On Asset Life Cycle Management for Offshore Wind Turbines

- A Case Study of Horns Rev 1

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Abstract

The world's first large scale offshore wind farm, Horns Rev 1, is approaching the decommissioning phase the profitability of future investments therefore has to be investigated further. Investment decision-making requires the consideration of several perspectives based on a life cycle view of the asset's condition and profitability. In order to contribute to the economical perspective of Asset Life Cycle Management, a business case model has been developed in two parts, one that represents the whole wind farm and one for a single wind turbine. Through the two models, the user can examine the profitability of a wind farm from a system perspective as well as on a more detailed level. The purposes of these models are to assist in the budget planning of Horns Rev 1 and provide support for investment decision-making.

Key words: *Asset Life Cycle Management*, *ALCM*, *end of lifetime*, *wind turbine*, *business case*

Sammanfattning

Världens första storskaliga havsbaserade vindkraftpark, Horns Rev 1, närmar sig slutet på sin livscykel och lönsamheten av kommande investeringar bör utredas ytterligare. Investeringsbeslut kräver att hänsyn tas till ett flertal aspekter ur ett livscykelperspektiv baserat på tillgångens tillstånd och lönsamhet. För att bidra till det ekonomiska perspektivet inom kapitalförvaltning ur ett livscykelperspektiv har ett kalkyleringsverktyg tagits fram bestående av två delar, en som representerar hela vindkraftparken och en för en enda vindturbin. Genom de två modellerna kan användaren undersöka lönsamheten för en vindkraftpark ur ett systemperspektiv samt på en mer detaljerad nivå. Syftet med dessa modeller är att underlätta budgetplaneringen för Horns Rev 1 och ge stöd för investeringsbeslut.

Nyckelord: *kapitalförvaltning ur ett livscykelperspektiv, tillgångens slutskede, vindkraft, kalkyleringsverktyg*

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Caroline Broliden & Linn Regnér
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Abbreviations

ALCM	Asset Life Cycle Management
BU	Business Unit
CMS	Condition Monitoring System
DKK	Danish crowns
DK1	Denmark price area 1
DK2	Denmark price area 2
EBIT	Earnings Before Interest and Tax
EBITDA	Earnings Before Interest, Tax, Depreciations and Amortisation
FiT	Feed in Tariff
IRR	Internal Rate of Return
NPV	Net Present Value
O&M	Operations & Maintenance
PI	Performance Index
RCM	Reliability Centered Maintenance
RQ	Research Question
WACC	Weighted Average Cost of Capital

1 Introduction

This first chapter of the thesis will give a brief overview of wind power in general as well as a short introduction to the wind farm Horns Rev 1. The aim is to provide a basic understanding before the presenting purpose, research questions and limitations of the study.

1.1 Background

Wind power has become one of the fastest growing sources of renewable power. The installed capacity of wind power reached almost 340 000 MW in June 2014, contributing to about 4% of the worlds electricity demand (WWEA, 2014). The rapid growth in wind power is a result of its increased competitiveness compared to other energy sources, although some of the increase is thanks to subsidies and emission taxes. These incentives lower the barriers to invest in wind power and thus promote a more sustainable mix of energy sources (International Energy Agency, 2009). However, sceptics are raising the issue that increasing intermittent energy sources (such as wind and solar) in our system will increase the need for back-up capacity to retain a reliable system. In other words, excess capacity will be needed together with a more flexible system that can handle larger fluctuations (Manwell, McGowan & Rogers, 2009).

Nevertheless, wind power is expected to continue the rapid expansion and the CEO of Vattenfall made a statement that indicates that wind power will play a central part in the energy system in the future. Denmark has been proposed as the central place for this development due to the large amount of knowledge acquired through several years of wind power expansion (Vattenfall, 2014b). Vattenfall owns and operates a large number of wind farms, both onshore and offshore, in for instance Denmark. Among these is the oldest large-scale offshore wind farm, Horns Rev 1. The wind farm is situated 15-20 km off the cost outside of Esbjerg, Denmark, and consists of 80 Vestas V80-2MW turbines. The total production is around 600 MWh per year, which corresponds to the consumption of 150 000 households and 2% of Denmark's total electricity consumption. When Horns Rev 1 was first built in 2002 by Elsam, the cost was 2 billion DKK and it was the first large-scale offshore wind farm in the world. The farm is since 2006 owned by the joint venture of Vattenfall (60%) and Dong Energy (40%) (Petersen, 2015; Vattenfall, 2014a).

The recent development in offshore wind power has led to an increase of competitiveness to other types of energy. However, offshore turbines still have some disadvantages, for example expensive maintenance due to difficulties with logistics and accessing the turbines. This is especially the case when the weather is harsh. While the turbines are in need of reparations and are temporarily shut down, the wind farm will not generate any electricity and thereby will Vattenfall not receive any revenues (Petersen, Madsen & Bilberg, 2013).

Due to the sensitive revenue streams, major investments in wind turbines have to be compared to the expected revenues that the turbines will generate in the coming years. As Horns Rev 1 is approaching the decommissioning phase, the profitability of future investments has to be investigated further. A broader perspective is needed to be able to see Horns Rev 1 from a system perspective to detect unprofitability during the remaining lifetime of the turbines. Vattenfall would benefit from detecting unprofitability at an early stage regardless if a turbine would have an unexpected breakdown or a planned upgrade of components. Asset Life Cycle Management (ALCM) is an integrated approach to optimise the asset during the entire life cycle through planning, analysing and execution (Haffejee & Brent, 2008).

1.2 Aim and Research Questions

The upcoming situation at Horns Rev 1 leads to the need for Vattenfall to increase the knowledge regarding investment decision-making. Although investment decisions can be influenced by several perspectives such as environmental complications, political opinion and technical possibilities, this thesis will focus on the economical perspective. The economical perspective will foremost refer to how the profitability is affected by changes in revenues and costs. This is seen a crucial aspect since Horns Rev 1 is approaching end of lifetime, which also opens up for the need of having a life cycle perspective during the remaining asset lifetime. Based on this identified opportunity, an overall aim and research question of the thesis have been developed.

The *overall aim* of the study is to provide further support in the investment decision-making process for the offshore wind turbines of Horns Rev 1, through the development of a business case-model. The aim will be achieved through the process of answering the main research question, which is:

How can an extended business case be applied to meet the need for rational investment decisions in the final stage of Horns Rev 1 through an ALCM perspective?

The main research question will be answered through the following four research questions.

RQ1. On what basis is investment decisions made today for Horns Rev 1?

RQ2. How can an ALCM perspective contribute to the operation and maintenance of Horns Rev 1?

RQ3. How can budget planning, from an ALCM perspective, increase decision rationality?

RQ4. How does the uncertainty of different input variables affect the profitability of Horns Rev 1?

If these questions are answered, a more effective use of the wind turbines might be possible and thus save the owner money and time over the lifetime of the turbines. Furthermore, by making more rational investment decisions, unprofitability could be avoided to a greater extent.

1.3 Delimitations

Vattenfall consists of several business divisions and several units within each division. This thesis will cover the work of the Nordic Generation Wind (N-GW) unit in Denmark as Horns Rev 1 have been chosen as subject for the case study. Even though the study will have a life cycle perspective, it will only cover the final years as the wind farm already have been in operation for over a decade.

Data that is used in this thesis project, for example predictions of future spot prices, is acquired through Vattenfall. The reason is that the project is a case study and the relevant data is consequently only available at Vattenfall. Data collection was further restricted since some numbers are confidential.

2 Asset Life Cycle Management

In this chapter, the concept of Asset Life Cycle Management (ALCM) will be described. First an overall system perspective is presented, followed by the five perspectives included in ALCM. The technical perspective will give the reader a basic understanding of how a wind turbine works as well as a few maintenance strategies. The economical perspective presents theory behind rational investment decisions and how business cases can be used as financial decision support. This will be followed by a description of the commercial, compliance and organisational perspectives.

Asset Management is a broad concept and is often used to optimise life cycle costs and revenues of assets. The Institute of Asset Management defines Asset Management as the "*coordinated activity of an organization to realize value from assets*" where an asset is "*an item, thing or entity that has potential or actual value to an organization*" (The Institute of Asset Management, n.d.). However, Asset Management is criticised for being too short-term oriented (Komonen et al., 2012; Waeyenbergh & Pintelon, 2002). To further highlight the holistic perspective it is therefore referred to as Asset Life Cycle Management (ALCM), which will be the term used in this thesis.

ALCM is a multidisciplinary approach and can be discussed from a technical, economical, commercial, compliance and organisational perspective. While technical and economical impacts are the most common to discuss, these do not give a complete picture of the asset (Petersen, 2015; Haffejee & Brent, 2008). The perspectives are shortly described as:

- *Technical*: The asset needs to have a certain technical standard and degradation, which is affected by for example wear and rust.
- *Economical*: The asset is expected to deliver economical value to the owner, thus costs for maintenance and spare parts have an impact on the asset.
- *Commercial*: The asset has to fulfil the requirements of the customer and the market. Factors such as performance and innovations have an impact on this aspect.
- *Compliance*: The asset must comply with norms and regulations regarding for example safety and working conditions.
- *Organisation*: The organisation needs the right expertise, knowledge and data to be able to operate the asset.

These five perspectives will be further explained in this chapter, with the major focus being on the technical and economical aspects. However, the other three perspectives are important to complete the picture of why certain decisions are made, contributing to the overall system perspective.

2.1 System Perspective

Making changes within a system requires a holistic perspective as well as awareness of how things affect each other and what changes can lead to. Changes of one aspect within the system will most likely result in changes of other aspects as well (Meadows, 2008). For example, wind power leads to lower emissions connected to its production but it also creates issues with larger fluctuations in the energy system (Vattenfall, 2011). In the same way, a system perspective is needed when looking at the profitability of wind power. In order to increase the competitiveness of wind power, the whole value chain has to be optimised, engaging all parties in the various steps of the life cycle. Discussions about how manufacturers can ease the operation and maintenance (O&M) and how other industries have

acted on similar problems are crucial to reach the possible progress within the field (Johansen, 2015). A larger market would furthermore lead to increased competition, and a standardisation of processes could result in shorter lead time and cost reductions (International Energy Agency, 2013).

The system perspective can also be applied on the spot price. As the price of electricity in the Nordic countries is determined by supply and demand, changes in one part of the system can affect the rest of the system. A transmission constraint or power failure in one area can affect the price in another area. Figure 1 shows, in a simplified way, how the spot price is determined through the intersection of the supply and demand curve. With this system the highest accepted bid sets the system price, in other words is it the most expensive energy source in use for a given hour that determines the spot price for that hour (Amelin & Söder, 2011; Nord Pool Spot, n.d.).

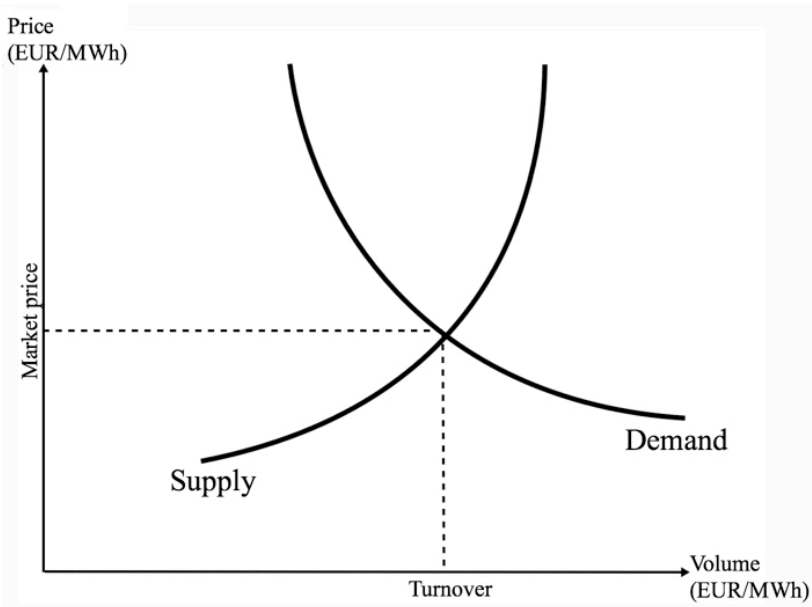

Figure 1. Spot price determined through supply and demand (Nord Pool Spot, n.d.)

When the wind blows, it naturally blows over a large area and thus impact several wind farms simultaneously. In areas with a high number of wind turbines this means that there either is no wind power in the system or a lot at the same time. A large share of wind power in the system could be said to make the supply curve in Figure 1 to shift to the right and thus lower the price. Figure 2 shows how the proportion of wind power in the system influences the spot price. The figure is based on an analysis of how the day-ahead spot price market is affected by wind power forecasts in Denmark (Jónsson, Pinson & Madsen, 2010). The impact of this has to be taken into account when looking at how wind power affects the system. A value factor is therefore often used when calculating future expected revenues from wind power (Attermo, 2015).

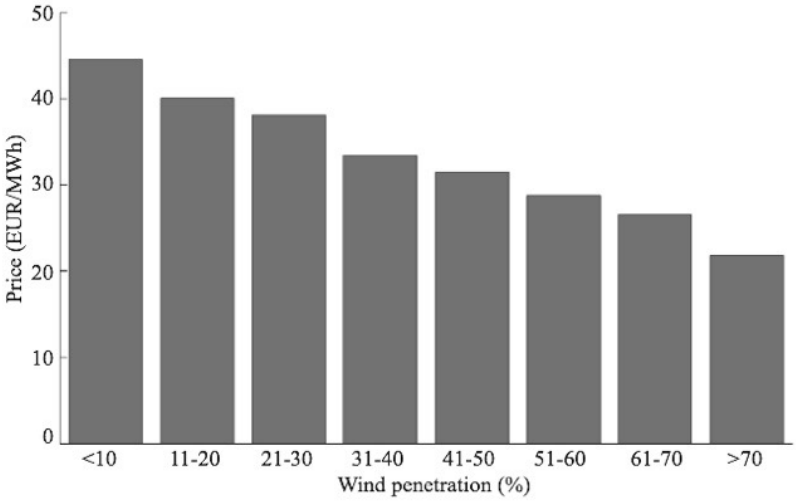

Figure 2. Average spot price, categorised by intervals of forecasted wind power penetration in DK1 for January 2006 - October 2007 (Jónsson, Pinson & Madsen, 2010)

The earnings from wind power are related to the current spot price. In order to promote investments in wind power, the Government of Denmark guarantees a subsidy for projects during the initial planning phase. For Horns Rev 1, a fixed price of 453 DKK/MWh for the first 42 000 full load hours was set. This limit was reached in 2014 and now the subsidy is 100 DKK/MWh up to a total maximum of 350 DKK/MWh (spot price + subsidy). Other wind projects have similar agreements as a way of encouraging sustainable investments by minimising the risks (Danish Energy Agency, 2013 & 2014; Johansen, 2015). In the last years, the electricity price in Denmark has decreased (Nord Pool Spot, 2015). Horns Rev 1 belongs to price area DK1 as it is located outside Esbjerg on the west coast of Denmark. This part of Denmark is connected to the European grid and the spot price is therefore dependent on a larger geographical area. The eastern part of Denmark (price area DK2) is instead connected to the Nordic system (ENTSO-E, 2014).

The above examples illustrates why it is necessary to have a system perspective in mind when discussing economics and profitability of wind power. However, the system view can also be applied in a "smaller" context, such as one single wind turbine. All the components are connected and makes up a complex system in itself. If one component breaks down, it can lead to failures in other parts of the turbine as well. At the same time, failure data is recorded on an item level. Kortelainen et al. (2015) argue that this is important because components that are causing high maintenance costs can more easily be identified. It is also discussed that a "top-down" view is needed to be able to go from the system view to the item level in order to first identify a problem area and then the specific improvement targets. In this way the components can be analysed in a system context.

When dealing with systems, no matter if it is an energy system or the system of components in a wind turbine, a boundary has to be set. There is no single, legitimate boundary that could be drawn around a system and it has to be chosen depending on the purpose of the system and who is observing or using it. The boundary has to be chosen in a way that does not limit the system by being too narrow or too large (Meadows, 2008). Horns Rev 1 is the main objective of this case study and thus is the centre of the system. As a long-term and holistic perspective on maintenance of wind turbines is important, Asset Life Cycle Management (ALCM) could be applied. In the concept of ALCM the entire lifetime of the asset, in this case the components of a wind turbine, is perceived as a system (Petersen, 2015; Life Cycle Engineering, 2009).

