Amperius\,VK-250\,in\,Lichtenegg) = 1.51 \cdot 10^{0} \tag{20}$$

$$h_{ice\,throw}(Amperius\,VK-250\,with\,ice\,sensor) = 9.05 \cdot 10^{-1} \tag{21}$$

Darrieus turbines like the Amperius VK-250 in contrast to HAWT do not have any aerodynamic system to reduce the power input. To prevent overvoltage a load resistor is used. As a consequence the brake intervenes relatively early at wind speeds of 14 m/s. From the turbines installed in Lichtenegg it could be observed, that this system is reducing the frequency of *burning* due to overspeeding (equation 18). Nevertheless, due to the lack of an aerodynamic reduction of the power input the turbine still is statically exposed to the high winds.

The Amperius VK-250 has a grounding throughout the tower which is leading the current of the stroke into the ground as soon as it reaches the tower. The blades of the Amperius-VK 250 are not protected from lightning strikes. Taking into account that the blades have a higher probability to break than to burn due to a lightning strike, the protection system is reducing the probability of *burning*, but is not reducing the probability of *falling parts*. Concerning *material* *failure*, the turbine installed in Lichtenegg does not have any system to detect *material failure* in advance. It can only be detected during maintenance. No special protection system is present. The influencing factor F1 regarding the axial-orientation is increasing failure frequency, while the influencing factor F2 is decreasing the frequency, because the turbine has a nominal capacity of 5 kW. The occurrence frequency of *falling parts* can therefore not be reduced by the system like shown in equation 19.

As examined in chapter 5.1 the occurrence frequency of ice accumulation in Lichtenegg can be assumed as 1.51 times per year. Looking at the first branch of the ET presented in figure 5.5 the detection and stopping mechanisms of the turbine are taken into account. The manufacturer refers to a synoptic sensor for detecting ice accumulation on the turbine. The sensor measures temperature and humidity to detect meteorological conditions for ice accumulation. If they occur, an alarm signal is sent to the operator of the turbine. Further the operator can decide if the turbine should be shut down. Hence, the Amperius VK-250 does not have an automatic shut down system, but can possess a detecting sensor, which transmits a signal for manual shut down. Equation 21 shows the occurrence frequency of *ice throw* if that kind of sensor is installed. The Amperius VK-250 tested in Lichtenegg is not possessing that sensor. The turbine is situated in a rural area with nobody passing by directly under the SWT and warning signs for *ice throw* are installed. No detection, stopping or de-icing systems are installed. Due to the fact that no protection system preventing *ice throw* is installed at the Amperius VK-250 in Lichtenegg the annual frequency of *ice throw* shown in equation 20 is equal to the frequency of the initial hazard. Regarding de-icing, the manufacturer recommends manual deicing by using deicer and a high pressure cleaner or chipping the ice down from the rotor blades. The deicing system would not influence *ice throw*, but would reduce the frequency of *ice fall*.

To present the worst case scenario, *falling parts* was also calculated for a VAWT with a nominal capacity < 5 kW and no protection system. Like shown in equation 22 falling parts are calculated to occur nearly five times per year for that type of turbine.

$$h_{falling\,parts}(VAWT\ <\ 5\,kW\,in\,Lichtenegg) = 4.74 \cdot 10^0 \tag{22}$$

5.5 Results Ecovent 10

The second example is the VAWT Ecovent 10. The calculations for the Ecovent 10 are based on the values presented in table 12. As for the Amperius VK-250, the values are based on experiences and information on the protection systems, which are presented in this chapter.

Table 12: Presumed operators for the frequency calculation of the three unwanted events for the Ecovent 10

operator	value	operator	value	operator	value
		P_1	$1.6{\cdot}10^{-9}$		
f_1	10589	$P_1{'}$	$3.6{\cdot}10^{-7}$		
f_2	0.019	P_2	10^{-2}	F_1	0.457
f_3	0.2	$P_2{'}$	0.6	F_2	0.4
$f_4 + f_5$	1.508	P_3	10^{-3}		
		P_{4+5}	0.2		

$$h_{burning}(Ecovent\,10\,in\,Lichtenegg) = 2.07 \cdot 10^{-4} \quad (23)$$

$$h_{falling\,parts}(Ecovent\,10\,in\,Lichtenegg) = 1.52 \cdot 10^{-2} \quad (24)$$

$$h_{ice\,throw}(Ecovent\,10\,in\,Lichtenegg) = 3.02 \cdot 10^{-1} \quad (25)$$

Ecovent 10, as already mentioned in the methods, is a HAWT running leeward. Its nominal capacity is 10 kW. The SWT was used as an example in the present analysis, because it is the largest SWT tested at the research site and possesses the highest amount of protection systems. The turbine reaches its nominal capacity at wind speeds of about 6 m/s. At wind speeds of about 12 m/s the pitch system starts intervening and at wind speeds of 25 m/s the turbine turns of. The Ecovent 10 principally has two types of protection systems: a hydraulic flyweight governor and electronic sensors. It is a redundant system. The hydraulic governor, which is the primary system, is regulating the angle of attack of the blades. In low winds the blades are in vane position. At the starting wind speed of 2.5 m/s the hydraulic pitch system will bring the blades in full angle of attack to get as much energy out of wind as possible. At wind speeds higher than 12 m/s the preloaded spring adjusts the blades to reduce the bearing pressure. If any failure of the electronic system occurs, the spring brings the blades back in vane position.

