What goes up must come down

- Modelling economic consequences of wind turbine decommissioning

Olga Pérez & Emma Rickardsson

ISSN: 1651-0100
Examensarbete nr 165/2008
ISSN 1651-0100
ISRN LUTVDG/TVTM2008/5165--/SE

Abstract

Title:	What goes up must come down - Modelling economic consequences of wind turbine decommissioning
Authors:	Olga Pérez and Emma Rickardsson
Tutors:	Lennart Thörnqvist – Department of Energy Sciences, Lund University. Stefan Yard – Department of Business Administration, Lund University. Fredrik Ardefors – Consortis Producentansvar AB.
Problem:	The wind power industry is currently expanding in Sweden. As turbines are erected there is a clear awareness that they will have to be decommissioned due to their limited economic and technical lifetimes. There is, however, an evident lack of experience and knowledge about the economic consequences of such decommissioning.
Purpose:	The purpose of this study is to develop a model that estimates the economic consequences of the decommissioning of wind turbines currently being built in Sweden.
Method:	Information presented in this study has to a large extent been gathered from primary sources. The decommissioning scope was defined by interviewing governmental authorities in Sweden. Information about the decommissioning process and characteristics of wind turbines was gathered through interviews with experts and by reviewing available data. The data collected was analysed to find cost objects and cost drivers and how these were affected by turbine characteristics. Thereafter, a model was developed and tested. Sensitivity analyses were performed to assess the validity and robustness of the model. Once the model was established to be robust, analyses were conducted to identify how predicted costs may be affected by future developments.
Conclusions:	At the time being, there is limited experience within turbine decommissioning in Sweden, and the economic effects are unknown. Despite this, there are expectations that revenues generated by sales of materials will cover decommissioning costs. The model developed identifies thirteen parameters that vary between different types of turbines and that affect the economic consequences of decommissioning. The three most important parameters are turbine location, tower material, and the scope of decommissioning. Trends in the wind energy industry show that these three factors are developing in a manner that increases decommissioning costs dramatically. The model also shows that the economic consequences of decommissioning are very sensitive to price changes. One of the most important factors affecting the economic outcome of decommissioning is the price of metals found in the turbine. Since decommissioning will take place in twenty years, it is certain that prices will have changed. Therefore it is risky to assume that decommissioning costs will be covered by the future scrap value of the turbine.

Key words: Decommissioning, wind turbine, economic consequences, model, cost, revenue, forecast

Foreword

Our master's thesis has been performed as part of a larger study conducted by Consortis Producentansvar AB and Svensk Vindenergi.

We would like to extend a great thank you to everyone that has collaborated in this study by participating in interviews, answering questions, or reviewing information. We would especially like to thank Arne Rahbeck from Vattenfall with whom we had the pleasure to drive around Denmark visiting wind turbines. A warm thank you is also extended to Lars Nedergaard from A2SEA for his patience with our questions and his many helpful tips.

Our gratitude to our supervisors cannot be understated. Fredrik Ardefors, from Consortis Producentansvar, has been invaluable to this study. Without his involvement, support, and readiness to provide input we are uncertain this study would have been possible to complete. We would also like to extend a thank you to our tutors at Lund University; Lennart Thörnqvist and Stefan Yard. Although this study may initially have struck them as somewhat unusual they seemed interested to see what findings it would lead to. Throughout its progress their support has been greatly appreciated. Without any doubt their comments and advice have greatly lifted the quality of this report.

Olga Pérez & Emma Rickardsson

Lund, 07 May 2008

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1. Introduction

In this chapter the reader is introduced to the problem examined in this master's thesis. First a brief the background to the matter of this study is presented. Thereafter a problem discussion is held which culminates in a problem statement. The relevance and scope of the problem is then discussed and an overview of the disposition for this paper is presented.

1.1. Background

The global interest for wind energy has increased dramatically during the past years. Discussions about climate change and the impact of chosen energy sources on carbon dioxide emissions have gained attention from politicians and the general public. As the awareness of the disadvantages with conventional energy sources increases opportunities for renewable energy sources are created. Governmental commitment is expressed as targets and programmes are approved and implemented. For example the European Union introduced a legally binding target for 20% of the regions energy to come from renewable sources by 2020. As a consequence of these developments the global market for wind power grew with 30% in 2007. During the same year wind power accounted for 40% of all new power generation instalments made in the European Union. (EWEA Annual Report 2007)