2.2 Technical Perspective

The technical perspective of ALCM will be discussed from two angles: the actual technology of a wind turbine and possible maintenance strategies. These are important parts for understanding how and when investments have to be made.

2.2.1 Technology of a Wind Turbine

The technology has developed greatly in the last decades, contributing to the rapid expansion of wind power. This has for example increased the capacity factor[1] and made improvements on the design, which makes it possible to seize more of the energy from the wind (Wizelius, 2007). The rated size of the turbines has increased from 75 kW during the 1980s to 8 000 kW during the 2010s. Although, the average installed capacity has not yet reached this high, most installed turbines are of the size between 1 500 kW to 2 500 kW (International Energy Agency, 2013; Vestas, 2014). A more efficient turbine design could bring down costs of installation and O&M, as well as higher yields by increased production. However, this development requires extensive R&D and in the last years the cost for installation has instead increased as the turbines are becoming larger and situated further offshore (Sun, Huang & Wu, 2012).

A wind turbine consists in broad terms of a foundation, tower, nacelle and blades, as can be seen in Figure 3. The function of the foundation is to support the tower and attach the turbine to the soil. The type of foundation that is used depends on if the turbine is placed on- or offshore. In the offshore case, the type of soil and the water depth are crucial aspects. New types of solutions with floating foundations are currently being tested. The advantage would be to save costs at greater depths if the tower does not have to be attached to the seabed (Sun, Huang & Wu, 2012; Wizelius, 2007). However, at Horn Rev 1 a monopile is driven 25 m into the seabed to which the tower is attached through a transition piece (Petersen, 2015).

The turbines of Horns Rev 1 are divided in ten rows of eight turbines. Each row of turbines is connected to substations, and then connected to shore through a joint cable. The impact of a cable failure is thus depending on where it occurs. A failure in a cable in one row only affects between one and eight turbines, while a failure in the main cable affects all 80 turbines (Petersen, 2015).

[1] The capacity factor is a measure of how large proportion of the time that a turbine produces electricity. (Wizelius, 2007)

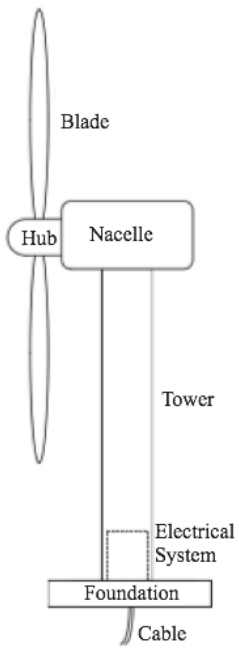

Figure 3. Simplified illustration of a wind turbine (Besnard, 2009)

The tower is usually made of steel and has no complex technical function. Usually the nacelle is accessed from the tower by an elevator and a ladder on the inside. The tower also holds the cables in which the generated electricity is transmitted to the electrical system. Included in the tower is the yaw system, which has the purpose of turning the nacelle in the right wind direction. How this is done depends on the type of turbine (hydraulic motors/cylinders or electrical machines). However, the turbine cannot be turned according to every change in wind direction since this would lead to too much wearing. Therefore, the yaw system only turns the turbine when the change in wind is considered to be long lasting. The system gets data on wind speed and direction from an anemometer ((1) in Figure 4) at the top of the turbine and automatically turns in the optimal angle. The yaw system (7) is the part between the tower and the nacelle that makes the entire nacelle turn in the optimal wind direction (Wizelius, 2007; Yesilbudak, Sagiroglu & Colak, 2015).

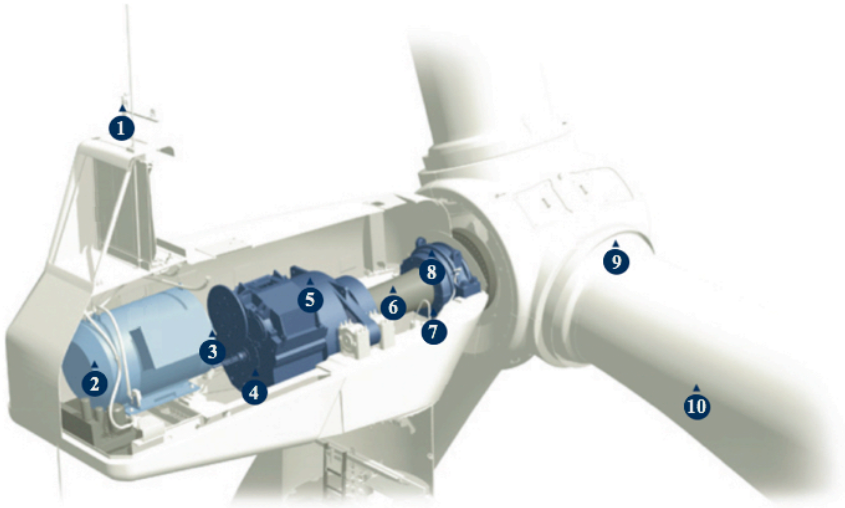

Figure 4. Simplified picture of a nacelle (Vestas, 2008)

The nacelle covers the drive train of the turbine and contains among other things a gearbox (5) and a generator (2), which can be seen in Figure 4. It is in the drive train that the rotational energy from the blades (10) is transformed into electricity, using the main shaft (6) and main bearing (8). The purpose of the gearbox is to convert the low speed mechanical power to a high-speed rotational power suitable for the electrical machine (Jha, 2010; Vestas, 2008).

A failure in the gearbox can result in different problems such as long downtimes. Gearbox failures cause, in average, the longest downtime and consequently impact the availability of the turbine to a high degree (Fischer, Besnard & Bertling, 2012). For Horns Rev 1, downtime due to gearbox failure constituted 24% of the total downtime during the period 2009-2010 which is more than twice as much as any other sub-system (Besnard, 2013). This type of failure also entails a large share of the total cost of corrective maintenance due to the need of expensive equipment (Fischer et al., 2012).

The generator converts the mechanical rotational energy into electricity. Generator failures are most often caused by bearing or winding failures, where bearing failures constitute more than half of the failures in generators for turbines larger than 1 MW. The most frequent reason for this is friction due to cracks of flakes (Fischer et al., 2012; Wizelius, 2007). Included in the nacelle are also couplings (3) (used to transform energy from one part to another inside of the nacelle), a service crane (used to winch spare parts to the nacelle) and a break (4) (used as a backup to the pitch and when maintenance is performed) (Wizelius, 2007; Petersen, 2015).

Usually, wind turbines have three blades but there are turbines with one, two and more than three blades as well depending on the application of the turbine. The blades are usually made from fibreglass strengthened with plastic, carbon fibres or laminated wood. The blades have a design similar to the wings of airplanes, with one suction side and one pressure side, using the lifting force to gain movement (Hayman, Wedel-Heinen & Brøndsted, 2008; Jha, 2010). To make sure that the turbine is not exposed to too high loads when wind speeds are high, the pitch ((9) in Figure 4) regulates the angle of the blades, reducing the lift. When the wind speed is low, however, the pitch makes sure that as much lift as possible is gained (Yesilbudak, Sagiroglu & Colak, 2015). The function of the hub is to transmit the rotational speed from the blades to the main shaft (6) of the drive train in the nacelle. The rotor has a low downtime per year compared to other sub-systems. For Horns Rev 1 it contributed to only 8% of the total downtime during the period of 2009-2010 (Besnard, 2013). Examples of failures are cracks in the blades due to fatigue, ice and lightning strikes (Yang & Sun, 2013).

2.2.2 Maintenance

As earlier mentioned, O&M contributes to a large share of the total cost for wind turbines. Research has shown that O&M costs constitutes up to 30% of the initial investment costs (Blanco 2009). The corresponding costs for onshore wind farms are not as high, mainly due to the increased complexity of planning and accessing offshore wind turbines (Sun, Huang & Wu, 2012). Choosing the right maintenance strategy is therefore of great importance as it is the only way to influence expenses after the turbine has been built. Maintenance costs are sometimes seen as a *cost* that needs to be minimised and not as a strategic *investment*. If the risk, connected to insufficient maintenance, is linked to the cost of downtime or safety problems, it becomes clear that maintenance can, and in many cases should, be seen as an investment (Arthur, 2004). Optimisation of maintenance is therefore of great interest. However, research has shown that current maintenance for wind turbines is not optimised and that opportunities exist for large savings in both cost for maintenance activities and costs due to production losses (Fischer, Besnard & Bertling, 2012; Igba et al., 2013; Petersen, Madsen & Bilberg, 2014).

The concept of maintenance involves a combination of technical and related administrative actions, with the aim to maintain or restore a system in a state that enables it to perform its required functions. In brief, the objective of maintaining an asset is to ensure a functioning system. The combination of the reliability, availability, efficiency and capability of the systems should be high, which is not the same as to maximise each factor separately. The ideal combination is determined by factors such as minimising costs, ensuring a safe environment and keeping the required state of performance (Dekker, 1996). Figure 5 shows how the cost of having a close to 100% availability is unrealistically high if compared to cost of lost revenue and total cost of direct O&M. Instead the optimal availability (theoretically) is instead a bit lower (GL Garrad Hassen, 2013; Tavner, 2012). Horns Rev 1 currently has an availability of 97,3%, which is relatively high compared to similar offshore farms (Petersen & Ruitenburg, 2015).

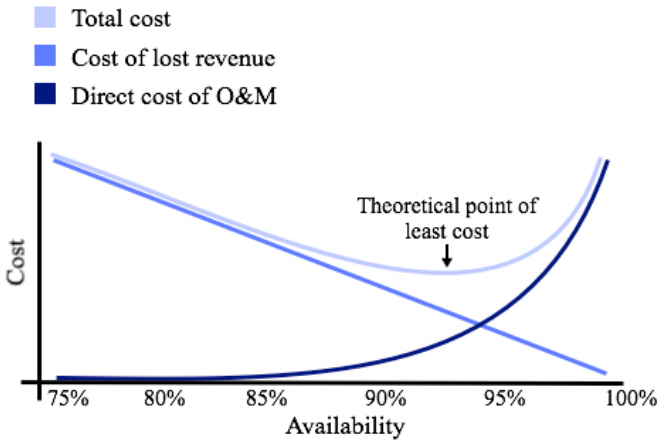

Figure 5. Description of relationship between O&M costs and lost revenues (based on figure from GL Garrad Hassan, 2013)

Maintenance can be classified into different subcategories depending on when it is performed in relation to a failure and how the component is monitored. The different types of strategies can be combined to ensure that the system fulfils the stated requirements. Firstly, maintenance can be divided into corrective and preventive maintenance, where corrective maintenance is carried out after a failure has occurred while preventive is carried out to avoid failure. Preventive maintenance could either be carried out at certain time intervals (time based) or when the turbine reaches a certain state (condition based) (Waeyenbergh & Pintelon, 2002). The state or condition of the turbine can be determined through inspection at sight or through a Condition Monitoring System (CMS). CMS is a common term for systems that observe the current state of an asset (Bertling et al., 2006). However, CMS are not used to its full potential today as the cost in some cases exceeds the benefits. The type of strategy is determined by for example cost of spare components, lost revenues due to downtime and cost of inspections. It is also depending on if the maintenance can be planned long in advance as it then can be scheduled at the same time as for example a routine inspection (Besnard, 2013; Petersen, Madsen & Bilberg, 2013; Waeyenbergh & Pintelon, 2002).

A failure can be classified as minor or major, and refers to the amount of logistics that is needed. Major failures or tasks often require crane-ships and more technicians and consequently demand additional planning. Examples of major tasks are reparations of blades and the generator. Some special tasks are even outsourced which further requires additional processes. Usually, major failures are not as frequent as the minor, which is why it is not always profitable to keep the knowledge in-house. Minor failures, such as check of oil

pressure, are usually simple and repetitive tasks. Some of these tasks are scheduled at certain intervals and others are incorporated into the schedule when a failure occurs (Petersen, 2015).

As there are a number of ways to perform maintenance it is difficult to know the optimal way of combining these strategies. Factors such as weather, availability of technicians and unpredicted breakdowns make it hard to plan maintenance on beforehand. If the time from when a failure occurs until it is possible to repair the component is long, revenues from production is lost. An unexpected failure can therefore be costly as the availability of the turbine decreases. Maintenance optimisation models can be used to find strategies to combine preventive and corrective maintenance to facilitate planning of maintenance activities (Dekker, 1996; Tavner, 2012). Through successful optimisation of maintenance the system availability and safety can increase, whereas overall costs decrease and equipment reliability can be improved. One of the most common methods for maintenance optimisation is Reliability-Centered Maintenance (RCM) (Arthur, 2004; Ruitenburg, Braaksma & van Dongen, 2014).

RCM is focused on the condition of the asset and how this changes over time. Thus it is a predictive strategy instead of preventive or corrective. It is a systematic way of looking at the assets system functions and in what ways a function can fail, taking consideration of safety and economics with the goal of identifying appropriate preventive maintenance tasks. The overall objective of RCM is usually to lower maintenance costs by focusing on the right maintenance tasks at the right time (Rausand & Høyland, 2004). Maintenance is carried out at a component level and based on the relation between the reliability of the component and the probability or consequences that it will fail during normal operation. By analysing the system's functions, it is possible to make a priority-based consideration of which actions that are most important at the time (Petersen, Madsen & Bilberg, 2014). RCM focuses on knowledge of experts as the main source of information, as these are expected to be able to make the priorities based on several perspectives (Ruitenburg, Braaksma & van Dongen, 2014).

However, RCM has also received criticism as the logic decisions only focuses on the short-term maintenance and not the long-term. As the life expectancy of a wind turbine is 20 to 25 years, important strategic opportunities might be overlooked when only considering the immediate future (Petersen, Madsen & Bilberg, 2014). This criticism highlights the value of keeping an ALCM perspective on maintenance to not overlook the long-term benefits.

2.3 Economical Perspective

When deciding on whether to install wind turbines or not, an economical analysis is crucial. If wind turbines are to be profitable, the income from generating electricity has to exceed the expenditures connected to investments as well as operation and maintenance (O&M). These cash flows have shown to be highly dependent on whether the turbines are built onshore or offshore (International Energy Agency, 2013). Costs for O&M are higher for the offshore cases due to limited access to the turbines and harsher natural conditions.

During the last years, the costs connected to offshore wind farms have been increasing due to a number of reasons. Increasing costs for material and labour as well as the projects being further from shore are a few reasons. The future development of the costs is uncertain and dependent on innovation, increasing competition and improvements in O&M (Heptonstalla, Grossa, Greenacreb & Cockerillc, 2012). There are other sources that predict a decreasing

average cost of wind power in the near future even though the magnitude of this is debatable (International Energy Agency, 2013; Lantz, Wiser & Hand, 2012).

The development of costs can follow different patterns during the lifetime of an asset. Sometimes the costs of for example O&M are referred to as following a bathtub curve, as illustrated in Figure 6. This means that the costs are high in the beginning of the lifetime of the asset, gradually declining and then increasing while approaching the end of lifetime. It is also argued that the costs can follow other patterns where it, for example, increases in the middle due to several failures of main components. Another example could be continuously preventive maintenance and thus avoid the increase in the end. In the end of lifetime of the turbines, it might not be profitable to do further replacement investments and this period might then be referred to as the "harvest" period (Bode, 2015; Smith, 1993). The choice of maintenance strategy can therefore have an effect on the pattern that the cost development follows.