The electronic system measures several parameters and is automatically shutting down the turbine if any failure occurs. Next to the control of the generator's parameters, the system is measuring wind speeds using an anemometer as well as vibrations using a vibration sensor. If the vibrations or the wind speeds get close to the limits of machinery, the system is automatically turned off and can only be turned on again by the manufacturer himself, after controlling the functionality and safety of the SWT. Vibrations occur if the turbine gets imbalanced. This can occur for example due to ice accumulation, wind turbulences or material failure. Therefore, this sensor prevents different unwanted events (Hoffmann, 2017). Regarding *material failure*, both influencing factors, F1 and F2, decrease the failure frequency, because it is a HAWT and has a nominal capacity of $\geq 5\,kW$.

Combining the calculated frequencies of occurrence of the initial hazards with the information about the protection systems as well as the experiences of the manufacturer, the occurrence frequencies of the unwanted events are shown in equations 23, 24 and 25.

6 Discussion

Some assumptions on the reliability of SWT themselves as well as on the protection systems can already be made referring to the five years of testing in Lichtenegg. Nevertheless, five years are a short time of evaluation, considering the prospected life time of 15 to 20 years. Five out of the seven failures observed in Lichtenegg occurred within the first two years of operation, which is typical for machines. Failures due to wrong installation or bad dimensioning mostly get visible early. Long time evaluation could further show, whether the failure frequency is decreasing over the years and if it fits the bathtub curve: Typically, a hardware's reliability function shows three phases of life. In the early life phase, known as *Burn-in*, high failure rates occur and decrease over the time. In the middle life phase, known as the *random failure* period, failure rates are constantly low. In the late life phase failure rates increase due to *wear out*. These phases fit a reliability function looking like a bathtub (Grams, 2008).
The findings shown in chapter 4 and 5 are discussed in this chapter. It is started by considering the reasons for some criteria having a significant influence on *material failure*. It is discussed what could be the reason for *nominal capacity* and *axial-orientation* having a significant influence on *material failure* and what could be a reason for *certification* not having an influence on *material failure*. Further on, the protection systems are taken into account. It is discussed, which are the most suitable protection systems and where more effort is needed to reduce the risk of failure. Following the relevance for urban use as well as the interaction with economical safety is discussed. Finally the tool PSA and its adaption on SWT are evaluated.

6.1 Reasons for influences on material failure

Unlike expected *certification* was the only criteria tested, which has no significant influence on *material failure*. In this section it is discussed what might be a reason for the results of the testing of the influencing criteria. Additionally other criteria are named that are interesting to test with a bigger amount of data available. In general it should be mentioned here, that the negative testing does not mean that all SWT under 5 kW nominal capacity as well as all VAWT have high failure frequencies. There might be some turbines within those groups which are highly reliable. The results are means of SWT groups and should be assessed carefully.

6.1.1 Increased material failure related to nominal capacity smaller 5 kW

Within the testing of influence criteria, shown in chapter 3.2, it was identified that size A SWT, having a nominal capacity smaller than 5 kW, are more exposed to *material failure* than SWT with a higher nominal capacity. To interpret this result correctly, a closer consideration of the amount of turbines, the testing months as well as the full load hours of the two sizes is necessary. The testing is based on seven failures that happened in five years of testing with a generated power of 370 000 full load hours. Even though ten out of the 15 turbines are size A, the full load hours of the size B turbines are nearly double the hours of the size A turbines. By considering the amount of months the turbines were tested for, it becomes visible that three size B SWT were tested for nearly 60 months, while most of the size A SWT were tested for a few months only. The longest period that a size A SWT was tested for accounted 32 months. Regarding the contribution of the total testing time, therefore, the amount of tested months of size A and size B SWT are comparable. Still the accumulated full load hours of size B SWT are more than double the full load hours of size A turbines (see table 9). This can be explained by the fact that some size A turbines showed a very low productivity compared to their nominal capacity. This might be related to a bad fitting to the side or a poor quality of the turbine. Therefore, if the testing would have been based on installation-time (months) instead of production-time (full load hours), nominal capacity would not significantly influence *material failure*.