At the end of 2007, there were approximately 900 operating wind power turbines in Sweden with a total of 778 MW rated power. During the same year, the energy production from these turbines was 1.43 TWh. This corresponds to approximately 1% of the yearly national electricity production (Official Statistics of Sweden, 2008-03-25). Comparing these figures with Denmark and Germany, considered pioneering countries within the adoption of wind power and whose example in recent years has been followed by Spain, can be helpful to gain perspective. In 2007 Denmark had 5,267 operating turbines with a total power of 3,125 MW. These turbines produced 7.16 TWh of electricity, corresponding to approximately 20 % of the nation's yearly electricity demand (Danish Wind Industry Association, 2008-03-25). In Germany the 22,247 MW of installed wind power generated 39.5 TWh of wind electricity, corresponding to 7.2% of the nation's electricity demand. Spain relies on 15,145 MW of wind power to supply 10% of the country's electricity demand. In 2007 alone 3,522 MW of wind power were installed in Spain. (EWEA Annual Report 2007, pp. 8-10)

Preliminary results from an ongoing study of wind prospective in Sweden showed that there is potential to generate 500 TWh of electricity from land-based wind turbines (Swedish Energy Agency 2007, p. 10). This clarifies the obvious; there is wind power potential currently unexploited in Sweden. As many other renewable energy sources, wind energy has received increased attention as an alternative to conventional energy sources. In 2007 the Swedish Energy Agency adjusted its national planning target for the expansion of wind power. The new target was set at a production of 30 TWh of electricity by 2020. This figure can be compared with the previous target instituted in 2002 of 10 TWh by 2015. Although the national planning target states the capacity for which governmental entities must plan, and not the actual planned establishments, it provides a clear indicator that wind power is becoming an increasingly interesting energy source in Sweden.

1.2. Problem discussion

To reach the targeted electricity production of 30 TWh by 2020 between 3,000 and 6,000 new wind turbines must be installed in Sweden. The Swedish Energy Agency states that 20 TWh should be obtained from offshore installations and 10 TWh from land-based installations (Swedish Energy

Agency 2008-01-17). As mentioned previously these are planning targets, and not planned projects - which may also be of interest to the reader. In February 2008 the Swedish Energy Agency stated that there are prospects to erect between 2,123 and 2,773 wind turbines with a power capacity of 11 GW (Swedish Energy Agency, 2008-03-25). With an assumed annual production of 2,000 hours at rated power, this indicates that these prospects might produce about 22 TWh - a figure rather close to the planning target. These figures may in fact understate the real expansion to be expected in the coming years since installations with a power under 25 MW are not required to report building intentions to the Swedish Energy Agency.

Table 1 Wind turbine installations in Sweden

Year	Number of turbines	Number of turbines installed	Average rated power of turbines	Increase in average rated power
2007	856	72	N/A	N/A
2006	784	24	1262	13%
2005	760	37	1118	5%
2004	723	41	1065	13%
2003	682	62	942	7%
2002	620	50	882	2%
2001	570	43	867	26%
2000	527	41	687	-4%
1999	486	58	713	21%
1998	428	86	587	7%
1997	342	38	550	10%
1996	304	N/A	500	N/A

Table 1 shows the historical wind turbine installations in Sweden based on yearly statistics presented by Elforsk (Driftuppföljning Vindkraft, 2008-04-29). As can be seen, the number of turbines installed increased notably in 2007 compared with the ten previous years. The number of prospects presented to the Swedish Energy Agency in 2008 suggests that a high expansion rate can be expected to continue for some time ahead. Another observable development is the increase in average rated power for the wind turbines installed. The turbines erected in Sweden during year 2006 had an average rated power of 1,262 KW. Compared with those installed ten years earlier there has been a 150% increase. This trend follows the industry development towards larger turbines with increased rated power.

As is often the case when industries expand heavily, there is, on behalf of many persons, enthusiasm when describing the potentials for wind power. For example CNN published an article in 2005 titled *Wind power could meet current energy needs* where reference is made to a study conducted at Stanford University. The study explains that “...harnessing even 20 percent of that [wind] energy would produce eight times more electricity than the world consumed in 2000”. Fortunately, in some senses we have learned from the past. It is currently better understood that new technologies are rendered obsolete as time passes, and this cannot be ignored, especially when the new technology has a limited technological and economical lifetime.

Swedish legislation requires permit holders to cover dismantling and site restoration costs when their wind turbines are decommissioned. In some cases financial guarantees are requested by the county’s administrative board to secure that funds are available when turbine removal takes place in the future. Although focus is presently on the expansion of wind power, it is clear that wind turbines have a limited economic and technical lifetime of approximately 20-25 years. It is therefore certain that the turbines erected today will have to be taken down in a not too distant future.