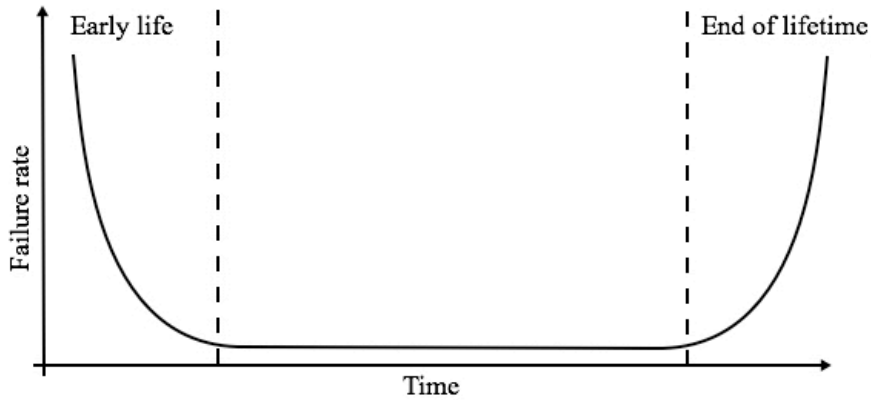

Figure 6. Simplified illustration of a bathtub curve (based on figure from Smith, 1993)

Here after, an investment will refer to investments in already existing wind turbines. Example of such could be a replacement of a gearbox or an upgrade of the blades. Simply put, the difference between maintenance work and an investment is the amount spent on the replacement or reparation (Attermo, 2015). The background to how investment decisions are made based on economical calculations, so-called business cases, will be given in the following subchapters. Rational investment decisions will have to be made in order to increase the profitability of the wind turbines, making it more competitive to other alternative sources.

2.3.1 Investment Decisions

When an investment decision is made there are a few steps to follow in order to evaluate the options (Holmström & Lindholm, 2011). These steps are:

1. Specify the problem
2. Develop alternatives and find out more about the consequences
3. Make calculations and sensitivity analysis
4. Draw conclusions and make recommendations

The purpose of the first step is simply to understand what the actual problem is. As a consequence of the detected problem, step two is to identify several alternatives on how to solve the problem (Holmström & Lindholm, 2011). An example of such alternatives could be to evaluate the consequences of replacing or repairing a damaged component. When different

alternatives are developed, several perspectives have to be taken into account in order to gain as much information as possible about the alternative solutions (Haffejee & Brent, 2008). Consequences such as how the performance, the availability and the need of future maintenance of the asset are affected by the proposed solution. Through the knowledge from experts within the organisation, such consequences can be considered when developing alternative solutions (Ruitenburg, Braaksma & van Dongen, 2014).

In step three, calculations of the effect of the proposed solutions have to be made. These investment calculations are often referred to as a business case. Economical calculations constitute a large part in many investment evaluations. The economical calculations are sometimes overrated when making investment decisions, while aspects that cannot or are hard to evaluate in monetary terms are underrated (Holmström & Lindholm, 2011; Lester, 2013). Engwall et al. (2014) suggests that consequences that are not easily quantifiable should be investigated further outside of the calculations to visualise its total value.

The purpose of economic evaluations is to present enough information to be able to make rational decisions regarding investments. There are several factors to consider when determining which type of calculations to make, and which level of detail that is needed. When developing a calculation tool, one has to know for what purposes it is to be used and who is supposed to use it, since this affect what is required from it. As the available tools have different strengths and weaknesses, they are commonly used together to provide a more extensive picture of the case (Andersson, 2010; Holmström & Lindholm, 2011). Common performance indices are presented in Chapter 2.3.2.

To improve the outcome of investment decisions, the risk and probability for certain events should be taken into account. One should be aware of the sensitivity that the different variables bring to the calculations, especially the ones that are based on predictions with a great deal of uncertainty (Holmström & Lindholm, 2011). This should be done to prove the reliability and trustworthiness of the calculations. In this, different variables that have been found to influence the actual outcome should be varied within a feasible range. In this way, the variables affect on the result and what the lowest expected level of earnings is can be investigated further. Some of the developed alternatives will show a higher degree of sensitivity, which is something that has to be taken into account (Andersson, 2010; Engwall et al., 2014). For wind turbines, data collection through Condition Monitoring Systems can be used in order to get knowledge of failure statistics and probability (Petersen, 2015).

Prognostics of the future are often used to predict events that might occur and to control risks. However, research has shown that a large part of these prognostics are based on the experience and intuition of people who are working with the asset. This makes it harder to accumulate knowledge and pass the experience on to the younger work force (Merchant & Van der Stede, 2012). In addition, the accuracy and reliability of human decision-making can be questioned when dealing with complex and interrelating possible failure scenarios. Research has therefore focused on reducing the dependence on key individuals in business through the development of prognostic models. There are several models that could be used for prognostics, and choosing the most appropriate one for the business is complicated (Sikorska, Hodkiewicz & Ma, 2011).

By making an analysis of potential risks and impacts, future events and failures might be possible to delay, stop or eliminate. It is thus important to have in mind that decisions made today affect the future status of the asset. A decision to not repair a component due to high

costs, might result in even higher costs later on in the assets life cycle. To make this more prominent, maintenance actions should be calculated based on the contribution to life cycle profits (Sherwin, 2000).

In the fourth and final step, conclusions from each alternative should be drawn based on the acquired knowledge. The different perspectives that have been brought forward have to be considered in order to make rational decisions. Some investments are carried out even though they are not profitable in monetary terms since the company is obliged by law or pressured by public opinion, or provide other value to the company (Holmström & Lindholm, 2011). As an additional step, all investment decisions should also be evaluated in retrospect since the conditions and knowledge of the system constantly change (Holmström & Lindholm, 2011; Engwall et al., 2014).

2.3.2 Business Case

Business cases are usually used by companies for justification of a proposed project in the form of a document or presentation as a part of an investment decision. A business case should specify how money and other resources should be used and how this will benefit the project and the business as a whole. It can be used for larger projects as well as for investments within a current project, but often considers an isolated event (Attermo, 2015; Lester, 2013).

When a wind turbine fail and major investments has to be done, a business case can be used to investigate whether the required maintenance will be profitable or not. This is based on calculations of costs for spare parts, maintenance and transport compared to the revenues the investment will generate. For smaller investments a business case might not be necessary, as it is commonly accepted that the wind turbine will produce enough electricity in the remaining lifetime to motivate the investment (Bode, 2015). However, as the wind turbines approach their end of lifetime, it might be necessary to calculate and motivate even smaller investments with a business case. Unexpected failures might increase for aging assets due to wear and fatigue. Keeping a system perspective will become important when approaching end of lifetime (Haffejee & Brent, 2008; Smith, 1993).

Business cases are often based on long-term predictions and the investment might have a long payback time (Attermo, 2015). The probability that further maintenance and investments have to be done is therefore high. Moreover, each failure mode has different triggers and deterioration patterns, resulting in diverse possible scenarios in the future, even under the same operating condition. If the prerequisites change, either through operating conditions, maintenance actions or other failures, the deterioration might accelerate or change (Sikorska, Hodkiewicz & Ma, 2011). Including possible future scenarios into a business case is therefore of great importance, especially when approaching the end of lifetime, to determine the sensitivity of an investment.

How an investment is funded (for example savings, loans, bonds) further affect the economical cash flows connected to an investment. The interest rate of a loan implies extra expenditures that the revenues from the investment have to cover in addition to other costs. A predetermined, company specific, discount rate is often used in calculations to estimate the cost of capital. This rate is called the WACC (Weighted Average Cost of Capital), and could be used to evaluate the profitability of an investment (Brealey, Myers & Allen, 2006).

As a part of a business case, different Performance Indices (PI) are calculated. As these have different strengths and weaknesses, they are commonly used together to provide a more extensive picture of the case (Andersson, 2010).

EBITDA and EBIT

Earnings Before Interest, Tax, Depreciations and Amortisation (EBITDA) and Earnings Before Interest and Tax (EBIT) are two measurements commonly used. These are both used as rough calculations of the organisations current profitability (Brealey, Myers & Allen, 2006). EBITDA is calculated as:

$$EBITDA = Revenue - Expenses\ (excluding\ tax, interest, depreciation\ and\ amortization) \tag{1}$$

EBITDA is not a general accepted financial measurement but is still often used when analysing a company's performance. EBIT (also known as operating profit), however, is calculated as:

$$EBIT = Revenues - Expenses\ (excluding\ tax, interest) \tag{2}$$

EBIT is commonly used in bookkeeping and financial analysis of a company's performance (Brealey, Myers & Allen, 2006).

Net Present Value

The Net Present Value (NPV) is the sum of the present values of future cash flows over a specified period of time. The cash flows are all the revenues and expenses for a specific year and are discounted back into the present value, as time has an impact on the value of money. In other words, a sum of money is worth more today than what the same amount will be in a few years time. The discount rate is usually identified in relation to the expected rate of return of other investments with similar risk.

$$NPV = -C_0 + \sum_{i=1}^{T} \frac{C_i}{\sum(1+r)^i} \tag{3}$$

Where C_0 = Initial investment [DKK]
C_i = Cash flow [DKK for year *i*]
r = Discount rate [%]
T = Time [Year]

The NPV of future cash flows can be compared to the initial investment to determine whether the investment is profitable or not. This PI is often used, as it is simple and an easy indication of the profitability of the investment. A negative NPV indicates that the investment will have a lower Internal Rate of Return (IRR) than what the company require it to be. When comparing different investments, it is common that the one with the highest NPV is perceived as the most profitable. However, when doing comparison between different investments one have to be aware of for example the magnitude of the initial investments, the difference in risk, changed market conditions and new regulations (Holmström & Lindholm, 2011).

Internal Rate of Return
NPV can be used to calculate the IRR, an indication on the return on investment. IRR can be compared to the company's discount rate, where investments with higher IRR than the discount rate fulfil the company's requirements on depreciation. IRR is determining the rate at which NPV equals zero and is a way of showing the relative profitability between investments. The equation that is used to solve for IRR is (Holmström & Lindholm, 2011):

$$0 = C_0 + \sum_{i=1}^{T} \frac{C_i}{(1 + IRR)^i} \tag{4}$$

Where C_0 = Initial investment [DKK]
C_i = Cash flow [DKK for year *i*]
T = Time [Year]

Payback Method
One of the simplest investment calculations is the payback method. This method calculates the time for an investment to repay. The advantages of the method are its simplicity and intuitively. By using the payback method, one get a hint on how long the investment will take to repay and when comparing two alternatives, which investment that will repay quickest. One of the downsides though, is that the method does not take the years after the repayment has been done into account. The equation that is used to calculate the payback period is:

$$Payback\ Period = \frac{Initial\ investment}{Net\ annual\ cash\ inflow} \tag{5}$$

By using the payback method in addition to other methods, the disadvantages are diminished (Engwall et al., 2014).

2.4 Commercial Perspective

As has previously been stated, the importance of the commercial perspective is that the asset has to fulfil the requirements of the customer and the market. Factors such as performance and innovations have an impact on this aspect. There are several stakeholders connected to Horns Rev 1 with various opinions to be aware of. For example, Vattenfall is obliged to produce electricity through Horns Rev 1 until 2022, independently of whether it is profitability or not. This is an exceptional requirement for Horns Rev 1 that has to be taken into account when making investment decisions (Bode, 2015). The requirement was set as the Danish Government requested the development of offshore wind power as a part of the national initiatives within the field (Bode, 2015; Vattenfall, 2014a).

Since Horns Rev 1 was first built, there has been an expansion within the field of renewable energy and it is further expected that this development will continue in the future (Lund & Mathiesen, 2009). Groups interested in environmental issues are usually positive to increased installations of wind power. A large share of the population is further positive to policies steering for reductions of green house gases. Although, individual projects encounter resistance from locals with arguments relating to for example the visual impact, effects on property values and the health of animals in the area (International Energy Agency, 2013). This is often referred to as a concept called "*not in my back yard"* (NIMBY) which in the energy sector refers to that people are positive to changes towards renewable energy sources

but not too close to their own property if there is a possibility of disturbance (Devine-Wright, 2004).

Studies have found that such a resistance is dependent on where the project is planned, with a higher acceptance for offshore farms than onshore. The study furthermore indicated that there are correlations between attitudes towards wind power and for example age, gender and earlier experience with offshore wind farms (Ladenburg, 2008). By increasing the knowledge of wind power and mitigate concerns connected to the technology this type of resistance and the delays of projects could be reduced. However, critics are still raising the question of security of supply and back up capacity. With an increasing share of intermittent power production the spot price is expected to vary significantly which the market sees as an issue (International Energy Agency, 2013).

2.5 Compliance Perspective

In order to be allowed to operate a wind farm, norms and regulations regarding for example safety and working conditions must be complied. In Denmark, it is regulated by law that an inspection of every turbine in operation has to be performed twice a year. This is in order to detect failures at an early stage and thereby avoid unnecessarily dangerous situations (Bode, 2015).

At Horns Rev 1 the safety has top priority. Therefore, when it is considered necessary, decisions are taken that is not viable in an economical aspect. For example was a problem with a service lift in one of the turbines detected, which led to a control of the lifts in the other turbines as well. When safety issues are detected, scheduled maintenance might have to be postponed into the future to give room for corrective actions. This is done due to the pronounced attitude towards safety issues and how they should be handled (Bode, 2015).

Since the sector of wind power is a subject to a high degree of development, with for example larger and more effective turbines, additional safety requirements might be up for discussion and decided upon. In order to fulfil new types of requirements, the asset can in some cases have to be modified but in other cases a replacements of the entire asset would be more economical viable (Ruitenburg, Braaksma & van Dongen, 2014). Due to such changes, the ones in charge of Horns Rev 1 must stay updated on the latest regulations and how these affect the farm.

Included in the compliance perspective are also for example sustainability, working conditions and norms. However, these are perceived as falling outside of this study and will therefore not be further discussed.

2.6 Organisational Perspective

To be able to operate a wind farm such as Horns Rev 1, the organisation needs the right expertise, knowledge and data. As for the current stage of Horns Rev 1 there are 16 experienced technicians working at the farm. In their daily work, they are free to make decisions on what to do when present at the turbines. However, if major reparations are to be done, this has to be discussed with and approved by the Site Manager or at even higher instances within the organisation (Bode, 2015).

However, Horns Rev 1 is one of the first offshore wind farms approaching its end of lifetime, a situation that might require additional and different knowledge than available today. By

benchmarking other industries that have gone through similar issues, a lot of knowledge can be acquired. One such example is benchmarking towards the onshore wind industry where knowledge on how to decide when to decrease the maintenance of the turbines and only "harvest" for as long as possible. Essential knowledge regarding issues due to the offshore location of the turbines can be benchmarked from the oil and gas industry, where solutions for issues regarding how to decommission the wind farm might be found. By using benchmarking this way, additional knowledge for the offshore wind sector can be gained in order to increase performance during the end of lifetime (Johansen, 2015).

It is further an organisational issue that when Horns Rev 1 is approaching its end of lifetime, important technicians might move to other sites, ensuring their own employment rather than staying faithful to a certain employer and wind farm. Due to this, one challenge for Vattenfall will be to keep the required experience and knowledge within the organisation during the years to come. In addition to the technicians that work exclusively with Horns Rev 1, there are also a stock keeper and a site coordinator. Vattenfall also have a few analysts that are monitoring the performance of several of the wind farms in Denmark in order to detect failures and decode error messages (Bode, 2015).

3 Research Method

This chapter will present the research design and the process of the thesis project. Each stage of the project will be presented in chronological order. The research questions will be linked to the relevant stage of the process.

The study, for which this thesis is based on, has been performed at the Nordic wind generation department, NG–W, at Vattenfall in Denmark. The methodology that has been used throughout the project is a case study, and Horns Rev 1 was chosen to be the main objective.

3.1 Research Design

The process of a case study commonly contains several different stages such as introduction (including selecting the case and preliminary investigations), data collections, data analysis, drawing conclusions and writing the report (Collis & Hussey, 2014). Within this specific study there was one additional main stage; the development of two business case models. Figure 7 present an overview of how the process has been for this specific study. As can be seen in this figure, the study has been an iterative process where for example the model-development has led to the need of additional data, which has required further literature to be reviewed. The problem formulation and research questions has further been revised and modified during the project, based on changing conditions in the different stages. The thesis has been written continuously alongside the case study.