These findings could be related to the fact that there are more SWT within that size A on the market. There are a lot of manufacturers of SWT under 5 kW nominal capacity who do not have longtime experience. Size A SWT are a good opportunity to start a business and figure out if the turbine's design is adequate. The past has shown that a lot of turbines within size A remain on the market for only a few years. When experience had shown either inefficiency or high failure frequencies, they were removed from the market. The same of course happens to size B SWT as well. Nevertheless, most of the size B SWT are technically more complicated and further matured. Therefore, the result of size A SWT being more prone to *material failure* has to be treated carefully. There are some size A SWT that have no problems with *material failure*, but especially due to the great market diversity the average of size A SWT is more prone to *material failure* as a SWT with a capacity greater 5 kW nominal capacity.

This should be taken into account by investing in a SWT. One should not only consider the manufacturer's values, but investigate if some of the turbines have already been running for a certain time and if they are recommended by experts. The identified influence of size on material failure frequency could be a secondary effect of *material failure* that is not directly related to the size, but to the technical experience. In conclusion, the lower material failure frequency of size B turbines might be a secondary effect of more experience of their manufacturers. This assumption could explain the tested influence of size, but it still has to be proven in further research with a bigger amount of data.

6.1.2 Increased material failure related to the vertical design

The vertical design also has been identified to significantly influence *material failure*. Even though there were only three VAWT with 44 months of operation within the data set, the huge amount of failures which occurred in that short period indicate a direct correlation between *material failure* and the *axial-orientation*. During dialogues with experts it was often mentioned that VAWT have to cope with high vibrations due to the rotor partly running against the wind as well as the resonance of the turbines eigenfrequency and the towers frequency (Banzhaf, 2016). This could be a reason for the high *material failure* frequency of VAWT. Already some research regarding the vibrations of VAWT is being done, see for example Thiemke *et al.* (1996); Peppoloni (2016). To solve this problem vibration isolators are in development and in the process of testing. Much more experience is present concerning HAWT than concerning VAWT due to decades of industrial research and development. Nevertheless, it has to be taken into account that only three VAWT have been tested in Lichtenegg. The calculated influencing factor F1 = 9.091 is extremely high. The emphasis might be extreme due to the small amount of data. Therefore, one has to be careful by using this influencing factor for failure frequency calculations. If a bigger amount of SWT data would be available another test of independence would be helpful to see whether the calculated factor is viable. Still it can be assumed that the vertical design still is in need for further technical improvement.

6.1.3 No influence of certification

Surprisingly no influence of *certification* of a SWT on *material failure* could be identified. A few more failures happened within the group of not certified turbines, but two certified turbines failed as well due to *material failure*. The distribution within the tested turbines does not seem to be the problem. As shown in table 6 the number of turbines as well as the hours of testing are similarly distributed between certified and not certified turbines. So the result can not be explained by an inequality of the data. In literature SWT with a certification are highly recommended and are presumed to be from high quality (Twele, 2013). It is often criticized that certification is too expensive, so that young SWT companies can not afford it. It is also often mentioned, that the different country specific certifications rely on the international standard DIN EN / IEC 61400-2 (IEC, 2006). So there should not be much variance between the different certifications of SWT. Certified SWT should fail less than not certified ones, if we stick to the common sense of experts. During the feedback meeting of the Arbeitsgruppe Kleinwindkraft Wien (2016) it was mentioned that wrong installation as well as missing protection systems can easily lead to failures of reliable SWT, even though they are fulfilling all criteria for a certification. Moreover, some SWT got sold without towers. The towers as well as the connecting part between tower and turbine are critical components, at which some failures could be observed at the testing site. Therefore, the result of the test of influence shows, that *material failure* concerns more than the turbine itself. *Material failure* often happens at the tower or the connecting parts and can occur due to wrong installation even at a high quality turbine. Hence it can be recorded that a safe usage of a SWT not only depends on the turbine itself, but also heavily on the tower and the installation. The certification in contrast is done just for the turbine itself and not for whole system, including the tower and the way of installation. It might be a wrong conclusion that certified turbines are as failure-prone as not certified SWT. However, the results show that certification of the turbine is not the only criteria which should be taken into account concerning safety of the whole system.

6.1.4 Criteria recommended to test

Even though the set of failure data was extremely small, the testing of influencing criteria illustrated the main problems arising on the SWT market. The test of independence is an easy method to gather information about reasons of failure. It helps to identify which groups of turbines are more prone to *material failure*. The following criteria arose from expert dialogues to further be interesting to test. The data of the present research project has not been big enough to test these criteria, but by collecting more data from individual operators of SWT, they could be evaluated by using the same method.

1. Vibration isolators for VAWT are designed to reduce the failure frequency. Vibrations can occur due to imbalance, incorrect installation, defects or load alternation. They can lead to failure of the blades, weldings or screw joints (Thiemke *et al.*, 1996). Vibrations have been identified as the most challenging problem regarding VAWT. Vibration isolators are being designed to reduce these vibrations and their resulting dynamic loads (Banzhaf, 2016). The use of those could not only reduce vibrations, which are noticeable in the building the SWT is built on, but also the wear of the SWT itself. Therefore, *material failure* due to wear of the turbine related to high dynamic loads could be reduced by a vibration isolator. Anyway, already shortly after the testing period of the present study, *material failure* of a VAWT with vibration isolator could be observed. Whether an isolator is reducing the turbine's *material failure* frequency could be tested by collecting data from several SWT run by different people at different sites. Using ten turbines with a testing period of at least five months some assumptions already could be made.