Due to the recent launch and expansion of wind power in Sweden, there is a lack of experience regarding the final life cycle stages of wind power turbines. Permit holders – which are expected to cover decommissioning costs in the future – as well as governmental institutions – which are currently defining the size of financial guarantees required from operators – lack insight about the costs and revenues associated with decommissioning of wind turbines.

Few countries – such as Germany, the United States of America, and Denmark – have had wind power long enough to be concerned with decommissioning of older wind turbines. The availability of studies on this subject is very limited. Moreover there is a lack of knowledge about what economic consequences to expect for wind power turbines that are built today. Despite this there is a dominating assumption within the industry that decommissioning costs will be covered by revenues generated from the sale of the turbine’s materials and components. The validity of this assumption can easily be questioned by observing the trends towards significantly larger turbines, offshore installations, and the use of new materials in the wind power plant. These factors may very well imply increased complexity and costs related to decommissioning.

1.3. Problem statement

In this thesis, an investigation is made of the economic consequences of a future decommissioning of wind turbines currently being installed in Sweden. To do so the processes followed when decommissioning wind turbines and their economic effects were examined. Based on these findings a model was developed. This model is aimed at helping participants within the wind power industry predict costs and revenues related to the decommissioning of wind turbines currently being erected in Sweden.

1.4. Purpose of the study

The purpose of this study has been to develop a model that can help industry participants foresee the economic consequences of a future decommissioning of wind turbines.

Simultaneously a method has been developed that can be used to predict the economic consequences associated with dismantling, scrapping, recycling, and site restoration after technology that is rendered obsolete.

1.5. Importance of the study

Throughout the progress of this study it has become apparent that there is a considerable interest in the findings that will be presented. There is substantial uncertainty on behalf of governmental authorities as well as private actors regarding the economic effects of decommissioning of wind turbines. Much focus is currently placed on the expansion of wind power in Sweden. This can easily be established by reviewing information about governmental programs, industry growth, and press coverage. Although this development is welcomed by many, there is a risk that an overly excited industry may wake up to less welcome news in the future. The aim of this study is to increase the information available about the economic consequences that will materialize in 20 years time.

The findings are expected be of equal interest to supporters and opponents of wind power expansion. Most important, however, are the consequences of the findings for governmental entities and wind turbine operators. Governmental entities are currently defining the size of financial guarantees for decommissioning of wind turbines. The results presented may be helpful to establish the expected decommissioning costs – and thereby the need for and size of financial guarantees – in a more reliable manner. Turbine operators are expected to cover decommissioning costs in the future. For them it may be of great value to be able to appreciate the future economic consequences of decommissioning.

Decommissioning will take place in the future. Consequently there is a considerable uncertainty regarding the actual costs and revenues that will be incurred when the decommissioning takes place. However, it is of great importance to clarify the factors affecting the expected economic consequences of decommissioning.

1.6. Scope of the study

This study will focus on the economic consequences of decommissioning of wind power turbines currently being installed in Sweden. The intention is not to provide a detailed report of the costs and revenues that will be incurred, but rather an estimate of what can be expected and which factors are important when predicting the economic consequences of decommissioning. The perspective is focused on the future but is based on historical and current circumstances. As a consequence there will be a very limited discussion about potential developments in for example materials and technology used in wind power turbines and how these can affect decommissioning costs for turbines installed in the future.

1.7. Disposition

An overview of the disposition of this thesis is found in Figure 1.