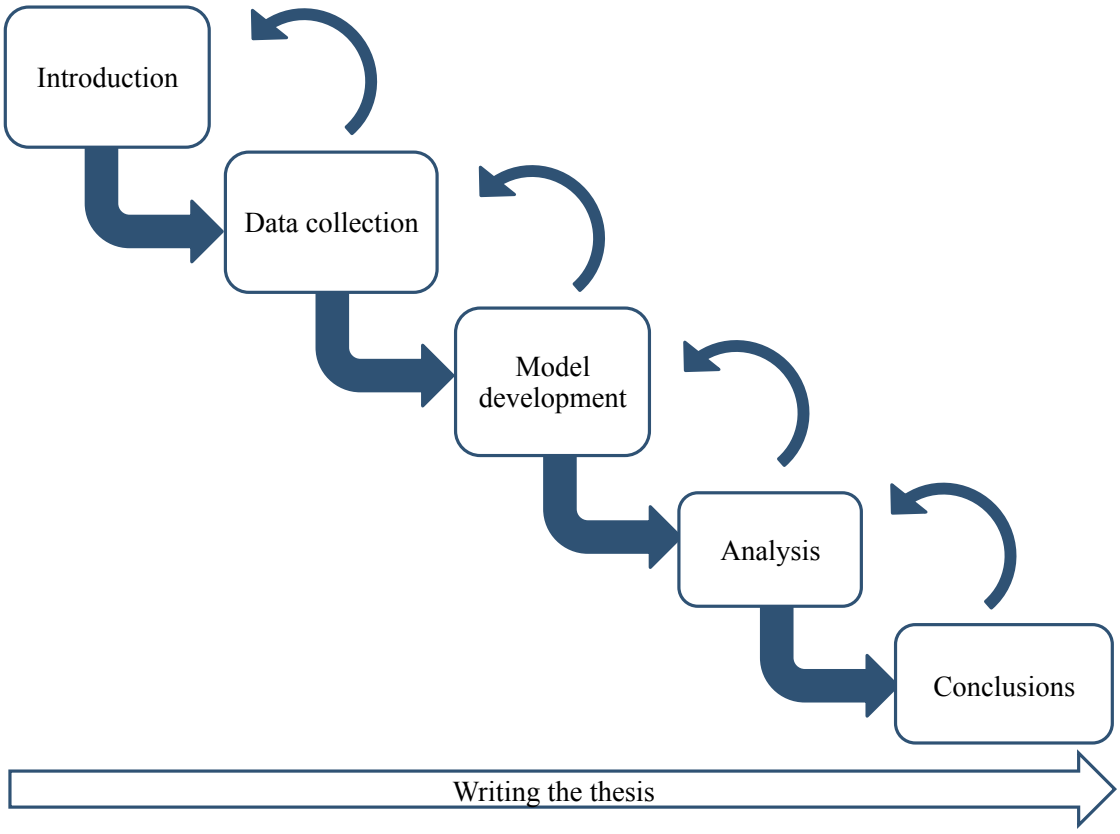

Figure 7. Schematic process of thesis project

The following subchapters describe the research design of this study in more detail, based on the different stages in Figure 7.

3.1.1 Introduction

The study started out with a pre-study of relevant literature in order to formulate a preliminary problem statement and research questions. As a part of this, three initial and unstructured interviews were conducted to get an understanding of the current situation at Vattenfall. The interviews further highlighted different fields within the literature that was relevant for the study. The interviewees that were a part of these introductory interviews were recommended by the supervisor at Vattenfall as people that had extensive knowledge within the field. These three persons where Head of Generation, Site Manager for Horns Rev 1 and a PhD student that has been studying the department for several years.

The initial interviews were held as videoconferences and the spoken language was English. These interviews were all between 40-60 minutes long and recorded with the permission from the interviewees. Both researchers were present at the occasion of the interviews to avoid interviewer bias (Collis & Hussey, 2014). Brief notes were taken during the interviews and later complemented while listening to the recordings.

In addition to this, meetings where held with the supervisor at the Royal Institute of Technology in order to discuss the focus of the thesis project. Recommendations on literature were also given in connection to these meetings. Based on these articles, a review of the literature within the relevant fields where initiated. Journals, books and other published work (such as internal reports) have been used within this review. These have foremost been found through different search engines such as KTH Primo, Science Direct and Google Scholar. The words that were used in the initial searches were for example: “wind power”, “Asset Life Cycle Management”, “Reliability Centred Maintenance”, “investment planning”, “business case” and different combinations of these.

Even though the review of the literature played an important part of the introduction of the study, this is something that has been a continuous process were new literature has been reviewed along the way. This is due to the iterative approach that has been used were new findings in following stages has required new fields of literature to be reviewed.

Based on this introductory stage, a thesis proposal was written. This was done to clarify what was going to be included in the study, what the stated problem was and how the study would contribute to the field of interest. The thesis project is a part of a larger study conducted by a PhD student at Vattenfall. The focus of the thesis has developed as a dialog between the researchers and the PhD student.

3.1.2 Data Collection

The data used in this study is mostly primary research data with a qualitative form. This is since interviews have constituted a large part of the data collection, especially to gain understanding in order to be able to answer RQ1:

> *On what basis is investment decisions made today for Horns Rev 1?*

However, secondary research data (existing sources and databases) has been used as a basis when answering the research questions, mainly regarding ALCM in RQ2:

> *How can an ALCM perspective contribute to the operation and maintenance of Horns Rev 1?*

All interviews within the study were held as semi-structured in order to collect data in an efficient and flexible way. The researchers had prepared a number of questions for each interview but the order of these was flexible. Furthermore, these questions were used in order to encourage the interviewees to talk about the central topics of the interview. If new questions arose during the interviews these were asked and if the researchers felt like one or a couple of the prepared questions had already been answered, these did not have to be put forward. In the end of the interviews, the interviewees were asked if there was something that they found important that had not been covered during the interview. This was done to make sure that relevant topics were not missed out on.

Most interviews were held as videoconferences as the interviewees were situated in Esbjerg, Denmark and the researchers in Stockholm, Sweden. Although, one of the interviews was held face-to-face in Stockholm. The interviews that were held as videoconferences were kept in English while the face-to-face interview was in Swedish. All interviews were recorded with permission from the interviewee. As with the initial interviews, both researchers were present at all the interviews in order to avoid interviewer bias (Collis & Hussey, 2014). The interviews lasted for 30-60 minutes.

The interviewees in this stage were chosen through natural sampling since the requested knowledge is site specific and only a few persons are familiar with it. Since this study covers a broad range, interviewees were required from different departments within Vattenfall. The interviewees were:

- Site Manager of Horns Rev 1
- Site Manager of Lillgrund and Kalmarsund
- Business Controller at BU Wind
- Data Analyst for Horns Rev 1
- PhD student at Vattenfall

In addition to these, a associate professor from the department of Industrial Economics and Management at the Royal Institute of Technology was consulted. Furthermore, a number of meetings were held where two or more employees at Vattenfall were present. At these meetings, the findings from the interviews were discussed in order for the researchers to get further understanding.

3.1.3 Model Development

Two different business case models have been developed in order to answer RQ3 and RQ4, which are:

> *How can budget planning, from an ALCM perspective, increase decision rationality?*
>
> *How does the uncertainty of different input variables affect the profitability of Horns Rev 1?*

Both models are based on similar calculations but one is developed for a single turbine whereas the other is developed for the whole Horns Rev 1. When the models were developed, an agile approach was used. This was done in order to start with a small and specific model, developed in a short period of time and specific for the particular case. From this, the researchers expanded the models to make it generate the results required to answer the

research questions. The overall aim when developing the models was to keep them simple and transparent to make sure that the user could understand them and their values. Therefore, prototypes were developed and shown to the supervisors at Vattenfall and the Royal Institute of Technology on a regular basis.

A conceptual description of the models is presented in Figure 8. In the first step, the user can choose to either keep the default values that have been entered as inputs or change it to the desired ones. Thereafter, the model automatically makes a number of economical calculations and generates output in the form of several Performance Indices (PI). Some of the results are presented as graphs in order to increase the understanding.

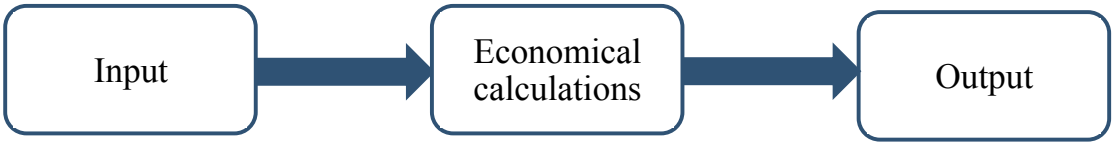

Figure 8. Conceptual description of the business case models

When the two models were developed, a system approach was used. In order to do this, the researchers were continuously aware of *how* and *by who* the models would be used. By defining system boundaries on what to be included and not in the models, the strengths and weaknesses appear to the user. The intention of the models is to create an indication on what strategy to use for Horns Rev 1 based on several inputs such as the budget and an investment plan. It should be noted that the models only indicate the trend of a possible future development and further investigations and evaluations will therefore be required before major decisions are made. The model and how it works is explained in Chapter 4.

3.1.4 Analysis Method

When analysing the data that had been collected, a general analytical procedure was chosen. This procedure contained three different steps which were (1) reducing the data, (2) displaying the data and (3) drawing conclusions and verifying the validity of those conclusions (Collis & Hussey, 2014). These steps were done in parallel to the data collection as well as each other throughout the study.

The first step, reducing data, was necessary due to the amount of data that was collected at all time. By doing this, the relevant data for the study was selected, which increased the focus of it towards the main research field. In order to be able to reduce the data, different categories were developed throughout the study into which the data was arranged. When reducing the data, the researchers had to reflect over what data in the different categories that was relevant for the study and not. This reflection increased the awareness of what data that was further required to complete the study.

In the meantime as the data collection and reduction was done, the researchers discussed how the different categories was related to one another, how they affected the studied system and how this in turn affected the usage of the data. By using a network approach to display these relationships there was a high degree of awareness of the research process during the whole time and a systematic approach was kept. These categories further eased the collection of new data since it pointed out where data was missing but also in what way such data could contribute to the study (Collis & Hussey, 2014).

Since data collection, reduction and displaying was done throughout the whole process, the knowledge within the field increased continuously. This made it possible for the researchers to draw conclusions and revise these as new information was put forward. The final conclusions of the thesis have been drawn based on findings from literature, interviews and the results from the models.

3.2 Reliability and Validity

Reliability refers to the repeatability and accuracy of measurements in a study, which is generally low for case studies as the researchers can interpret the collected information differently. A high validity is achieved if a study is accurately reflecting what the researchers attempts to assess (Collis & Hussey, 2014). This thesis project is conducted as a case study, which allows for multiple data gathering methods that improves both validity and reliability through triangulation. For example, the results from this study have been compared to similar existing values for Vattenfall. The close relationship to the employees at Vattenfall and the study's iterative approach has also led to higher validity.

When reviewing literature, secondary sources from legitimated journals were used. Independently of which type of source that was used, the reliability and validity of these were carefully considered by analysing the research methods of these. By doing this, unreliable sources could be excluded whereas reliable sources where taken into account for the study. In addition to this, a triangulation of the data that was collected at the interviews was performed. This was done by the usage of several different sources, for example different interviewees that were asked similar questions. On the other hand, the reliability and validity can be questioned since neither the questions nor the answers from the interviews have been included in the thesis. Furthermore, the reliability of some of the findings from the interviews is low since it contains personal opinions of the system and how it works. The interviews were recorded and transcribed in order to balance the negative effects on the studies reliability and to ensure that details was not missed or misunderstood. It also allowed for the researchers to go through the interviews at a later stage in the process when new knowledge had been gained.

Lastly, the fact that this study was performed during a period of only 20 weeks might have affected both the reliability and validity. The researchers had to limit the study in a way that probably would not have been done if a longer time period had been available. One example of this is that by looking at other wind farms, similarities and differences between these could have been found. The models could then have been altered to see if the results would have been similar for other wind farms in order to investigating whether or not the findings are generalisable. Further limitations of the model are discussed in Chapter 4 and recommendations of future research are presented in Chapter 7.2.

4 The Model

In this chapter, the business case models that have been developed as a part of the thesis project, both for a single turbine and the whole Horns Rev 1, will be explained. The concepts and terms used in the economic calculations will be briefly described to make it easier for the reader to understand the results. The sensitivity and uncertainty is further discussed to increase the user's understanding of the benefits but also the weaknesses of the models.

In this thesis project, an extended business case has been developed in Microsoft Excel to support future decisions in maintenance investments for Horns Rev 1. Hereafter the business case model will be referred to as "*the model*". An *investment* in the model refers to investments in already existing wind turbines. Example of such could be a replacement of a gearbox or an upgrade of the blades. The difference between maintenance work and an investment is usually in the amount spent on the replacement or reparation.

Two separate models have been developed, one for a single turbine and one for the whole Horns Rev 1. The models are based on similar calculations, with the difference that the model for the whole park is put forward from a system perspective while the model for a single turbine is developed to focus on the component level. This is needed to fully understand how investments affect the farm as a whole as well as how unprofitability can be detected at an early state in a specific turbine. The models are a result from the observations made of how decisions are made today at Vattenfall and how literature argues that it should be done.

4.1 Model of a Single Turbine

As has already been stated, the model for a single turbine is to be used as a tool when deciding whether to make a certain investment in a specific turbine or not. The purpose is also to help the user of the model understand the uncertainty of future investments. A conceptual description of this model is presented in Figure 9 in order to give the reader a brief understanding of how the model is structured. Further explanations of each part of the figure are given in Chapter 4.1.1 – 4.1.4.

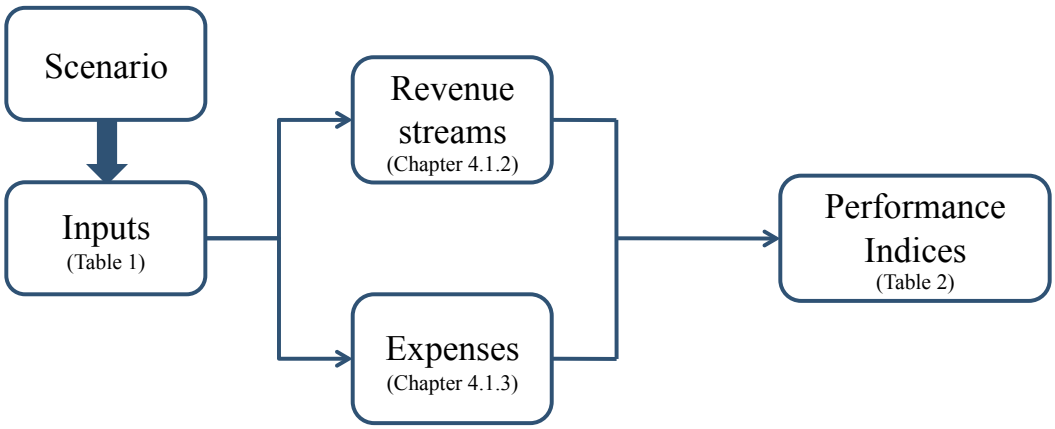

Figure 9. Conceptual description of the model for a single wind turbine

The inputs that are presented in Table 1 are in the model influenced by the chosen scenarios for production, spot price or total costs. The inputs are used to calculate revenue and expense streams separately for each year of the turbine's remaining lifetime.

Table 1. Input parameters for the model of a single wind turbine

Input	Unit	Comment
Years of operation	Year	Current and final year of operation
Number of turbines	-	Number of turbines currently in use at the whole wind farm
Production	MWh/year	Budgeted production for the whole wind farm
Budgeted costs	DKK/year	Total costs, divided by cost item based on annual budget
Investment	DKK	The size and time frame for the studied investment
Spot price	EUR/MWh	Predicted annual spot price given by Vattenfall
Value factor	%	Predicted effect on spot price due to increased share of wind power in system
Exchange rate	DKK/EUR	Predicted annual exchange rate given by Vattenfall
Residual value	DKK	Economical worth of wind turbine after decommissioning
Feed in Tariffs (FiT)	DKK/MWh	Subsidy for produced electricity
Maximum revenues (spot price + FiT)	DKK/MWh	Upper limit of revenues to still receive FiT
Company tax	%	Given by Vattenfall
Tax depreciation on balance	%	Given by Vattenfall
Inflation rate	%	Given by Vattenfall
Discount rate	%	Given by Vattenfall

All inputs will be covered in Chapter 4.1.1-4.1.3. Based on these inputs several performance indices, presented in Table 2, are calculated. The output of this model is the performance indices, graphs of the accumulated cash flows and the scenarios effect on the economical flows.

Table 2. Performance Indices for the model of a single wind turbine

Performance Index	Unit	Equation (see Chapter 2.3.2)
EBITDA	DKK/year	(1)
EBIT	DKK/year	(2)
NPV	DKK	(3)
IRR	%	(4)
Payback period	Year	(5)

4.1.1 Input

In order to create an interactive model that the user can influence based on his/her knowledge and predictions, there are various different inputs that can be changed in the model. The importance of these inputs is further explained and motivated below, as well as how the sensitivity of the model is affected.