2. Another criteria mentioned by the experts is whether the tower does originally belong to the turbine or not. The connection between tower and turbine has been identified as a weak point of the construction and therefore it is crucial to use a connection which is well calculated and tested. Further the tower itself was observed to be prone to *material failure*. This could relate to the fact that often there is less effort put into the tower selection than into the selection of the turbine itself. Nevertheless, if the tower collapses it is a severe accident, which can destroy the whole turbine and may harm people. This risk could be eliminated by the manufacturer directly selling the tower together with the turbine, so that new calculations for every turbine would not be necessary. Since in Lichtenegg the towers that were used for testing the different turbines always remained the same, this criteria could not be tested. Therefore, it would be necessary to have data from different operators of SWT.

3. The third point that was mentioned by several experts from industry considers who installed the SWT. There may be a difference regarding *material failure* between turbines installed by the manufacturer himself or engineers trained by the manufacturer and turbines installed by the operators, who are less experienced with the specific SWT. An accurate installation is crucial for reducing the wear of the SWT. The turbine has to be balanced and secured correctly. Again, this criteria could not be tested in Lichtenegg due to the fact that all turbines are installed by the same engineers.

6.2 Shaping possibilities concerning protection systems

In this chapter the failure frequencies of the different SWT using different protection systems are compared to deduce which protection systems reduce failure frequency efficiently. It is examined where there is more research and development needed to further reduce the failure frequencies. It is shown which failure frequencies can already be significantly reduced. Figure 6.1 illustrates the frequency bandwidths of the turbines tested in Lichtenegg calculated using PSA (green) as well as the observed failure frequencies of Piggott turbines (Sumanik-Leary, 2013) in a logarithmic graph. Due to their designs it is assumed, that the two examples of SWT used for the calculations illustrate the highest and lowest failure frequencies. Concerning *falling parts*, the highest failure frequency is not the one calculated for the Amperius VK 250, but for a small VAWT as described in 5.4.

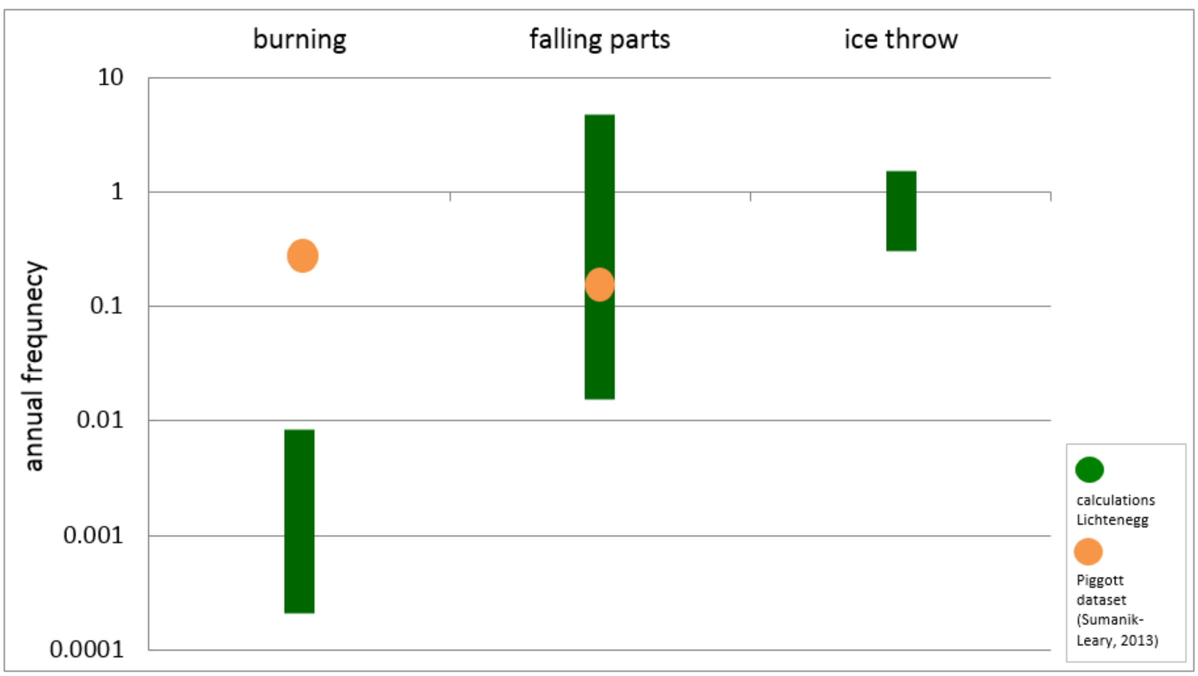

Figure 6.1: Occurrence frequency bandwidths of the three unwanted events calculated by PSA for the example SWT in Lichtenegg (green) and observed failure frequencies of the Piggott dataset (orange) (own figure)

