The Potential of Eliminating Government Subsidies in the Wind Power Business Case

- A business assessment from a technological perspective at E.ON Vind

Preface

This project marks the end of our master's studies in Industrial Engineering and Management, at the Faculty of Engineering, Lund University. Spending the spring at E.ON Vind has truly been an inspiring time and has given us the opportunity to learn more about the wind power industry.

We would like to take this opportunity to thank everyone at E.ON Vind for all the support and the willingness to take time to contribute to this project. Also, a special thanks to our supervisor Henrik Malmberg for giving us the chance to perform this study and with his professionalism and passion inspired us to work our hardest.

We would also like to thank our never-ending source of industrial wisdom – Bertil I. Nilsson – for his guidance and support during this project. His valuable insights as well as the feedback given by our opponents – Hannes Teder and Gustav Wiklund – have helped us in producing this report.

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Abstract

Title	The Road to Profitability through Technology Development. - A wind power business assessment at E.ON Vind.
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Supervisors	Henrik Malmberg – Team leader, Project Development, E.ON Vind Sverige AB. Bertil I. Nilsson – Adjunct Professor, Department of Industrial Management and Logistics, Lund Institute of Technology, Lund University.
Issue of study	For the past ten years there has been a remarkable growth in the wind power industry. During 2003 – 2010 the production capacity increased by 456 % in Sweden, corresponding to total capacity of 2019 MW. An additional 754 MW was installed in 2011, and there is a planned capacity installation of 950 MW for 2012. This will, according to a prognosis from Svensk Vindenergi, generate a power production of 7.7 TWh in 2012 and 11 TWh in 2013. Furthermore, if the expansion continues at this rate, wind power will correspond to about 10 % of the total power production in Sweden by 2015. Despite the rapid growth wind power projects are still dependent on government subsidies, i.e. green certificates. However, as the business continues to grow so do the technological advancements, thus providing new and more efficient wind turbine designs. Both incremental

as well as novel solutions have been developed over the years. In order to find new dominant designs they need to be evaluated both from a technical and a business point of view.

Purpose

The purpose of this study is to investigate the possibility for technology development to further strengthen the Swedish wind power business case, and ultimately examine the potential for eliminating the need for government subsidies.

Objectives

The objectives of this thesis are the following:

- Scan for trends in technology development and choose areas according to the scope and delimitations of the study.
- Evaluate the chosen technical areas – both financial and non-financial aspects.
- Depending on the outcome in the previous evaluation discuss the implications for the case company.

Methodology

A case study with an analytical approach has been performed for the development of the evaluation method, which consists of both qualitative and financial measurements. The qualitative aspect is covered by a method for technology concept selection, which assesses technologies based on several criteria. These criteria have been developed through literature studies and interviews with concerned stakeholders in the wind power industry. The financial aspect is covered by a capital budgeting model, intended to assess the cost of the wind power case including all costs over its lifetime, capital expenditure, operations and maintenance, and cost of capital.

Conclusion

A potential for single technology advancements to sustain the business case's independence from green certificates has been identified. The technological development is mainly focused on increasing turbine size, i.e. generator output and rotor diameter. However, other incremental implementations have shown potential of business case improvements as well.

Key words Green certificates, technology development, onshore wind power, wind turbine generator (WTGs), business case evaluation

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1. Introduction

This chapter is intended to provide the reader with the background of this thesis. The current situation in the wind power industry is initially presented in order to give the reader an understanding of the purpose and objectives of the thesis. Furthermore, delimitations and target group are presented.

1.1 Background

E.ON is one of the largest investor-owned power and gas companies in the world, and operates globally in a wide range of businesses within the energy sector. In recent years increased efforts have been focused towards the expansion of renewable energy production, where wind power plays a key role.

By the end of 2007 the power production from wind turbines in Sweden amounted to 1.43 TWh, corresponding to approximately 1 % of the total power production.[1] The same year, EU adopted the 20/20/20 target, which states that the union's greenhouse gas emissions are to be reduced by 20 % by the year 2020, relative to 1990 emission levels. The EU target furthermore states that 20 % of the energy consumption should come from renewable energy sources.[2]

Consequently, this demand for renewable energy has led to the introduction of financial incentives for the development of wind power production. The Swedish green certificate system is a market-based support system, intended to stimulate the expansion of power production from renewable sources. Producers of renewable electricity are allocated one certificate unit for every MWh they produce, which are then sold to suppliers who are obligated to purchase a certain quota of certificates.[3] The

[1] Energimyndigheten (2011c)
[2] Energimyndigheten (2011a)
[3] Swedish Energy Agency (2011)

Swedish national aim is that by 2020 the production of electricity from such sources shall amount to 25 TWh annually.[4] In addition, the Swedish government has set up a planning framework for wind power development equivalent to an annual production capacity of 30 TWh, of which 20 TWh onshore and 10 TWh offshore.[5]

For the past ten years there has been a remarkable growth in the wind power industry. During 2003 – 2010 the production capacity increased by 456 % in Sweden, corresponding to total capacity of 2019 MW.[6] An additional 754 MW was installed in 2011, and there is a planned capacity installation of 950 MW for 2012.[7] This will, according to a prognosis from Svensk Vindenergi, generate a power production of 7.7 TWh in 2012 and 11 TWh in 2013. Furthermore, if the expansion continues at this rate, wind power will correspond to about 10 % of the total power production in Sweden by 2015.

Despite the rapid growth wind power projects are still dependent on government subsidies, i.e. green certificates. However, as the business continues to grow so do the technological advancements, thus providing new and more efficient wind turbine designs. Both incremental as well as novel solutions have been developed over the years. In order to find new dominant designs they need to be evaluated both from a technical and a business point of view.

1.2 Issue of study

Technology development

The first mass-produced wind turbines had an average output of about 22 kW, which at the beginning of the 1990s had increased to approximately

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[4] Energimyndigheten (2011a)
[5] Näringsdepartementet (2010)
[6] Energimyndigheten (2011a)
[7] Vindkraftsnytt (2012)

200 kW.[8] Today there are turbines with an output of several megawatts, ranging from 2-5 MW, and even larger including turbines at the prototype stage. However, the average capacity for installed wind turbines in Sweden was 1.9 MW in 2010, which is an increase from 0.6 MW in 2003.[9]

Alongside with the increase in turbine output, there has been a gradual development towards larger turbines, e.g. higher towers and longer rotor blades. Furthermore, incremental design changes have continuously been developed in order to achieve more efficient turbines, and subsequently improved profitability.

Currently, the typical WTG (wind turbine generator) for large-scale commercial use is a horizontal three-blade turbine around 2 MW, with a welded steel tower. The conceptual design of these turbines are similar, however, technical features differ depending on the manufacturer.

Maturing market

In 2004 the Swedish Energy Agency specified a number of sites considered particularly suitable as wind power locations. Furthermore, in 2008 additional sites were included, adding up to a total of 2.2 % of Sweden's surface.[10] As the expansion continues, the competition for the most favorable sites hardens.

This growth has also led to a shift in the power balance between different stakeholders. From being a technology mostly applicable on a small scale by individual energy consumers, today's turbines are used in large-scale commercial projects.[11] This naturally provides commercial developers with more leverage over turbine manufacturers. Furthermore, on the manufacturer side, the playing field have become somewhat leveled as

[8] Energimyndigheten (2011c)
[9] Ibid.
[10] Energimyndigheten (2011b)
[11] Malmberg (2012)

new entrants are emerging, seeking market positions in the growing wind power industry, while existing suppliers seek to consolidate their positions. The larger, more established, manufacturers such as Vestas, Enercon, and Gamesa have faced a decline in activity over the years, while others such as GE Wind, Siemens, and Repower have increased their market shares.[12]

In the current situation, with an increasing number of suppliers, the developers are given a wider range of choices, thus enabling them to influence the development of technology in the desired direction. This is an important premise given the described situation, i.e. the dependency of green certificates and the limited number of appropriate sites. As the focus on these aspect surfaces it becomes clear that new turbine designs will be required to continue the expansion at the current pace.

1.3 Purpose

The purpose of this study is to investigate the possibility for technology development to further strengthen the Swedish wind power business case, and ultimately examine the potential for eliminating the need for government subsidies.

1.4 Objectives

The above described purpose will be achieved through the following objectives:

- Scan for trends in technology development and choose areas according to the scope and delimitations of the study.
- Evaluate the chosen technical areas – both financial and non-financial aspects.
- Depending on the outcome in the previous evaluation discuss the implications for the case company.

[12] Engström et al. (2010)

1.5 Delimitations

Delimitations are established with regards to the project timeframe. This thesis will focus on commercial onshore projects within the wind power industry in Sweden.

1.6 Target group

The target group for this thesis is the wind power industry as a whole, but more specifically stakeholders within wind power project development.

1.7 Report outline

Chapter 1: *Introduction* – This chapter is intended to provide the reader with the background of this thesis. The current situation in the wind power industry is initially presented in order to give the reader an understanding of the purpose and objectives of the thesis. Furthermore, delimitations and target group are presented.

Chapter 2: *Methodology* – In this chapter an overview of the methodological choices that have been made are presented and discussed. Initially, in order to understand the choices made the general characteristic of the thesis is discussed. Subsequently, the chosen methodological approach, which is central to this study, is presented along with the research strategy and data collection methods.

Chapter 3: *Theoretical framework* – This chapter presents the theoretical framework used for this thesis. The presented framework has been chosen as a result of the methodical approach and the evaluation model. At first, the theoretical background regarding general wind energy is highlighted. Then, the theory that will constitute the business evaluation method is presented. At first, the necessary financial aspects concerning investment appraisal will be accounted for. The second aspect is the qualitative measure which implies a more strategic approach. For this measure a concept selection method will be presented along with the SWOT analysis. All tables and figures in this chapter have been produced by the authors.

Chapter 4: *Case company – E.ON Vind* – This chapter is intended to provide a short insight to the case company and the activities involved in the process of developing, constructing and operating onshore wind farm projects.

Chapter 5: *Wind turbine design* – This chapter presents the current characteristics in wind turbine technology. More specifically, the fundamental parts of the wind turbine, including foundation, tower and machine house, will be described in different possible layouts. It is necessary to understand the historic trends and limitations affecting technology development leading up to now. This will help understand chosen focus areas in chapter 6.

Chapter 6: *Technology development* – In this chapter the chosen areas of technology are presented, which are a result of the initial screening process. They constitute the different aspects of the WTG that will be further analyzed in the evaluation model. In this chapter only their technological features are described. A more detailed reasoning for including them in the study is later discussed in chapter 7.

Chapter 7: *Business case evaluation method* – This chapter will further describe the evaluation method, consisting of the financial model and the measuring of qualitative aspects. First, the model as a whole is discussed, followed by a review of each component regarding the underlying assumptions. Finally, the testing and validation of the model will be discussed.

Chapter 8: *Applying the model* – In this chapter the initial results from the business case evaluation is presented. A more extensive discussion regarding financial input parameters will follow. In addition, a sensitivity analyses in the qualitative dimension will be done by considering the criteria for each decision. Moreover, the second evaluation round will be presented. For detailed information regarding input parameters and assumptions made, see Appendix 3. Also, in appendix 4 the full results of the qualitative evaluation can be found.

Chapter 9: *Additional evaluation rounds* – This chapter will present the evaluation rounds following the previous results, as well as a sensitivity analysis regarding the final results. Further evaluation rounds were performed after having analyzed the initial outcome. Some of the areas were chosen to be examined further with the aim of applying a more systemic approach and thus performing more detailed estimations regarding some of the cost structures. Finally, a sensitivity analysis is performed regarding uncertain parameters in the financial model.

Chapter 10: *Discussion* – This chapter is intended to present further discussions regarding the outcome of the business model evaluation, as well as the sensitivity analysis concerning the results.

Chapter 11: *Conclusions and final remarks* – In this final chapter, conclusions relating to the purpose and objectives are presented. Furthermore, the general credibility of the evaluation model and results are discussed. Finally, remarks regarding improvements and areas for further study are suggested.

2. Methodology

The aim of this chapter is to provide an overview of the methodological choices that have been made. Initially, in order to understand these choices the general characteristic and aim of the thesis is discussed. Subsequently, the chosen methodological approach, which is central to this study, is presented along with the research strategy and data collection methods.

2.1 General characteristics of the study

In accordance with the first objective an initial screening process was conducted. Both existing and new technological areas that were considered to potentially have an impact on the business case were examined. The second objective consists of two different aspects that make up for the evaluation of each technology area. The first aspect of measure is strictly financial, with the aim of analyzing the financial impact of chosen technological areas. The second dimension aims to cover all those aspects that are not quantifiable as input in a financial model. The purpose of this was to establish a more comprehensive view of the business case.

Moreover, the impact of each technology was subject to a comparative analysis with a specific business case, which was chosen to represent a reference point. The intersection of the two dimensions represented the chosen reference site.

A financial model was established in order to perform the calculations required by the case company for their investment decisions. The model was intended for providing a quick but accurate assessment of specific parameters to be compared with other business case evaluations. Since each case was subject to the same simplifications and assumptions it is possible to establish their relative financial status.

The qualitative dimension was examined together with key stakeholders in the industry. More specifically, surveys were distributed, section 2.3, with the aim to measure the qualitative aspects of chosen areas relative to the corresponding solution at the reference site. Preceding interviews were held with employees at the case company as a part of the initial screening process. Furthermore, the outcome of these interviews, together with a SWOT analysis, was used for generating the qualitative measures used in the surveys.

2.2 Methodological approach

When conducting business research there are three different methodological approaches to be considered[13]; the analytical, systems, and actors approach, according to Arbnor & Bjerke (1997).

Analytical approach

The analytical approach assumes that reality has a summative character, i.e. the whole is the sum of its parts.[14] Accordingly, once the researcher learns about the different parts of the whole, they can be added together to obtain the whole picture. The knowledge generated from this approach is characterized as being independent of the observer, which means that knowledge advances by means of formal logic represented by specific judgments independent of subjective experiences.[15] Therefore, the result of the analytical approach provides pure cause-effect relations, logical models, and representative cases.[16]

Systems approach

The systems approach, which partly originated as a reaction to the analytical, is based on the assumption that reality is arranged in such a way that the whole differs from the sum of its parts. This means that the relationship between the parts is just as essential as the parts themselves,

[13] Arbnor & Bjerke (1997)
[14] Ibid.
[15] Ibid.
[16] Ibid.

due to synergy effects. The knowledge developed through this approach depends on systems, i.e. the parts are explained or understood through the characteristics of the whole, of which they are part.[17]

Actors approach

The actors approach states that the whole is understood by the characteristics of its parts, assuming that reality is a social construction intentionally created by processes at different levels of meaning structures. Knowledge is therefore based on actors, or individuals, where the whole is understood through the individuals finite provinces of meaning. Along with metatheories and other contributions the researcher is trying to understand relations among interpretations made by actors. These relations are various interpretations and factors mutually, and in constant transformation, influencing each other in a continuous developmental process.[18]

Choice of approach

The analytical approach was chosen for this thesis, since it enables the study of each variable in closer detail. The system was comprised of a single WTG, which ultimately was seen as part of the greater system, i.e. the general business case at the case company. While isolating all elements and then modifying them one at a time, the aim was to conclude rules that allows for the prediction of properties for a general system. However, the value of the analytical approach depends on the level of complexity in the studied system, where in a highly complex system it might be preferable to have a systemic approach. When aiming at deriving the optimal business case, the level of complexity rises due to the many more aspects needed to be taken into consideration, compared to when isolating elements of a single WTG. Therefore, there is a need to investigate potential synergy effects that are the result of single variable alterations.

[17] Arbnor & Bjerke (1997)
[18] Ibid.

This aspect will be discussed at a later stage in the report. Finally, the actors approach is not considered appropriate for this study.

2.3 Research strategies

Depending on the character and aim of the research, there are several strategies to be considered. The four most relevant, regarding master thesis projects within applied science, are survey, case study, experiment and action research.[19]

The approach for a survey is characterized by the study of a phenomenon within a broad research area at a specific time, dependant on the use of empirical data.[20] Conclusions, regarding the target population, can be made by applying the survey on a chosen sample of the population, assuming the sample correctly represents the target population.[21]

The purpose of case studies is to describe an object or phenomenon in order to gain a deeper understanding of the area of study. This can be done by combining different types of data, as well as several research methods, which is encouraged when conducting a case study.[22] An important issue regarding case studies is the general application of the results, where one can argue that it is not possible to draw any general conclusions regarding a target population from the results of one specific case. However, it can also be argued that even if the case is unique in some regards it is possible to place it in a wider context and therefore be able to draw conclusions regarding similar cases that share important characteristics.[23]

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[19] Höst et al (2006)
[20] Denscombe (2009)
[21] Lekvall & Wahlbin (2001)
[22] Denscombe (2009)
[23] Ibid.

An experiment is usually conducted with the aim of establishing the cause for the changes in the case issue at hand. The purpose is to determine the dependant variables from the independent variables, why it is important to arrange the experiment in such a way so that the results confirm this relationship.[24]

The fourth and final research strategy is action research, which is characterized by the desire to not only gain a better understanding of a phenomenon, but also manage a change within the studied issue. The process is iterative, where the initial results provide a suggested solution, which is then implemented and evaluated. The evaluation will subsequently be the basis for further studies, as this process is repeated until a desired solution is obtained.[25]

Choice of research strategy

The case study was considered to fit the overall purpose of the thesis. It is also compatible with the choice of the analytical approach. The studied reference site and the business case it represents were chosen as the case study. Also, the written survey strategy was included in this study as a part of the qualitative evaluation.

2.4 Data collection

It is important to distinguish between two types of data. Secondary data is information that has already been gathered and presented elsewhere. Primary data on the other hand is collected by the researcher from the original source, e.g. through interviews and observations. Research based solely on primary data rarely exists, however, it is possible to conduct research entirely based on secondary data, why it is important to scan for

[24] Denscombe (2009)
[25] Ibid.

existing data before gathering primary. Primary data is mainly gathered through different types of questioning and observation methods.[26]

Both primary and secondary data can be categorized in more or less detailed ways. According to Yin (2003) there are several sources of data when conducting case studies. There is no data source more advantageous than any other, which is why they should be used to complement each other.[27] Furthermore, the use of multiple sources is an important method for enhancing the thoroughness of the research.[28]

Interviews

Lekvall & Wahlbin (2001) presents four typical ways of communicating with respondents when conducting interviews, i.e. written survey, telephone interview, personal interview, and interview via Internet. In the written survey, questions are asked and answered on a questionnaire that is distributed and returned by the inquirer and respondent without any mediation from an interviewer. A telephone interview is performed by an interviewer, where questions are asked and answered orally during a telephone conversation. The personal interview is similar to the latter, besides the fact that the interviewer and respondent have a personal encounter. Lastly, the interview via Internet is a relatively new way of conducting interviews. As with the written survey, there is no interviewer acting as a link between the inquirer and the respondent. Depending on the situation, each way of communication has its advantages and disadvantages. The personal interview is dynamic in terms of the possibility to ask any type of question and the opportunity to conduct an extensive interview, nevertheless, it is rather expensive and time consuming. The written survey and Internet interview are less expensive, thus appropriate for large samples. The telephone interview is somewhat a hybrid between

[26] Lekvall & Wahlbin (2001)
[27] Yin (2003)
[28] Robson (2011)

the personal interview and written survey, since it utilizes some of the advantages of the personal interview, yet less expensive and not as time consuming.[29]

Direct observations

If a specific location of interest exists, within the scope of the case study, it can be subjected to a direct observation, which can be either formal or casual. For the formal observation certain protocols can be developed as part of the case study protocol, and the field-worker may be asked to measure the incidence of certain types of behavior during specific periods of time. Furthermore, by using multiple observers the reliability will be increased.[30]

Participant-observation

When conducting a participant-observation the observer may take on a variety of roles within a case study situation and even participate in the studied event. The main advantage is that participant-observations can provide the opportunity to observe a certain setting that would be inaccessible to scientific investigation. On the other hand, there are issues concerning potential biases when actively participating in a specific group or event.[31]

Choice of data collection method

The main source of primary data was through personal interviews. However, both telephone interviews as well as interviews via the Internet were performed, since personal interviews are time consuming and also more difficult to arrange due to different schedules. Furthermore, written surveys were distributed for gathering qualitative data. For each technology area two respondents were chosen to perform the survey.

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[29] Lekvall & Wahlbin (2001)
[30] Yin (2003)
[31] Ibid.

Regarding the collection of financial data it consists of two aspects. Namely, the cost structure for the investigated areas, which were gathered as both primary data through interviews, as well as secondary data using previously performed studies. Second, production simulations were performed using the wind assessment software WindPRO, in order to acquire production estimations for the investigated areas.

In some cases the respondents were reluctant to reveal financial data and also situations where the requested input was nonexistent due to lack of industry experience. In these cases, interviews were held in order to ask the respondent to make qualified assumptions, based on their position within the field of study.

The respondents were first approached by email, explaining the aim and prerequisites of the interview, and then asked to schedule a personal meeting if possible. The interviews were recorded in order to ensure full acquisition of information. Furthermore, written surveys were distributed among respondents internally at the case company. The intention of this was to quantify those aspects of technological enhancements that could not be taken into consideration in the financial model.

Furthermore, the data collection was characterized by several unstructured conversations and complementing questions due to the closeness to many of the sources. Complementing questions in the form of personal, telephone and email conversations were conducted in order to gain answers to additional questions, as well as verifying previously given answers.

Direct observations were performed early in the work process, in the form of field visits to specific sites. The purpose of this was to gain a deeper knowledge regarding the specific case study. In addition, participant-observations were performed, since the authors spent most of the project duration at the case company's office.

2.5 Qualitative and quantitative data

The distinction between the qualitative and quantitative research method is connected to the character of the collected data, i.e. whether or not the data is expressed in mere numbers, or in words and images. Furthermore, the research method partly coincides with the choice of research strategy, where case studies usually are more suitable with non-calculating methods, surveys and experiments generally with mathematic-statistical methods. However, it is possible to conduct mathematical calculations on qualitative data as well as performing a qualitative analysis on numerical data. According to Lekvall & Wahlbin (2001) the research strategy is more important, in regards to the outcome of the research, than the way which data is expressed.[32]

Choice of method

Both qualitative and quantitative data was collected during the project. Initially, when researching the trends within technology development, a qualitative approach was used; e.g. interviews and literature studies. The qualitative evaluation of the different aspects of technological development was quantified with the distribution of surveys. Second, the data used for the financial input was gathered as both primary and secondary data regarding the cost structures, as well as production simulations as a base for the revenue input. In the case of these retrieval methods failing to deliver the required input the financial data was based on qualitative assumptions.

[32] Yin (2003)

2.6 Credibility

There are three important aspects of valuation that should be taken into account when conducting a scientific study. Namely, validity, reliability, and representativity.[33] Validity has to do with whether or not the data collection method measures what it is intended to measure.[34] Reliability determines the consistency of the measurements, i.e. whether or not the results will be the same at repetition, and are not influenced by random errors.[35] Representativity is to which extent the results are applicable in other cases.[36]

Achieving credibility

In order to achieve a high reliability multiple sources were used. Furthermore, all questions were formulated with the aim of being explicit and clear from bias. Also, whenever conflicting sources were found they were both confronted when possible. The use of multiple sources will, together with the efforts to increase reliability, ensure a high validity as well. The financial model was validated through the testing of known cases. Furthermore, a draft of the survey was initially performed on key employees before finalized. In addition, the reference site was chosen to represent the typical business case at the moment, and consequently an effort to strengthen the generalizability of the results. Finally, as the outcome of this study was presented the authors received valuable feedback from both the case company and academia that was used to further strengthen this thesis.

2.7 Source criticism

With the purpose of looking into the future development of the onshore wind business, there will be a certain degree of uncertainty affecting the

[33] Rosengren & Arvidsson (2002)
[34] Lekvall & Wahlbin (2001)
[35] Ibid.
[36] Rosengren & Arvidsson (2002)

data. Some of the data regarding the financial input can only be based on assumptions, due to the lack of commercial projects from which data can be acquired, or the fact that existing projects are reluctant to reveal the actual outcome. Also, the qualitative evaluation of the chosen technology areas is likely to be subject to uncertainty, which is presumably due to operational inexperience among the respondents at the case company. In order to reduce the level of uncertainty that arises as a result of subjectivity it is important to ensure that the respondents receive explicit boundaries for each specific technology field so that they are able to make as qualified assumptions as possible. Furthermore, it is important to choose respondents that have particular experience in reference to each field.