Production

When making this type of business case, the *budgeted production* is used as a prediction on how much electricity that will be produced during one year. The budgeted production is rarely the same as the actual output but is used as an indication on how much electricity that can be expected from the wind farm each year (Attermo, 2015). The annual variations in production can be seen in Figure 10 (Lindoe Offshore Renewables Center, 2013; Petersen, 2015).

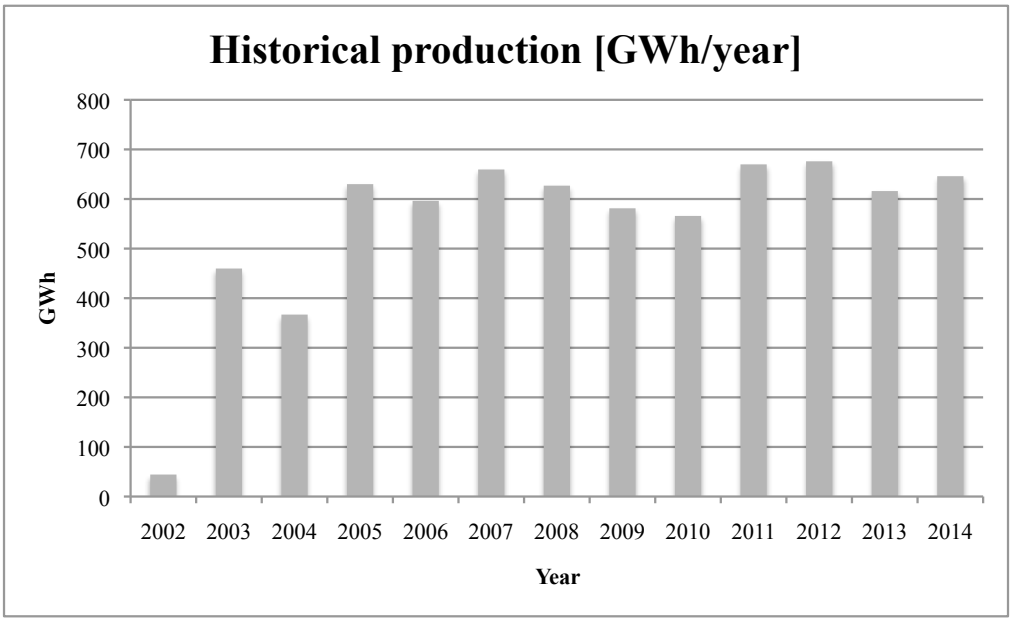

Figure 10. Historical annual production for Horns Rev 1 in GWh/year

Since the production-input contributes to an increased sensitivity of the model (due to the variations on the yearly basis) a scenario has been created to indicate the magnitude of this effect. The actual outcomes of produced electricity from 2005 to 2014 are used to illustrate how the result is affected. By using these, the value of the variable range from about 560 to 680 GWh as seen in Figure 10. The first three years (2002-2004) are excluded from the model since the production is significantly lower due to failures in the beginning of the wind farm's early life (Lindoe Offshore Renewables Center, 2013; Petersen, 2015).

O&M Costs

The costs that are relevant as inputs in the model are different types of costs connected to the operation and maintenance (O&M) of the wind turbine. The total cost used in the calculations is the sum of different cost drivers that will be further presented in Chapter 4.1.3. In the model, these inputs are taken from the budget of Horns Rev 1 for 2015. However, these costs are subject to large fluctuations and are difficult to predict, which is why a scenario has been put up to indicate on the sensitivity that this variable bring to the model. In order to decide the change of input level, the actual costs for O&M during the period of 2010-2014 have been used.[2]

Investments

The model for a single turbine is developed in such a way that the economic impact of specific investments can be illustrated. The inputs that are required is the year the investment is going to occur and how large the investment is expected to be, given in DKK. The user can also enter several investments for separate years, in chronological order. By doing this, the model calculate the value of the different investments and whether or not they have time to be repaid before the next investment is made. When entering two or more investments at the same time, the user can look at the economical impact that each investment leads to but also how these affect the result altogether. By enabling the input of future investments, one can detect unprofitability at an early stage.

[2] Due to confidentiality the range of the total cost used for the scenario cannot be specified in this report.

This function is not conventional in business cases, but has been added to highlight the fact that an investment today might not be profitable if a second investment will have to be done within a few years. This is also interesting since Horns Rev 1 is approaching its end of lifetime and investment might not be economically viable. Usually a business case only makes the calculations for one investment.

Inflation Rate and Discount Rate
When performing calculations extending over a long time period, the inflation rate is commonly used to value future financial flows in today's currency. The inflation rate varies every year but when making calculations on future financial flows, long-term indices are typically used. These indices are only predictions of the future and it is therefore important to be aware of the fact that there is a high degree of uncertainty connected to these (Brealey, Myers & Allen, 2006). In the model developed within the study, the inflation rate is 2%.

The discount rate (WACC) has a large impact on investment calculations and should correspond to the required rate of return that the company has decided (Holmström & Lindholm, 2011). The discount rate used in the model was given by Vattenfall.

4.1.2 Revenues

The main revenue connected to a wind turbine comes from selling produced electricity at the market. How large the revenue streams are depend on how much electricity that is produced, to what price it is sold for and how large the additional Feed in Tariffs (FiT) are. Another type of revenue is if the turbine has a residual value when decommissioned.

Revenues from Sold Electricity
The largest income that derives from operating a wind farm is from selling the produced electricity to the market. How large the income is depends on what type of agreement that has been made on how to be paid. In this model, the income is calculated as the spot price for electricity plus the FiT that has been agreed on. The spot price that is used to calculate the revenues in the model is based on predictions of future prices made by Vattenfall. Horns Rev 1 is a part of price area DK1, which is why the prediction for this area has been used. The predicted spot price is given in EUR/MWh, and a predicted exchange rate between EUR and DKK has therefore been used, which is also given by Vattenfall. Since an increase of wind power influence the price by lowering the spot price as described in Chapter 2.1, a value factor in percentage (given by Vattenfall) has also been included in the calculations. When the project of Horns Rev 1 was first developed, there was an agreement on how large the FiTs were to be during its operation. These are currently 100 DKK/MWh with the maximum of 350 DKK/MWh in total (spot price + FiT) and will be so for the remaining years of the farm (Danish Energy Agency, 2013 & 2014; Petersen, 2015).

As can be noted, the revenues from sold electricity are based on several predictions of the future, which is why this alone contributes to a high degree of uncertainty, especially when looking far into the future. A scenario has been created in order to illustrate how this uncertainty of the variables affects the sensitivity of the model. In this scenario, the future spot price is changed, with a percentage, to show how this affects the profitability of the turbine. The degree of change in the input value is based on earlier year's spot price levels, ranging from 30.67 to 56.43 EUR/MWh (Nord Pool Spot, 2015).

Residual Value
When the turbine has reached its end of lifetime it is time for dismantling. If the turbine and its components are in a satisfactory condition, it could be sold on the second hand market. The residual value is then treated as a disposable income during the final year in the model. Residual value is common for turbines that have been situated onshore, where companies (usually in other countries) buy the old turbines and put them up in new environments. However, for offshore turbines, there have only been a low number of dismantled turbines and no standard on how to do this has been developed. Most offshore turbines has endured rougher climate, which affect the technical status of the turbines negatively. Due to this, the turbines on Horns Rev 1 will most likely not have any residual value and the dismantling will be characterised by costs instead (Bode, 2015). In the model the residual value has therefore initially been chosen as zero but can be changed by the user.

4.1.3 Expenses
When looking at the costs that come from operating a wind turbine, the model take the budgeted costs as well as taxes and depreciation into account. The largest share of the costs comes from the different cost items connected to the O&M while the taxes and depreciations contribute to a small, but yet significant, share.

Total O&M Costs
The total cost per turbine that is used in the model is based on the budgeted costs for Horns Rev 1, as seen in Table 3. The total cost is divided by the number of turbines in use the first year for which the calculations are made. This cost is then increased with the inflation rate for the remaining years.

Another option is to predict the development of the O&M costs over the years with a bathtub prediction (Chapter 2.3), with the highs being in the beginning and the end of the turbine's lifetime. The costs for Horns Rev 1 are however not expected to increase in the following years and it is therefore "enough" to only increase by the inflation rate (Attermo, 2015; Bode, 2015). Furthermore, the level of total costs for O&M for Horns Rev 1 has been high in the last couple of years due to several major reparations and is expected to decrease (Bode, 2015).

Table 3. Cost items of O&M as given in budget for Horns Rev 1

Cost	Unit	Character
Balancing power	DKK/year	Variable
Contractors external	DKK/year	Variable
Major components	DKK/year	Variable
Operator fee	DKK/year	Variable
Other O&M cost	DKK/year	Variable
Other personnel related costs	DKK/year	Variable
Personnel costs (salary and related)	DKK/year	Variable
Reimbursable fee	DKK/year	Fixed
Spare parts and material	DKK/year	Variable
Surveillance fee	DKK/year	Fixed
Transportation	DKK/year	Fixed

The character of each cost item is also presented in Table 3 as these have an effect on some of the calculations that will be presented in Chapter 4.2. The cost items are only stated as fixed or variable based on how the costs would be affected by the number of turbines in use. Which costs that are considered fixed and variable is based on the opinion of the Site Manager of

Horns Rev 1 (Bode, 2015). Some of the cost items are more likely to be semi-fixed, meaning that they are fixed until a certain number of turbines are closed down and then decrease significantly. For example if one of the transportation vessels is sold as they no longer need all of them. The prediction of future cost developments can be changed in the model but have in this thesis project been chosen to be either fixed or variable (based on number of turbines in use).

There are only a few small-scale offshore wind farms that are "ahead" of Horns Rev 1 in its life cycle, which increase the uncertainty of the cost development. Due to this, there is a scenario showing how changes in the total cost affect the profitability of the wind turbine. The calculations connected to the scenario are made based on the total costs, even though the figures are entered in the model for each cost item separately.

Tax, Company Tax and Depreciations
The model follows the standard for how Vattenfall calculates taxes and depreciations for investments as well as taxes for operating results. Values used for tax rates have been given by Vattenfall as these are company specific.

4.1.4 Performance Indices

In order to make the user aware of how the different inputs affect the result of the model, various Performance Indices (PI) are calculated and presented in the model. When looking at these, it can be determined whether a specific change has a positive or negative impact on the economy for the specific turbine. Several PIs are used to be able to evaluate the potential profitability from different perspectives. Common PIs are described in Chapter 2.3.2 and will in this chapter only be mentioned in the context it is used in the model.

In the model, it has been chosen to use several PIs as they are commonly used in Vattenfall's previous business cases. *Earnings before Interest and Tax* (EBIT) is used to calculate the operating profit margin (Chapter 4.2.2), but is also presented as a PI in itself. The *Net Present Value* (NPV) of the investment is both used as a PI in itself and to describe the value of other cash flows in today's monetary value to facilitate comparisons. EBIT and NPV both give a measure of the magnitude of the earnings from the investment but do not in themselves say anything about the profitability if not compared to the initial investment. The *Internal Rate of Return* (IRR) is therefore used to give an indication of the profitability of the investment in relation to Vattenfall's required level of return. Furthermore, the *payback method* is used as a PI in the model as it calculates the time for an investment to repay. In this way it could be determined if the investment will be repaid before the end of lifetime of the turbine or before another major investment has to be done.

4.2 Model of Horns Rev 1

As already highlighted, the model for Horns Rev 1 is similar to the one for a single turbine. Overall, both models are based on similar calculations that lead to calculating the same PIs. Even the input of the model is somewhat similar but with the major difference being how future investments are entered. As seen in Figure 11, this model further calculates the critical mass of Horns Rev 1 and an operating profit diagram. The parts that have not yet been described will be presented in the following subchapters.

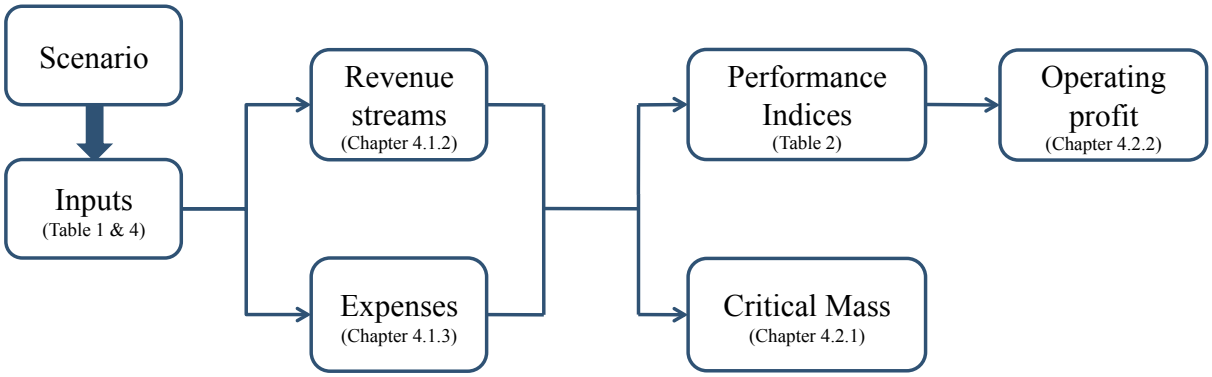

Figure 11. Conceptual description of the model for Horns Rev 1

The inputs that are used in the model, additional to the ones used for a single turbine (Table 1), are presented in Table 4. For Horns Rev 1, there is a prediction on which and how many components that will need to be invested in during the remaining years of the wind farm and how much these costs in average. These predictions form the basis for the investment plan that is used in the model. By using this plan, the model adopts a system perspective, which is desirable when looking at the whole wind farm while it is not relevant when looking at a single turbine. This is due to the fact that it is, as of today, only possible to estimate in large numbers what will happen to the wind farm, not what will happen to a specific turbine. The investment plan includes the following components: gearbox, generators, blades, main bearing, transformer, blade bearing and with the possibility to add other components as well. The minimum operating profit margin is used for calculating additional investment possibilities, as is further explained in Chapter 4.2.2.

Table 4. Additional input parameters for the model of Horns Rev 1

Input	Unit	Comment
Investment plan	Number of components per year	Predicted investments that will be made in the coming years
Average cost per investment	DKK/component	Predicted average costs per component connected to investment plan
Minimum operating profit margin	%	Required level of profit margin for the wind farm

4.2.1 Critical Mass

In order to make the user of the model aware of when it is time to close Horns Rev 1, the critical mass is calculated. The critical mass corresponds to the volume of where the revenues from produced and sold electricity pay for the fixed and variable costs that comes from operating the turbines (Holmström & Lindholm, 2011). The result from calculating this could for example be used when a number of turbines are to be turned off in advance and the profitability of the remaining of Horns Rev 1 is examined. In order to calculate the critical mass, the different cost drivers have been divided into fixed and variable costs, as was

presented in Table 3. For example, the transportation costs and different fees are fixed whereas the costs connected to the balancing power is variable (Attermo, 2015; Bode, 2015). The total costs are, in a diagram, put in respect to the total revenues. The critical mass is found where the costs and revenues meet (Andersson, 2010).

4.2.2 Operating Profit

The operating profit is another term for EBIT (Chapter 2.3.2), and refers to the earnings from business operation. This PI can be compared with Vattenfall's other wind farms to show how Horns Rev 1 is performing. Based on this PI, a required profit margin can be determined as a minimum limit if Horns Rev 1 still should perform in the top segment (Attermo, 2015; Bode, 2015). Such a profit margin can then be compared with the effect from the planned investments in order to see how much more that can be invested in the farm and still perform above what is required. This can thus be a useful tool for the Site Manager when preparing long-term investment and operating plans.

In the model, the operating profit was used in two different ways, the first was the required profit and the second was the operating profit when taking the investment plan into consideration. In order to calculate the required profit, a percentage operating margin based on how other wind farms of Vattenfall is performing today was used. This was further multiplied with the revenues from operating the wind farm. When taking the investment plan into consideration, the amount for the planned investments was subtracted from the operating profit. By doing this calculation, the Site Manager can get an understanding of how much that can be invested in Horns Rev 1 during the years to come.