6.2.1 Efficient reduction of burning

Comparing the occurrence of *burning* within the data of Piggott SWT to commercial SWT, pitch systems and brakes significantly reduce the frequency of *burning* due to overheating (see figure 6.1). An annual frequency of 0.37 was observed for the event of *burning* due to *high wind speeds* in Sumanik-Learys data on Piggott turbines. No *burning* occurred within the seven failures in Lichtenegg. By using a redundant braking system together with an aerodynamic power regulation system, the frequency of *burning* due to *high wind speeds* can be reduced down to $1.69 \cdot 10^{-5}$. In dialogue with experts *burning* was not totally excluded from being possible to occur on commercial SWT, but no one has observed it yet (Arbeitsgruppe Kleinwindkraft Arbeitsgruppe Kleinwindkraft Wien, 2016). While Piggott turbines use a mechanical furling system to reduce bearing pressure from *high wind speeds*, commercial SWT need to have a redundant braking system. Piggott turbines do not have a brake. As Sumanik-Leary (2013) already mentioned, brakes successfully reduce the occurrence frequency of *burning*. Pitch systems also seem to be able to successfully ensure energy production in higher wind speeds without the risk of overheating. Especially for turbines with a redundant braking system, the occurrence frequency of *burning* due to overheating is extremely low.

Burning related to *lightning* could neither be observed by Sumanik-Leary (2013) considering Piggott turbines, nor within the five years of testing commercial SWT in Lichtenegg. An expert from industry reported on a lightning strike hitting a turbine. Even though the turbine did not have a lightning protection system, but only a grounding within the tower, only an electrical failure occurred (Hoffmann, 2017). In order to ensure that no risk for people will arise in case of a lightning, a grounding within the tower is necessary. An earthing with a radius great enough to derive the lightning, can successfully prevent a burning of the generator, but still all measuring instruments will melt (Hoffmann, 2017). In conclusion, concerning the risk for people using commercial SWT in urban areas, *burning* seems to be a minor one. Despite these differences, it is possible to make some assumptions on the protection systems on the basis of these values.

6.2.2 Huge variance regarding falling parts

Regarding *falling parts* an annual frequency of 0.17 was observed for Piggott turbines. The calculated value for the Amperius VK-250 is 0.74 failures per year. For a small VAWT it is even higher, up to more than once per year (figure 6.1). The values can not directly be compared because of the entirely different sites the data has been collected as well as the different ways of calculating. While the value for the Piggott turbines is calculated on actual data from the past, the values for Lichtenegg are prospective frequencies calculated by using PSA. Considering the sites, a comparison of the annual mean wind speeds shows that in Cajamarca in Peru even higher wind speeds than Lichtenegg occur. So the failure frequency might have been different for a Piggott turbine installed in Lichtenegg.

The Ecovent 10 shows the lowest failure frequency of 0.015 failures per year. The Piggott turbine uses a furling system for aerodynamic power regulation whereas the Amperius VK-250 uses a redundant braking system. While the braking systems seem to protect much more efficient from *burning*, concerning *falling parts*, no significant reduction was detected. The observed value of 0.17 failures per year for the Piggott turbines lies within the bandwidths for the turbines in Lichtenegg. Additionally, VAWT are much more prone to vibrations. By using a vibration-sensor the Ecovent 10 can effectively reduce the occurrence frequency of *falling parts*. Nevertheless, the frequency of *falling parts* is still much higher than the frequency of *burning*.
Concerning the initial hazard *lightning* the occurrence frequency of *falling parts* is also less reduced than the occurrence frequency of *burning*. Due to the fact that blades of the SWT are not protected against lightning strikes, *the* occurrence frequency of *material failure* can not be heavily reduced due to the lightning protection systems. If the lightning hits the blade, which is highly probable according to Cooray (2015), it can brake and consequently lead to severe accidents.
Material failure showed to be a major cause for *falling parts*. It is hard to differentiate which failure was mainly caused by *high wind speeds* and which was caused by *material failure*. It seems to be the combination of a wrong installation or wrong dimensioning of the turbine and high wind speeds that most likely leads to *falling parts*. Further the calculated influencing factors F1 and F2 have a high influence on the resulting failure rate. It is assumed that the vertical design is increasing *material failure* by the factor F1 = 9.091. This is highly influencing the output values of *falling parts*.
All in all an efficient overspeed protection system as well as a reliable material and installation seem to reduce occurrence of the unwanted event *falling parts*. A vibration sensor can further reduce the it.