3. Theoretical framework

This chapter presents the theoretical framework used for this thesis. The presented framework has been chosen as a result of the methodical approach and the evaluation model. At first, the theoretical background regarding general wind energy is highlighted. Then, the theory that will constitute the business evaluation method is presented. At first, the necessary financial aspects concerning investment appraisal will be accounted for. The second aspect is the qualitative measure which implies a more strategic approach. For this measure a concept selection method will be presented along with the SWOT analysis.

3.1 Wind power theory

Wind energy

Wind energy is the kinetic energy of air in motion. The wind's kinetic energy can be determined with the following formula, where P_{kin} [W] is the kinetic energy; p [kg/m^3] the air density; A [m^2] the area of the cross section, and v [m/s] the wind speed passing the cross section:[37]

$$P_{kin} = \frac{1}{2} * pAv^3$$

The implications of this formula are that power increases eightfold when the wind speed doubles, which emphasizes the importance of choosing appropriate sites in regards to wind conditions. The amount of energy a turbine can produce is determined by the wind's kinetic energy multiplied by the time it is producing, typically expressed in kilowatt-hours, kWh. However, it is not enough to know the mean wind speed at a location in order to assess the potential production, since the frequency may differ for two sites with the same average wind speed.[38] The wind conditions for

[37] Wizelius (2007)
[38] Ibid.

each site are therefore carefully assessed by conducting wind measurements in order to determine the wind speed distribution.

The energy in the wind is converted to electricity by the turbine's rotor and generator. However, it is not possible to utilize 100 % of the wind's energy. If the turbine was to consume all of the incoming wind energy then the wind speed would be zero after the turbine, thus inhibiting more wind to pass through.[39] In order to keep the flow of wind through the turbine it is necessary that not all of its energy is consumed. A WTG is most efficient when the wind speed is reduced by 1/3 at the rotor and by an additional 1/3 after the rotor. The proportion of the wind's kinetic energy that can be utilized by a WTG is determined by Betz's law and corresponds to the power coefficient C_{pmax} = 0,593. The maximum power a turbine can generate is consequently:[40]

$$P_{kin} = \frac{1}{2} * pAv^3 C_p$$

This is the theoretical upper limit that can be obtained by a turbine. In practice, C_p will be lower due to aerodynamic and mechanical friction losses.[41]

Turbulence

When moving air encounters obstacles it will move around it, creating air vortexes along the primary wind direction. These air waves are measured as short variations in wind speed and direction, i.e. turbulence. With increased height the turbulence is generally lower since the winds are farther away from obstacles in the terrain.[42] The avoidance of turbulence is an important aspect of wind power production, since the sudden changes in wind speed and direction have a strenuous effect on turbine components.

[39] Wizelius (2007)
[40] Ibid.
[41] Ibid.
[42] Ibid.

Therefore, it is necessary to aim at avoiding turbulence, but also designing the WTG to be able to handle the inevitable turbulences.

3.2 Capital budgeting

In order to determine a wind energy system's commercial feasibility it is first necessary to be able to assess its relative economic benefits. This method should be easy to understand, free from detailed economic variables and easy to execute.[43]

When it comes to making investment decisions in general it is necessary to analyze profitability, and primarily making sure the investment fulfills certain requirements. Profitability alone is, however, not a sufficient enough measure when determining the appropriateness of an investment.[44]

The size of the investment for wind power projects will naturally depend on the size of the wind farm, but still the typical wind power project is characterized by large investments and a long project life time. For this reason, it is important to have a good understanding of the cost driving activities and cash flows, during the entire lifetime, in order to be able to conduct a reasonable profitability analysis. However, there are other important aspects of investment decision making which need to be taken into consideration, for example strategic fit as well as other qualitative assessments. Yet, simple capital budgeting methods are used as a financial measure to determine the strength of specific investment proposals.[45]

Investment criteria[46]

One of the most fundamental financial principles is that money has a time value. This means that receiving dollar today is considered to be worth

[43] Manwell et al. (2002)
[44] Yard (2001)
[45] Ibid.
[46] Ibid.

more than receiving a dollar tomorrow. This is the case since it is possible to invest the amount of money received in the today to generate a future profit. So when evaluating an investment proposal it is not accurate to compare cash flows that occur at different times without discounting them to a mutual date.[47] When doing so it is possible to see the amount of money needed today so that the future payments can be made.

In order to calculate the present value of an investment proposal the opportunity cost of capital is used as discount rate. The cost of capital is the expected rate of return that is being given up by investing in the project. Therefore, a project's expected future payoff should be discounted using a known rate of return offered by equivalent-risk investments in the capital market. The present value then corresponds to the market value of the project.[48] The present value is then compared to the required investment, which represent the net present value (NPV). Consequently, the NPV is the amount of money that the project will add to shareholder wealth. This results in the decision rule of accepting all projects that have a positive net present value. This rule can be applied to projects of any length.

The internal rate of return (IRR) of a project corresponds to the discount rate for which the NPV is zero. Hence, comparing the IRR to the opportunity cost of capital will answer the question whether or not to accept the project. If the IRR is higher than the opportunity cost of capital the NPV will be positive and consequently negative when the IRR is lower. This means that the NPV rule and the rate of return rule are equivalent.[49] However, this is only true as long as the NPV declines smoothly as the discount rate increases. Such a NPV profile is shown in the figure below.

[47] Yard (2001)
[48] Brealy et al. (2001)
[49] Ibid.

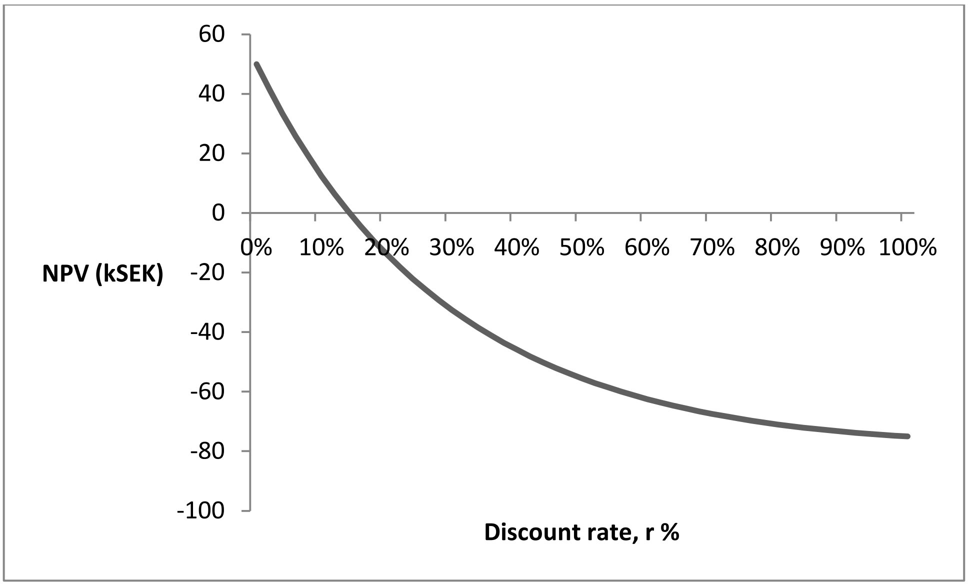

Figure 1 – A generic NPV profile when the NPV and IRR rule are equivalent. Authors own.

Opportunity cost of capital[50]

The choice of discount rate can be crucial, particularly when large capital expenditures are involved and/or when the project lifetime is very long. It is therefore important to think about what the company cost of capital is, and what it is used for. It is defined as the opportunity cost of capital for the firm's existing assets, which are used in order to value new assets that have equivalent risk. Since most companies issue debt as well as equity, the company cost of capital is a weighted average of the returns demanded by debt and equity investors. This weighted average cost of capital (WACC) will take into consideration the capital structure of the company, i.e. the proportion of debt (D) and equity (E), and the expected rate of return required from both debt (r_{debt}) and equity (r_{equity}) holders.

$$WACC = \frac{D}{D+E} * r_{debt} + \frac{E}{D+E} * r_{equity}$$

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[50] Brealy et al. (2001)

Companies can raise money from many different sources, e.g. convertible debt, warrants, options, preferred stock, etc. These different sources of finance are expected to generate different returns, thus making WACC calculations increasingly difficult as the firm's capital structure becomes more complex. The formula above is, however, easily extended, consequently adding additional weighted securities with its expected rate of return. However, for the WACC to be an appropriate discount rate, each project must be in accordance with the firm's existing business. Furthermore, the cost of capital must be based on what investors are actually willing to pay for the firm's outstanding securities, i.e. the securities' market values. Consequently, the company cost of capital depends on how its investors value the firm's securities, which in turn depends on future profits and cash flows.

Finally, when calculating cash flows for a specific project it is considered to be all equity-financed, regardless of the structure of the financing.

Pitfalls with the IRR

As previously mentioned, the IRR rule will only provide the same answer as the NPV rule as long as the NPV is declining as the discount rate increases. Common pitfalls that may occur when it does not will be illustrated with a few examples:[51]

First, looking at the projects in Table 1, both of them have the same IRR, indicating that they are equally attractive investments. However, when considering their net present value it becomes clear that project B is a poor choice of investment. In project A, money is being lent out at a 50 % return rate, whereas in project B, money is being borrowed at a 50 % return rate. Consequently, the IRR rule, as earlier stated, does not apply in this case.

[51] Brealy et al. (2001)

Project	C_0	C_1	IRR	NPV at 10 %
A	-1,000	1,500	50 %	364
B	1,000	-1,500	50 %	-364

Table 1 – Cash flows, IRR, and NPV for two arbitrary projects. All figures are in kSEK. Authors' own.

The NPV profile for project B, shown in Figure 2 below, shows that the net present value increases as the discount rate increases, implying that the IRR rule is reversed in these cases. This project must have an IRR less than the opportunity cost of capital in order for it to be considered as an attractive investment.

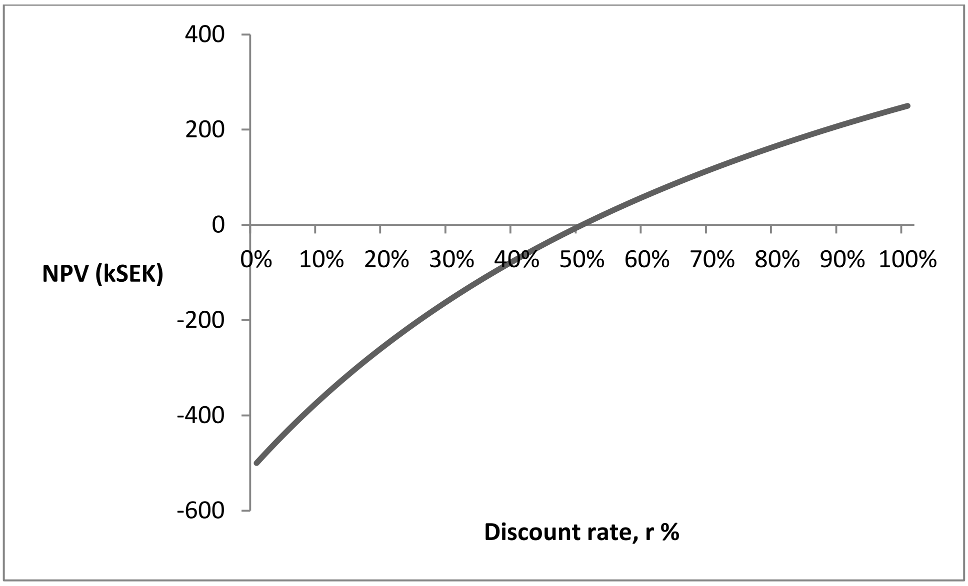

Figure 2 – NPV profile for project B from Table 1. Authors' own.

Project C in Table 2 below has two different internal rates of return. The reason for this is the double sign change in front of the last cash flow.

There can be as many internal return rates as there are sign changes.[52] This implies that the general IRR rule does not work here either.

Project	C_0	C_1	C_2	C_3	C_4	C_5	IRR	NPV at 10 %
C	22	15	15	15	15	-40	6 % & 28 %	0,7

Table 2 - Cash flows, IRR, and NPV for an arbitrary project. All figures are in kSEK. Authors' own.

The NPV profile for project C, Figure 2, shows that the investment has a positive outcome when the opportunity cost of capital is in the interval 6 – 28 %, which is confirmed by the positive NPV in the same range.

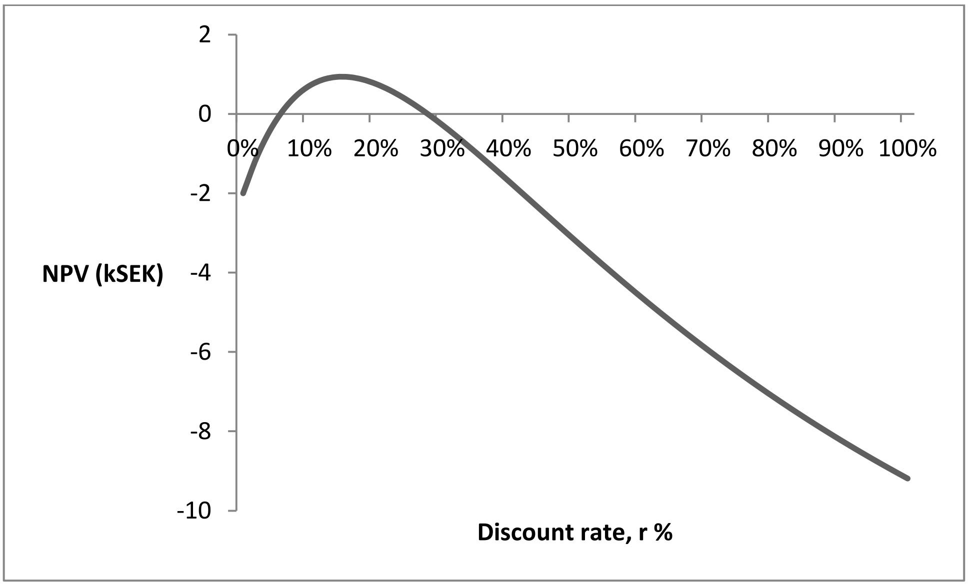

Figure 3 – NPV profile for project C from table 2. Authors' own.

Finally, caution should be taken whenever considering mutually exclusive projects. In practice firms do not have unlimited resources to spend on projects, but instead they must choose among several possibilities. Considering project D and E in Table 3, both can be said to be good

[52] Brealy et al. (2001)

investments since the NPV is positive. However, the project with the highest NPV is not necessarily the one with the highest internal rate of return. The IRR rule does in this case favor the quick payback of project D, which has a higher percentage return but lower NPV.

Project	C_0	C_1	IRR	NPV at 10 %	NPV at 60 %
D	-10,000	20,000	100 %	8,182	2,500
E	-20,000	35,000	75 %	11,818	1,875

Table 3 – Cash flows, IRR, and NPV for two arbitrary projects. All figures are in kSEK. Authors' own.

In figure 4, the NPV profiles for both projects are plotted. Clearly, the choice between the two projects depends on the firm's opportunity cost of capital. The projects' NPV profiles intersect at a discount rate of 50 %, which implies that if this is the firm's opportunity cost of capital both projects are equal according to the NPV rule. However, when the opportunity cost of capital is lower than 50 % project E is the better investment, and project D is consequently better when the cost of capital is higher than 50 %.

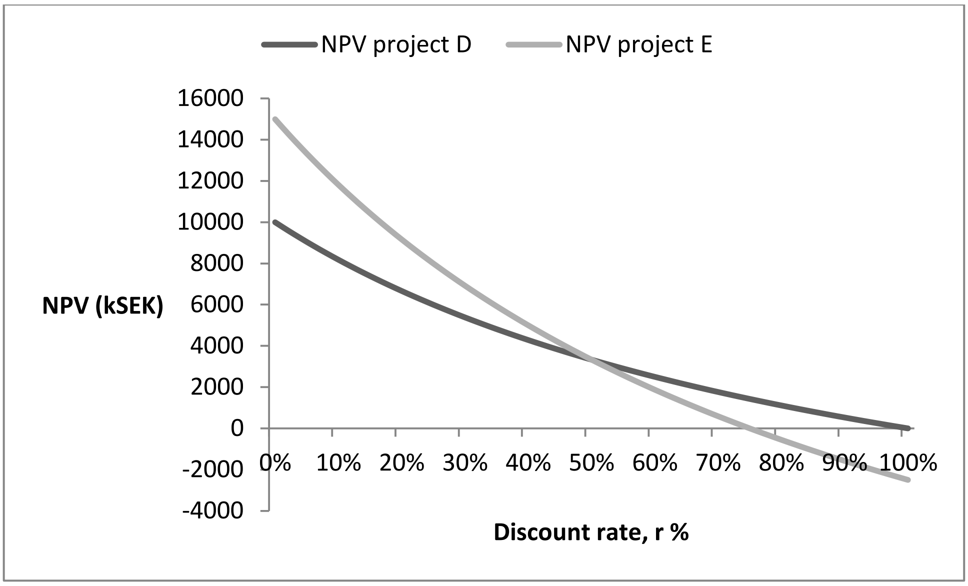

Figure 4 – NPV profile for projects' D and E from table 3. Authors' own.

To conclude, the IRR rule is not always a sufficient measure by itself. The principle behind making good investments is choosing activities that increase the value of the firm. Projects that earn a good rate of return for a long time usually have a higher NPV compared to those who offer a high percentage rate of return for a shorter period of time.[53]

Forecasting cash flow[54]

Perhaps the biggest challenge in capital budgeting is forecasting the cash flows. Often there is only raw data available, which need to be processed before it can be used. Also, most financial forecasts are based on accounting principles that do not necessarily recognize cash flows when they happen. When identifying cash flows it is important to recognize investment expenditure as they occur, since it is the generated cash that determines if a project is financially attractive. The accounting profit differs from cash flow, in the sense that the profit can occur before it has generated any cash.

[53] Brealy et al. (2001)
[54] Ibid.

A project's cash flow should be based on the incremental cash flow, i.e. the additional cash flow it produces compared to the option of not proceeding with the investment. In doing so, all indirect effects of accepting a project should be included as well. There is an opportunity cost related to the resources involved in a project, that is equal to the cash generated by selling the resource, and therefore it is a relevant cash flow when evaluating the project. Furthermore, sunk costs should not be included, since they remain the same whether or not the project is accepted, thus having no impact on the net present value.

Furthermore, investments in working capital need to be accounted for. The net working capital is the difference between a company's short-term assets and liabilities. Most projects require additional investments in working capital, since cash outflow occurs when inventories are built up or customers are slow to pay. Depending on the characteristics of the business and the payment requirements toward customers and suppliers the required investment in working capital will vary. However, the investment in working capital will be recovered at the end of the project life time.

The third component of project cash flow comes from operations, which can be calculated in several ways. One method is to subtract all cash expenses and taxes paid from the revenues. Alternatively, looking at the accounting profit and adding back any deductions made for noncash expenses, e.g. depreciation. A third way is to calculate net profit assuming no depreciation ((revenues – cash expense) * (1- tax rate)) and then adding back the tax shield created by depreciation (+ (depreciation * tax rate)). Although the depreciation deduction is a noncash expense it does affect net profit and taxes paid, which is a cash item. All three methods will give the same answer.

To conclude, a project's cash flow can be considered as the sum of three components; investments in fixed assets, investments in working capital, and cash flow generated from operations.

Real vs. nominal cash flows

The distinction between nominal and real cash flows and interest rates is another important aspect of capital budgeting. Interest rates are usually expressed in nominal terms but the real interest rate on a bank deposit depends on inflation as well. Therefore, if the discount rate is nominal it is required that the cash flows are estimated in nominal terms as well, thus having to take into account trends in selling price, labor, material costs, etc.[55] Applying a single assumed inflation rate to the cash flow is not sufficient enough, since some costs and prices may increase faster than inflation while others increase slower.[56] It is also possible to discount the real cash flows instead of the nominal, although it is not commonly done. However, real cash flows discounted at a real discount rate will give the same present value as nominal cash flows discounted at a nominal discount rate.[57]

Inflation is defined as the overall increase in prices.[58] This increase, in the general level of prices, means that the purchasing power of money has weakened. A way of keeping track of the general level of prices is the use of different price indexes. The consumer price index (CPI) is the most common used measure for tracking the price development, and thus inflation[59]. CPI is intended to show, on average, how consumer prices are developing for the private domestic consumption. Accordingly, the percentage increase in the CPI from one year to another corresponds to

[55] Yard (2001)
[56] Brealy et al. (2001)
[57] Ibid.
[58] SCB (2012)
[59] Ibid.

the inflation rate. Sveriges Riksbank, the Swedish central bank, is responsible for the monetary policy in Sweden, thus responsible for maintaining the national inflation target, which has been set to 2 %.[60]

3.2 Technology concept selection[61]

The decision-matrix method developed by Stuart Pugh is a way of quantifying multi-dimensional options, in order to be able to rank them and thereby support the decision making process. It is frequently used in engineering field, often to solve construction and design issues, though applicable in any situation involving a set of choices.

When facing a decision or problem, the first action will be to determine a set of alternative solutions. Second, people with knowledge regarding aspects that will influence the choice are asked to list certain criteria and weight them according to the impact that each criterion has on the decision. Thereafter, each possible solution will be graded based on how well they meet each criterion. In order to be able to value the possible solutions, a reference point is used, which could be an existing product or approach that is the current solution to the problem. Nonetheless, the reference point is used as a benchmark when evaluating the different concept solutions. Therefore, it is given the value 0, thus enabling each concept to be graded as either better (> 0) or worse (< 0) than the reference, or equivalent (=0) to it. Any scale seen fit can be used, however a scale ranging from -2 to +2 is frequent implemented, where each step corresponds to the following valuation: much worse than, worse than, equal to, better than, and much better than the reference for the specific criterion.

When the grading has been finalized, the results can be computed in several ways. It is possible to simply summarize the grades for each alternative, which will provide the total score. Also, the number of plus

[60] Sveriges Riksbank (2010)
[61] Virginia tech (2010)

scores and minus scores can be shown separately in order to visualize the spread. It is possible that an alternative with the highest total score has a high spread, thus perhaps making the choice of that alternative questionable. However, the total score should be seen as guidance in the decision making process, furthermore if the two top alternatives have similar scores they need to be examined closely. The weighted total can also be acquired, by applying the proportion of importance to each criterion, i.e. summarizing each score multiplied with their weighting factor, thus giving each grade a more relevant significance.

Following is an example of a generic matrix representing a decision process with three possible solutions. The criteria have been chosen by the level of significance they have on the decision, and weighted accordingly. Each alternative has been graded on a scale from -2 to +2, as previously described, based on how well the alternative is considered to perform in each criterion, relative to the reference point.

	Weight factor	Reference	Alt. 1	Alt. 2	Alt. 3
Criteria 1	10	0	-1	1	2
Criteria 2	20	0	0	-2	1
Criteria 3	20	0	-2	-2	-1
Criteria 4	50	0	1	2	-2
Total +			1	3	3
Total -			3	4	3
Sum			-1	1	0
Weighted sum			0	30	-80

Table 4 – Results from a generic decision-matrix. Authors' own.

Alternative 1 has a weighted sum of 0, indicating that it performs just as well as the reference case. However, not considering the weighting of the criteria will indicate that this alternative is worse than the reference. Nonetheless, since criterion 4 has a substantial impact on the decision it will strongly favor any alternative with a positive grade in that dimension. Provided that the weightings display an accurate view of the problem situation, the weighted sum will present a more dynamic decision basis.

This method is an effective approach of handling decision-processes with a set of multi-dimensional options. Furthermore, it is beneficial since it is possible to easily conduct sensitivity analyses, i.e. see the required change for a specific alternative before it becomes a high rank option.

3.3 Strategic decision making[62]

The SWOT analysis is a widely used planning tool for strategic decision making. It is applicable when evaluating projects or business ventures and their effects on strategy development. The aim of the analysis is to identify key internal and external factors that are significant in the process of achieving specific objectives. The internal factors include all the strengths and weaknesses of the project, which consequently can be managed within in the firm. The external factors take into account the opportunities and threats that lie in the surrounding environment. These are however much more comprehensive, including aspects of macroeconomics, technological developments, legislation and policy change etc.