4.3 Sensitivity

As already mentioned, the sensitivity of the models is significant and it is of great importance that the user is aware of this when using them. The models are of a simple kind that could be used as a reference when evaluating the profitability of Horns Rev 1, especially connected to the O&M and investments. However, these results should not form the basis for any decisions alone, but require additional calculations, human expertise as well as experience in order to be well founded. ALCM should therefore be used to highlight the need for several perspectives beside the results from the models.

It is also important for the user of the model to remember that it is developed in order to fit today's system. When the system or the prerequisites changes the models might have to be altered to better describe the new system. Therefore, the models are built in a way that makes it possible to change several of the inputs but also to some extent how the calculations are made.

4.4 Assumptions and Limitations of the Model

The model is built on several assumptions in order to be able to grasp parts of the system without making it too complex. Some of these assumptions are common when making business cases within Vattenfall and are thus generally accepted.

- The predicted spot price is given as an annual value, although it varies greatly during the year in reality. The same applies for the exchange rate.
- An annual value factor is used in order to decrease the spot price, as it is usually lower when the amount of wind power increases in the system.
- The costs are from the current budget and are assumed to increase with inflation in the future.
- It is assumed that the production is constant during all years of operation.
- Each turbine is assumed to produce 1/79 of the total production volume even though in reality the production is not equally distributed.[3]

There are a few ways in which these calculations can be done as the taxes, for example, are affected by the overall result from all of Vattenfall's businesses. As this was not possible to take into account in the study, the user has to be aware of the effect these economical flows has on the profitability of the investment.

The model is limited by the availability of data needed to perform the calculations. For example is statistics and probability not included in the model. This type of data that is collected by Vattenfall today is not processed to any greater extent and therefore not usable within the delimitations of this thesis project.

[3] There are currently 79 turbines in use at Horns Rev 1. In the model the number of turbines in use can be changed.

5 Results

In this chapter the results from the models will be presented. The results are divided into four parts as they give slightly different angles on the aim of the thesis, which is to contribute to more rational investment decisions being made at Horns Rev 1. In the discussion (Chapter 6), the results from the models will be connected to the findings from the interviews and literature review in order to answer each research question.

Due to confidentiality, the actual results from the models have been divided with a certain number between 1 and 10, only known by the researchers and concerned employees at Vattenfall, when presented in this chapter. In this way, the importance of the results magnitude and relations between these is kept for the reader to take part of while the confidentiality is assured. However, this does not affect the IRR and the payback time that are calculated but only PIs where monetary values are calculated such as NPV and the cash flow.

5.1 Investment Example

In the model for a single turbine, the different variables can be altered indefinitely and thus give an infinite number of different results. For the reader to understand the following discussion in the thesis, an example of how an investment affects the result will be presented. In this example an investment of corresponding size to a gearbox replacement is used as an input in 2015, where the effect of this is presented in Figure 12. This fictive investment was chosen because it is a common replacement to do during the lifetime of a wind turbine. The presented example will be referred to as the "*base case*" from now on.

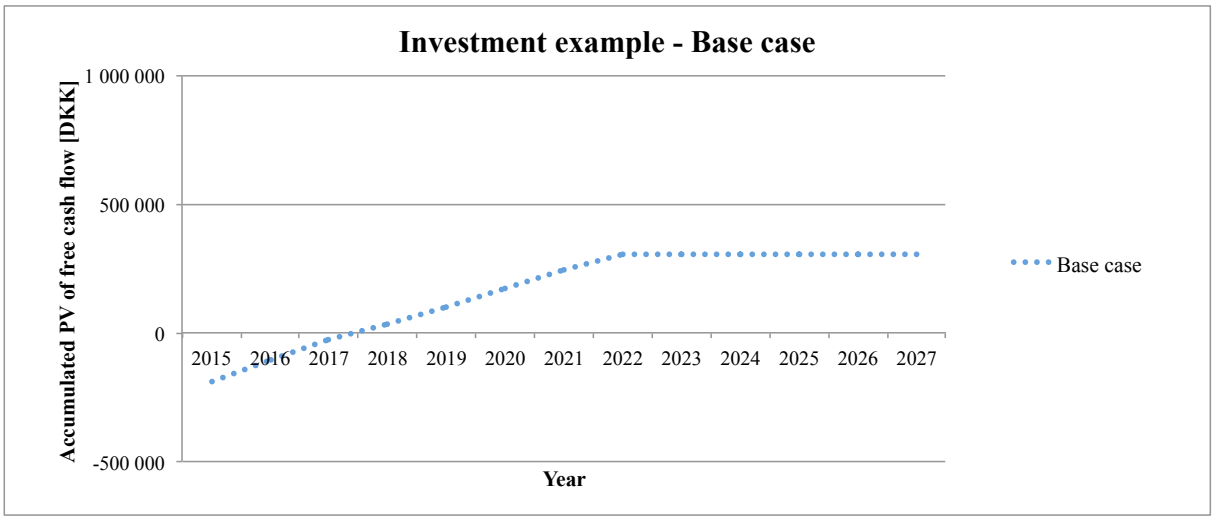

Figure 12. The effect on accumulated cash flow from one investment made in 2015 (base case)

As can be seen, the investment results in a negative cash flow the first year and is repaid in the end of 2017, where the line intersects the x-axis. The line is furthermore relatively linear between 2015 and 2022, having stable streams of revenues and expenses. As has been discussed before, Horns Rev 1 is expected to be taken out of service 2022, which is why the accumulated PV of the free cash flow comes to a standstill after this point. However, the agreement of the wind farm is that the geographical area can be used for five more years, until 2027. During this period financial flows, unknown today, might occur that affect the profitability of the farm which is why this entire period is visible in the graphs. An example of a cost that could be added here is the cost for the decommissioning of the farm.

If another investment, similar in size, where to be done in 2019 this would further affect the profitability connected to the specific turbine. How such an additional replacement would affect the profitability of the specific wind turbine is presented in Figure 13. Such a replacement is not as likely as the first one, but is supposed to give an indication of whether it still would be profitable to make the first replacement if a second investment, of the same monetary size, would have to be done a few years later.

In Figure 13, the difference between only doing the first investment and both investments are shown. This is to illustrate for the user of the model how the economy of the wind turbine is affected if a second investment is required.

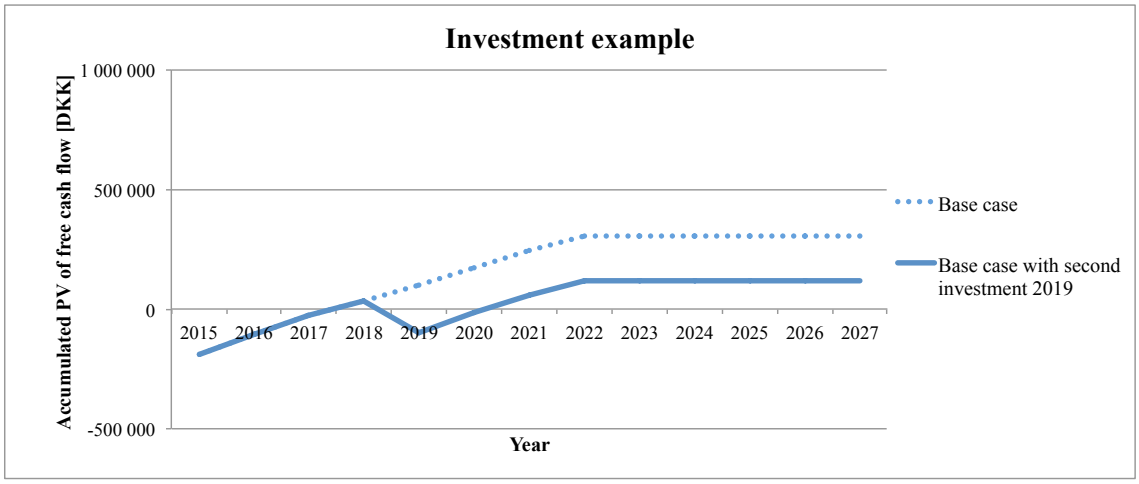

Figure 13. The accumulated cash flow, base case compared to two investments.

As can be seen in Figure 13, the profitability of the turbine is highly affected if a second investment has to be done. The first investment is repaid at the same time as it was in the previous example (Figure 12), in the end of 2017. When the second investment is done in 2019, the profitability turns negative and it takes until 2020 for it to turn positive again.

The calculations of the base case have been compared to the results from an existing business case at Vattenfall, showing similar results. However, when adding two investments in the existing model the result of the second one looks more profitable than it is ought to. This is because revenues, from previous operation, are used to pay back the second investment, not evaluating the profitability of the two investments separately. This makes it difficult to understand the profitability of the second investment in itself in Figure 13. However, when studying the effect of the two investments together, the results are similar and in the same range of magnitude.

In the model the user can, besides the graph, also see what IRR [%] and payback time [year] the two investments has separately as well as together, presented in Table 5. The IRR of the first investment is 14% and has a payback of 2.2 years. For the second investments, the IRR is 30% with a payback of 1.7 years. The IRR for the different investments is highly dependent on when the second investment is made. If it is forwarded one year, to 2020, the IRR of the first investment increase to 25% and the second is lowered to 18%. The payback is not exactly the same for the two different investments, the reason for this is due to the fact that present value is used, making equal economical flows appear smaller in the future than they currently are and therefore repaying quicker. The IRR for the two investments together, looking at a life cycle perspective, is 27%. The total payback time for the two investments is the summation of the two separate investments, 3.9 years.

Table 5. Comparison of PIs for one and two investments

Investment	IRR [%]	Pay-back [year]
Investment 2015 (base case)	14%	2.2
Investment 2019	30%	1.7
Investment 2015 & 2019	27%	3.9

It should be remembered, that the model do not consider depreciations of the initial investments or profit margins in these calculations. In other words, all revenues are in the models used to pay back the investments that are currently studied.

5.2 Scenario

The model have, as all models, several variables that makes the result sensitive to changes. Therefore, three variables have been chosen to illustrate the sensitivity of the model but also how the uncertainty of the system affects the results. The *production volume, spot price* and *total cost* has been chosen since these have historically shown to differ from the prediction and between the years. The scenarios are illustrated with the base case used in the previous section, and are presented as the present value of the accumulated free cash flow [DKK].

5.2.1 Production

The production volume that is used in the model is Vattenfall's budgeted production for 2015. The actual production each year varies greatly and has since Vattenfall acquired Horns Rev 1 in 2006 fluctuated between 560 GWh and 680 GWh. To include these values and show how the fluctuations affect the base case, the budgeted production is changed 10% up and down in the scenario. Table 6 shows how the change of production volume affect the output of accumulated free cash flow (in relation to the base case). As can be seen, a 10% increase/decrease of the production, as an input, has a much higher percentage affect on the output.

Table 6. Change of input compared to output for production scenario in the model

Change of Input	Change of Output
+10%	+57%
+5%	+28%
+2%	+11%
0%	0%
-2%	-11%
-5%	-28%
-10%	-57%

When taking part of these results, one have to be aware of the fact that in this scenario, it is only the production [MWh/year] that has been changed and not the costs associated with this. Changes in production volume would logically lead to increased/decreased costs (for example due to balancing power costs). However, this has not been considered in the scenario, as it would make the scenario to complex and subject to further sensitivity. Instead the user will have to keep this in mind and use the scenarios as an indication on how the result is affected based only on the changes in the initial prediction for the production.

The result of the scenario is further shown in Figure 14 as a graph to illustrate how the accumulated free cash flow adds up over the years, from the investment in 2015 until end of life in 2022.

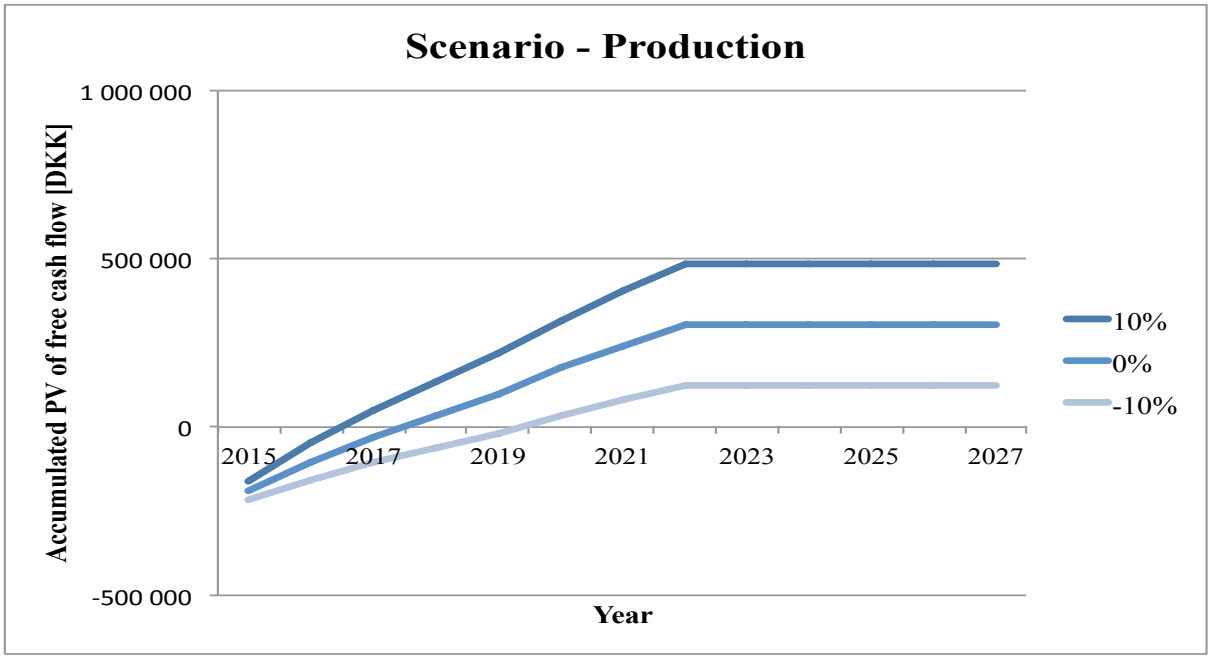

Figure 14. Production scenario's effect on base case

In the figure, the intersection between the different scenarios and the x-axis symbolise at what point the investment is repaid. With a 10% increase in production, this occur at the end of 2016 while a 10% decrease postpone such an intersection until late 2019. Figure 14 also clarifies how the changes of the production affect the output presented in Table 6.

5.2.2 Spot Price

The spot price constitute the primary base for the revenues for Horns Rev 1 and is therefore of interest to present as a scenario. The spot price is difficult to predict as it fluctuates to a great extent in reality. In the model, a predicted mean value for the years, developed by Vattenfall is used. As previously mentioned, the predicted spot prices are given in EUR/MWh and an exchange rate has to be used to get the price in DKK/MWh. The price is then altered with a value factor as the price usually decreases when a large share of the produced electricity comes from wind power. Consequently, there are several uncertain factors in the model that affects the revenues and makes it an interesting subject for a scenario analysis. How the spot price affect the result as a change of output is presented in Table 7.

Table 7. Change of input compared to output for spot price scenario in the model

Change of Input	Change of Output
+30%	+66%
+20%	+55%
+10%	+26%
0%	0%
-10%	-30%
-20%	-64%
-30%	-104%

The value in Table 7 shows that a percentage change of the predicted spot price has a large impact of the output, even greater than the production scenario. However, as can be seen in Figure 15, a spot price at a 30% lower level than the prediction would mean that the investment would take more than 7 years to repay, and no investments and O&M would be profitable to carry through. Although, this case is unlikely since most operators on the electricity market, would have trouble with profitability if spot prices got this low. This is further discussed in Chapter 6.