6.2.3 Poor prevention of ice throw

Ice throw is calculated to happen 1.51 times per year without any protection system. This unwanted event in neither affecting the turbine itself nor is a harm resulting if there are no people crossing the area of the throwing distance of the SWT. Therefore, a lot of SWT for rural use do not have a protection system to reduce the occurrence of *ice throw*. Nevertheless, no matter if it is a Piggott turbine or a vertical Amperius VK-250, if placed in areas where ice and snow are likely to occur and where people are near the turbine, some kind of ice throw prevention should be appended. Several types of detection and stopping mechanisms concerning *ice throw*, are already explained in chapter 2.3.3.
The synoptic sensor recommended by Amperius, could reduce that risk if it is combined with a direct reaction of the operator. Synoptic sensors tend to predict positively wrong often. In January 2016 35 % of the time the humidity was 90 % or higher and the temperature was 0.5°C or lower. If the SWT would stop automatically every time, it can dramatically reduce the production rate

during winter time. Therefore, the synoptic sensor is only used in combination with an alert signal send to the operator, who has to examine if there is ice on the SWT and decide whether the SWT should be shut down. Manual shut down adds a human factor to the protection system. Since SWT are normally not full-time observed, the risk arises that no one directly respond to the alert signal. Using the ET it was calculated that the occurrence frequency of the unwanted event *ice throw* can be reduced to 0.9 times per year by a well observed alert system, including a camera. This system makes it possible to detect ice accumulation by the operator without being on site (see figure 6.1).

Vibration sensors seem to be more efficient in reducing the occurrence frequency of *ice throw*. Especially if greater ice packs (more than 200 g) have accumulated on the blades, they bring the turbine in imbalance and therefore can be detected by a vibration sensor. In contrast to a synoptic sensor, the vibration sensor is normally not detecting ice accumulation positively wrong. A vibration sensor combined with a direct shut down mechanism, like used in the Ecovent 10, was calculated to reduce the unwanted event *ice throw* to 0.3 times per year (equation 25). The vibration sensor only detects relevant amounts of ice. Small loads will not be detected. Even though the protection systems are reducing the occurrence frequency of *ice throw*, the occurrence frequency is still high.

6.3 Relevance for urban use of Small Wind Turbines

The evaluation showed that most of the turbines as well as their protection systems are designed for rural areas. If SWT are used for generating power for a farm, they are installed at least 100 m away from the center of living. Therefore, the urgency of valid protection systems is much smaller. Nevertheless there are more and more turbines present on the market directly made for urban use. These turbines often do not have more efficient protection and control systems than the ones designed for rural use. There are some SWT for urban use without any protection system at all, so that the turbines are more affordable as well as smaller, lighter and easier to handle. The evaluation of the data from the research site in Lichtenegg showed that the use of SWT without any control sensors are not save enough for urban use. The commonly used protection systems seem to not be made for people passing close to the turbine.

Burning is the only unwanted event that can be efficiently reduced by the braking systems. *Ice throw* and *falling parts* in contrast, become more crucial when it comes to urban installations. The occurrence of *ice throw* has to be evaluated site specifically. In climates where snow and ice are common, sensors detecting the occurrence of ice and shutting down the turbines when the ice load gets higher than 200 g per blade seem necessary. These technology prevent *ice throw* and lead to *ice fall*. Some technologies are in use already, which indicate that there are detection possibilities within the financial feasibility, as for example the vibration sensor used by the Ecovent 10. There are also some sensors on the market, which can be retrofitted to SWT.

One example is the Eologix Sensor System, which consists of one receiving unit and a number of sensing units which are distributed over the blades (Eologix sensor technology gmbh, 2017). If the use of retrofitted sensors is profitable for a SWT operator has yet to be evaluated.
Active de-icing does not prevent ice throw, but is used to let the ice fall off controlled after detection. Thereby, the time the turbine has to stand still due to ice accumulation is reduced. Nevertheless, it is not often used for SWT, because it does not pay off due to high system costs. Additionally, the accumulation of ice on standing objects is very present in cities. There are buildings, street lamps, street signs and other high utilities coping with the same problems. Therefore, regarding safety, measures have to be taken generally, not specifically for SWT.
Falling parts does heavily depend on the design of the SWT. All sorts of criteria like design, material and safety systems are influencing the occurrence frequency of *material failure*. Nevertheless the occurrence is very present within the evaluated data and has severe accidents as a result. Therefore, a dramatic reduction of *falling parts* for the urban use of SWT is necessary. Next to the improvement of the material, early detection would dramatically reduce failure frequency. The risk of wrong installation or material fatigue can not completely be eliminated, therefore a detection system is recommended.