The analysis is typically visualized with a matrix, and Karppi et al. (2001) suggests the following actions to be implemented after the SWOT analysis has been established: “Build on strengths, eliminate weaknesses, exploit opportunities, and mitigate threats.” This is to ensure the successful execution of long-term projects.

[62] Johnson et al (2008)

The method itself is however not particularly preferable for in-depth analyses since it lacks some matters that should require attention. However, if these shortcomings are adjusted for it could act as balance favoring the long-term perspective. Some of the intended concerns are displayed below. [63]:

- The length of the lists.
- No requirement to prioritize or weight the factors identified.
- Unclear and ambiguous words or phrases.
- No obligation to verify statements or opinions with data or analyses.
- No resolution to contradictions in itself.
- Single level of analysis is all that is required.
- No logical link with implementation phase.

3.4 Linking theory with the study

An understanding of wind power theory and the physicality of wind energy is required for both identifying potential focus areas and furthermore necessary for the performed production simulations and estimations of power curves for increased rotor diameter (see Appendix 4 – Increased rotor diameter).

Theories regarding capital budgeting were used in order to ensure that the financial model functions according to the necessary economic principles and still applicable as a comprehensive and accurate, yet user-friendly tool. In order to maintain this aim it was necessary to make certain assumptions and simplifications, however the theoretical background was intended to ensure that the model fulfills the fundamentals of financing. These assumptions are further described in section 7.2.

[63] Johnson et al. (2008)

The SWOT-analyzes was incorporated in the early stages of the project, serving as the premise for the initial meetings within the case company. The purpose of these interviews was to function as part of the technology screening process but also for mapping out the qualitative measures.

To summarize, the main aspects of the presented theoretical framework will constitute the basis for the evaluation method. The framework used for the financial model will constitute one dimension in the evaluation. The second dimension will be comprised of the qualitative aspects of the business case, which will be quantified using the Pugh concept selection approach.

4. Case company - E.ON Vind

This chapter is intended to provide a short insight to the case company and the activities involved in the entire process of developing onshore wind farm projects.

4.1 E.ON Vind

E.ON Vind is headquartered in Malmö, Sweden and operates in Denmark, Norway and Finland as well. Its activities to achieve their aim of customer satisfaction are described by four main processes. Namely, Identify and secure business opportunities, Develop project, Construct site, and Operate and maintain site.

Identify and secure business opportunities[64]

A project is initiated by the search for a business opportunity, i.e. finding an appropriate site and searching for potential business partners. The potential project is evaluated further by conducting an investment calculation. However, at this stage, there are no detailed wind assessments or decisions regarding turbine specifications, thus making the initial project evaluation a rough estimation. The emphasis in this process is to secure the project by negotiating with land owners, as well as focusing on the strategic fit of the project. As the project is secured it can be planned more specifically and consequently handed in for a Gate 1 decision. Finally, when the project is approved at G1 it will then proceed to the project development phase.

Develop project[65]

Once the project has received its G1 clearance, the process of conducting more detailed site studies and investment calculations can take place. Several technical evaluations are performed, namely wind assessments,

[64] E.ON intranet (2012)
[65] Ibid.

site layout and production estimations, road planning and geotechnical assessments, as well as the technical aspects of grid connection. If the results from these evaluations are satisfactory, negotiations with subcontractors are initiated. This enables more detailed investment calculations, which will be an important input for the G2 decision. Parallel to the technical evaluations, the process of applying for authorization of environmental and building permits is initiated. In order to receive the proper authorization an environmental impact assessment needs to be conducted, which will cover any environmental aspects that may be in danger due to the planned project. Once all the technical evaluations are satisfactory, permits have been approved, and an extensive investment calculation has been made the project will be subject to a G2 decision, which will determine if the project is attractive enough to continue on to the construction phase.

Construct site[66]

After the G2 approval the project is handed over to a construction project manager. Initially, the contracts with suppliers and subcontractors, regarding turbines, grid connection, roads and foundations etc., are finalized. Next, the construction phase is prepared and coordinated. Each turbine is inspected thoroughly before commissioning. Once the wind farm is commissioned and all documentation is in place the project is finally handed over to O&M.

Operate and maintain site[67]

The Operation & Maintenance department is responsible for planning the operation of the wind farms, where the overall purpose is to ensure a high availability and thus an optimal production. Planning maintenance and service activities are important in order to guarantee a high availability.

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[66] E.ON intranet (2012)
[67] Ibid.

Furthermore, data is gathered from the SCADA system and evaluated in order to implement actions to ensure an efficient production. Finally, after 25 years when the turbines have reached their expected lifetime they are disassembled with the intention of restoring the site to its original state.

5. Wind turbine design

This chapter is intended to present the current characteristics in wind turbine technology. More specifically, the fundamental parts of the wind turbine, including foundation, tower and machine house, will be described in different possible layouts. It is necessary to understand the historic trends and limitations affecting technology development leading up to now. This will help understand chosen focus areas in chapter 6.

5.1 General design layouts

There are several fundamental wind turbine designs. A basic distinction is between horizontal axis (HAWT) and vertical axis (VAWT) wind turbines. A vertical turbine will operate regardless of the wind direction, while HAWT rotors must be oriented either upwind or downwind of the tower.[68] Therefore, a mechanism that maintains the correct orientation, as the wind direction changes, is required for HAWT. In addition, there are turbine designs where the number of blades varies from one to three. However, the most common type of turbine is an upwind three-blade HAWT.[69]

A typical WTG consists of a foundation, tower, rotor (rotor blades and rotor hub), control system, and the nacelle, which contains the generator, yaw control, drive train and other mechanical components. The transformer is also a part of the WTG, and is placed in the nacelle or at the bottom of the tower, either inside the tower or outside. Most manufacturers offer a variety of versions of their turbines, mainly concerning tower height and rotor diameter, but also other configurations. This provides the possibility to some extent tailor the turbines to specific sites.[70]

[68] Manwell et al. (2002)
[69] Wizelius (2007)
[70] Ibid.

5.2 Foundation[71]

The foundation of the WTG fills two purposes: it holds up the weight of the tower and nacelle, but also acting as a counterweight thus preventing the tower from tipping over. The conventional foundation structure is the gravity foundation, though each foundation is adapted to the WTG size, weight and height as well as the quality of the soil. Ordinarily, the foundation is constructed by first digging a 2-3 m deep square with a 7-12 m side and then filling it with concrete steel. An anchor cage is placed in the middle of the foundation, reaching the ground level, which acts as a socket for the bottom tower. Finally, the concrete is cast, and when it is hardened the tower can be assembled.

5.3 Tower

Theoretically, the tower should be as high as possible since winds are generally stronger with increased height and also since the winds are expected to be less turbulent. Consequently, the tower height is determined by the trade-off between energy output and cost[72], which in turn depends on the tower structure. Today, the most commercially proven tower design is conical steel towers. These towers are, depending on the height, assembled in sections on site. Larger WTGs with a height above 40 m are divided into sections for transportation purposes.[73] Each section is made from welded steel segments and has welded flanges at the top and bottom. These sections are bolted together and then bolted to the foundation and at the top to the nacelle.[74]

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[71] Wizelius (2007)
[72] Manwell et al. (2002)
[73] Wizelius (2007)
[74] Engström et al. (2010)

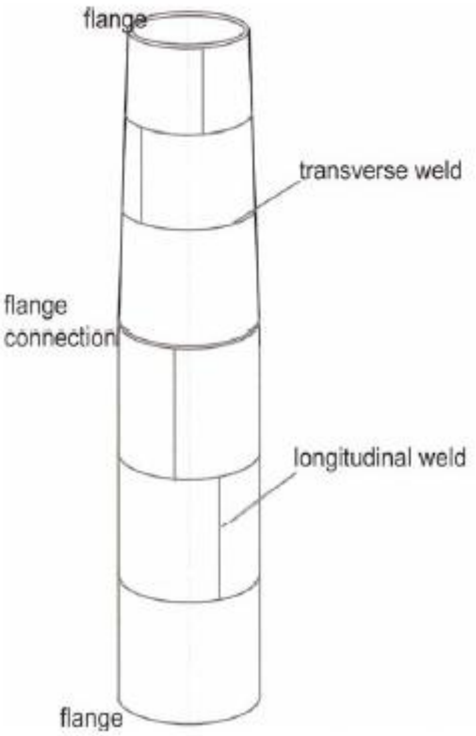

Figure 5[75] - Welded tubular steel tower.

The overall increase in turbine size challenges logistics services, since there are national regulations restricting the height and length of transported goods, seen in the table below. This implies a design limit on conventional steel towers, imposed by the height restriction of 4.5 m. A conical steel tower has a larger base diameter compared to the top diameter, since this design requires less material and is the most cost-effective. Consequently, the base diameter as well as the top diameter increases with the tower height. Then, in order to be able to transport the bottom section its diameter cannot exceed 4.5 m. A tower with a base diameter of 4.5 m enables a tower height of approximately 100 m. However, it is possible to construct higher towers and at the same time maintain a base diameter of 4.5 m, but only if the walls are reinforced.

[75] Engström et al. (2010)

Consequently, the potential tower height with this design becomes a trade-off between the increased material cost and the improved production.

Length	Width	Height	Weight
50 – 55 m	5.0 – 5.5 m	4.5 m	150 t

Table 5[76] – Swedish road transportation limits. The upper limit is granted by a special permit.

5.4 Rotor

There are several aspects of a wind turbine that determine the actual energy production. Namely, tower height, the effectiveness of crucial components, and the rotor swept area. The wind's output is directly proportional to the swept area of the rotor[77], meaning that a turbine will be able to produce more with a larger rotor. Consequently, the rotors have also increased over the years, however not as rapidly as the increase in turbine output. This has to do with the fact that a larger rotor is dependent on the development of higher towers. Normally, the desired relationship between tower height and rotor diameter is 1:1.[78]

The rotor component includes the rotor blades and the rotor hub, to which the blades are attached. Most commercial WTGs have a three-blade rotor, which provides a sufficient enough increase in aerodynamic efficiency to cover the increased cost of having more blades.[79] The blades must be designed so that they are able to withstand the loads they are being exposed to, as well as being aerodynamically efficient. Due to the constant load shifts the blade material need to handle fatigue well, which is why most blades are manufactured in some type of composite material with

[76] Engström (2010)
[77] Wizelius (2007)
[78] Ibid.
[79] Manwell et al. (2002)

fiberglass or epoxy.[80] Moreover, wood is a material that also handles fatigue well, but a blade material that is not commercially widespread, since it is technologically unproven.

Each turbine has a rated output, i.e. the maximum output the turbine can utilize, which is reached at a specific wind speed. When the wind speed exceeds this limit the additional power needs to be adjusted for, otherwise the generator will generate too much heat and eventually destroyed. One way of dealing with this is to allow for pitching of the blades, i.e. adjusting the blades' angle of attack, according to the wind speed and thus controlling the rotational speed.[81]

WTGs that are erected in cold climates need to be able to handle the issues with ice formation. The profile of the blades changes as a result of ice building up, and consequently the rotor's aerodynamic features.[82] In addition, there is a risk of increased loads on the rotor if the ice formation varies along the blades and hub.[83] If there is no system for handling the issues with ice the turbine will automatically shut down when loads reach a certain level.[84]

As with the conical steel towers, there is a design limit on the rotor blades imposed by the transportation restrictions. Once again considering table 5, the length restriction puts a limit on blade length resulting in a maximum rotor diameter of approximately 112 m. Vestas's V112 turbine is one of their more recent models and has a diameter of 112 m. Furthermore, if the site is

[80] Wizelius (2007)
[81] Ibid.
[82] Manwell et al. (2002)
[83] Wizelius (2007)
[84] Lindkvist (2012a)

located in mountainous terrain, the length restriction might be even lower, possibly 35 m.[85]

5.5 Control system

All commercial WTGs have advanced computerized control systems, which monitor every aspect of the turbine. The control system can be divided into three functions[86]: dynamic control, supervisory control, and operation follow-up, where the general aim is to maximize energy production, ensure safe turbine operation, reduce loads and increase fatigue life. The purpose of the dynamic control is to gather information from wind measurements, which is done with anemometers on top of the nacelle, and then signals the turbine to perform actions accordingly, e.g. yaw control and blade pitch control. The surveillance control ensures the safe operation of the turbine by monitoring temperature and vibrations in the mechanical components, and if necessary shutting the turbine down. The follow-up control gathers data regarding production and operation failure etc. This information is processed and displayed to both owners and manufacturers.[87]

5.6 Nacelle and yaw control

The nacelle is the unit at the top of tower, which houses all the generating components in the turbine. General components include a main shaft with bearings, generator and a yaw control system.[88] The yaw orientation system is necessary to keep the rotor correctly aligned to the wind. An active yaw drive, mostly used with an upwind HAWT, contains one or more motors, which operate according to the wind measurements from the anemometer, mounted on top of the nacelle.[89] A downwind rotor, on the other hand, allows the turbine to implement a free yaw, i.e. the rotor will

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[85] Engström (2010)
[86] Manwell et al. (2002)
[87] Wizelius (2007)
[88] Ibid.
[89] Manwell et al. (2002)

align itself automatically to the wind like a weather vane.[90] The remaining components vary, depending on design concept and manufacturer. E.g. some turbines incorporate hydraulics for blade pitch, while others use electrical devices.[91]

5.7 Drive train[92]

The drive train is made up of the rotating parts of the WTG. These usually include a low-speed shaft on the rotor side, a gearbox, and a high speed shaft on the generator side. Other components typically include support bearings, one or more couplings, a brake, and the rotating parts of the generator. The drive train is a critical aspect of the turbine in regards to wind loads, since these components will be subject to the continuous strain from these loads.

5.8 Gearbox

Manufacturers can offer turbines with either a gearbox or without. The purpose of the gearbox is to increase the main shaft's rotation speed to the speed required by the generator[93], which is in the range of 1000 – 2000 rpm.[94] Since the rotor speed for a larger turbine is in the range of 20 – 30 rpm this increase needs to be done in several steps. Moreover, the gearbox consists of many components and requires efficient lubrication and cooling, and therefore is a crucial aspect in terms of operation and maintenance. Therefore, reduced activity for O&M is an advantage that turbines without a gearbox provide. Furthermore, this design reduces the required amount of components substantially, thus reducing maintenance cost. However, they have approximately the same efficiency rate.[95]

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[90] Manwell et al. (2002)
[91] Wizelius (2007)
[92] Manwell et al. (2002)
[93] Ibid.
[94] Wizelius (2007)
[95] Ibid.

5.9 Generator

Most turbines have an asynchronous generator, where power is supplied through electromagnetic induction. An asynchronous generator needs to overcome a certain rotation speed for it to start producing power. In order to deal with this some manufacturers offer turbines with two separate generators, or a double fed induction generator (DFIG).[96] With this design it is possible to have the turbine operational at lower wind speeds as well.

A synchronous generator has the advantage of being able to operate at the same rotation speed as the rotor, which implies that a gearbox is not needed. This turbine design is however not the dominant one among manufacturers. The downside of a direct driven generator is that it increases in size significantly. Also, a generator that operates at a variable rotation speed will produce electricity with varying frequency, thus requiring advanced power electronics to handle the grid input.[97]

The size of the generator is specified by its rated output, but the power output is dependent on the wind speed. Each turbine will produce at its rated output when the wind speed is sufficiently high, otherwise at a lower output according to the specific wind speed.[98] This is illustrated in the power curve for each turbine type. Below is the power curve for a Vestas V90 2 MW, displaying the production capacity for different wind speeds.

96 Wizelius (2007)
97 Manwell et al. (2002)
98 Wizelius (2007)

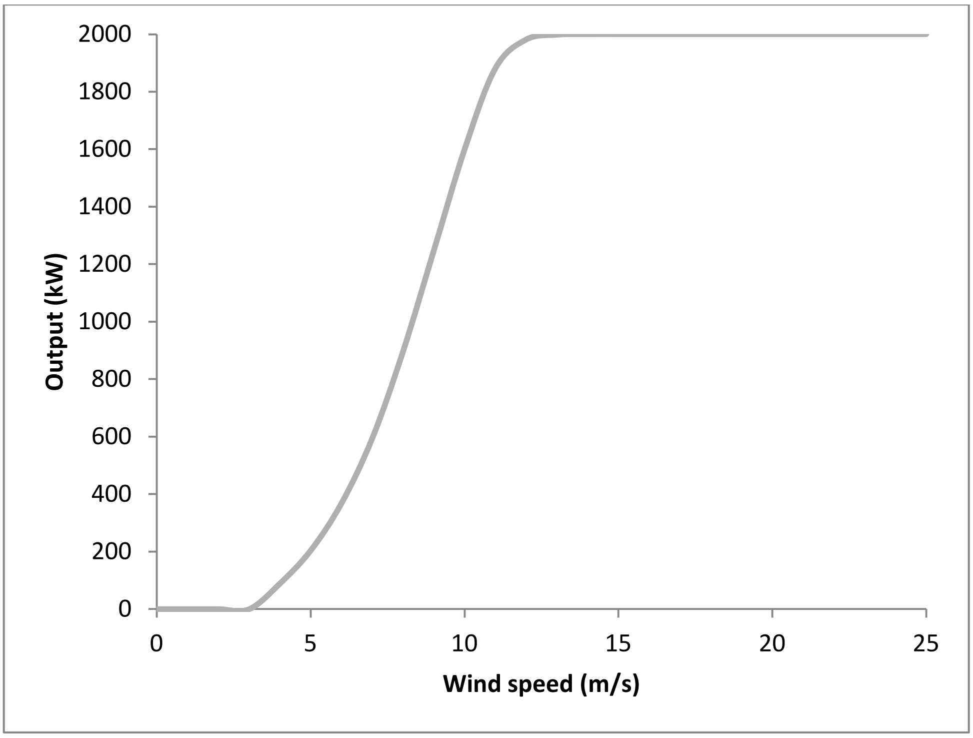

Figure 6 – Power curve for Vestas V90 2MW.[99]

5.10 Transformer

Today's WTGs usually have a voltage of 690 V, which means that they can be connected directly to industrial plants without a transformer. However, most WTGs are connected directly to the power grid through a transformer, which increases the voltage to high-voltage, i.e. 10 – 20 kV.[100] The transformer is either placed just outside the tower, or inside the tower at ground level. Some manufacturers place the transformer in the nacelle, acting as a counterweight to the rotor.[101]

[99] Vestas (2011)
[100] Wizelius (2007).
[101] Lindkvist (2012c)

5.11 Vestas V90 – reference site turbine[102]

The Vestas V90 wind turbine is a pitch regulated upwind HAWT with active yaw and a three-blade rotor. It has a double fed induction generator with a rated output of 2 MW and a 3-stage gearbox. The rotor diameter is 90 m and the hub height 105 m. The tower is made of four tubular steel sections which is anchored to the ground using a gravity foundation.

[102] Vestas (2011)

6. Technology development

In this chapter the chosen areas of technology are presented, which are a result of the initial screening process. They constitute the different aspects of the WTG that will be further analyzed in the evaluation model. In this chapter only their technological features are described. A more detailed reasoning for including them in the study is later discussed in chapter 7.

6.1 Rock anchoring foundations

In general, when constructing a foundation, its type and size will be governed partly by the geotechnical conditions of the site. Depending on the quality and volume of soil at the site the gravity foundation may require additional efforts to increase the load bearing capacity. If the conditions are sufficient enough, the loads from the WTG are transferred to the ground by a spread footing[103], seen in the figure below.

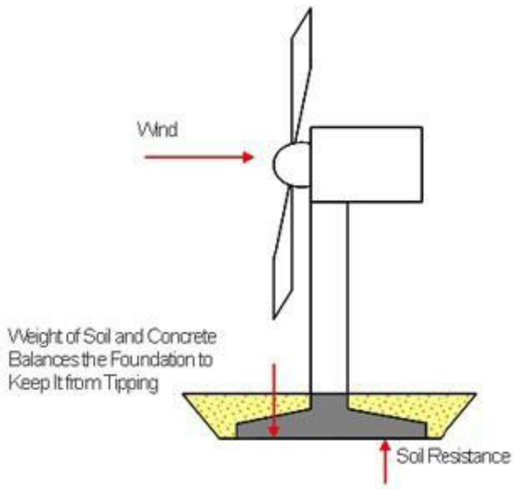

Figure 7[104] – Illustrating how the spread footing resists wind loads.

If not, piles might be needed to transfer the loads to a more rigid ground, e.g. the bedrock, thus creating a deep foundation system. The ability to

[103] Hassanzadeh (2012)
[104] Byle (2010)

resist tilting of the WTG is a result of the tension and compression resistances of the piles[105], which can be seen in Figure 8 a) and c).

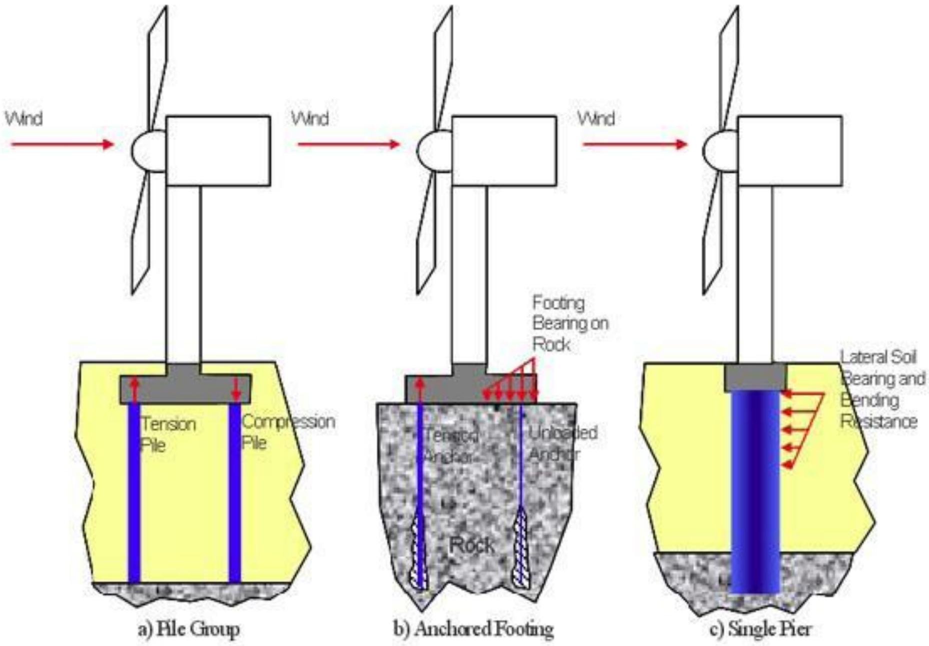

Figure 8[106] – Different deep foundation systems - a) spread footing supported by two piles, b) spread footing anchored to the bedrock, c) spread footing supported by a single pile.

In 8 b) there is no soil with sufficient bearing capacity, so the spread footing is anchored directly to the bedrock. This technique requires solid and homogenous bedrock, e.g. granite.[107]

There is an additional option involving rock anchoring which eliminates the spread footing, thus reducing the cost of concrete as well as the anchor cage. The technique, illustrated in figure 9, basically anchors the bottom tower directly to the bedrock using threaded bars that are attached deep into the bedrock. First, holes are drilled into the bedrock, which are injected with a type of expanding material. The threaded bars are then inserted and

[105] Byle (2010)
[106] Ibid.
[107] Mobjer (2012)

fixated at the ends, while the upper part of the bars are pulled and locked into place at the desired tension load.[108] According to Olof Mobjer, CEO of Mobjer Entreprenad AB, there are no additional O&M costs for this rock anchoring foundation, except occasional visual inspections. The foundation is designed to last the entire lifetime of the WTG. Should one of the bars disengage from its socket there is no way of reattaching it to the bedrock. However, according to Mobjer the foundation is dimensioned to have plenty more bars than required, thus allowing for several of them to disengage without risking serious harm to the WTG or surrounding area.