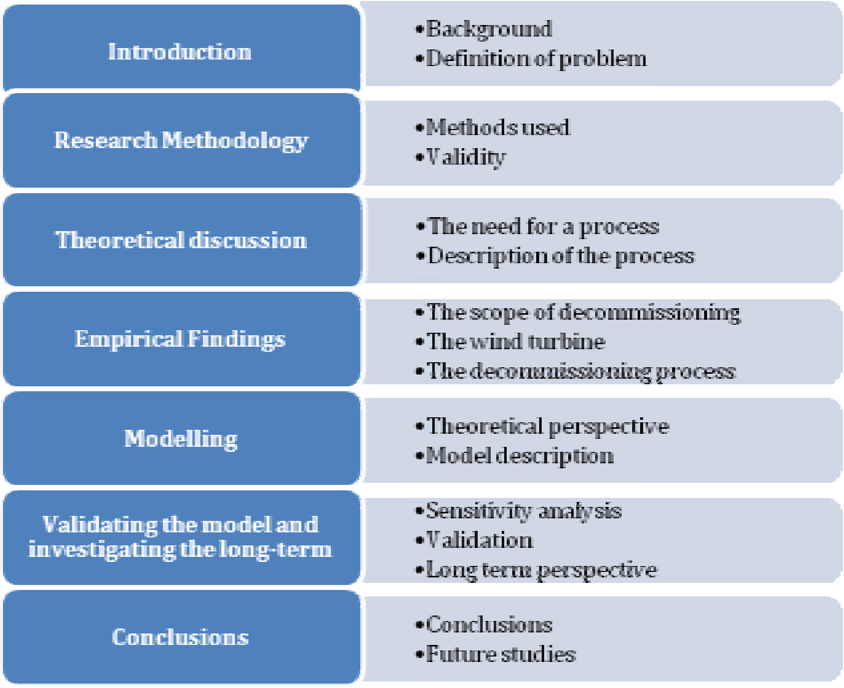

Figure 1 Outline of the thesis

In the introductory chaper the background has been presented and the problem to be examined has been defined.

The research methodology employed is presented in the second chapter. The first section of this chapter is aimed at presenting the methods for gathering and analysis of data. Following this an evaluation of the validity of the thesis is conducted.

In the third chapter the methodology employed to estimate decommissioning costs is discussed from a theoreticl perspective. The need for a framework or process to estimate decommissioning costs is first established. Thereafter existing frameworks are discussed. Lastly the methodology employed is described and analyzed.

In the forthcoming chapters of this thesis theories used are presented in connection to the section in which they are used. Descriptions of theories used are found in chapter three to five. This means that there is no chapter solely dedicated to presenting theoretical frameworks. This is motivated by a wish to clarify the practical relevance of the theories to this reaseach. To avoid confusion as to which texts introduce theories it is clearly stated in the beginning of each chapter which sections are part of the theoretical framework.

In the third chapter, empirical findings are presented. In this chapter's first section, the scope of decommissioning is described from a legal perspective. In the second section, a technical description of the wind turbine is presented. Thereafter, in the third section, the decomissioning process and its economic effects are described. To do so, the theoretical framework of Activity Based Costing was employed. Therefore, this framework is first presented and then applied to the decommissioning process. Once the process - and particularily its costs and revenues - have been defined, the model building can begin.

The fourth chapter begins with a theoretical description aimed at defining a model and describing important considerations when modeling. In the following section, the model that has been developed to predict economic effects of decommissioning is described. In the third section of this chapter the model is tested and a detailed account of the results is presented and analysed.

In the fifth chaper the model is examined from different persectives using sensitivity analysis methods. First, the models robustness is validated by performing a number of sensitivity analyses and discussing their results. Once the model is found to be robust a long term perspective is applied. Here, focus resides in predicting how future developments will affect the predictions made by the model.

In the sixth and final chapter of this study conclusions and recommended future studies are presented.

2. Research Methodology

The research methodology describes the way in which the study has been conducted and which approaches have been used to gather and analyse data. This information is important since it enables the reader to judge whether the information and results presented can be relied upon.

This chapter begins with a brief introduction to general approaches used to complete this study and stakeholders involved. A closer look is then taken upon data gathering methods, followed by a presentation of how the data was analysed. The validity of the research conducted is assessed by examining its reliability as well as internal and external validity.

This thesis has been written in collaboration with Consortis Producentansvar AB as part of a project for Svensk Vindenergi, the Swedish wind energy industry association. It has been important to confirm and review the work in progress with these stakeholders in order to ensure that the thesis fulfils their expectations. Since the issue examined has a high practical value and the thesis explores a relatively uncharted area an inductive research approach was preferred. This means that data was first gathered and then theories that could help describe, understand, and analyse the data were chosen. Both qualitative and quantitative approaches were used to gather information. For example, when initially understanding the decommissioning process it was necessary to maintain an open approach to information collected and deep interviews were helpful to gain a better understanding. Once the process was understood and had been confirmed by several sources a quantitative approach could be used to gather more detailed information from a more extensive number of sources.

2.1. Data gathering method

According to Jacobsen (2000) sources are commonly divided into three categories; primary, secondary and tertiary sources. Primary sources provide first hand and unprocessed information which is gathered for the first time by the researcher. Secondary and tertiary sources, on the other hand, provide processed information that has been gathered from primary sources through others. The difference between secondary and tertiary sources is the extent to which the information has been processed and summarised.

For this study information has mostly been gathered from primary sources. To understand the extent of decommissioning that will be required in the future it was necessary to initially conduct interviews with representatives from the counties administrative boards in Sweden. Questionnaires were sent to the twenty-one counties by electronic mail. Once a contact person with insights about how these terms were applied to the wind power industry had been identified telephone interviews were held. The decommissioning requirements applied to the wind power industry varied between different counties. Therefore information was also gathered from Sweden’s five environmental courts. Once clearer image of decommissioning requirements emerged focus was shifted towards private actors in the industry.