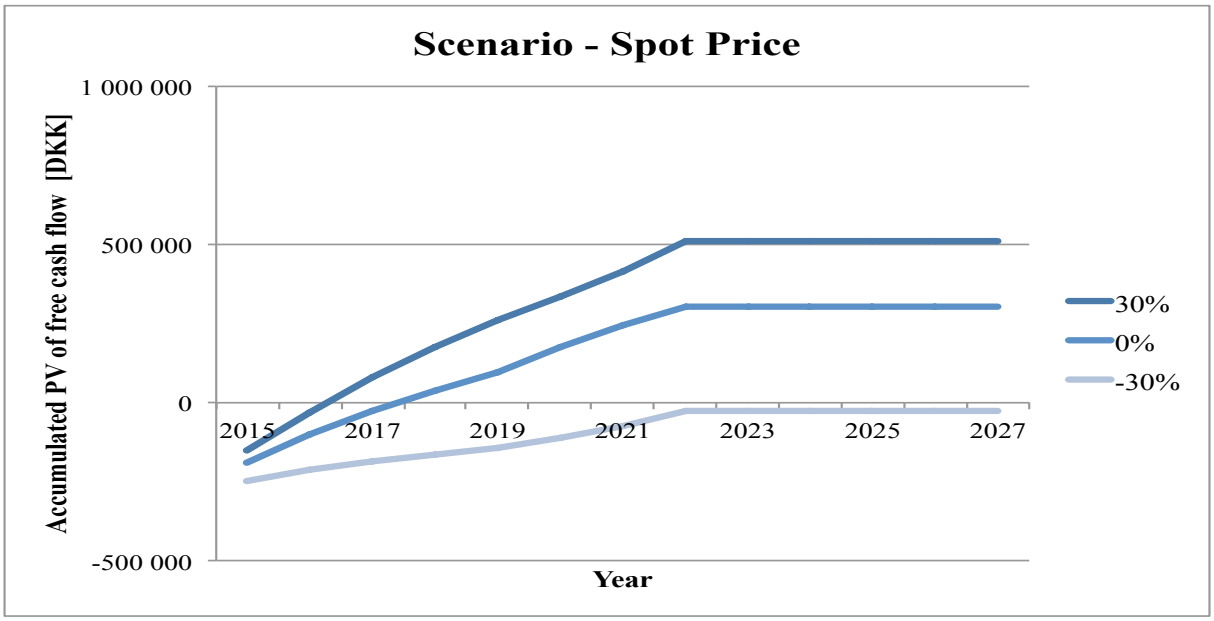

Figure 15. Spot price scenario's effect on base case

The three different scenarios that are put forward in Figure 15 show different years of intersecting with the x-axis. An 30% increase leads to repaying the investment during 2016 while a 30% decrease, as has already been discussed, means that the investment is not repaid before the farm is taken out of operation and is therefore not profitable to do based on these calculations.

In Figure 15, one can further see that an increase of 30% does not have the same effect as a corresponding decrease. This is because Horns Rev 1 receives a Feed in Tariff of 100 DKK/MWh and up to a fixed level of 350 DKK/MWh. Consequently there is no difference in the revenue streams if the spot price is between 250 DKK/MWh and 350 DKK/MWh. It is not until the spot price is higher than the fixed level that Vattenfall's revenues from Horns Rev 1 would increase (as the production level is the same in these scenarios). This dissimilarity can also be seen in Table 7, where an increase of +30% and a decrease of -20% lead to corresponding changes in output.

5.2.3 Total Cost

The total cost is the summation of all the cost items specified by Vattenfall's budget for Horns Rev 1. In this scenario, it is the summation of the costs that is changed with a specific percentage to determine how this would affect the outcome. It is actually each cost item that varies between the years and constituting different shares of the total cost. However, changing each cost item would not bring any additional value or understanding of the sensitivity to the user and it has therefore been chosen to change the total cost as a whole.

The percentage change is based on the maximum and minimum realised values that have been identified based on the budgets and follow-ups from 2009 to 2014. As the realised budget usually is below the predicted, the lower limit is set to -30% and the upper to +10%. How these percentage changes affect the outcome of the model is presented in Table 8.

Table 8. Change of input compared to output for total cost scenario in the model

Change of Input	Change of Output
+10%	-39%
+5%	-20%
0%	0%
-5%	+20%
-10%	+39%
-20%	+78%
-30%	+118%

Here, one can tell that a change of the total costs results in an inverted change of output that is larger (in percentage) than the initial change. Three of these scenarios are further shown in Figure 16 to illustrate the changes over time through accumulated PV of free cash flow.

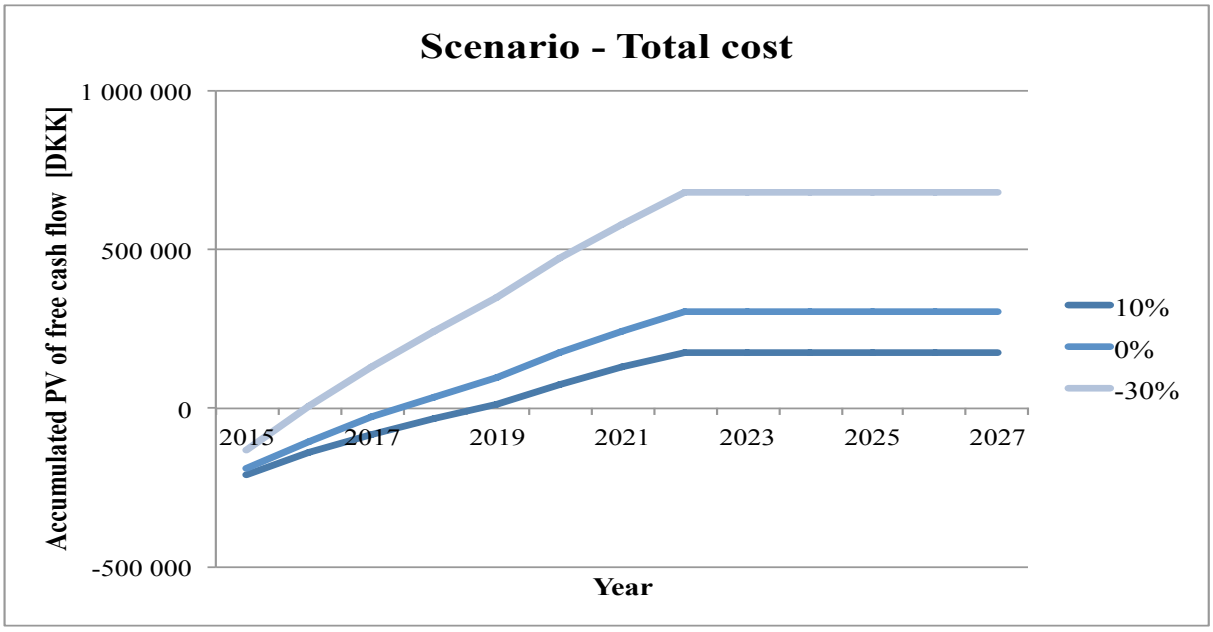

Figure 16. Total cost scenario's effect on base case

The point at which the investment appears to be profitable according to the model is ranging from early 2016 until late 2018, depending on how large percentage change that is used. The result from the scenario with a 30% decrease of the total costs is not to be likened with the 10% increase since these are not corresponding. These are the extreme values based on historical data that are used to make the user aware of how such changes affect the outcome.

5.3 Critical Mass

As part of the study, a critical mass for Horns Rev 1 has been calculated. In this context, critical mass refers to the number of turbines that has to be in operation to balance costs and revenues. The intersections between the lines in Figure 17 indicate the critical mass for Horns Rev 1. The light blue line represents the costs, including depreciations from the initial investment when Horns Rev 1 was acquired. The dark blue line represents the total revenues for the wind farm based on the number of turbines in use.

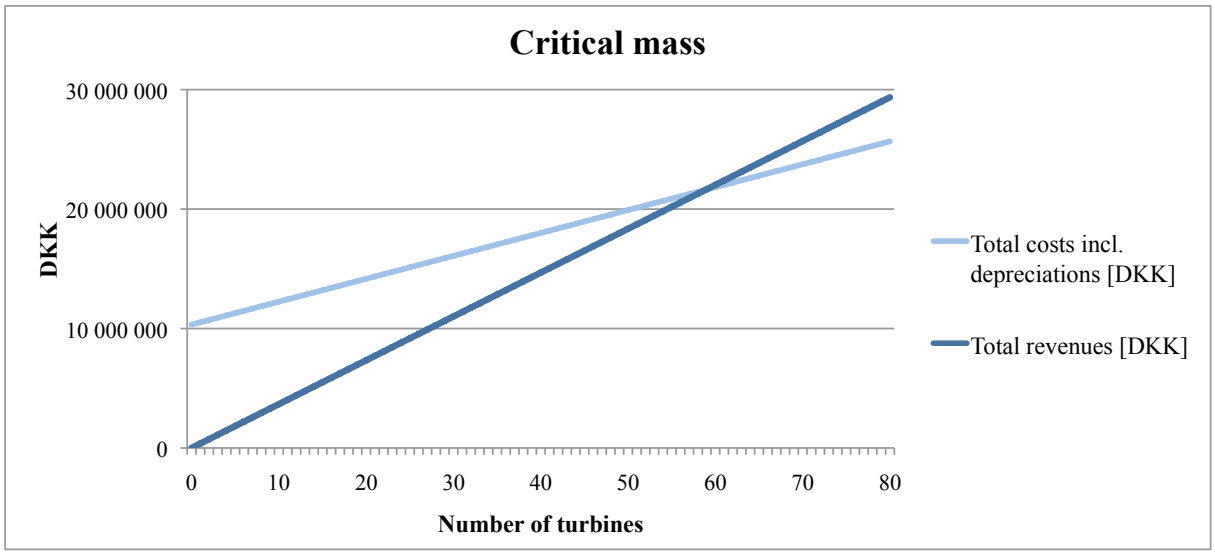

Figure 17. Number of turbines needed to balance O&M costs and revenues (critical mass)

Figure 17 shows the critical mass for Horns Rev 1 for 2015, with an intersection of the lines at 58 turbines. In the model it can be chosen to exclude the depreciations, resulting in a lower critical mass than presented here. The conclusions that can be drawn from the different results are discussed in Chapter 6.3. The critical mass also depends highly on which costs that are perceived as fixed respectively variable. If additional costs where perceived to be fixed, the light blue line would have started further up in the diagram but also have a lower gradient. This would have moved the intersection somewhat to the right in the diagram, making the critical mass appear higher. The result presented in this context is based on the definition made by the Site Manager of Horns Rev 1.

A limitation in presenting the critical mass in terms of number of turbines is that the contribution to the total production from the each turbine is actually not exactly the same, due to for example differences in placement and condition. The critical mass is therefore also presented in required production volume, which can be seen in Table 9.

Table 9. Critical mass expressed in number of turbines and production volume

	No. turbines	Production volume (MWh)
Critical mass	58	435 000

When studying the critical mass the effects of the previously used scenarios are of interest. In Table 10 the critical mass calculated with the same maximum and minimum boundaries used when presenting the different scenarios for a single turbine. This is for the reader to get an indication of the sensitivity of this result, and how the different scenarios affect the critical mass for Horns Rev 1.

Table 10. The scenarios effect on critical mass

Scenario	Best case	Worst case
Production		
Change of input	+10%	-10%
No. turbines	48	74
Production volume (MWh)	396 000	500 000
Spot price		
Change of input	+30%	-30%
No. turbines	45	>80
Production volume (MWh)	338 000	>600 000
Total costs		
Change of input	-30%	+10%
No. turbines	39	68
Production volume (MWh)	293 000	510 000

As can be seen in Table 10, the critical mass varies between 39 to 80 turbines depending on which scenario that is studied. The scenario where the total cost is lowered by 30% has the most positive effect on the critical mass, lowering the required number of turbines from 58 to 39. The change of input that has the most negative consequence on the result however, is a decrease of the spot price, leading to the fact that there is no intersection between total revenues and expenditures, which is why more than 80 turbines are required.

In the model, it is possible to change the year of which the critical mass is calculated. However, this change does not affect the result based on the numbers used in the current situation, which is why this is not presented or discussed further.

5.4 Operating Profit

As the final part of the models developed in the study, the future operating profit per year was calculated. This was done in two different steps, the first was the required profit, where a profit margin was used, and the second was the operating profit, when taking the investment plan into consideration. The results presented here have further been divided with the same number, between 1 and 10, as before due to confidentiality.

In Figure 18 this required profit given in DKK/year is displayed as the light blue bar and the dark blue bar represent the calculated operating profit based on the realised budget for Horns Rev 1 for 2014. When calculating the operating margin for Horns Rev 1, the total revenues are divided with EBIT every year. By doing this, a percentage on how large part of the revenues that is considered as profit is calculated. If this percentage is greater than the minimum required operating margin the profitability of the wind farm is greater than what is expected of it.

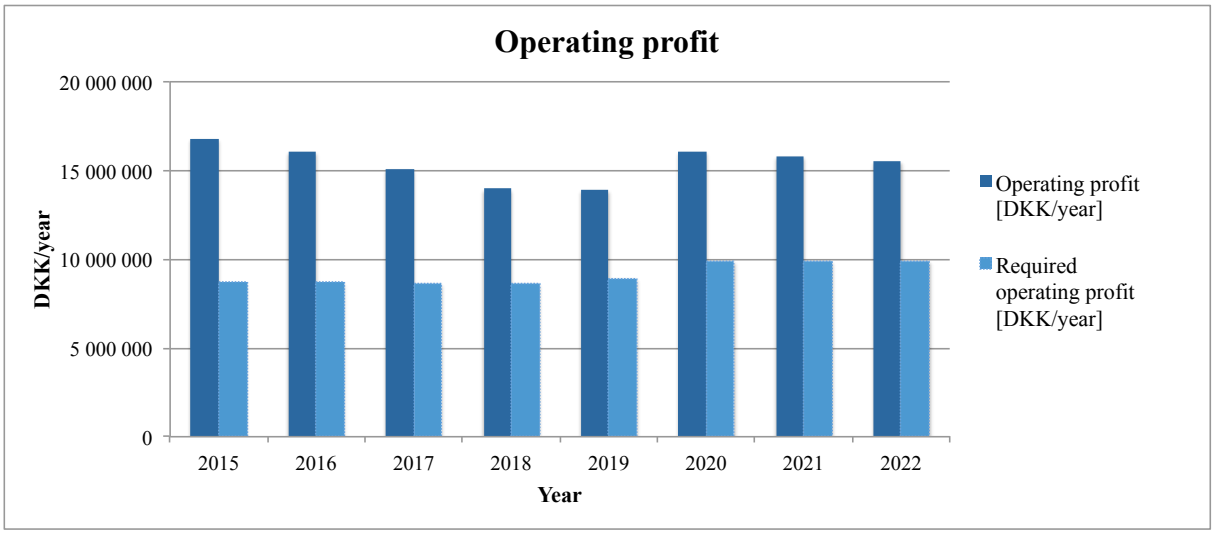

Figure 18. Operating profit compared to required level of operating profit per year of remaining lifetime of Horns Rev 1

As can be seen in Figure 18, the operating profit is greater than what is required for all years. The difference between the two bars appears to decrease in the four following years and thereafter increase again. This is due to the fact that the investment plan, which has been put up by the Site Manager for Horns Rev 1, implies depreciations and thereby changing and affecting the additional operating profit. In Figure 19, the difference between the two bars in Figure 18 after the amount in the investment plan has been included is presented.

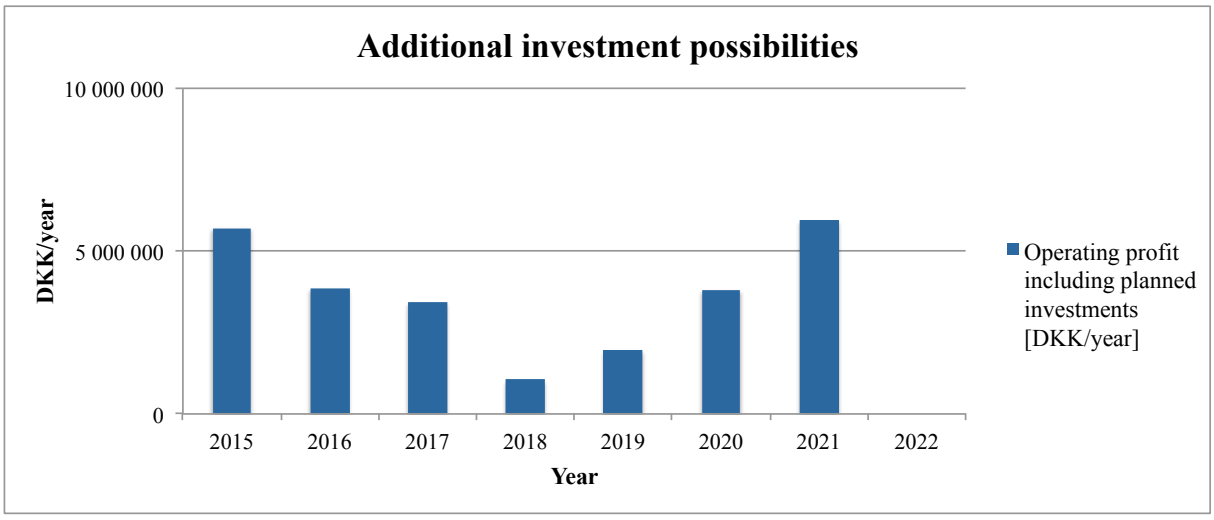

Figure 19. Additional investments possibilities compared to required profit margin per year of remaining lifetime of Horns Rev 1

In Figure 19 it can be seen that during the final years of Horns Rev 1, the planned investments are within the limits of the operating profit. The graph further indicates that an even greater amount of money could be spent on the farm if necessary; still performing better than what is required from it. The last year (2022) has been excluded even though the model suggests that an amount similar to the year of 2021 can be spent. The reason is that although the revenue from the last year can be spent on investments, it is in reality not likely that any large amounts will be invested in the wind farm the last year. It can also be questioned if it is rational to spend any large amounts in 2021.