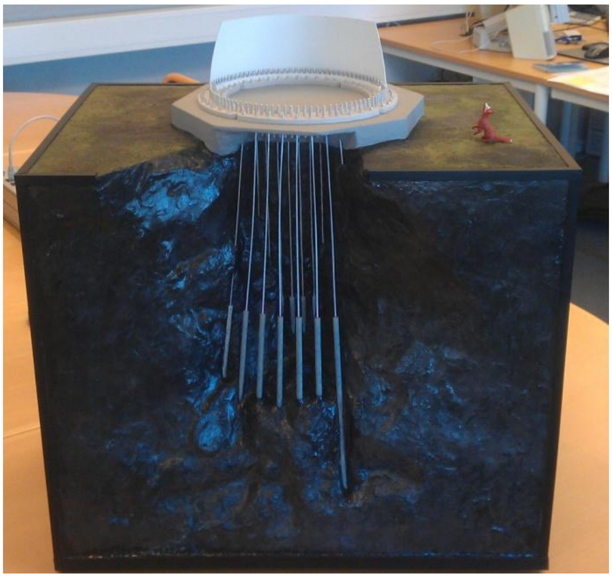

Figure 9 – The rock anchoring solution offered by Mobjer Entreprenad AB. The fox is in scale 1:1.

The main advantage of this rock anchoring technique is the low environmental impact, compared to gravity foundations, which usually requires a large amount of concrete.[109] When it is time for decommissioning the gravity foundation will implicate heavier interference with the surrounding area, due to the amounts of concrete that is either removed or

[108] Mobjer (2012)
[109] Ibid.

left behind. This is most likely an influencing aspect in regards to acquiring permits.[110]

In a cost-perspective the better of these two foundations types will be determined by the distance to a concrete station. When constructing a gravity foundation the soil that is dug up is used to create the necessary crane areas, however with the rock anchoring foundation the crane areas will have to be built by transporting additional material to the site.[111] Consequently, the advantages of rock anchoring, i.e. eliminated costs for concrete and anchor cages, will have to be weighed against the additional cost of creating the crane areas. However, the choice of foundation will first and foremost be decided by the geotechnical conditions on site, as well as turbine output and tower type.[112]

It is natural to presume that rock anchoring foundations will extend the amount of possible sites considerably. Mobjer estimates that the possible granite sites correspond to about 5-10 % of Sweden's surface, and probably more in Norway.

6.2 Jointed blades[113]

In order to be able erect turbines with a larger diameter, one commercially feasible solution is to divide the blades and assemble them on site. However, there are a limited number of suppliers that can offer this solution. Gamesa's 4.5 MW G 10X jointed blades are made entirely of composite material and has a 128 m diameter. The problem, however, is the fact that composite joints are difficult to make, thus increasing weight and cost. Enercon has a different solution with its E-126 turbine, as the outer portion of the blade is made from composite materials while the inner section is made from a load-bearing steel beam with an outer cladding of

[110] Mobjer (2012)
[111] Ibid.
[112] Hassanzadeh (2012)
[113] Engström (2010)

aluminum. Even though this solution increases the overall weight, it could nevertheless be cost-effective, since it is five to ten times cheaper to construct the load-bearing structure in steel rather than composite material. Furthermore, a steel-composite joint is more favorable than a composite-composite joint.

6.3 Tower

As the expansion of wind power has developed rapidly over years, the competition for the most appropriate sites hardens. Building wind turbines in flat terrain is favorable, in the sense that turbulence is generally lower, however, as these sites become occupied, the adaptation to less favorable terrain becomes necessary. Building wind turbines in forest sites, which have become common in both Sweden and Germany[114], requires that consideration is taken to turbulence and increased tower height. Since turbulence is usually stronger in the immediate vicinity above trees, there is a demand for higher towers in forest sites.

Even though conical steel towers dominate the market there are tower structures that are more or less technically and commercially feasible. These alternatives become increasingly interesting as the demand for higher towers rises. The conventional steel tower has its limitations when aiming at reaching higher heights, and therefore it might not be the most economically attractive design. It is possible to construct WTG towers in concrete and lattice, and even hybrid towers incorporating both steel and concrete. Also, wooden towers are being investigated as an alternative tower material.[115]

Friction joint

An alternative tower construction, hence avoiding the problem of transport limitations, is to assemble the tower using bolted joints instead of welding

[114] Engström (2010)
[115] Ibid.

the sections together. This will add the cost of bolts, however, the need for flanges is removed. Welds, which impose fatigue limitations, are also avoided, thus enabling the use of better steel qualities.[116]

Figure 10[117] - Tower with bolted friction joints both in longitudinal and lateral directions.

Concrete

Towers made entirely of concrete are technically feasible as well, however not as commercially proven as the tubular steel tower. In general, towers have been built using pre-stressed concrete for many years. Initially, they were usually constructed by slip form casting, but in recent years more often constructed from prefabricated elements, thus making it easier to control manufacturing conditions. Regarding technical aspects, both alternatives perform in the same way, since it is the pre-stressing that provides the tensile strength.[118] The main advantages of concrete towers

[116] Engström (2010)
[117] Hassanzadeh (2012)
[118] Ibid.

are their stiffness, robustness, and maintenance properties. A well designed concrete tower does not need any maintenance during its lifetime.

Figure 11[119] – Slip-formed cast concrete tower in production.

Hybrid

A hybrid tower, consisting of a concrete bottom part and upper tubular steel part has been shown to meet the requirements of strength, stiffness and natural frequency for turbine towers. About 2/3 of a hybrid tower, with a hub height if 120 – 140, m can be made out of concrete, and the remaining 1/3 of tubular steel. The structural concepts and production for the concrete part of the hybrid tower are quite similar to those of the concrete tower.[120]

[119] Hassanzadeh (2012)
[120] Ibid.

Figure 12[121] - Hybrid tower with a concrete bottom part and upper tubular steel part.

Lattice

The lattice tower is often used in Germany for towers up to 150 m. They are made of struts that are assembled in a specific order to attain a given structural strength and stiffness while using as little material as possible. The main advantage of the lattice tower is the low material consumption. Furthermore, the lattice structure enables the construction of quite large towers and since the towers are assembled on site there are no transportation issues. However, maintenance is the main disadvantage of lattice towers. There can be as many as 10,000 joint bolts in a lattice tower, and each bolt must be inspected three times during its lifetime. Furthermore, the risk of ice formation is an issue, since it could prevent access to the nacelle.

[121] Hassanzadeh (2012)

Figure 13[122] - Lattice tower.

Wood

Lastly, wooden towers are another possible alternative, which in relation to its strength is a cost-effective structural material.[123] However, wooden towers for wind turbines might be the least proven tower structure both commercially and technically.

6.4 Erection methods

The conventional method of erecting the tower and nacelle requires the use of a mobile crane, which may be either of crawler type or truck-mounted.[124] The number of cranes of the required size is limited, which is why the lifting activity is an important issue concerning tower height. In addition, the use of these cranes result in high set-up costs, and lifting restrictions for certain wind speeds (5-8 m/s), furthermore, the largest cranes require a 12.5 m

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[122] Hassanzadeh (2012)
[123] Engström (2010)
[124] Engström et al. (2010)

wide road or track width between sites.[125] Lifting towers, used in Sweden for Maglarp and Näsudden II as well as in Norway by Scanwind, might be necessary when performing lifts over 150 m. However, this method has its drawbacks as well, e.g. it requires a large number of personnel, and the erection time is longer than for a mobile crane. Consequently, the costs are significantly higher for the use of lifting towers.[126]

6.5 Individual blade pitch control with laser

Conventional blade pitch control, which controls the pitch of all blades collectively, has been used for quite some time. The application of individual pitch control is now being used by the larger turbine manufacturers.[127] Theoretically, there are indications of the possibility to reduce fatigue loads by 30 %, using individual pitch control. Experiments within the EU-supported Upwind project have shown that this desired reduction is possible to achieve.[128] However, in most cases the rotor blades are pitched according to the wind data collected from the anemometers' which are placed at the back of the nacelle, thus measuring the wind that has already passed the blades.[129] Using a LIDAR (Light Detection And Ranging) based wind measurement system for blade pitch control suggests that further optimization can be made.[130]

6.6 De-icing system

In areas with colder climate the risk of icing on the turbines becomes an important aspect for operation and maintenance. This problem is further emphasized by increasing tower heights, resulting in turbines that can be

[125] Engström (2010)
[126] Ibid.
[127] Ibid.
[128] Bossanyi (2010)
[129] Lindkvist (2012c)
[130] Mikkelsen (2012)

situated in low clouds for much of the year, and consequently subject to icing when temperatures fall.[131]

There are two main aspects of the icing problem, namely, increased maintenance and consequently production loss, as well as the risk of damage to person, both due to ice formation on the turbine and blades.[132] If the turbine is at a standstill and ice has time to build up on the rotor blades there is a potential risk of damage to person when the turbine is once again set into operation. The maximum ice throw can be calculated using the following formula, where H = tower height and D = rotor diameter: [133]

$$\text{Ice throw} = (H + D) * 1.5$$

Today, most turbine manufacturers offer some kind of ice-detection system, which signals when ice is formed, and the turbine is consequently stopped until it is removed. For the O&M department this is not the best solution since production is lost. Furthermore, the ice-detection systems available today are not considered to be sufficiently reliable[134], thus incurring "unnecessary" production losses when the system mistakenly signals for icing on the turbine. However, without a functioning de-icing system these production losses will have to be accepted, due to safety restrictions.

There are two fundamentally different de-icing systems available or under development.[135] One design involves distributing heated air inside the hollow blades which shuts down the turbine temporarily until the ice is removed. The other design incorporate heating coils placed on the blades' exterior. Only one supplier has a commercial de-icing system, which is the

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131 Mikkelsen (2012)
132 Lindholm (2012)
133 Lindkvist (2012a)
134 Høy-Thomsen (2012)
135 Lindkvist (2012a)

heated air solution, though several other suppliers are about to finalize their products, where both designs are represented.[136]

6.7 Synchronous generators[137]

High speed

Using DFIG requires a converter, which supplies power to the rotor, with only a capacity of about 30 % of the full generator output. However, with a synchronous generator the converter must be able to handle the full output of the turbine. This could be outweighed by the fact that the cost of converters has decreased, thus making synchronous generators an attractive alternative. The most important advantage of synchronous generators is the possibility for turbines to contribute to system stability. Also, they have a high efficiency, especially at part load, which is significantly important in wind power applications. Most of the larger manufacturers, such as GE, Gamesa, Siemens, and Vestas, have been applying this technology in some turbine models.

The permanent-magnets used for these generators consist of the rare earth metal neodymium, which contrary to its name is widely distributed in the earth's crust. Neodymium magnets are the most powerful magnets known and consequently used in a wide range of applications. However, the main issues with neodymium are that China controls nearly the entire world production, and that the mining process is extremely toxic.[138] Mining corporations, in the US foremost, have responded to this situation by expressing the need for reopening old mines, but at the same time solving the environmental issues associated with the mining process.[139] It remains to be seen how this situation will affect the price on neodymium in the future.

[136] Lindkvist (2012c)
[137] Engström (2010)
[138] The Atlantic (2009)
[139] Daily mail (2011)

Direct drive

A gearless turbine solution provides the advantage of reduced O&M costs, mainly due to the reduced amount of components and the elimination of gearbox replacements. The gearbox and its mechanical components are constantly subject to strain from wind loads and will eventually require a total of two or more replacement in order to sustain the expected turbine lifetime.[140] The elimination of these activities is highly desired from an O&M perspective, particularly in locations with a high amount of turbulence.[141] However, there are some uncertainties regarding the technology[142], partly due to limited industry experience and supplier alternatives. Furthermore, a direct driven generator is larger and heavier, and consequently more expensive.[143]

As previously mentioned, Enercon has basically been the sole supplier of direct-drive generators. However, nowadays five out of the ten of the largest manufacturers are either manufacturing or developing direct-drive turbines. Scanwind, which has been taken over by GE, is developing a commercial direct-drive plant for offshore installation. Chinese Goldwind is producing turbines developed by its wholly-owned German subsidiary, Vensys. Siemens has produced a 3 MW turbine with an outer-rotor generator, demonstrated in the Swedish NewGen-generator. Vestas is said to be developing a direct-drive design as well.[144]

6.8 Voltage converters

Traditionally, 690 V converters are most common in wind turbines, despite the fact that higher voltage converters are well established in industrial applications. For a turbine with an output in the megawatt range, it would

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[140] Flaig (2012)
[141] Lindholm (2012)
[142] Høy-Thomsen (2012)
[143] Lindkvist (2012)
[144] Engström (2010)

be natural to design the generators for a higher voltage[145]. A medium voltage converter enables the elimination of the transformer, thus reducing the weight of the nacelle (if the transformer is placed in the nacelle) as well as potentially reducing cable costs. A 3.3 kV converter would result in a more compact and lighter converter[146], however, capital equipment cost would increase by roughly 25 %, according to Desai & Troedson (2010). Furthermore, the equipment for the medium voltage converter is more sensitive to moisture, and requires de-ionized cooling water. However, there are expectations of a higher reliability and improved efficiency using a medium voltage converter, although experiences from industrial use do not necessarily prove the latter to be true. Both low voltage and medium voltage converters are in the efficiency range of 97.5 to 98 %.[147] Finally, incorporating a higher voltage converter in the turbine will require higher safety restrictions and trained personnel accordingly.[148] The number of available electricians with the required training is limited.[149]

[145] Engström (2010)
[146] Ibid.
[147] Desai & Troedson (2010)
[148] Rasmussen (2012)
[149] Dahlgren (2012)

7. Business case evaluation model

This chapter will further describe the evaluation method, consisting of the financial model and the measuring of qualitative aspects. First, the model as a whole is discussed, followed by a review of each component regarding the underlying assumptions. Finally, the testing and validation of the model will be discussed.

7.1 Building the model

The business case evaluation model is centered on three key aspects that represent the drivers for improving the business case.[150] Namely, wind turbine performance, operational expenditure, and capital expenditure. These are the main factors that will have a large impact on whether or not the business case will be regarded as attractive. More specifically, the aim is to increase performance, while reducing operational and capital expenditure.

Each of the chosen technological areas will be subject to both a financial analysis and a qualitative analysis, the latter intended to cover all those aspects that cannot be quantified and as input to the financial model. Covering both aspects is intended to ensure a more comprehensive view compared to merely conducting a financial analysis, which will not take into consideration the overall feasibility.

The chosen technology areas presented in chapter 6 are categorized accordingly and displayed in the table below.

[150] Malmberg (2012)

1) Performance	2) OPEX	3) CAPEX
1.1 Higher towers	2.1 Direct drive generator	3.1 Tower structures
1.2 Increased rotor diameter	2.2 De-icing system	3.2 Foundations
1.3 Increased generator output	2.3 LIDAR blade pitch	3.3 Jointed blades
1.4 Medium voltage converter		
1.5 Permanent-magnet generator		

Table 6 – Chosen technology areas. Authors' own.

Each focus area has been placed in either three categories depending on its impact in the specific category. However, this categorization is merely a visualization of what the internal drivers for each area are. For example, when investigating higher towers the impact it has on performance will be analyzed as well as the effect on capital and operational expenditure.

Regarding the Performance category, the inclusion of higher towers is in accordance with the need to develop wind farms in hilly terrain, which is driven by wind conditions. Furthermore, the rotor diameter is strongly correlated to the energy output, thus increasing blade length should provide a significant increase in production as well. Increasing the generator is also a clear inclusion to the category. As for including higher voltage converters and permanent-magnet generators, they are not expected to increase performance to the same extent as the other, but are still intended to rationalize the production.

For the OPEX category, a direct driven generator has the advantage of eliminating the need for a gearbox, which will have a substantial impact on maintenance costs. The de-icing system is a highly demanded component in areas with cold climate, where the main reason is concerning safety.

Nonetheless, icing issues have an impact on both production and maintenance. Furthermore, blade pitch control using a LIDAR system is also expected to affect both production and maintenance. They are both clear inclusions to the OPEX category since both systems are active processes that will be managed by the O&M department throughout the WTG lifetime. Finally, it should be stated that the estimations for O&M costs are only take into consideration the scheduled maintenance activities.

The CAPEX category does not consist of as many certain inclusions as the previous two, mainly since most new technological advancements will require an increased investment cost, where the trade-off between CAPEX and production increase will determine its feasibility. The demand for alternative tower structures is partly driven by the desire to reduce investment costs, and partly by the desire to build higher towers than the conventional method allows. Finding an alternative foundation structures is mainly driven by design requirements and geological constraints, however it has a direct impact on CAPEX. As for the development towards jointed blades it is powered by limitations in transportation and since the upper limit for this constraint has already been reached, jointed blades are a prerequisite for longer blades. Since they will have a clear impact on CAPEX they are included there.

As a final point, when selection each technology area for inclusion in the above mentioned categories it is important to recognize that they will impact all categories. The attractiveness of each technology area will consequently be determined by the trade-off between the outcomes in its respective category together with the other categories.

7.2 Financial model

The financial model is intended to be used as a quick and accurate assessment of potential investment decisions. The current model employed at the case company is a highly detailed tool, however not as efficient for numerous calculations. By reducing the elaborate cost break down structures and leaving out the extensive information required by an executive management, the aim is to create a model that accurately evaluates two projects, assuming they share several of the underlying assumptions.

The capital investment is considered a single cash outflow, which is required to initiate the project, occurring in the first year. In actuality, the capital expenditure can begin years prior to the construction and O&M phase, where technology has its greatest impact. However, the expenditure of activities required for a G2 proposal to be submitted is disregarded, since it would be considered a sunk cost.

Required investments in working capital need to be calculated for each specific project. The level of working capital required is affected by the payment contracts with both suppliers and customers. If the customer is granted a longer time period before payment than what is given by the supplier, the change in working capital will be negative. Working capital is calculated as the difference between current assets and short-term liabilities, which in turn are expressed as specific proportions of the revenue stream. Since the Knäred project has been chosen as the reference case, the same proportions for assets and liabilities will be used.

When it comes to the opportunity cost of capital the financial model assumes all projects to be entirely equity financed. This removes the financial income and expenses in the income statement, which however has no effect on the cash flows. In reality, the capital structure of corporate firms is rather complex and need to be properly assessed in order to provide an accurate WACC. For the case company, the weighted average cost of capital is determined by headquarters and acquired for each specific project. Consequently, the nominal post-tax WACC used for evaluating the Knäred project is used throughout this evaluation.

Consideration has been taken to the overall increase in prices, i.e. inflation. However, analyzing all variables that might have an impact on the price fluctuations neither fits the scope of this thesis, nor the timeframe. Furthermore, forecasting electricity prices 25 years forward is a comprehensive task and will nonetheless be characterized by uncertainty. Therefore, the model is subjected to a single assumed inflation rate, which corresponds to the national inflation target in Sweden, i.e. 2%.

The cost for decommissioning is regarded as a single cash outflow occurring in the final year. Alternatively, the decommissioning cost can be distributed evenly over the lifetime as a non-cash flow cost, evened out by a non-cash flow revenue the final year. This book-keeping maneuver will not affect the cash flows directly. However, it will lower EBIT (earnings before interest and tax) in the statement of income and consequently taxes paid. This implies a lowered cash outflow for year 1-24. Consequently, by treating the decommissioning cost in accordance with the theoretical framework, it will provide an undervaluing of projects.

The assumptions that constitute the basis for the financial model have been made with consideration to its primary purpose, which is to enable a quick and accurate project valuation. This involves some simplifications, as previously explained, which are intended to reduce the complexity of the existing model. However, consideration has been taken so that the assumptions and simplifications do not overvalue projects, or go against conventional investment decision praxis. The project's outcome is intended to provide a view of the project's attractiveness and enable a comparison between projects in order to be able to look at the effects of desired tweaks.

7.3 Decision matrix

The Pugh concept selection constitutes the second dimension in the business case evaluation method. Each of the chosen technology areas correspond to a decision to be viewed relative to the reference site's current configuration. Furthermore, the technological areas must present at least one specific alternative.

Each focus area represents a decision and is valued by grading each alternative according to the concept selection matrix. The criteria, by which each alternative is measured, are intended to cover a wide range of qualitative aspects that influence the potential decision of investigating new technology. This implies that some of the criteria will be more or less relevant to the different decisions. A criterion that has received a 0 in weighting is considered to be irrelevant to the decision in question. Furthermore, the possibility to contribute with additional criterion is offered. For all thirteen technology areas, i.e. decisions, 'construction time' was the only criterion added. This would suggest that the initial criteria, compiled from interviews, cover the better part of the relevant qualitative aspects. A complete overview of the criteria can be found in Appendix 4.

As previously mentioned, all decisions have one or more alternatives to be considered. In fact, for some cases there is only one alternative, which has to do with the decision being expressed as more or less binary. For example, the technology regarding permanent-magnet generators implies that the decision is about whether or not to buy this type of generator. On the other hand, when considering higher towers, the specific height is a variable that needs to be known when faced with the decision. This provides the possibility to create a more dynamic decision-matrix, which is the case for higher towers, increased rotor diameter, increased generator output, de-icing system, and tower structures. The decision regarding higher towers and larger rotor diameter incorporate three alternatives, namely 125 m, 150 m, 175 m, and 100 m, 126 m, and 164 m. For an increased generator output there are only two alternatives, 3 and 5 MW, mainly since a rated output of more than 5 MW is considered to result in severe practical implications for the onshore area. For the de-icing system there are two alternatives as well. Lastly, concerning tower structures, there are five different possibilities.

7.4 Combining the financial and qualitative aspects

The combination of the financial model with the qualitative analysis will constitute the business evaluation model. The intersection of the axes marks the reference point to which all projects are related. The horizontal axis displays both the relative and actual IRR, to the right if better than the reference case, and to the left if worse. The vertical axis displays the qualitative measure which has a maximum value of 200 and minimum -200, corresponding to the ratings much better and much worse than the existing configuration at the reference site. Each point will represent all the alternatives for each decision. Furthermore, it is also possible to compute desired scenarios and display them in relation to the case site.

Regarding the financial aspect the IRR will be used to display the financial status of investigated alternatives relative to the base case. However, in those cases where the IRR and the NPV rule show conflicting results the NPV will be used as the decisive factor. The reason for displaying the IRR is that it the most widely known measure and consequently the one people easiest can relate to.

The evaluation model is intended to be an iterative tool. Once the initial evaluation round has been finalized further refining can be made. The analytical approach, described in section 2.2, enables a broader study of different technological developments, since it focuses on single variable changes. The impact on the system is considered to consist only of the direct effects derived from this change. Each component of the WTG is considered to be part of the wind turbine system, and each turbine is in turn part of a greater system, i.e. the business case which is the issue of study. Consequently, after the first evaluation round there are possibilities to make further estimations and involve additional input data that should be accounted for in a systems perspective. This is mainly concerning the financial input but not exclusively. After each round the qualitative aspects could be reexamined as well and subject to additional surveys, which would further improve the reliability of the results. The focus areas that resulted in a positive outcome from the previous round will be subject to further examination.

7.5 Validating the model

The validation of the model was carried out according to the initial aim for ensuring a high credibility, which is described in section 2.6.

8. Applying the model

In this chapter the initial results from the business case evaluation is presented. A more extensive discussion regarding financial input parameters will follow. In addition, a sensitivity analyses in the qualitative dimension will be done by considering the criteria for each decision. Moreover, the second evaluation round will be presented. For detailed information regarding input parameters and assumptions made, see Appendix 3. Also, in Appendix 4 the full results of the qualitative evaluation can be found.

8.1 Choice of reference site

The Knäred project was initiated in 2010. Construction of the wind farm began in 2012 and will be completely commissioned by the end of 2012. The site is located in southwest of Sweden, Laholm county, and represents a typical onshore project today.[151] The wind farm consists of ten 2 MW turbines with a hub height of 105 m and rotor diameter of 90 m. Furthermore, the turbines are situated in a forest area, which is considered to be an appropriate location according to the field of study.

The Knäred case serves as the foundation from which all alternative decisions will be formed. Choosing Knäred as the reference site will naturally influence the outcome of the study. All underlying factors, such as forecasts and wind assessments etc., will consequently be passed on to the resulting cases.

8.2 Assumptions regarding financial input

In addition to the assumptions regarding the financial model, described in section 7.2, there are further assumptions made regarding the input parameters in the model. These cover assumptions regarding Euro exchange rates, cost of certificates and the price for electricity in the

[151] Axelsson (2012a)

different electricity price zones in Sweden. For the exchange rate, all costs that have been displayed in Euros have been subject to the same exchange rate of 9.26 SEK/Euro, which represents the rate used at the time for the initiation of the Knäred project. Regarding the price of green certificates and electricity they have been subject to a single assumption over the WTG lifetime, which can be seen in Table 7. The certificate price corresponds to the average price during the past five years.[152] The chosen electricity price assumption will later be scrutinized as a sensitivity analysis will be performed. Furthermore, the price for electricity has also been subject to a slight increase due to the location of Knäred in price zone SE4. This is further discussed in section 9.5.