6.4 Interaction between physical and economical safety

As mentioned in chapter 2.2.4 presently the LCOE as well as investment costs of SWT are high compared to other ways of energy production. Hence it is crucial to have a reliable technology to reach cost-efficiency. The most important factor for economic efficiency of an urban SWT is optimizing the placement (Drew *et al.*, 2013). But due to the sensitivity of cost-efficiency, not only the most important issues, like best wind speeds and efficiency of the turbine itself, should be taken into account. Especially at sites with moderate wind speeds and when using SWT with low capacities, mostly used in urban areas, costs for maintenance and repair can determine if the turbine is cost-efficient or not. The high occurrence of *material failure* showing up in the present analysis does not only represent potential harm for people, but also an economical threshold. Therefore, also regarding economic efficiency, it is crucial to reduce the probability of failure.
The insurance company *Oberösterreichische Versicherung* offered an insurance for SWT with investment cost up to 30 000 Euro between 2013 and 2015. It became apparent that not enough people are interested and too many failures happened. No valid balance of risk could be established (Aigner, 2016). In Germany there are still some insurance companies who offer an insurance for SWT with investment costs up to 10 000 Euro. The SWT can be included in the building insurance. Before a turbine will get included in the building insurance, an expert from the insurance company will decide whether the turbine fits the safety criteria of the insurance company. At present only HAWT, which are already well established on the German market and possess a full installation system including the tower, will be incorporated (Wengler, 2016). Roof-top SWT as

well as VAWT will not be incorporated to building insurances by the insurance companies the author was in dialogue with. A specific insurance for the SWT or insurances for production losses are offered, but in most cases they are not cost effective. Therefore, also regarding insurances for SWT, a reduction of failure frequency might have positive consequences. In dialogue with the experts from insurance companies the same failures as identified in the present analysis were mentioned to be the reason for the missing risk-balance and the reduction of insurance possibilities for SWT operators. The most recent failures have been damaged brakes and broken blades due to *high wind speeds*. The vibrations are named as the reason for roof top SWT not being covert by the insurance companies. *Lightning* as an initial hazard as well as *burning* as a result have been less challenging (Wengler, 2016). Therefore, reducing the occurrence of *falling parts* specifically might go along with better insurance possibilities for the operators. A combination of safer turbines and generally more installed SWT might make the market more interesting for the insurance companies. In consequence the financial risk for the operators could be reduced.

6.5 Tool evaluation: Probabilistic Safety Analysis for Small Wind Turbines

PSA is a well established tool for evaluating the risk of huge nuclear power plants. For smaller technologies with fewer safety systems it currently is not applied often. There has been some effort concerning large wind turbines, but it never had a big influence on industry. In the project of Pressl *et al.* (2015), it was first used to directly evaluate the risk of a smaller technology: Wastewater pipelines in Austrian lakes. Due to the effective use in that project, within the present study it has been adapted to another new technology. The present study revealed that a lot of information about the design of the specific turbine as well as many years of experience with the technology are necessary to generate valid values for calculation.

The steps of conduction showed to be comparable to the analysis of large wind turbines. Especially the way Rademakers *et al.* (1993) conducted the PSA is a comparable approach. Merely the last step of Rademakers *et al.* (1993) analysis', the *Structural Reliability Analysis* could not be adopted. This step is only possible and reasonable if a specific turbine shall be analyzed.

Due to the ETs and influencing factors generated in the present study, a first comparison of different turbines is possible. For a deeper understanding of the improvement potential of a specific turbine, more information and a greater amount of evaluated SWT of likewise designs would be necessary. The influencing criteria recommended to test in chapter 6.1 could be examined on their influence on *material failure*. If some of them are significantly influencing material failure, further influencing factors could be added to the equation for *material failure*. The PSA could further be used by manufacturers as a tool for the risk evaluation process according to the standard ISO 14121.

6.5.1 Challenges in adapting PSA to SWT

The biggest challenge in adapting PSA to SWT was finding out about the actual probabilities of the protection systems failure rates. In order to get valid values for failure rates much more data would have been necessary. Due to the fact, that at present not many SWT are in use and that there are no big operators, but separate households operating the SWT, it is very hard to get failure data of SWT. Nevertheless, thanks to the few years of evaluation in Lichtenegg complemented with data from Sumanik-Leary (2013) and the knowledge from experts in industry and research (Arbeitsgruppe Kleinwindkraft Arbeitsgruppe Kleinwindkraft Wien, 2016), rough estimations on failure frequency could be made.
A second challenge were the great difference between the considered SWT. The considered turbines are particularly different in size, design and the material used. Therefore, not only the safety measures are decisive for the differences in failure frequency. The integration of the influencing factors helped to solve this problem. Nevertheless, by now there are only two design differences (nominal capacity and axial orientation) included in the equation for *material failure*. More data of comparable turbine designs would have provided helpful information. With a bigger set of data also other influencing criteria could be tested. For example the influence of a vibration isolator on VAWT, like described in 6.1, could provide further helpful information.
Moreover a PSA normally includes a detailed consideration of the material used. In the beginning of the study it was tried to include material analysis, but again the huge differences between the turbines made it impossible to evaluate the entirely different material as well in the given time frame. By conducting a PSA for a specific turbine the consideration of the used material could be another interesting part.
A big difference to the PSA concerning nuclear power plants was the occurrence frequency of the initial hazards. While the occurrence frequencies of the initial hazards of nuclear power plants failure are rather small, the initial hazards for SWT failure like *high wind speeds* or *freezing rain* occur regularly. With the result, that the protection systems of SWT have to be built to intervene regularly. This results in totally different initial frequencies. The classical way of calculation to convert annual frequencies in probabilities also used by Pressl *et al.* (2015) is not suitable for frequencies close to once per year or higher. To avoid this problem, in the present study it was directly calculated with the actual annual frequencies.