6 Discussion

The structure of this chapter is based on the four research questions that have been stated for the thesis project. Each question will be addressed in its own chapter with the purpose to discuss the findings independently of each other. Thereafter, the main research question will be addressed to clarify how the sub questions together have answered it. The discussion is based on the findings from reviewing the literature as well as results from interviews and the two models.

As mentioned, the structure of the discussion will be based on the research questions (RQs) that have been put forward for the study. In order to refresh the reader's memory about which research questions that the study are to answer, these are given below.

RQ1. *On what basis is investment decisions made today for Horns Rev 1?*

RQ2. *How can an ALCM perspective contribute to the operation and maintenance of Horns Rev 1?*

RQ3. *How can budget planning, from an ALCM perspective, increase decision rationality?*

RQ4. *How does the uncertainty of different input variables affect the profitability of Horns Rev 1?*

These four questions are further used in order to answer the main research question of the study:

How can an extended business case be applied to meet the need for rational investment decisions in the final stage of Horns Rev 1 through an ALCM perspective?

6.1 Decisions Today

Through the meetings, interviews and mail correspondence with employees at Vattenfall during the study, a general way of how decisions are made today has been discovered. Decisions for Horns Rev 1 today regarding O&M are often based on the knowledge of one or a few individuals and their gut feeling about a specific situation. Due to this, the individuals understanding the view of the system, in which the assets are a part of, affect the decisions to a great extent. The technicians know the asset the best and are therefore responsible for the daily planning of maintenance work.

It is only for a number of major investments, for example exchange of a whole/large parts of turbines, where business cases are currently used. These are most often difficult to understand for people who are not familiar with business cases and the financial calculations behind it. Furthermore, the business cases that are currently used in these situations are usually developed to study one single investment. When two or more investments are entered at the same time, the earnings from previous operation are used to repay future investments. When studying results for the separate investments the later investment appears to be more profitable than it actually is. This causes an incorrect view of the profitability of future investments and how these affect the economy of the turbines life cycle.

During the years that have passed so far, the individual knowledge and gut feeling have provided a sufficient basis in order to make decisions. However, as was found when

reviewing the literature, it is important to use different perspectives to be able to make rational decisions. This is especially the case as Horns Rev 1 is approaching end of lifetime and the viability of even small investments can be questioned. Nevertheless, the financial side has to be complemented by other perspectives, which can come from individual knowledge, previous experience and quantification of impacts that do not have monetary value (for example external costs).

In summary, the way decisions are made today, based mainly on knowledge and previous experience, are good. However, the additional perspective of economical calculations further develops the decision founding. By extending the view even further to include all ALCM perspectives, an improved understanding of the system can be reached.

6.2 Contributions from ALCM

In this context, ALCM refers to the evaluation of the asset based on the *technical*, *economical*, *commercial*, *compliance* and *organisational* perspectives. Being aware of and using all five perspectives leads to a more complete picture of the system that the asset is a part of.

The turbines of Horns Rev 1 perform well in comparison to similar turbines, which can be seen by the high capacity factor as well as operating profit. The Site Manager and technicians of Horns Rev 1 has a good overview of the wind farm today and its current technical status. The disadvantage with this is that a lot of the information and knowledge is kept individually and not documented to any great extent. If something major were to happen, the knowledge of the technical status could get lost. If a Condition Monitoring System (CMS) was installed and used for relevant components this could further increase the understanding of the asset, the system and enable knowledge sharing to a greater extent than is possible today.

The economical perspective has always been an important part of Horns Rev 1. A budget for every year is used; stating expected future costs and revenues for the specific site. The costs and revenues connected to operating Horns Rev 1 have been observed as varying from year to year. The costs are dependent on several factors, for example accessibility, number of failures and material costs. The revenues are highly dependent on weather conditions and spot price, two variables that vary greatly from year to year. Consequently, it is hard to predict the total costs and revenues years ahead, but relevant approximations can however increase the understanding of what actions to take. The awareness of how different changes in the system affect the outcome has been low so far. By further developing this understanding, resources can be spent on things that lead to costs savings as well as increased revenues.

As for the commercial perspective, the asset has to be able to fulfil the demand from the market. In the literature, it was found that the amount of produced electricity from wind has increased drastically the last couple of years worldwide and is expected to carry on doing so. Wind power is thus expected to fulfil the commercial demands of renewable power production in the future. Security of supply is however still an issue that needs to be further investigated.

Connected to Horns Rev 1, there are several different rules and regulations that have to be complied. By being aware of these, necessary actions, such as yearly inspections, can be made and put in respect to the other perspectives. By being aware of what has to be complied, unexpected expenditures and actions can be minimised.

Vattenfall has been the operator of Horns Rev 1 since 2006, and therefore it can be expected that necessary knowledge, expertise and employees are available within the organisation. However, the farm is one of the first offshore wind farms and slowly approaching its end of lifetime which requires new expertise. By being aware of what is required to keep this perspective when operating and maintaining the wind farm, many difficult situations can be avoided.

By thinking in the five perspectives of ALCM, different views of the system can be taken into account when making decisions. The turbines can then be operated and maintained in a more ideal way to increase profitability. Additional economical calculations that show the current state as well as future possible developments, lead to an increased understanding of the system and which decisions to take based on this.

6.3 Decision Rationality

Today, there is a difference between how the theory argues that decisions should be made and how decisions are made for Horns Rev 1. This is since, as has already been discussed, many decisions today are based on individuals' knowledge but often lack the basis from, for instance, economical calculations. The theory highlights the importance of taking different perspectives, such as economy, risks, uncertainties and the current stage of the asset, into account when making decisions. It is important to establish investment decisions on predictions for the future and not only on what has been working in the past. The reason is that the aim should be to make the future as profitable as possible, independently of previous outcomes. However, this view is sometimes contradictory since knowledge from previous years of operation can prevent mistakes from being repeated.

Through the development of the models as a part of this study, the economical perspective for Horns Rev 1 has become more visible and comprehensible. The model in combination with a system perspective increase the understanding of what effect different decisions has on the profitability of the farm. Changed conditions and prerequisites can also be studied through the models. By being aware of this, decisions on where in the system to invest additional resources (material, research, RCM etc) can be taken in a more rational way. An example of such rational decisions can be to invest money in areas where an increase of profitability (e.g. increased availability) or a decrease of unprofitability (e.g. lower the costs) is likely. Without the models, variables influencing the economy of Horns Rev 1 might be neglected and perceived as unimportant since the affect of the variable is not understood.

The system of which this study is to depicture has two different levels, one for a single turbine and one as the whole wind farm. The budget is set for Horns Rev 1 as a whole while the actual costs and revenues are dependent on and vary slightly for each turbine. This is why two different models have been developed. The results from the model for a single turbine are to be used when examining whether or not a turbine is profitable at the moment and how the future could look like based on the assumptions that have been made. It is also supposed to increase the awareness of how possible required investments in the future affect what should and should not be done today. The results from the model for the whole Horns Rev 1 however should be used to understand the future profitability of the whole park as well as the sensitivity connected to this. By using both models in parallel, the understanding for the specific details as well as interconnections in the whole system will be increased.

Every year, a plan for major investments for the following years is set. In the model for Horns Rev 1 the plan is used as an input to calculate how much more money that can be invested and still perform above the required operating profit margin. This tool could be used in the budget planning in order for the Site Manger to see, in a visual way, how much that can be invested in the coming years. This, of course, has to be combined with knowledge about what is possible from a time, personnel and availability perspective.

The operating profit could be combined with the results from the calculations of the critical mass of Horns Rev 1. This part of the model shows how many turbines (or production volume) that are required in order for the wind farm to remain profitable and how it changes based on the different scenarios. The critical mass is highly dependent on how the cost items are specified in the model. They are either set as fixed or linearly variable based on the number of turbines in use, but it could be argued that specific cost items should be semi-fixed. Actually, the cost items probably follow a great variety of patters depending on how many turbines that are operating in reality. These patterns have not been studied and are therefore not predicted as these would not lead to better accuracy of the model. Instead the scenarios for spot price, total costs and production volume can be applied to the critical mass calculations to see how the result is affected by changed operating conditions.

The critical mass is dependent on whether the depreciation from the initial investment when Vattenfall acquired Horns Rev 1 is taken into account. If the depreciations are not taken into account, the critical mass will appear lower. It could be argued that it is more accurate to present the critical mass *without* depreciations, as investment decisions should be based on how the future could be as profitable as possible and therefore not take past investments into account. At the same time a lower critical mass might give the impression that a larger number of turbines could be closed down before 2022 without making the wind farm unviable. Therefore it is possible to choose to show the critical mass with or without depreciations in the model.

By being aware of the critical mass of Horns Rev 1 in advance, a trade-off can be done on which turbines to maintain and keep in operation, and which to turn off. It can also be estimated how much more that needs to be invested in the farm to keep the required number of turbines in use.

The models only show trends on how the economy can develop in the future, which is why a deeper analysis, taking all five perspectives into account, has to been done before major and vital decisions are made. Foremost, the knowledge that is kept within the organisation is of great value when evaluating the result of the models, taking things that cannot be put into a monetary value into account. The models are not able to do such considerations and are particularly only a simplification of the real, complex system. Due to this, the results from the model miss out on relevant parts where human knowledge has to be added in order to make rational decisions.

6.4 Scenarios' Effect on Profitability

Through the scenario analysis, the user's awareness of both the sensitivity of the model and the uncertainty of the real variables increase. In order to make the scenarios realistic, the change of input was based on historical values. The lowest spot price since Vattenfall acquired Horns Rev 1 was for example 30.67 EUR/MWh (2014) and the highest 56.43 EUR/MWh (2008) for price area DK1 (Nord Pool Spot, 2015). The interval between these two extreme values is covered in the scenario. The same procedure was applied for the production volume and the total cost scenario as well. This was done in order to make the user of the model aware of how large the changes of a specific variable historically has been and how this affects the profitability of the wind farm. However, by looking at the historical values, it is not guarantied that the actual outcome in the future is covered within the interval. There is always a possibility that the variables change, for the good or the bad, in an even greater extent than could be foreseen when making a decision. An investment can therefore appear to be profitable when making calculations but turn out to be unprofitable when implemented.

Two of the three variables that were used for the scenarios, the production and the total cost, are variables that to some extent can be affected by the decisions made for Horns Rev 1. For example does higher availability lead to increased production, which has a positive effect on the profitability and by doing a larger share of the maintenance preventively the total cost could be lowered. This does not mean that the availability should be maximised or the costs minimised, but there is always a trade-off to aim for. There is though not a specific static point to work toward since it always changes with the surroundings of the farm. Changes in the global economy, for example recessions and booms, leads to changes in costs and revenues and thereby the optimal point which should be strived for.

However, the third variable (the spot price) cannot be affected by decisions made by Vattenfall to any great extent. It is therefore only possible to try to understand how changes in the spot price affect the outcome and include this knowledge when making decisions. For example, an increase of the spot price from 250 DKK/MWh to 350 DKK/MWh does not have any effect on the revenues due to the guaranteed Feed in Tariff. A corresponding decrease would however have a significant effect on the revenues. The base case investment is for example never repaid if the spot price is lowered with 30%. This example is an unlikely scenario since this reduction would make even cheaper energy sources unprofitable, leading to a decrease of available electricity and in this way lead to increases in price. However, it is still important to discuss what these kinds of scenarios might lead to and how they should be avoided or handled.

The different scenarios can be combined in the models in order to understand what effect this would have on the results. By being aware of how the different variables impact the outcome the knowledge and understanding of the economy of Horns Rev 1 can be increased. Using such knowledge and working actively on applying it can affect the profitability of the farm for the better. This can further be used for dissemination of knowledge to other wind farms owned by Vattenfall.

6.5 Final Discussion

The model that has been developed within this study, is ought to be used as a first step of the decision support for Horns Rev 1. It is to be used as a part of the five perspectives; *technical*, *economical*, *commercial*, *compliance* and *organisation*. By using these perspectives the decision rationality can be increased through the combination of experts' knowledge and financial calculations. This is since the model, in combination with a system perspective, improve the understanding of what effect different decisions has on the profitability of the farm but also how different changes in the surroundings influence it. However, people using the model have to be aware of the sensitivity of it and how dependent the results are of the different input variables.

The intention of this study has been to increase the understanding of how decisions are made today, which perspectives that should be considered and how the economy of wind power is affected by different variables. This is especially since Horns Rev 1 is approaching its end of lifetime and the economical justifiable is about to be challenged.

7 Closure

The findings from each research questions will here be summarised and conclusions based on this will be drawn. In the final paragraph, the main research question will further be addressed and answered based on the findings from the underlying research questions. Recommendations on future work will also be presented.

7.1 Conclusions

Investment decisions are based on knowledge and earlier experience of the employees at Horns Rev 1, Vattenfall. Financial evaluations have mostly been made for larger investments, while the daily work has not been evaluated in this way. The technicians, analysts and Site Manger have extensive knowledge regarding the turbines, which is why this way of working has been successful so far.

However, based on ALCM, a broader perspective is needed when evaluating upcoming investments as Horns Rev 1 is approaching the end of lifetime phase and the profitability of these investments are not as evident. ALCM contributes to the O&M of Horns Rev 1 by highlighting the need to evaluate investments from a technical, economical, commercial, compliance and organisational perspective. With a life cycle perspective, unviable investments can be avoided and profitability increased over the entire lifetime of the turbines.

Through the study, it has been apparent that the usage of business cases will need to increase in the coming year for Horns Rev 1 in order to avoid unprofitable investments. As a part of the economical perspective of ALCM, two business case models have been developed. The purposes of these models are to assist the budget planning of Horns Rev 1 and provide support for investment decision-making. Therefore, one model is based on the economics of a single turbine and the other of the whole wind farm. The profitability of one or several investments can be calculated for a single turbine, while budget planning is assisted through calculations of the critical mass of Horns Rev 1 and the expected operating profit based on planned investments. With this knowledge, more rational decisions can be taken.

All business cases are built on predictions of future developments in a large set of variables. Scenarios have therefore been developed in order for the user of the models to understand how a change in the system could affect the investment. Changes in the spot price is not possible to influence, but it is nevertheless important to understand how much longer it will take for an investment to repay if the spot price decrease. If the production at the same time would decrease due to lower availability or unusually low wind speeds, the investment might not even have time to repay. This risk then has to be weighted against the possible benefits.

Through the process of reviewing each research question, one at a time, the main research question can be answered. An extended business case model could be used in order to assist the investment decision process. The models, in combination with a system perspective, increase the understanding of what effect different decisions has on the profitability for Horns Rev 1 as it is approaching its end of lifetime. The use of ALCM as a system perspective further highlights the need to evaluate the circumstances from several viewpoints in order to make rational investment decisions.

7.2 Future Work

One limitation of the conducted case study is that the results are specific for Horns Rev 1. Repeating the research questions for wind farms in other settings would lead to a possibility to generalise the findings and gain understanding from an even wider system perspective. Due to the limited amount of time for this study, the economy was chosen as a main perspective. It is therefore proposed that future studies could evaluate the four other perspectives that are a part of ALCM and what affect these have on wind farms. The last suggestion of future works is to adjust the model, adding data regarding statistics and probability of the asset at Horns Rev 1 when such becomes available.

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