Financial input

Euro exchange rate	9.26 SEK/Euro
Certificate cost	0.25 SEK/kWh
Electricity price	0.50 SEK/kWh
Electricity price (including supplement charge for SE4)	0.58 SEK/kWh
WTG Lifetime	25 years

Table 7 - Assumptions made concerning financial input. Authors' own.

8.3 Overview decision alternatives

Below is a complete overview of the chosen areas within the current technology development for onshore wind projects. There are a total of 11 focus areas, corresponding to 21 decision alternatives, which can be seen in Table 8 below. Most of the alternatives have been chosen instinctively according to the current developments in each area. For increased tower height, rotor diameter and generator output the alternatives represent current commercially feasible solutions as well as extreme values.

[152] Swedish Energy Agency (2011)

1) Performance	**2) OPEX**	**3) CAPEX**
1.1 Higher towers	**2.1 Direct drive generator**	**3.1 Tower structures**
i) 125 m	i) Direct drive generator	*i) Friction joint*
ii) 150 m	**2.2 De-icing system**	*ii) Concrete*
iii) 175 m	*i) Heating coil*	*iii) Hybrid*
1.2 Increased rotor diameter	*ii) Heated air*	*iv) Lattice*
i) 100 m	**2.3 LIDAR blade pitch**	*v) Wood*
ii) 126 m	*i) LIDAR blade pitch*	**3.2 Foundations**
iii) 164 m		*i) Rock anchoring*
1.3 Increased generator output		**3.3 Jointed blades**
i) 3 MW		*i) Jointed blades*
ii) 5 MW		
1.4 Medium voltage converter		
i) 3.3 kV converter		
1.5 Permanent-magnet generator		
i) Permanent-magnet generator		

Table 8 – Chosen focus areas including all decision alternatives. Authors' own.

8.4 First round results - Performance

Here, the results from the evaluation of Performance areas are presented. For increased tower height, rotor diameter, and generator output all alternatives displayed a financial improvement of the base case, though all performed worse than the base case regarding qualitative aspects. Incorporating medium voltage converters and permanent-magnet generators in the turbines, only reduced the attractiveness of the business case.

Higher towers

There is an improvement of the business case following the increase in tower height. Both the IRR and NPV rule suggest that a 175 m tower is the most attractive alternative. However, it should be pointed out that the 175 m alternative is a hybrid structure with concrete and welded steel segments. The reason for this inconsistency is simply because a 175 m tower with the design employed at the reference site is not considered feasible.[153] Other possible tower structures at this height are steel towers with friction joints and the wooden structure. However, the hybrid structure was chosen since it is financially more attractive.

The grading of the qualitative aspects displays the reversed situation. As the tower height increases, so does the liability regarding non-financial aspects. For the 175 m alternative the grading -88 corresponds to the increase in height, while the -27 grading represent the change in tower structure to a hybrid tower.

	IRR	Qualitative grade, higher towers	Qualitative grade, tower structure	NPV
Base case	9.8%	0		92,497
Welded Steel, 125m	10.2%	-24		114,023
Welded Steel, 150m	10.4%	-69		135,698
Hybrid, 175m	10.7%	-88	-27	156,796

Table 9 – Results for increased tower height. Authors' own.

153 Engström et al. (2012)

For different heights the production was simulated using the wind assessment data from the reference site. Furthermore, the input data for these alternatives are based on the assumption that the base diameter is kept within the transportation restrictions. However, for the 175 m alternative the base diameter is allowed a size of 11.75 m, which is not an issue since it is a hybrid tower with a concrete bottom part, either slipformed or assembled on site using pre-fabricated concrete elements. The results, with a financial improvement following the increase in tower height, were expected. In addition, the qualitative aspects, reflecting the greater uncertainty with higher towers, were not surprising either. For the financial outcome there is room for a more comprehensive analysis. The initial input data for capital investments do not include costs for transportation, lift and foundation. The assumption behind this approach is that once the technology is implemented at a regular basis these costs will be at a level corresponding to the base case. The additional costs of transportation, lift and foundation for increased heights are mainly the result of heavier tower parts, thus requiring larger cranes etc. and perhaps reinforced foundations.

The qualitative aspects that were considered to be most important for the development of higher turbine towers mainly concerned public acceptance and the uncertainties of unproven technology. Public acceptance is an important factor when developing wind power projects and may be hindering when applying for necessary permits. Moreover, when reaching heights above 125 m there is limited amount of experience and knowledge in the industry, which is further articulated in the negative grading for manufacturer alternatives. Finally, concerns regarding maintenance and accessibility are raised with increasing tower heights.

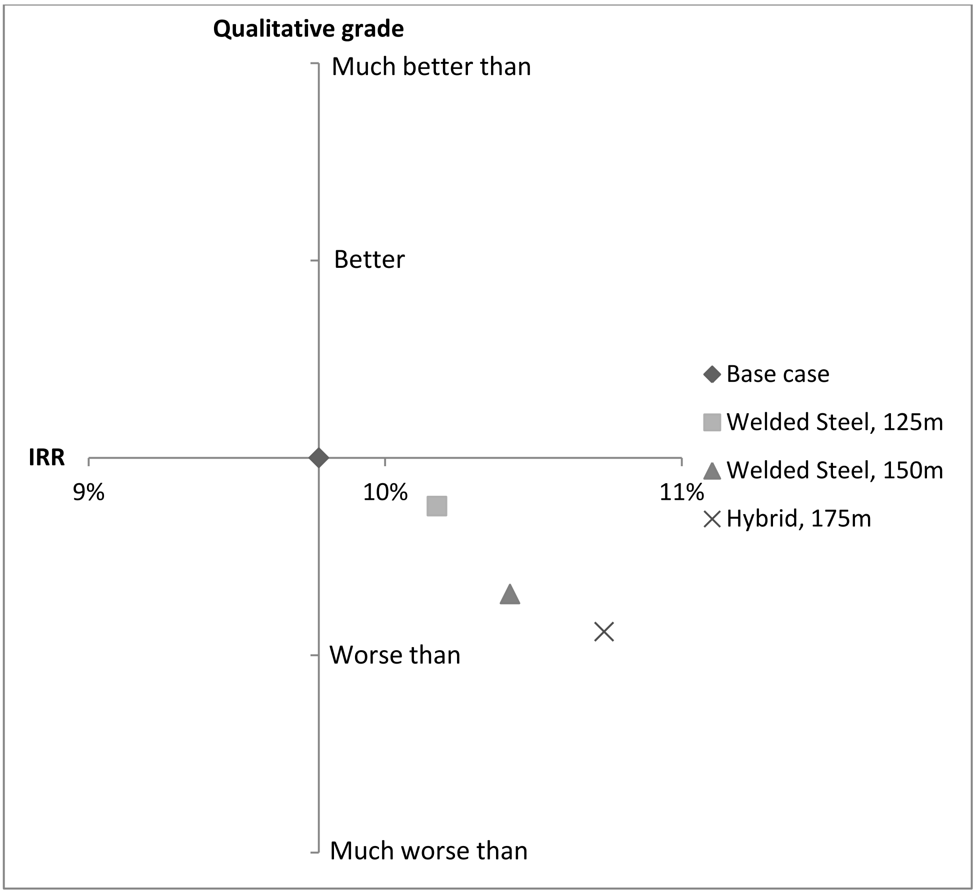

Figure 14 – Results for increased tower height. Authors' own.

Increased rotor diameter

For the increased rotor diameter the business case shows a significant improvement following the increase of blade length. Both IRR and NPV suggest all three alternatives perform better than a 90 m diameter, which is employed at the reference site. However, regarding the qualitative aspects, all three alternatives perform worse than for the diameter at the reference site.

	IRR	Qualitative grade, increased rotor diameter	NPV
Base case	9.8%	0	92,497
100 m	13.9%	-33	213,192
126 m	15.4%	-96	302,195
164 m	16.7%	-163	408,120

Table 10 – Results for increased rotor diameter. Authors' own.

The financial evaluation is based on estimations of increased capital investment, OPEX and performance increase due to longer blades. Power curves for a 2 MW turbine with the desired rotor diameter were needed to perform the production simulations. Since these power curves could not be found they had to be estimated by using several turbines with the desired output and existing diameters. The improved financial outcome is unsurprising, mainly due to the strong correlation between energy output and rotor swept area. However, the cost inputs only take into consideration the increase in CAPEX due to material increase, and assumptions for increased maintenance. One major aspect for the two longer alternatives are the transportation restriction, which will probably further reduce their attractiveness if taken into consideration. Perhaps the only feasible solution is to divide the blades for those exceeding the restricted length of 55 m.

The above mentioned difficulties with longer blades are emphasized in the qualitative assessment. The main concerns involved different aspects of logistics. First, the site delivery is an issue when transporting long blades by road. Second, construction logistics, which involve lifting and construction of roads at the site, is a limiting factor as well. Furthermore, the loads on both nacelle/blades and the tower/foundation may potentially have a negative impact and need to be investigated further. Finally, the issue of acquiring necessary permits is once again raised, which is a highly relevant concern as turbines grow larger.

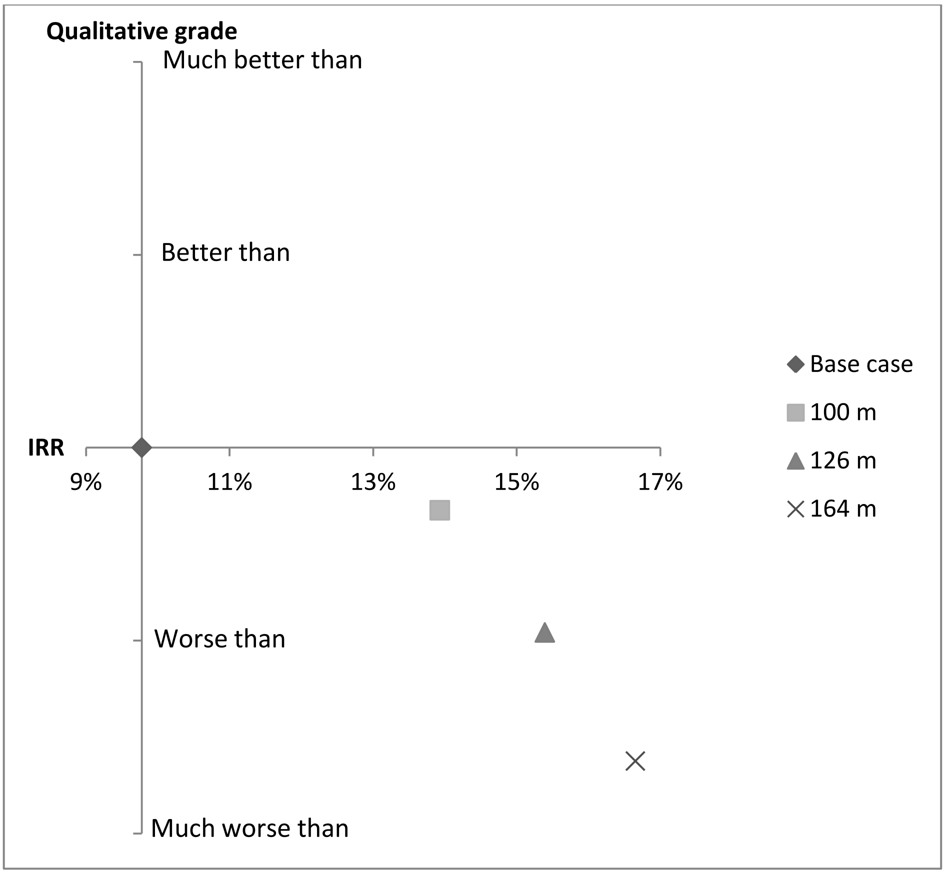

Figure 15 – Results for increased rotor diameter. Authors' own.

Increased generator output

For the two alternatives for higher generator output the results are similar to the previous. Both the IRR and NPV rule supports a 3 MW generator over the 2 MW employed at the reference site, and ultimately the 5 MW option above both. However, it must be stated that for both cases the improvements in IRR and NPV are also a result of increased rotor diameter. The outcome of the 3 MW case is based on a rotor diameter of 112 m, and the 5 MW case on a diameter of 126 m. This will naturally, as seen in the previous table, act as an additional factor impacting the business case. The reason for this approach was due to difficulties of acquiring power curves for generators of the desired size with a rotor diameter of 90 m.

Also similar to the previous results, both alternatives perform worse than the base case regarding qualitative aspects and increasingly so with higher generator output.

	IRR	Qualitative grade, increased generator output	Qualitative grade, larger rotor diameter	NPV
Base case	9.8%	0		92,497
3 MW	16.9%	-14	-33	344,357
5 MW	20.7%	-68	-96	528,386

Table 11 – Results for increased generator output. Authors' own.

The generator alternatives show a significant financial improvement and as previously stated the results are enhanced due to the use of power curves that also are based on turbines with larger rotor diameters. Furthermore, the capital and operational expenditure only take into consideration the cost of the actual generator and the operation and maintenance of it, as well the same for the longer blades. However, incorporating a generator with higher output will affect the entire design of the turbine, including other mechanical components and power electronics. These aspects will most likely reduce the financial improvements.

Furthermore, the criteria impacting the qualitative assessment are widespread. Concerns regarding logistics are raised due to the followed increase in size for the generator as well as other components. This concern is also expressed in the measure for nacelle weight, which is expected to increase as well, thus possibly affecting tower and foundation dimensioning. Moreover, HSSE issues are raised due to increased safety risks when working with larger components. Lastly, none of the output alternative is considered to be proven enough to be without uncertainties.

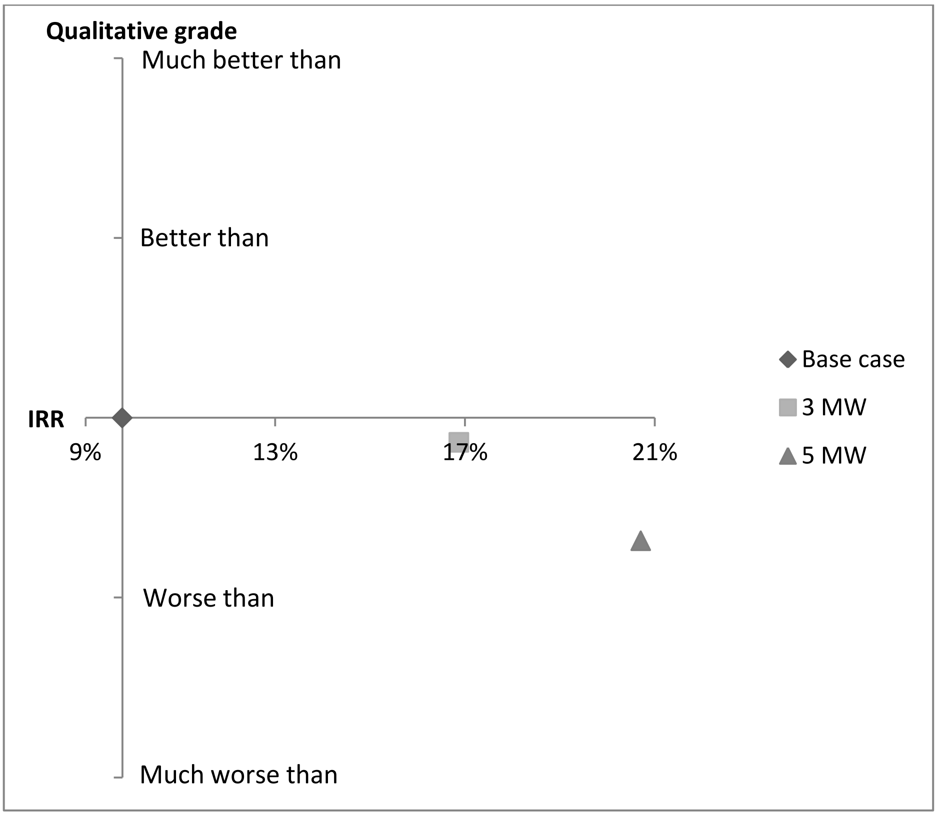

Figure 16 – Results for increased generator output. Authors' own.

Medium voltage converter

Incorporating a medium voltage converter in the turbines has a negative effect on the business case. Both financial and qualitative aspects are reduced and consequently this is the first decision alternative that performs worse than the base case in both dimensions.

	IRR	Qualitative grade, medium voltage converter	NPV
Base case	9.8%	0	92,497
3.3 kV	9.6%	-80	88,184

Table 12 – Results for the 3.3 kV converter. Authors' own.

The estimations made for a 3.3 kV converter include the additional cost for the converter, increased maintenance costs due to need for highly trained personnel, as well as the specified efficiency rate. Theoretically, there are expectations that a higher voltage converter would reduce some of the losses that occur when transforming the current. However, this has not been possible to estimate which is why the medium converter does not amount to any effects on performance. Consequently, the negative financial outcome of this decision corresponds to the increase in both CAPEX and OPEX.

The main qualitative aspect of implementing a higher voltage converter has to do with the increased safety risk. When a component reaches a voltage output of 1000 V it is required to have service personnel with additional electric training is required. Further criteria that resulted in the negative evaluation concern mainly proven technology and manufacturer alternatives. The use of higher voltage converters is almost non-existent in the lower megawatt range.

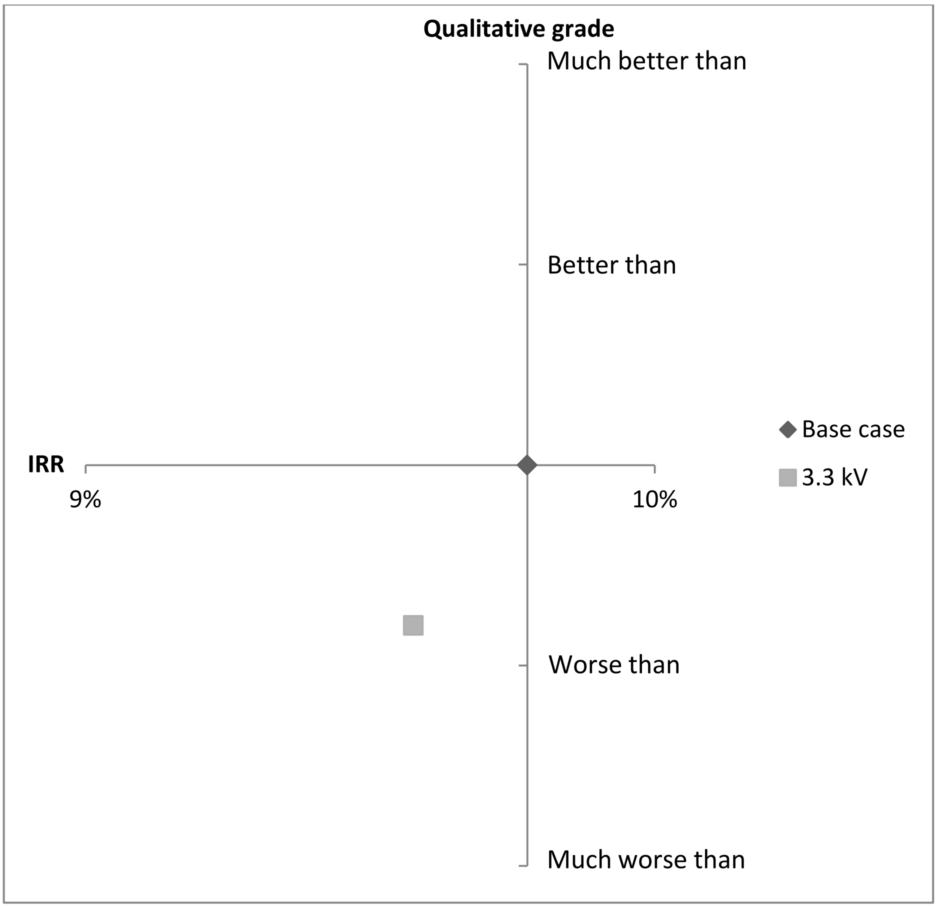

Figure 17 - Results for the 3.3 kV converter. Authors' own.

Permanent-magnet generator

Regarding the permanent-magnet generator it performs quite similar to the voltage converter, however not as bad in the qualitative aspects. Nevertheless, this alternative performs worse than the business case in all three measures.

	IRR	Qualitative grade, permanent-magnet generator	NPV
Base case	9.8%	0	92,497
Permanent-magnet generator	9.6%	-1	89,239

Table 13 – Results for the permanent-magnet generator. Authors' own.

The estimations made for a permanent-magnet generator include the additional cost for the generator, increased maintenance costs since the synchronous generator is larger, as well as the corresponding power curve for a 2 MW turbine with a permanent-magnet generator. The results are somewhat surprising, since it is expected that a synchronous generator can produce more since it operates at a variable rotation speed. However, the production simulation for the chosen permanent-magnet generator resulted in a similar production as the base case turbine.

The qualitative evaluation of the permanent-magnet alternative is only somewhat negative in relation to the base case. One major aspect supporting the choice is the strong compliance to grid demands expected by a synchronous generator. Furthermore, concerns regarding HSSE issues and maintenance accessibility are once again raised. This is mainly due to the fact that a permanent-magnet generator will increase in size and incorporate strong magnets, thus increasing the liabilities concerning safety and maintenance.

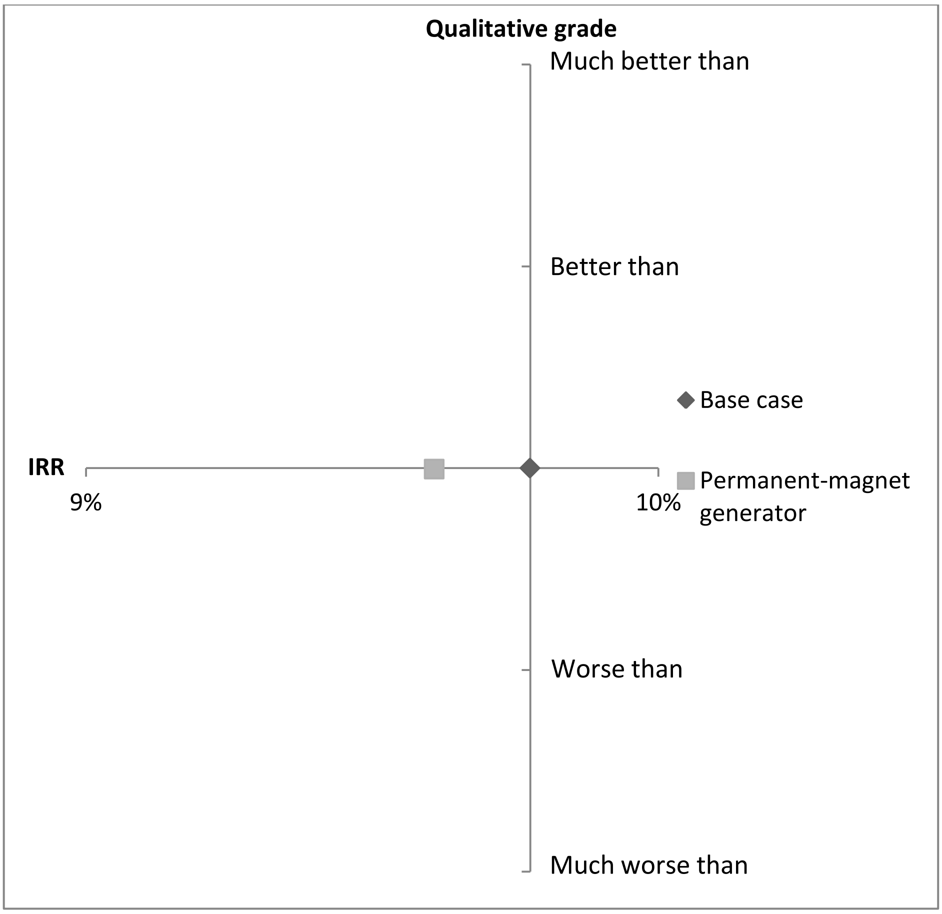

Figure 18 – Results for the permanent-magnet generator. Authors' own.