6.5.2 Potential for further use of PSA regarding SWT

Two different applications of further use of PSA on SWT could be identified. On one hand, it can scientifically be used to compare different technologies and protection systems. On the other hand, a tool is provided, which can be used by manufacturers to evaluate a specific type of turbine and to find out where improvement could be needed and which protection systems are suitable.
Starting with the scientific potential, further improvement of the adaption of PSA to small tech-

nologies in general as well as SWT in particular could generate a more valid tool for individual and general adaption. The calculation of influencing factors showed to be an important part for the use of PSA for small technologies. Fisher's Exact Test showed to be suitable for that use. When more data is available, the χ^2-test can also be used (Pressl *et al.*, 2015). In contrast to big power stations, like nuclear power plants or even large wind turbines, there are much less protection systems used considering small technologies. The evaluation of the protection systems is helpful, but often there is simply no protection system at all or only one, what makes a consideration of the technology itself and its weak points even more important. By testing more criteria on their influence, SWT can be compared in detail. Thereby more recommendations for operators could be provided.

Concerning industry, due to the fact that SWT are a small technology, an evaluation tool, which neither needs much financial nor much time investigation, is needed. By using the ETs provided within the present study as well as the influencing factors, manufacturers can use the tool easily to evaluate which protection system would be helpful to improve the turbines' safety. It could also be used for the risk evaluation necessary to fulfill the guidelines for machinery (ISO, 2007) and to give valuable information to their clients. The ETs can be complemented by using FTs for consideration of the specific protection systems. Again it should be mentioned, that the frequencies are only approximate values, which can never include all influencing events. Not the actual value is providing the useful information, but which systems can significantly reduce the output value.

7 Conclusions

The aim of the study was to identify what are the potential failures of SWT, which may physically harm people and to determine how often they occur. The Probabilistic Safety Analysis was adapted to SWT to identify failure frequencies and possibilities to reduce them. Using event-trees different protection systems were examined.

Three events which may physically harm people were identified: *burning*, *ice throw* and *falling parts*. The risks of *ice throw* and *falling parts* are highly present regarding SWT. Without protection systems *ice throw* happens about 1.5 times per year and *falling parts* about 0.7 times per year. Regarding *ice throw* it is unclear how heavy the ice loads are and how far they get thrown, therefore more effort on evaluating *ice throw* of SWT is needed. Regarding *falling parts* serious accidents have been observed, so sensors for early warnings as well as the reduction of the initial hazards are highly recommended. *Burning,* in contrast, can be reduced efficiently by commonly used braking systems.

Further five initial hazards leading to the unwanted events could be determined: *high wind speeds, lightning, material failure, fog* and *freezing rain.* Except *material failure*, these hazards are weather conditions, which can be examined site specific. *Material failure,* in contrast, is turbine specific. *Material failure* is the most present initial hazard related to *falling parts* and further the most regular source of failure. It is related to serious accidents especially concerning VAWT and turbines smaller than 5 kW nominal capacity. Technical improvement, correct installation and permanent monitoring might help to reduce *material failure*. Especially dynamic loads seem to be underestimated often and lead to *material failure*.

The analysis showed that the urban use of SWT requires different safety measures than the rural use. For an urban use the risk is often not adequately reduced. Financial feasibility was further determined to be influenced by risk reduction. Due to the current electricity tariff in Austria in relation to the investment costs of a SWT, a profitable use of SWT is nearly impossible at present. Therefore, cost reduction is a highly discussed topic regarding SWT. Especially regarding SWT under 5 kW nominal capacity, repairing costs as well as costs regarding the permission procedure are a significant part of the total costs. A reliable design combined with an easier permission procedure could help to make SWT profitable. A detailed evaluation about which SWT should be installed and what site is most suitable is highly recommended before installing a SWT to increase its efficiency and safety. Reducing failure frequencies can further lead to more insurance opportunities.

In the present study the Probabilistic Safety Analysis was adapted to SWT the first time. PSA showed to be a helpful tool to evaluate the risk of unwanted events related to SWT. The ETs combined with the influencing factors make an easy comparison of different designs and safety systems possible. Further research concerning the influencing factors would improve the tool. It proved to be helpful to identify weak points and shaping possibilities as well as which safety measures should be taken into account and which protection systems are efficient.

List of Tables

List of Figures

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