8.4 First round results - OPEX

Here, the results of the evaluation for the OPEX category are presented. The results for these three focus areas all share a similar pattern in the outcome of the financial dimension, and in the positive qualitative grading for all alternatives. Furthermore, all the better alternatives displayed a lower IRR than the base case while having a higher NPV. A higher net present value states that the project has earns the highest value over the entire lifetime. This will be further discussed following the presentation of the results.

De-icing system

Looking at the two de-icing alternatives they perform quite similar to each other. The heated air option is slightly better financially than the heating coil. Nevertheless, none of the two perform better than the base case according to the IRR. However, the heated air system has the better NPV suggesting that this alternative performs better. As previously mentioned this will be addressed further later on.

Considering the qualitative grading both alternatives perform better than base case. The heated air alternative is yet again the stronger choice, consequently having an overall positive impact on the business case.

	IRR	Qualitative grade, de-icing system	NPV
Base case	9.8%	0	92,497
Heating coil	9.6%	108	90,624
Heated air	9.7%	132	92,799

Table 14 – Results for the de-icing systems. Authors' own.

When evaluating the de-icing systems the assumption is made that they will eliminate the entire production loss due to icing. For the heated air alternative this production loss is not entirely eliminated since the turbine is stopped temporarily while the ice is being removed. The data for the production loss are from production simulations during winter months at a site with similar conditions as the Knäred site. The CAPEX is included, as well as cost estimations for operation and maintenance. In addition, both designs require a certain energy consumption for removing the ice, which is however not included in evaluation due to difficulties of acquiring this information for both designs.

The major qualitative aspect that is highlighted for both alternatives is the improved safety aspects concerning work environment and third party risk, as a consequence of implementing systems that can efficiently detect and remove icing on turbines. Maintenance accessibility is also considered a positive consequence, as well as the increased amount of potential project sites. On the other hand, some concern was raised on aspects regarding the time to commercial development.

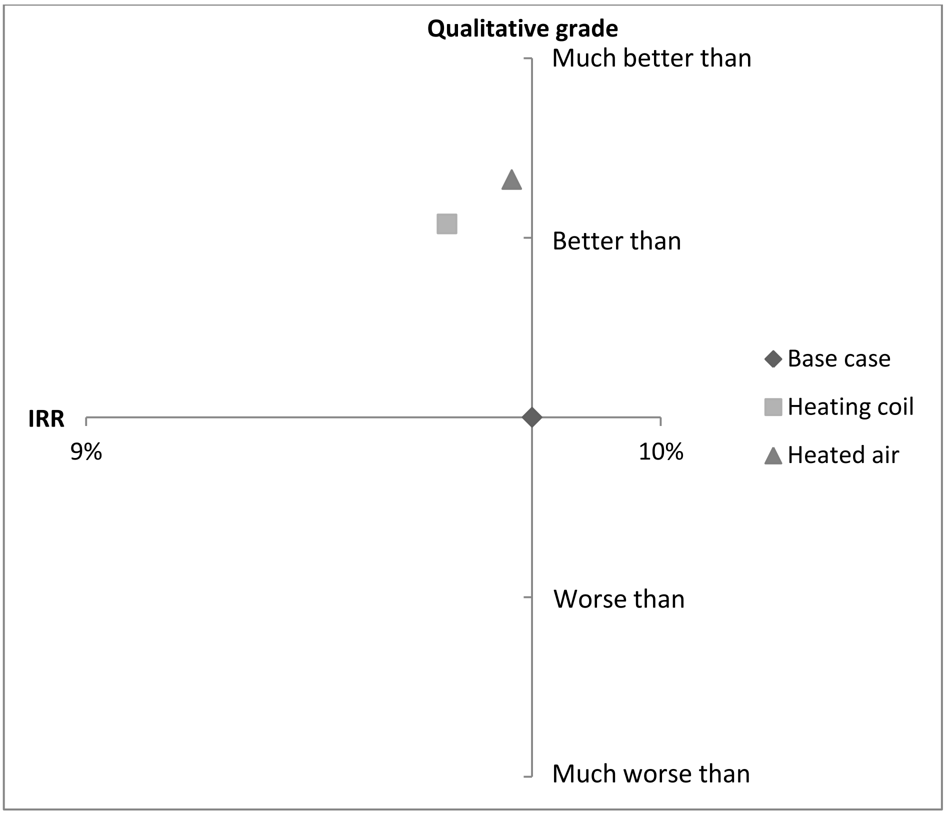

Figure 19 - Results for the de-icing systems. Authors' own.

LIDAR based blade pitch control

The resulting evaluation for the LIDAR based blade pitch system shows the similar situation as for the heated air de-icing system. The NPV is higher than for the base case but the IRR suggests the reversed ranking. Furthermore, there is a minor improvement in the qualitative dimension as a further consequence.

	IRR	Qualitative grade, LIDAR blade pitch	NPV
Base case	9.8%	0	92,497
LIDAR blade pitch	9.7%	33	93,236

Table 15 - Results for LIDAR pitched control system. Authors' own.

For the pitch control solution the CAPEX for the system is included, as well as estimations regarding operation and maintenance, as well as the estimated load reduction. Furthermore, the percentage of estimated load reduction as a result of LIDAR based blade pitch is assumed to correspond proportionally to a reduction in OPEX. However, no consideration is taken to the necessary configuration of the blades since the exact layout of the pitch control is not specified. Therefore, the assumption is that the LIDAR system can be implemented with the current individual blade pitch control.

The positive outcome in the qualitative grading is mainly due to the expected reduction of loads on the rotor and thus mechanical components. Subsequently, the number of site possibilities increases as well the possibility to construct WTGs at closer distance to each other. Aspects that remain uncertain involve the stability of the system and key component availability.

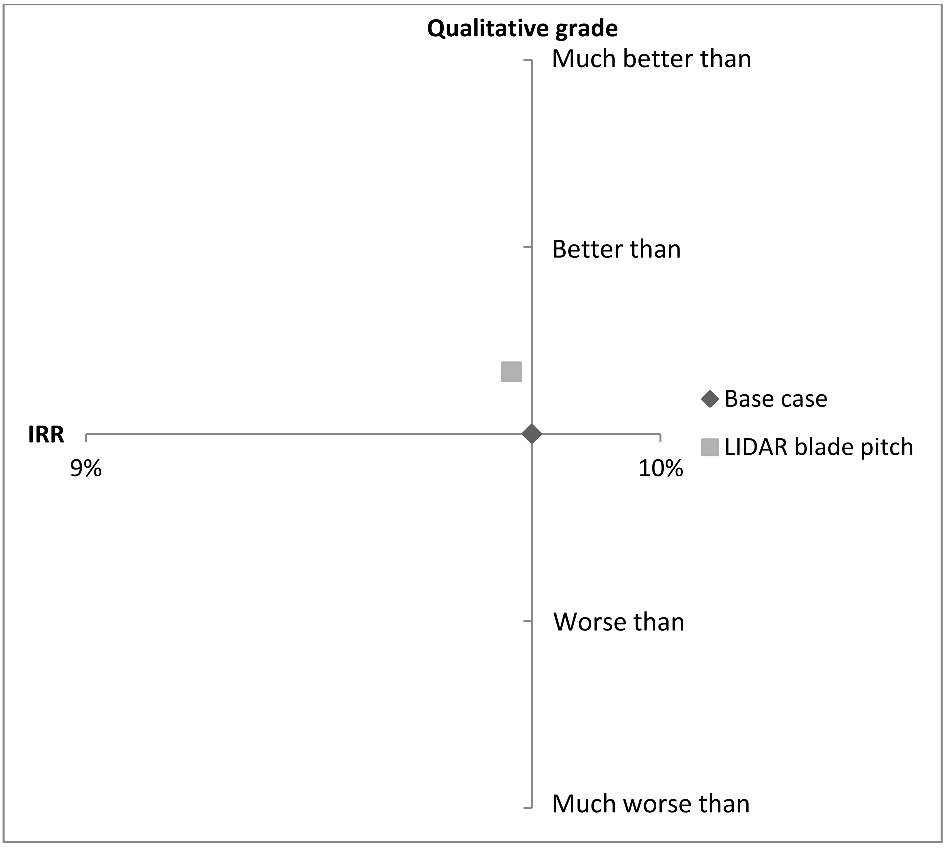

Figure 20 - Results for LIDAR pitched control system. Authors' own.

Direct drive generator

The results for the direct drive system are treated similarly by the IRR and NPV rule, i.e. the IRR suggest the base case is the better while NPV and the qualitative assessment indicate otherwise.

	IRR	Qualitative grade, direct drive generator	NPV
Base case	9.8%	0	92,497
Direct drive generator	9.7%	28	99,696

Table 16 – Results for direct drive generator. Authors' own.

When evaluating the option of using a direct drive generator the assumptions were made with emphasize on the structural design of such a turbine, since it proved difficult to acquire this information otherwise. Starting with the base case turbine, the generator is replaced with a 2.3 MW synchronous generator, and the gearbox is entirely removed. The CAPEX for this arrangement will increase with the additional cost of the generator, while it is reduced with the removal of the gearbox. The OPEX will be favored due to the elimination of gearbox changes, while performance is estimated to be similar to the base case.

For the results of the qualitative evaluation the same reasoning as for the permanent-magnets is applied. Furthermore, the aspects of proven technology where raised as the biggest concern, as well as the limited number of manufacturer alternatives.

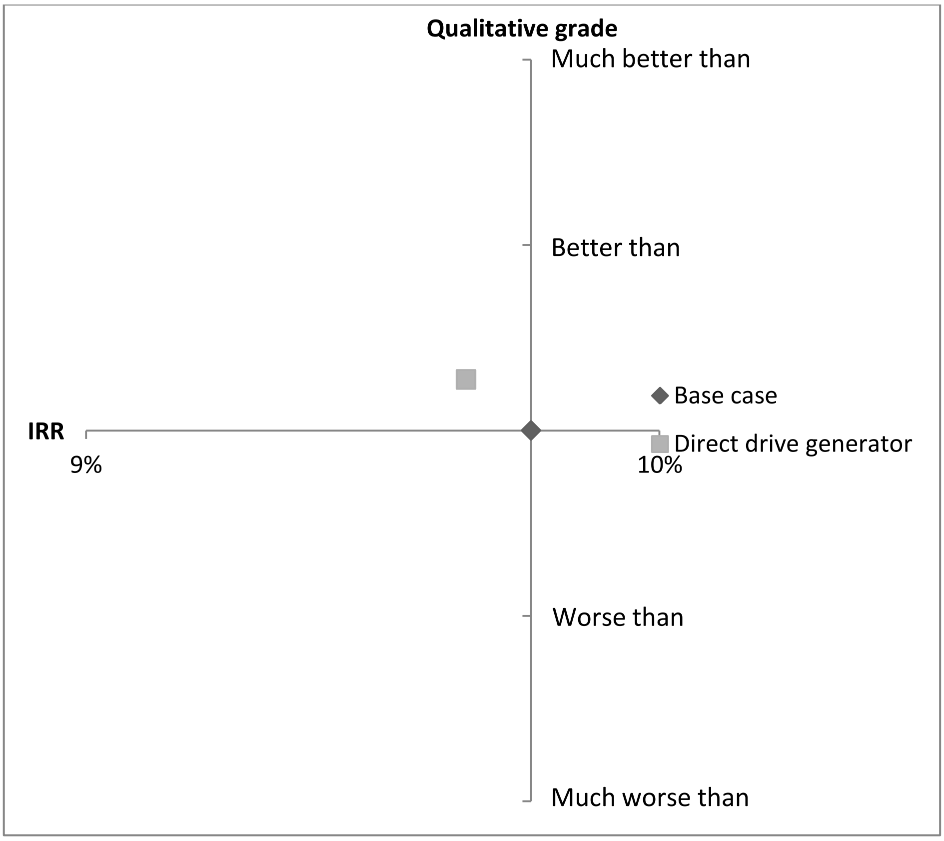

Figure 21- Results for a direct drive generator. Authors' own.

8.5 First round results - CAPEX

The results regarding the CAPEX alternatives are presented below. Regarding tower structures they all perform quite similar but there are only two alternatives that perform better than the base case, i.e. wood and lattice. However, they all receive a negative grading in the qualitative dimension, which could be expected due to their limited track record. Furthermore, the structures with the most limited track record are perhaps lattice and wood, which might imply a greater uncertainty in the financial input.

Tower structure

For all tower structure alternatives there is no inconsistency concerning the IRR and NPV rule. For the concrete, hybrid, and steel friction joint structures both NPV and IRR suggest a reduced attractiveness of the business case, and in comparison to each other they perform quite similar. The hybrid structure is slightly better however. The lattice and wooden structures result in a financial improvement of the business case, with the wooden tower as the ultimate winner.

The overall qualitative grading is negative for all alternatives. Worth noting is that the two most financially attractive alternatives are the ones with the highest qualitative uncertainties. The hybrid and steel friction joint towers are the two most attractive options in the qualitative perspective.

	IRR	Qualitative grade, tower structure	NPV
Base case	9.8%	0	92,497
Concrete slipformed	9.1%	-74	80,125
Hybrid	9.5%	-27	86,412
Lattice	9.9%	-84	95,689
Steel shell friction joint	9.4%	-35	85,608
Wood	10.2%	-70	99,508

Table 17 – Results for tower structures. Authors' own.

The estimations of the CAPEX and OPEX for different tower structures are based on a report that aims at conducting a cost analysis of different tower structures.

The main uncertainties for all tower structures concern the lack of sufficient industry track record, since welded tubular steel towers have been the dominant design for many years. Furthermore, HSSE issues are raised for the friction joint, concrete and hybrid towers. Wood structures would require increased efforts in establishing the technology. Concrete towers will have a negative impact on logistics because of heavy transportation to the site. Lattice towers involve further concerns regarding public acceptance since the visual feature of the tower might be considered to have a negative impact. To conclude, there are more or less uncertain aspects influencing all alternatives due to the lack of experience.

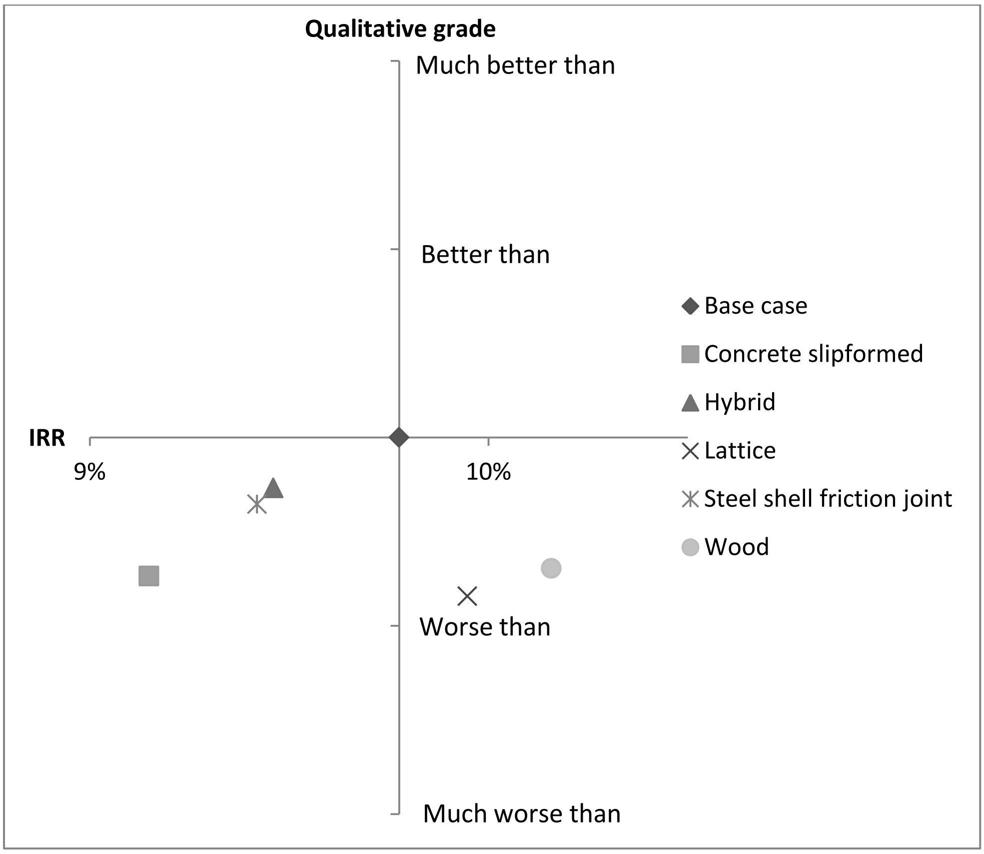

Figure 22 – Results for tower structures. Authors' own.

Rock anchoring foundation

The rock anchoring foundation has a positive outcome in both aspects of the business case. However, the assumptions behind the data are uncertain and furthermore the result from this case will be difficult to generalize to a wider extent. The financial improvement is based on the assumption that the relative economic improvement for the rock anchoring solution compared to the gravity foundation corresponds to the cost reduction when no long requiring the anchor cage. The data for this input is a reasonable assumption based on multiple sources. However, the circumstances that affect the choice of foundation are not entirely geotechnical. When taking into consideration the distance to a concrete station it may eliminate the cost reduction, since the additional material for crane areas will be required. Nevertheless, in these calculations it is assumed that the concrete station is sufficiently far away and that the issue with the crane areas is solved.

The qualitative assessment showed a positive impact regarding construction time, permit process and construction logistics. Concern was mainly raised on maintenance issues and uncertainties about the effect on WTG lifetime.

	IRR	Qualitative grade, foundation	NPV
Base case	9.8%	0	92,497
Rock anchoring	10.0%	10	96,410

Table 18 - Results for rock anchoring foundation. Authors' own.

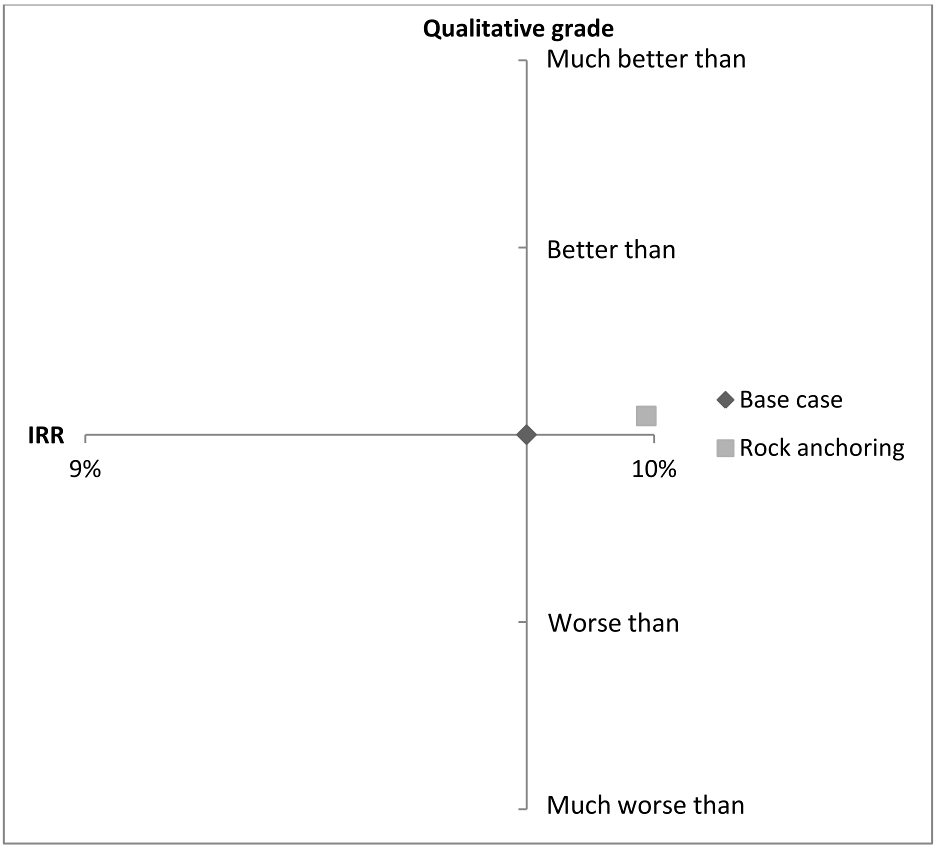

Figure 23 - Results for rock anchoring foundation. Authors' own.

Jointed blades

For the final decision alternative jointed blades have only been subject to the qualitative assessment. The reason for this is partly due to difficulties in acquiring financial data. Most onshore projects that are being developed today do not incorporate turbines with blades that exceed the length restriction imposed by transportation. Therefore, there are a limited number of suppliers that can offer this solution. However, jointed blades are included since they are basically a necessity when it comes to building turbines with larger rotor diameters. There is probably several other solutions for getting by the transport restriction but they are assumed to be more costly.

The qualitative grading is overwhelmingly negative. The main uncertainties can yet again be derived from the lack of industry experience. Additionally, there are concerns regarding loads and fatigue on the rotor, as well as the logistics around the assembly on site. The total weighted sum for the assessment of jointed blades corresponds to -123.

9. Additional evaluation rounds

This chapter will present the evaluation rounds following the previous results, as well as a sensitivity analysis regarding the final results. Further evaluation rounds were performed after having analyzed the initial outcome. Some of the areas were chosen to be examined further with the aim of applying a more systemic approach and thus performing more detailed estimations regarding some of the cost structures. Finally, a sensitivity analysis is performed regarding uncertain parameters in the financial model.

9.1 Second round results - Performance

Higher towers

The further approximations include estimations in additional capital expenditure for transportation, lift and foundation costs for the different tower height alternatives. When taking this into account the two highest tower alternatives have reduced their attractiveness, mainly due to substantial costs for lifting at 150 and 175 m. The changes are presented below in table 17.

	IRR	Qualitative grade, higher towers	Qualitative grade, tower structure	NPV
Base case	9.8%	0		92,497
Welded Steel, 125m	10.0%	-24		109,673
Welded Steel, 150m	9.5%	-69		114,085
Hybrid, 175m	8.3%	-88	-27	89,954

Table 19 – Results for higher towers in the second evaluation round. Authors' own.

Increased rotor diameter

In the further examination of the cost structure for longer blades the assumption is that, for blades exceeding the transportation limit of 55 m, they are divided into two parts. This will lead to an increase in transportation costs, resulting in the outcome below, table 20.

	IRR	Qualitative grade, larger rotor diameter	NPV
Base case	9.8%	0	92,497
100 m	13.9%	-33	213,192
126 m	15.3%	-96	296,670
164 m	16.4%	-163	397,501

Table 20 - Results for increased rotor diameter in the second evaluation round. Authors' own.

Increased generator output

When analyzing the impact on the turbine assumptions are made for additional costs for components that inevitably need to be adjusted for. The results are somewhat lowered, however both are still considered to be attractive. Interestingly, the 3 MW is favored by the IRR rule due do its higher percentage of return, but the choice of a 5 MW generator will still provide the highest value project. The results can be seen in table 21 below.

Medium voltage converter

No further approximations are made. However, there are additional costs due to the salary increase for qualified personnel corresponding to approximately 400 SEK/h.[154]

Permanent-magnet generator

No further approximations are made.

	IRR	Qualitative grade, increased generator output	Qualitative grade, larger rotor diameter	NPV
Base case	9.8%	0		92,497
3 MW	14.6%	-14	-33	306,159
5 MW	13.0%	-68	-96	364,683

Table 21 - Results for increased generator output for the second evaluation round. Authors' own.

[154] Sjöbeck (2012)

9.2 Second round results – OPEX

De-icing system

No further approximations are made. However, there is a need to look closer into the energy consumption of the de different systems.

LIDAR based pitch control

No further approximations are made. However, there is an interesting aspect in the implementation of yaw control using LIDAR which could be complemented with the blade pitch control, and thus increasing performance further.

Direct drive generator

No further approximations are made. One aspect for potential concern is the weight of the nacelle due to a direct drive solution. However, the overall weight is expected to decrease as a result of the direct drive design. If not, this could affect the structural design of towers and foundations, as well as increased transportation and lifting costs.

9.3 Second round results - CAPEX

Tower structure

The further approximations include similar estimations in capital expenditure as made for higher towers, i.e. additional costs for transportation, lift and foundation due to the different tower structures. For some structures this implies reduced costs for these activities and therefore improves their financial attractiveness. These can be seen in table 22.

	IRR	Qualitative grade, tower structure	NPV
Base case	9.8%	0	92,497
Concrete slipformed	9.3%	-74	82,643
Hybrid	9.4%	-27	85,389
Lattice	9.8%	-84	93,728
Steel shell friction joint	9.4%	-35	85,401
Wood	9.8%	-70	92,197

Table 22 - Results for towers structures in the second evaluation round. Authors' own.

Rock anchoring foundation

No further approximations are made. A scenario analysis could be done in order to estimate the break-even distance for the concrete station, thus implying when each alternative is most advantageous.

Jointed blades

No financial evaluation was made for jointed blades.

9.4 Third round results

The third and final evaluation round is performed in order to identify cases that are profitable without the additional revenues from certificates. The following table presents the IRR and NPV, with the same qualitative grading as previous, for the cases from the second evaluation round, with the exception that the subsidies are removed. As can be seen, the Knäred project has a negative NPV and consequently a non-attractive project financially. The best case is unsurprisingly provided with a 164 m rotor diameter, which is also the one with the lowest qualitative grading. Furthermore, both generator options are included as well as the remaining two increases in rotor diameter.

	IRR	NPV
Base case	5.6%	-12,737
100 m	8.9%	79,591
126 m	10.1%	133,033
3 MW	9.8%	134,963
5 MW	8.8%	145,019
164 m	11.1%	198,099

Table 23 – Financial results without green certificates. Authors' own.

In Table 24 below, the alternatives are shown that financially improve the base case when the certificates are removed. However, none of them manage to make it independent from subsidies.

	IRR	NPV
Base case	5.6%	-12,737
LIDAR blade pitch	5.6%	-11,986
Lattice	5.6%	-11,503
Rock anchoring foundation	5.8%	-8,816
Welded Steel, 125m	5.9%	-5,737
Direct drive generator	5.9%	-5,216

Table 24 – Financial results without green certificates. Authors' own.

In Table 25 below, the remaining focus areas with the certificates removed are present. All of them contribute to reducing the financial attractiveness of the base case to some extent. Noteworthy, is that the tower height increase to 150 m displays a relatively positive IRR while the NPV is lower than for the base case.

	IRR	NPV
Hybrid, 175m	5.0%	-46,243
Concrete slipformed	5.2%	-22,608
Hybrid	5.3%	-19,858
Steel shell friction joint	5.3%	-19,845
Medium voltage converter	5.4%	-17,118
Permanent-magnet generator	5.5%	-16,001
De-icing coil	5.5%	-15,367
De-icing air	5.6%	-13,188
Wood	5.6%	-13,037
Welded Steel, 150m	5.7%	-12,839
Base case	5.6%	-12,737

Table 25 – Financial results without green certificates. Authors' own.

9.5 Sensitivity analysis

In order to identify the margin for uncertainty a sensitivity analysis has been performed. This analysis focuses mainly on the price of electricity since it is perhaps the most volatile parameter in the financial model and thus difficult to forecast, while at the same time it has a large impact on the outcome. Furthermore, the analysis focuses on the total cost of the WTG, in order to see how sensitive the results are to changes in factors that are considered to be included in the price of the turbines, e.g. material and labor costs etc. The mentioned results that have been subject to this sensitivity analysis are from the outcome of the third evaluation round, i.e. the technology areas that show potential of eliminating the certificates from the business case. In the Figure 24 below the initial analysis regarding the electricity price is presented. These alternatives manage to be profitable without the certificates, and the results from the sensitivity analysis show that they are able to maintain this profitability in the case of a price reduction of about 20 – 30 % relative to the flat electricity price assumed in the financial evaluation.

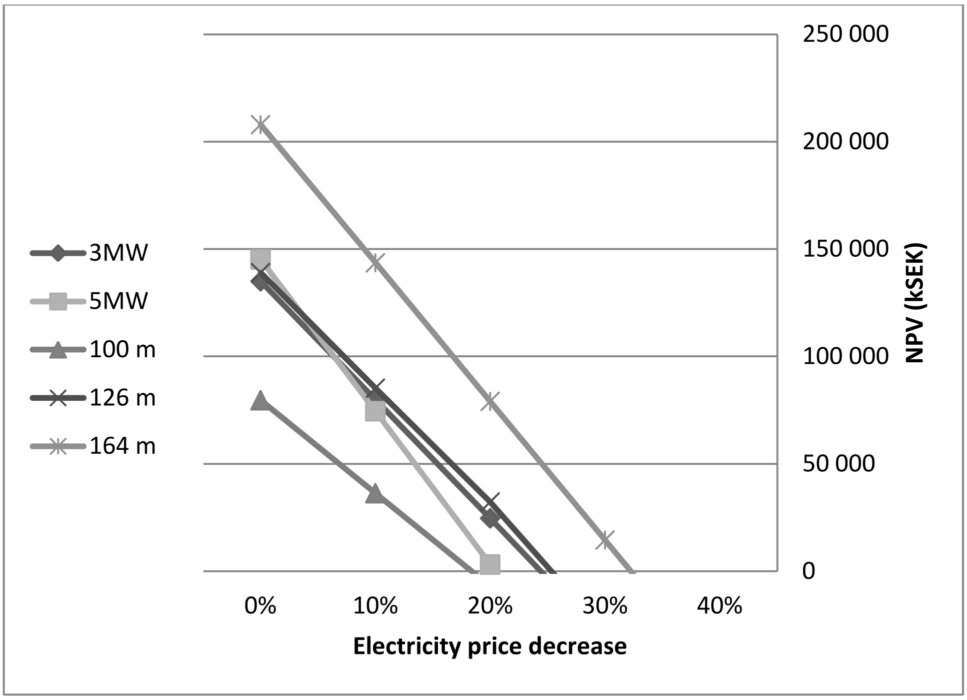

Figure 24 – Result of sensitivity analysis for the NPV as the electricity price is reduced. Authors' own.

Furthermore, the table below shows the actual break-even price for the analyzed areas along with a comparison to the mean spot price per kWh in price zone SE4, which corresponds to 0.44 SEK/kWh.[155] The 5 MW and the 100 m rotor diameter turbine require a minimum electricity price that is slightly higher than the average spot price in price zone SE4, thus implying they would not receive enough revenues to maintain profitability without certificates. For the remaining areas they manage to receive a sufficient revenue stream to maintain profitability without certificates, however not significantly.

[155] The mean price is based on the Nordpool spot price during 2006-2010 before the price zones were implemented together with the mean price for price zone SE4 from the time of its introduction. The basis for this estimation is found in Appendix 1.

	Min. price limit (SEK/kWh)	Relative to mean spot price (SEK/kWh)
3 MW	0.44	0
5 MW	0.46	- 0.02
100 m	0.48	- 0.03
126 m	0.43	0.01
164 m	0.39	0.05

Table 26 – The minimum required electricity price for the areas that displayed profitability without certificates, compared to the average spot price on electricity in SE4. Authors' own.

In Figure 25 below, an analysis has been conducted regarding a cost increase for the entire turbine, which could be a result of increased material costs for example. All alternatives manage to withstand a substantial cost increase for the turbine and still sustain a profitable business case without green certificates.

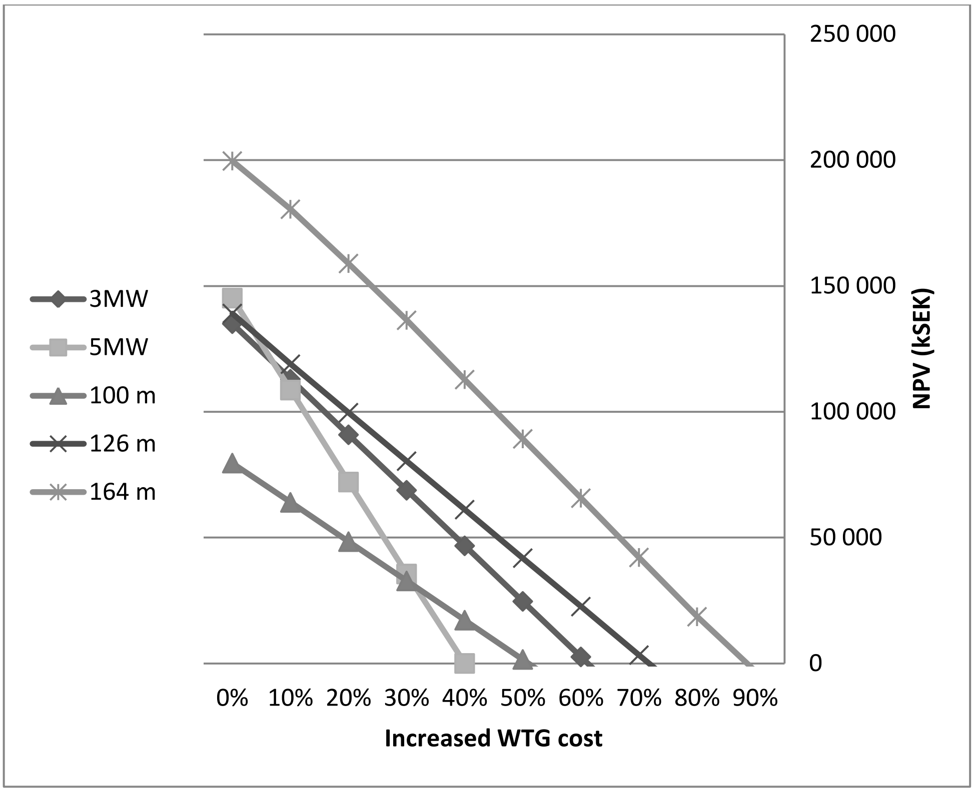

Figure 25 - Result of sensitivity analysis for the NPV as the overall turbine cost increases. Authors' own.

In addition, a LCOE[156] (Levelized Cost of Energy) analysis has been performed on the third round evaluation results, which can be seen in the table below. The LCOE determines the price that a specific source of energy requires in order to break even. It is an economic assessment of energy systems, taking into account all costs over its lifetime. However, compared to financial model employed in this study the LCOE does not take into consideration effects of possible accounting procedures, e.g. depreciation, corporate tax etc. Nevertheless, comparing the results from the LCOE analysis to the break-even prices based on NPV shows that they are nearly identical. This is perhaps not too surprising since the input parameters are the same. However, comparing these to other LCOE

[156] A more detailed description can be found in Appendix 2.

studies and energy sources further enables the possibility to investigate the competitiveness of the different alternatives.

	LCOE (SEK/kWh)	Price break-even for NPV (SEK/kWh)
3 MW	0.46	0.44
5 MW	0.48	0.46
100 m	0.50	0.48
126 m	0.45	0.43
164 m	0.41	0.39

Table 27 – LCOE and break-even price based on NPV (Table 26). Authors' own.

10. Discussion

This chapter is intended to present further discussions regarding the outcome of the business model evaluation, as well as the sensitivity analysis concerning the results.

10.1 First evaluation round

In the first evaluation round for *higher towers* the best performing alternative was the 175 m hybrid tower. For the remaining heights and with the welded tubular steel structure the second best was the 150 m followed by 125 m heights. However, for the 150 and 175 m options there are substantial qualitative factors that are limiting. Furthermore, these factors will result in a lowering of the financial attractiveness when taken into consideration, which is done in the second evaluation round. Assuming a further developed industry that has adapted to the uncertainties expressed in the qualitative assessment the results are more likely to represent the actual outcome.

The results for increased *rotor diameter* show a significantly improved business case following the increase in blade length. This is as previously stated due to the strong correlation between energy output and the swept area. In addition, the estimations for material and maintenance costs are considered linear. However, the major concerns are with the transportation regulations, as well as public acceptance and the acquiring of permit. Implementing jointed blades is a technically feasible solution to the problem with logistics. Further implications regarding the financial aspect should therefore be investigated.

The results for increased *generator output* also show a significant improvement of NPV and IRR. However, these results are misleading since the production simulations are based on power curves from turbines that have larger blades as well. What can be concluded from this inconsistency is that the combination of a larger generator and rotor diameter is interesting to investigate further. However, the cost analysis for a turbine that implements a larger generator should involve an analysis of the effect on other components. The attempt to estimate these additional costs is done in the second evaluation round.

From the results concerning the *higher voltage converter* the conclusion can be drawn that a medium voltage converter does not improve the business case with the current circumstances. At least as long as the potential elimination of production losses cannot be estimated. However, for very large turbines these production losses may be substantial enough for further investigation, as well as for the offshore market. Furthermore, there are some practical implications that are reasonably considered as decisive in favor for the current low voltage converter, i.e. the safety requirements for components above 1000 V.

The results for the *permanent-magnet generator* suggest that it does not offer a sufficient enough improvement to be included. Also, the situation regarding the supply of neodymium magnets is another limiting issue. However, in a qualitative aspect the p-m generator performs pretty much similar to the base case. The major expectations are that it will contribute to stabilizing the grid, but at the same time there are concerns regarding its track record. Furthermore, the production estimations are the same as for the regular generator, which will disfavor this option as long as there is no additional production increase. Finally, given the situation the results do not suggest that implementing a permanent-magnet generator will improve the business case as a whole.

As for the financial results for the OPEX alternatives there were several cases showing a lower IRR but higher NPV than the base case. This is an interesting finding, since the general investment decision rule states that for mutually exclusive projects the project with the highest NPV should be chosen. It is furthermore interesting to see that this is the case for the outcome in the OPEX category. This suggests that these alternatives are disfavored due to the fact that cash flow occurring later are considered to be less valuable. Consequently, the rate of return will reward projects that pay back faster. However, looking at the entire lifetime of the project the best decision is the one with the highest NPV.

The evaluation of the *de-icing systems* shows that there is a significant demand for a functioning de-icing system, and that it even has the potential of improving the business case. For developers the main incentive for implementing a de-icing system is safety concerns, even at a point where it costs more than it increases the value of the project. However, if there is a financial incentive involved as well it might speed up the technology development. Furthermore, the simulated production losses are from a site located in southern Sweden with relatively low ice formation. This suggests that a functioning de-icing system would enable the development of wind farms in even colder climates. The results indicate that the heated air solution is the one to prefer since it performs better in all measures. However, for further analysis the energy consumption is a determining factor as well and should be included.

The *LIDAR based blade pitch control* shows the same results as the heated air de-icing system, namely a higher NPV and qualitative grading than the base while displaying a lower IRR. The main conclusion is that it might be profitable to implement a LIDAR system in the turbine. However, the main uncertainty concern the configuration of the blades, so the results are assuming the system is incorporated with the current pitch control. Furthermore, there are studies suggesting that using the LIDAR system for the yaw control as well could boost performance by some percentage.

Also, for the *direct drive* solution the NPV and qualitative grading support the implementation of this design. The overall advantage of the direct drive system is the elimination of the gearbox replacements as well as the overall reduction of maintenance. The cost for not having to deal with gearbox changes have a great impact on the business case, which can be seen by looking at the NPV, but it does not yield a higher rate of return since the changes occur after several years. Furthermore, the main concern with implementing a direct drive solution involves proven technology and limited number of suppliers that can offer the solution. The design has been used by Enercon for many years which further suggest that once the initial obstacles are overcome it is potentially an attractive solution. This is further supported by the increasing number of turbine supplier emerging with a direct drive solution.

The initial results for *tower structures* suggest that *wooden towers* are the financially most attractive choice, followed by the *lattice structure*. Affecting these results are the limitations in data especially for these two alternatives. Furthermore, adding the qualitative assessment to the discussion, which proved to be the two lowest score, it seems that both wooden and lattice towers display too many uncertainties to viewed as competitive alternatives. Wooden towers mainly have concerns with the limited experience for wind turbine applications. Lattice towers are on the other hand perhaps more applicable on a commercial scale, but the public acceptance will still have a strong impact on the decision. *Concrete and friction joint towers* are proven to be less financially attractive than for the welded steel structure in the base case. Concrete towers will require more labor and for the friction joints they will induce higher maintenance costs. The final structure, consisting of both a concrete bottom part and a welded tubular steel part, does not perform better either. This has most likely to do with the fact that the tubular steel tower has been rationalized for many years, thus serving as the most cost-efficient tower design. However, at heights beyond a hundred meters there should be an opportunity for alternative structures to emerge as a commercial alternative. This is suggested by the results in the second evaluation round for increased tower height. Since a 175 m tubular steel tower was not considered feasible a hybrid structure was chosen to be able to keep the 175 m alternative. As the results suggest, the opportunity may lie in the increase in production for higher towers, thus allowing alternative structures some margin to establish the technology.

The financial outcome for the *rock anchoring foundation* is perhaps too uncertain to be able to draw any general conclusions. However, the qualitative aspects have highlighted a foundation design that is the preferable solution. Also, under the right circumstances it may also contribute to improving the business case. This trade-off can easily be calculated for each project. Furthermore, the rock anchoring solution has a lower environmental impact and reduces the amount of heavy transportation to the site. It will also contribute to an increase in number of site possibilities. To conclude, this foundation is considered to be a highly interesting design given the right circumstances.

10.2 Second evaluation round

In the second evaluation round the *tower height* alternatives were subject to a more comprehensive cost analysis. When including the estimations of the additional costs for transportation, lifting, and foundation the highest tower alternatives became less attractive. This resulted in the 150 m height as the financially most interesting with the 125 m alternative followed after. On the other hand, a 150 m welded tubular steel tower is at the upper limit of what is considered economically feasible while keeping the base diameter fixed, which leads to believe there is perhaps a greater uncertainty in this positive outcome. This together with the qualitative grading in mind suggests that a 125 m is the better option, at least with the current design.

The further evaluation for increased *rotor diameter* have been subject to additional cost estimations for dividing the blades, which resulted in reduced NPV for the two alternatives exceeding the transportation limit.

However, the costs for the joints to be made and assembled on site were not possible to acquire, but should however be examined further.

The second round results for the two *generator* alternatives reduced the attractiveness in the same manner as for the rotor diameter. Consequently, there is no change in the ranking of the 2, 3 or 5 MW generator. However, when considering the qualitative aspects the 5 MW turbine seems to be the least feasible alternative. The main issue is the substantial increase in size, not only for the generator itself but most WTG parts, and the issues that follows with it, i.e. maintenance and safety issues, public acceptance and permit issues, as well as increased difficulties for logistics services.

The second evaluation round for *tower structures* where subject to the same additional parameters as for the increased tower heights. To no surprise all alternatives are lowered in the financial dimension, thus resulting in the lattice tower as the ultimate winner. Since the results display pretty much the same situation as after the initial evaluation the same reasoning is applied here.

10.3 Third evaluation round

The third and final evaluation round is performed in accordance with the overall purpose of this study. In order to draw conclusions on whether or not the general business case can sustain its profitability without subsidies, all decisions are evaluated disregarding the additional revenue streams from certificates. The result from this evaluation displays a rather consistent choice of technology areas. This has mostly to do with the fact that they have a strong impact in the performance input. Increasing generator output as well as rotor diameter should be suggested as actions to further enable sustainable projects, which is accordance with the historic development. However, the limitations for onshore projects are imposing constraints on further development, which is currently starting to be recognized. Perhaps this is most visible for the development of towers, where limitations due to size increase are already affecting the business case. There are 125 m welded steel towers under construction but with reinforced walls in order to meet load requirements. This explains the reduced improvements for higher towers despite the substantial performance increase. Regarding the qualitative aspects the same reasoning is applied here. When weighing all this in the choice most likely to succeed is the 3 MW turbine, which also has a rotor diameter of 112 m. Given the current circumstances in transportation restrictions this is more or less the upper limit regarding the continued technology development for onshore turbines.

10.4 Sensitivity analysis

The sensitivity analysis regarding the price for electricity reveals a rather low margin of profitability. The previously five top performing alternatives are reduced to three, since the 5 MW and 100 m rotor diameter turbine requires a minimum price for electricity that is higher than the mean price in price zone SE4. Furthermore, the additional revenue stream as a result of a higher price in this area is necessary for the remaining alternatives to sustain their profitability independent of certificates. Also, since the Swedish electricity price zones only have been in effect for less than a year it is difficult to draw any general conclusions regarding the price development. However, the LCOE analysis and the break-even prices based on NPV (Table 25, 26) show that the required price for sustaining profitability are reasonably competitive. Comparing the outcome from the sensitivity analysis to the cost of energy from studies on wind power projects similar to Knäred, which corresponds to 0.57 SEK/kWh, shows that the LCOE for the third round alternatives is in the range of 0.07 – 0.16 SEK/kWh less, without subsidies and using an almost identical WACC.[157]

Regarding the margin for increasing the overall capital expenditure the analysis shows that the five top performing alternatives can maintain

[157] Nyström et al. (2011)

profitability despite a substantial increase in WTG cost. This margin is considered highly important since it is likely to be exploited by the manufacturers since they will require coverage for R&D activities etc. Furthermore, some of the calculations are based on material costs at a given time for a given Euro exchange rate, which with fluctuations in both material and labor cost together with currency variations will impact the financial status of the projects.

11. Conclusions and final remarks

In this final chapter, conclusions relating to the purpose and objectives are presented. Furthermore, the general credibility of the evaluation model and results are discussed. Finally, remarks regarding improvements and areas for further study are suggested.

11.1 Conclusions and suggested actions

The purpose of this study was to investigate the possibility for technology development to strengthen the Swedish wind power business case, and ultimately examine the potential for eliminating the need for government subsidies. The following objectives were established:

- Scan for trends in technology development and choose areas according to the scope and delimitations of the study.
- Evaluate the chosen technical areas – both financial and non-financial aspects.
- Depending on the outcome in the previous evaluation discuss the implications for the case company.

The initial technology focus areas and the conclusions concerning each decision are presented below:

Performance

This category represents the greatest opportunity for improvements. More specifically, this is the case for the alternatives with increased rotor diameter and generator output.

- For towers with the current welded steel structure the 125 m alternative is the most feasible and financially attractive alternative.
- The general conclusion for increased rotor diameter is that this development is expected to have a substantial impact on the business case. In fact, this provides the best opportunity for

sustaining profitability without green certificates. However, jointed blades are considered necessary for the continued development of longer blades.

- Considering all aspects the 3 MW generator provides the best potential for improving the business case.
- The medium voltage converter does not suggest that is of interest for onshore turbines in the current megawatt range.
- The conclusion for the permanence-magnet generator is similar to the previous, i.e. not interesting as long as no performance increase can be shown.

OPEX

The general conclusion drawn from the OPEX category is that efforts favoring O&M activities contribute to a qualitative improvement and a NPV in the same range as for the base case, while the rate of return seen to the whole period is not affected to the same extent. However, none of the investigated areas have the potential to alone be able to eliminate the need for certificates.

- The heated air solution is the preferred alternative concerning the de-icing systems.
- The LIDAR based pitch control system proves to interesting in both aspects. However, further studies concerning the technical potential are required.
- For the direct drive design, it is suggested that efforts are directed at introducing this technology in at least one project.

CAPEX

The general conclusion from the CAPEX category is that none of the chosen areas provided any further improvements on the business case.

- The conclusion for tower structures is that alternative structures are not interesting at the current height of about 100 m. However, for higher towers the hybrid structure is considered the most viable.
- It is recommended that the rock anchoring foundation should be implemented and evaluated when given the opportunity.
- The jointed blades solution has not been subject to any financial evaluation, which is why no further conclusions can be drawn.

Suggested efforts for E.ON Vind

The results from the third evaluation round strongly indicate that increasing the rotor diameter and generator output is the best approach for further improving the financial outcome. However, the concerns raised in the qualitative dimension is regarded as limiting factors, thus requiring further efforts in the previously specified areas in order to implement the suggested actions. The uncertainties in the financial input may be influenced by a wide range of aspects that is not possible to fully account for. On the other hand, issues concerning limitations due to low or non-existent demand are considered to be eliminated with further technology development. With this in mind, the suggested actions for implementing the concluded choices are focused on reducing the qualitative aspects that may have a negative impact on the business case as a whole. Consequently, these actions should be considered at an early stage in project process, preferably in the project development phase.

Challenges for E.ON Vind

The main challenges for E.ON Vind are concerning those aspects that have emerged for almost all alternatives which imply a substantial turbine size increase.

- Concerns regarding logistics and the regulations for transportation will results in substantial challenges, due to the constraints imposed on blade length and tower height.

- The process of acquiring the required permits is a crucial aspect for project development. When developing project with larger WTGs the permit process will be of further importance.
- Public acceptance is also considered to be a critical factor that ultimately may decide the feasibility of the entire project.

11.2 Final remarks

Potential improvements and suggestions for further research

The general approach of this study has been to investigate a wide spectrum of technology areas, since the authors' personal aim has been to identity as many technological developments as possible, thus aiming at delivering a more holistic view of potential business case outcomes. Paradoxically, this resulted in the choice of the analytical approach, since it allows for the execution of single variable analyses. This enables the study of many single parameters at a time with no regard to the possible impact on other technology areas. However, this would suggest a natural next step for further studies, i.e. choosing one of the proposed areas and perform a full systemic study. Furthermore, combining several focus areas and studying the possible effects of synergies for different scenarios may also be suggested for further research. As for the evaluation model there is a need for, and the opportunity of, conducting the qualitative assessments to a larger extent. The broad approach in this study results in limiting amounts of surveys that could be distributed, due to the given timeframe. When conducting a further systems approach the distribution of surveys can be increased, thus providing a higher reliability.

General applicability of the results and model

Regarding the applicability of the results they are highly dependent on the assumptions that have been made. The initial aim was to perform a broader study applicable in all of Sweden. However, the outcome from the sensitivity analysis regarding the price of electricity shows that the results are dependent on the price level in SE4, where the Knäred project is located. The electricity price is probably the most important input affecting the results, but at the same time very difficult to forecast. However, the price level that has been used for this study's calculations are considered reasonable, and the sensitivity analysis shows that the alternatives potentially independent from subsidies can sustain its own profitability at a price that is in the range of historic electricity prices.

Concerning the business evaluation model it is comprised of a financial model that calculates the present value of the entire cost of constructing and operating an energy generating plant over a specified life cycle, and a quantifiable technology concept selection model which takes into consideration the non-financial aspects. The strength of this evaluation method is that it covers a wide perspective when aiming at investigating technological advancements. It is considered to be applicable in basically all industries when facing decisions regarding new technology.

One aspect to consider for future improvements regarding the business evaluation model is to employ a more sophisticated financial model. However, this is not considered to have any dramatic effect on the outcome, since the financial model used in this study covers all basic financial principles as well as taking into consideration pretty much all costs for building, operating and dismantling the turbines. Furthermore, the most relevant improvements to consider are those regarding the input parameters, since it is primarily these and not the financial model that will affect the results. For example, a long time prognosis for the electricity price 25 years ahead would increase the credibility of the results.

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Appendix 1. Nordpool electricity prices 2006 - 2012[158]

Elspot prices in [EUR/MWh]						
	SYS	SE	SE1	SE2	SE3	SE4
12 - Jun	-		-	-	-	-
12 - May	28.50		29.31	29.31	30.00	31.99
12 - Apr	31.71		31.51	31.51	31.52	33.80
12 - Mar	29.20		28.30	29.02	29.02	29.72
12 - Feb	49.06		48.40	48.40	50.80	52.75
12 - Jan	37.18		37.14	37.14	38.20	38.26
11 - Dec	33.74		33.21	33.21	33.22	34.45
11 - Nov	41.18		41.60	41.60	43.52	49.88
11 - Oct	27.96	30.49				
11 - Sep	28.94	32.10				
11 - Aug	40.14	42.13				
11 - Jul	38.78	39.78				
11 - Jun	48.40	48.55				
11 - May	54.49	54.47				
11 - Apr	53.84	53.60				
11 - Mar	64.22	63.29				
11 - Feb	64.46	64.53				
11 - Jan	69.62	69.72				
10 - Dec	81.65	91.86				
10 - Nov	54.78	56.26				
10 - Oct	49.66	51.32				
10 - Sep	49.37	51.20				
10 - Aug	42.89	43.21				
10 - Jul	45.43	45.81				

[158] Nordpool (2012)

Elspot prices in [EUR/MWh]

	SYS	SE
2012	-	
2011	47.05	-
2010	53.06	56.82
2009	35.02	37.01
2008	44.73	51.12
2007	27.93	30.25
2006	48.59	48.12
2005	29.33	29.76
2004	28.92	28.08
2003	36.69	36.49
2002	26.91	27.62
2001	23.15	22.86
2000	12.75	14.24
1999	13,46	
1998	-	
1997	-	

Appendix 2. LCOE formula[159]

$$LCOE = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I_t= Investment expenditures in year t

M_t = O&M expenditures in year t

F_t = Fuel expenditures in year t

E_t = Electricity generation in year t

r = Discount rate

n = Life of the system

159 Wikipedia (2012)

Appendix 3. Overview of financial input

All numbers have been rounded and are shown to provide rough estimations of the financial input.

Higher towers	Relative CAPEX cost (kSEK)	Source[160]	Relative OPEX and replacement cost (kSEK/y)	Source	Produ-ction (GWh)	Source
Welded steel 125 m	**First round:** 3000 **Second round:** 500	**First round:** Market price 2.3€/kg including material and work. Tower weight is 335 metric tons.[161] **Second round:** Transportation, lifting and foundation at 125 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	6.08	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 125 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.9 % of production.[162]

160 Engström et al. (2010)
161 Egard (2012)
162 Sottini (2012)

Welded steel 150 m	**First round:** 6000 **Second round:** 2500	**First round:** Market price 2.3€/kg including material and work. Tower weight is estimated to 490 metric tons, based on linearization of 105 and 125 meter. **Second round:** Transportation, lifting and foundation at 150 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	6.69	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 150 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 1.1 % of production.[163]

[163] Sottini (2012)

Hybrid – concrete and welded steel 175 m	**First round:** 8500 **Second round:** 8000	**First round:** Tower cost is estimated to 1394 k€, based on interpolation of tower weights and top tower weights for 3 and 5 MW at 175m. **Second round:** Transportation, lifting and foundation at 175 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	7.18	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 175 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 1.3 % of production.[164]

[164] Ibid.

Higher output	Relative CAPEX (kSEK)	Source	Relative OPEX (kSEK/y)	Source	Relative replacement cost (kSEK)	Source[165]	Production (GWh)	Source
3 MW	**First round:** 3500 **Second round:** 8000	**First round:**[166] Generator cost is [redacted] k€. Rotor blades cost [redacted] k€. **Second round:**[167] Based on generic formula for entire WTG as with output and hub height as parameters: 3 [MW] * 1000 k€ + 90 k€ * [every 10 m over 100 m hub height]	5	The relative OPEX cost is [redacted] k€ for the generator and [redacted] for the blades.[168]	500	Relative cost for replacement of blades is [redacted] k€ in year 18.	9.04	Production simulation based on power curve for V112 3MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[169]

165 Flaig (2012b)
166 Ibid.
167 Malmberg (2012)
168 Flaig (2012b)
169 Sottini (2012)

5 MW	**First round:** 6,000 **Second round:** 27,000	**First round:**[170] Generator cost is [redacted] k€. Rotor blades, [redacted] k€. **Second round:**[171] Based on generic formula for entire WTG as with output and hub height as parameters: 5 [MW] * 1000 k€ + 90 k€ * [every 10 m over 100 m hub height]	10	The relative OPEX cost is based on 2 % generator failure rate and 3 % extra failure rate of the total CAPEX. Relative OPEX costs for 126 m rotor diameter are added.[172]	500	Relative cost for replacement of blades is [redacted] k€ in year 18.	11.60	Production simulation based on power curve from RePower 5 MW 126 m diameter and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[173]

[170] Flaig (2012b)
[171] Malmberg (2012)
[172] Flaig (2012b)
[173] Sottini (2012)

Longer rotor diameter	**Relative CAPEX cost (kSEK)**	**Source[174]**	**Relative OPEX (kSEK/y)**	**Source[175]**	**Relative replacement cost (kSEK)**	**Source[176]**	**Production (GWh)**	**Source**
100 m	0	Same cost as for the base case - [redacted] k€.	None.	No additional O&M are considered.	None.	Cost for replacement is already included in base case - [redacted] k€.	7.05	Production simulation based on power curve from V100 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Assumed that, Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[177]

174 Flaig (2012b)
175 Ibid.
176 Ibid.
177 Sottini (2012)

126 m	**First round:** 5,000 **Second round:** 50	**First round:** Based on the assumption that CAPEX is linear to the cost of rotor blades for a V90 and V112. **Second round:** Based on the assumption of additional transportation due to dividing of the blades. This cost is added linearly to the existing transportation cost.	5	Additional OPEX are assumed to increase linearly.	500	Relative cost for replacement of blades is [redacted] k€ in year 18.	8.64	Production simulation based on estimated power curve. The power curve is based on interpolation of a V80, V90, V100 2MW turbine and then extrapolated to 126 m diameter combined with wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Assumed that, Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[178]

[178] Sottini (2012)

164m	**First round:** 10,000 **Second round:** 100	**First round:** Based on the assumption that CAPEX is linear to the cost of rotor blades for a V90 and V112. **Second round:** Based on the assumption of additional transportation due to dividing of the blades. This cost is added linearly to the existing transportation cost.	10	Additional OPEX are assumed to increase linearly.	1000	Cost for replacement is [redacted] k€ in year 18.	10,53	Production simulation based on estimated power curve. The power curve is based on interpolation of a V80, V90, V100 2MW turbine and then extrapolated to 164 m diameter combined with wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Production losses due to icing are included and correspond to 0.7 % of production.[179]

[179] Ibid.

Permanent -magnet generator	Relative CAPEX cost (kSEK)	Source	Relative OPEX and replacement (kSEK/y)	Source	Production (GWh)	Source
Permanent -magnet generator	400	Cost of P-M generator is [redacted] k€.[180]	5	Relative OPEX cost is [redacted] k€/lifetime and replacement cost is [redacted] k€.[181]	5.54	Production simulation based on power curve from V.90 2MW - Gridstreamer and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[182]

[180] Flaig (2012b)
[181] Ibid.
[182] Sottini (2012)

Voltage converters	Relative CAPEX cost (kSEK)	Source	Relative OPEX (kSEK/y)	Source	Relative replacement cost (kSEK)	Source	Production (GWh)	Source
3.3 kV converter	400	Cost is 25 % more than for the 690 V which is [redacted] k€.[183]	None.	No additional costs are assumed. Salary increase for qualified personnel is discussed in the qualitative evaluation.	400	Cost for replacement is [redacted] k€ in year 18.[184]	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[185]

[183] Engström (2010)
[184] Ibid.
[185] Sottini (2012)

Direct drive generator	Relative CAPEX cost (kSEK)	Source	Relative OPEX (kSEK/y)	Source	Relative replacement cost (kSEK)	Source	Production (GWh)	Source
Direct drive	5,500	Cost of 2.3 DD generator from Siemens is [redacted] k€, which replaces the cost for both the previous generator and the gearbox entirely.[186]	10	3 % extra failure rate of CAPEX cost.	-6,500	Reduced cost of 2 * [redacted] k€ due to the elimination of gearbox replacements.[187]	5.54	Production simulation based on power curve from V90 2MW - Gridstreamer and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[188]

[186] Messing (2012)
[187] Ibid.
[188] Sottini (2012)

De-icing system	Relative CAPEX cost (kSEK)	Source	Relative OPEX and replacement costs (kSEK/y)	Source	Production (GWh)	Source
Heating coil	1,000	Cost of heating coil system is [redacted] k€.[189]	None.	Assumption is that no additional O&M is required.	5.58	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are assumed to be 0.[190]
Heated air	500	Cost of heating coil system is 40 k€.[191]	None.	Assumption is that no additional O&M is required.	5.58	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are assumed to be 0.[192]

[189] Messing (2012)
[190] Sottini (2012)
[191] Ronsten (2012)
[192] Sottini (2012)

Blade pitch control	CAPEX cost (kSEK)	Source	Relative OPEX (kSEK/y)	Source	Production (GWh)	Source
LIDAR blade pitch	500	Cost of LIDAR blade pitch system is [redacted] k€.[193]	-50	The cost is 5 % of the CAPEX cost and 2 hours of man work á 0.1 k€.[194] The system can generate a 2 % load reduction which is considered to correspond to a 2 % reduction of planned maintenance.[195]	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[196]

[193] Lindelöw (2012)
[194] Ibid.
[195] Ibid.
[196] Sottini (2012)

Tower structure 105 m	Relative CAPEX cost (kSEK)	Source[197]	Relative OPEX and replaceme nt cost (kSEK/y)	Source	Product ion (GWh)	Source
Hybrid – concrete and welded steel	**First round:** 1,000 **Second round:** 100	**First round:** Tower cost is estimated to 555 k€, based on interpolation of tower weights and top tower weights for a 3 and 5 MW turbine at 105 m hub height. **Second round:** Transportation, lifting and foundation for a concrete steel hybrid tower at 105 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[198]

[197] Engström et al. (2010)
[198] Sottini (2012)

Steel shell friction joint	**First round:** 1,000 **Second round:** 20	**First round:** Tower cost is estimated to 567 k€, based on interpolation of tower weights and top tower weights for a 3 and 5 MW turbine at 105 m hub height. **Second round:** Transportation, lifting and foundation for a steel friction joint tower at 105 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[199]

[199] Ibid. (2012)

Concrete slip-formed	**First round:** 1,500 **Second round:** -500	**First round:** Tower cost is estimated to 642 k€, based on interpolation of tower weights and top tower weights for a 3 and 5 MW turbine at 105 m hub height. **Second round:** Transportation, lifting and foundation for a slip-formed concrete tower at 105 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[200]

[200] Ibid.

Lattice	**First round:** -500 **Second round:** 250	**First round:** Tower cost is estimated to 427 k€, based on interpolation of tower weights and top tower weights for a 3 and 5 MW turbine at 105 m hub height. **Second round:** Transportation, lifting and foundation for a steel lattice tower at 105 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[201]

[201] Sottini (2012)

Wood	**First round:** -1,000 **Second round:** 1,000	**First round:** Tower cost is estimated to 375 k€, based on interpolation of tower weights and top tower weights for a 3 and 5 MW turbine at 105 m hub height. **Second round:** Transportation, lifting and foundation for a wooden tower at 105 m.	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[202]

[202] Ibid.

Foundation	Relative CAPEX cost (kSEK)	Source	Relative OPEX (kSEK/y)	Source	Production (GWh)	Source
Rock anchoring	-500	Cost reduction as a result of elimination the anchor cage required for the gravity foundation.[203]	None.	Assuming only additional O&M in the form of visual inspections with no substantial cost increase.[204]	5.54	Production simulation based on power curve from V90 2MW and wind data from the reference site at a height of 105 m. The simulations were performed with the software WAsP 10 and WindPro 2.7. Noise mode 0, Air density kg/m^3 1.225. Production losses due to icing are included and correspond to 0.7 % of production.[205]

[203] Mobjer (2012)
[204] Ibid.
[205] Sottini (2012)

Appendix 4. Results from qualitative assessment

The presented outcome comes from the merger of all surveys for each focus area.

Tower height			
Measure	**125m**	**150m**	**175m**
# of site possibilities (wind)	8	15	15
Construction logistics (cranes, roads etc.)	0	-6	-11
Decreased distance between WTGs	4	4	4
Decreased ice formation	-3	-6	-6
General HSSE issues	-3	-3	-3
Increased park size (# of WTGs)	2	7	7
Key component availability (i.e. supply chain)	-4	-10	-13
Maintenance accessibility	-7	-10	-10
Manufacturer alternatives	-5	-12	-15
Noise reduction	0	0	0
Operation availability	-3	-5	-5
Other logistics (i.e. site delivery)	0	-5	-5
Permit process (MKB etc.)	-6	-8	-11
Proven technology	-5	-14	-19
Public acceptance	-7	-13	-13
Reduced grid demands	0	0	0
Reduced loads/fatigue (nacelle/blades)	7	7	7
Reduced loads/fatigue (tower/foundation)	-2	-7	-7
Reduced nacelle weight	0	0	0
WTG lifetime	-2	-2	-2
Total	-24	-69	-88

Increased rotor diameter			
Measure	**100-110m**	**116-124m**	**140-164m**
# of site possibilities (wind)	3	7	7
Construction logistics (cranes, roads etc.)	0	-16	-32
Decreased distance between WTGs	-3	-7	-7
Decreased ice formation	-3	-7	-7
General HSSE issues	0	0	0
Increased park size (# of WTGs)	-3	-9	-12
Key component availability (i.e. supply chain)	0	-3	-7
Maintenance accessibility	0	0	0
Manufacturer alternatives	0	-3	-9
Noise reduction	0	0	0
Operation availability	0	0	0
Other logistics (i.e. site delivery)	-13	-16	-32
Permit process (MKB etc.)	-3	-7	-7
Proven technology	0	-3	-22
Public acceptance	-3	-7	-7
Reduced grid demands	0	0	0
Reduced loads/fatigue (nacelle/blades)	-3	-9	-12
Reduced loads/fatigue (tower/foundation)	-3	-9	-12
Reduced nacelle weight	0	-3	-3
WTG lifetime	0	-3	-3
Total	-33	-96	-163

Generator output		
Measure	**3 MW**	**5 MW**
# of site possibilities (wind)	0	-3
Construction logistics (cranes, roads etc.)	0	-13
Decreased distance between WTGs	-3	-3
Decreased ice formation	-3	-3
General HSSE issues	-3	-3
Increased park size (# of WTGs)	0	0
Key component availability (i.e. supply chain)	0	-3
Maintenance accessibility	5	13
Manufacturer alternatives	0	-8
Noise reduction	0	0
Operation availability	0	3
Other logistics (i.e. site delivery)	-10	-23
Permit process (MKB etc.)	0	-3
Proven technology	0	-8
Public acceptance	0	-1
Reduced grid demands	5	8
Reduced loads/fatigue (nacelle/blades)	-1	-3
Reduced loads/fatigue (tower/foundation)	-1	-3
Reduced nacelle weight	-3	-8
WTG lifetime	0	-10
Total	-14	-68

Permanent magnet generator	
Measure	**P-M**
# of site possibilities (wind)	0
Construction logistics (cranes, roads etc.)	0
Decreased distance between WTGs	0
Decreased ice formation	0
General HSSE issues	-20
Increased park size (# of WTGs)	0
Key component availability (i.e. supply chain)	4
Maintenance accessibility	-15
Manufacturer alternatives	-4
Noise reduction	0
Operation availability	0
Other logistics (i.e. site delivery)	0
Permit process (MKB etc.)	0
Proven technology	5
Public acceptance	0
Reduced grid demands	25
Reduced loads/fatigue (nacelle/blades)	0
Reduced loads/fatigue (tower/foundation)	0
Reduced nacelle weight	0
WTG lifetime	4
Total	-1

Medium voltage converter	
Measure	**3.3 kV**
# of site possibilities (wind)	0
Construction logistics (cranes, roads etc.)	0
Decreased distance between WTGs	0
Decreased ice formation	0
General HSSE issues	-45
Increased park size (# of WTGs)	0
Key component availability (i.e. supply chain)	-10
Maintenance accessibility	-5
Manufacturer alternatives	-10
Noise reduction	0
Operation availability	-5
Other logistics (i.e. site delivery)	0
Permit process (MKB etc.)	0
Proven technology	-20
Public acceptance	0
Reduced grid demands	0
Reduced loads/fatigue (nacelle/blades)	0
Reduced loads/fatigue (tower/foundation)	0
Reduced nacelle weight	15
WTG lifetime	0
Total	-80

Jointed blades	
Measure	**Jointed blades**
# of site possibilities (wind)	5
Construction logistics (cranes, roads etc.)	5
Decreased distance between WTGs	-3
Decreased ice formation	0
General HSSE issues	0
Increased park size (# of WTGs)	-8
Key component availability (i.e. supply chain)	0
Maintenance accessibility	0
Manufacturer alternatives	-15
Noise reduction	-5
Operation availability	0
Other logistics (i.e. site delivery)	5
Permit process (MKB etc.)	0
Proven technology	-75
Public acceptance	-3
Reduced grid demands	0
Reduced loads/fatigue (nacelle/blades)	-18
Reduced loads/fatigue (tower/foundation)	-5
Reduced nacelle weight	0
WTG lifetime	-8
Total	-123

De-icing systems		
Measure	**Air**	**Coil**
# of site possibilities (wind)	15	13
Construction logistics (cranes, roads etc.)	0	0
Decreased distance between WTGs	0	0
Decreased ice formation	30	30
General HSSE issues	53	40
Increased park size (# of WTGs)	1	1
Key component availability (i.e. supply chain)	-6	-6
Maintenance accessibility	-3	-5
Manufacturer alternatives	-4	-2
Noise reduction	7	7
Operation availability	3	3
Other logistics (i.e. site delivery)	0	0
Permit process (MKB etc.)	18	18
Proven technology	14	7
Public acceptance	6	6
Reduced grid demands	0	0
Reduced loads/fatigue (nacelle/blades)	0	0
Reduced loads/fatigue (tower/foundation)	0	0
Reduced nacelle weight	-1	0
WTG lifetime	0	-1
Sparepart availability	0	0
Total	132	108

Direct drive generator	
Measure	**Direct drive**
# of site possibilities (wind)	0
Construction logistics (cranes, roads etc.)	0
Decreased distance between WTGs	0
Decreased ice formation	0
General HSSE issues	3
Increased park size (# of WTGs)	0
Key component availability (i.e. supply chain)	0
Maintenance accessibility	23
Manufacturer alternatives	-13
Noise reduction	3
Operation availability	15
Other logistics (i.e. site delivery)	0
Permit process (MKB etc.)	3
Proven technology	-15
Public acceptance	0
Reduced grid demands	-3
Reduced loads/fatigue (nacelle/blades)	0
Reduced loads/fatigue (tower/foundation)	0
Reduced nacelle weight	5
WTG lifetime	8
Total	28

Pitching w. LIDAR	
Measure	**Pitching w. LIDAR**
# of site possibilities (wind)	8
Construction logistics (cranes, roads etc.)	-1
Decreased distance between WTGs	5
Decreased ice formation	0
General HSSE issues	-1
Increased park size (# of WTGs)	5
Key component availability (i.e. supply chain)	-3
Maintenance accessibility	-3
Manufacturer alternatives	-2
Noise reduction	1
Operation availability	-4
Other logistics (i.e. site delivery)	-1
Permit process (MKB etc.)	0
Proven technology	-40
Public acceptance	0
Reduced grid demands	-1
Reduced loads/fatigue (nacelle/blades)	12
Reduced loads/fatigue (tower/foundation)	4
Reduced nacelle weight	2
WTG lifetime	53
Total	33

Tower structure					
Measure	**1. Steel shell friction joints**	**2. Concrete**	**3. Hybrid**	**4. Lattice**	**5. Wood**
# of site possibilities	0	0	0	0	0
Construction logistics (cranes, roads etc.)	8	-9	3	-9	-5
Decreased distance between WTGs	0	0	0	0	0
Decreased ice formation	0	0	0	0	0
General HSSE issues	-10	-12	-10	-15	-2
Increased park size (# of WTGs)	0	0	0	0	0
Key component availability (i.e. supply chain)	-9	-5	-5	-5	-9
Maintenance accessibility	-8	0	-5	-12	-12
Manufacturer alternatives	-9	-5	-5	-9	-14
Noise reduction	0	0	0	-2	0
Operation availability	-3	0	0	-7	-3
Other logistics (i.e. site delivery)	10	-12	0	0	3
Permit process (MKB etc.)	0	-7	0	-9	0
Proven technology	-11	-11	-6	-11	-21
Public acceptance	0	-5	0	-9	5
Reduced grid demands	0	0	0	0	0
Reduced loads/fatigue (nacelle/blades)	0	0	0	0	0
Reduced loads/fatigue (tower/foundation)	3	3	3	7	-2
Reduced nacelle weight	0	0	0	0	0
WTG lifetime	0	0	0	0	-3
Construction time	-5	-12	-3	-3	-7
Total	-35	-74	-27	-84	-70

Foundation	
Measure	**Rock anchoring**
# of site possibilities (wind)	-5
Construction logistics (cranes, roads etc.)	13
Decreased distance between WTGs	0
Decreased ice formation	0
General HSSE issues	0
Increased park size (# of WTGs)	0
Key component availability (i.e. supply chain)	-3
Maintenance accessibility	-13
Manufacturer alternatives	-10
Noise reduction	0
Operation availability	0
Other logistics (i.e. site delivery)	15
Permit process (MKB etc.)	15
Proven technology	-8
Public acceptance	5
Reduced grid demands	0
Reduced loads/fatigue (nacelle/blades)	0
Reduced loads/fatigue (tower/foundation)	-3
Reduced nacelle weight	0
WTG lifetime	-5
Construction time	8
Total	10