Questionnaires were sent out by electronic mail to members of Svensk Vindenergi. These questionnaires were intended at clarifying the expectations and attitudes of the industry participants regarding decommissioning. As expected, few could provide specific information about decommissioning processes and even fewer had been involved in these types of projects. To better understand practical aspects of decommissioning experts from Denmark and Germany were interviewed. The information gathered from these experts was used to identify companies on the

Swedish market performing services related to wind turbine decommissioning. If experts on the Swedish market existed they were interviewed in order to clarify costs that may be expected in Sweden. If this was not the case the price data gathered from international actors was used.

Data about wind turbines was gathered from wind turbine manufacturers. Most of the information was received from Vestas and Enercon which are the two biggest turbine manufacturers on the Swedish market. This information was used to understand dimensions, components, and materials used and how these characteristics varied between different turbines. The information was confirmed by additional sources such as wind power industry associations. In order to understand the revenues that may be produced by different components and materials scrap dealers and representatives on second hand markets were interviewed.

Data was also gathered from secondary sources. These include reports released by governmental institutions and other reliable sources as well as press releases about the developments in Swedish wind power. These sources provided data about the trends in number of installations, sizes, and types of wind turbines currently being installed.

An extensive literary review was conducted to find appropriate theoretical tools using sources such as books, magazines and articles available through Lund University’s library resources and databases. Internet sources were also used in this study. In such case care was taken to secure the trustworthiness of the site by using data from recognized sources or by triangulating the information. Triangulation involves confirming information with additional sources.

2.2. Analysis of data

The analysis of data has been performed in several steps since different issues have been examined. In order to understand legal views and requirements on decommissioning the information gathered from governmental entities was analysed and summarised. A somewhat fragmented image emerged and it was concluded that no standardized decommissioning definition exists applicable to all cases. Since certain steps in the decommissioning process may be discretionary this would have to be accounted for in the model.

Information gathered regarding processes employed to decommission wind turbines was used to identify companies that could perform required services in Sweden. As information was gathered about expected costs and revenues cost objects and cost drivers for decommissioning activities could be identified. The model emerges as cost drivers were connected to different characteristics of a wind turbine. In this process, parameters defining costs and revenues related to the turbines end-of-life were identified. In an effort to limit the number of parameters simplifications and assumptions were made based on empirical data. In order to test the validity of the model it was applied to a number of cases created by the authors. To test the models reliability when computing material values approximations presented by the model were compared with results using more detailed data about the turbines. To confirm parameters would have a logical effect when varied calculations were also performed on various different turbine types.

It was considered important to carry out these sensitivity analyses since many assumptions and simplification underlie the model. By performing sensitivity analyses on decommissioning activities characterized by high uncertainty the validity and robustness of the model could be established. This clarified the effect of errors in the model. It was also considered relevant to investigate the effects of future developments on expected decommissioning costs. This is relevant since the model estimates costs and revenues that will be incurred in the future. By conducting sensitivity analyses on the most uncertain cost and revenue parameters their effect on the estimated economic consequences of decommissioning could be established.

2.3. Validity

According to Jacobsen (2000) the validity in an academic report should be analysed departing from thee different criteria; reliability, internal validity, and external validity. It is important to present information about and discuss these criteria since this may help the reader assess the validity of the report. In this section a brief discussion and evaluation of these criterions will take place.

2.3.1. Reliability

Reliability assesses whether the data presented is trustworthy (Jacobsen 2000). Since the findings in this paper to a large extent are based on interviews with primary sources there is a risk that the sources may adjust their answers in the future. To minimize the risk of using erroneous data an effort has been made to validate information with several sources. Also, the selection of sources was made based on the reliability of the data provided by them. In some cases, mostly relating to the decommissioning of offshore instalments, the information gathered to a considerable extent is based on expectations from experts involved in installation at offshore sites. Since there is no previous experience in these processes these were considered to be the most reliable sources. During the interviews note-taking was employed as a method to reduce the risk of losing data.

2.3.2. Internal validity

According to Jacobsen (2000) internal validity relates to whether or not the research succeeds in answering the questions it intends to answer and if these questions are answered correctly. The aim of this masters' is relatively straight-forward. Therefore there was a limited risk of losing focus during the work process. On the other hand, there is a significant degree of uncertainty relating to the model built and the results produced.

In order to minimize the risk of presenting erroneous information a detailed account of the calculation methods, assumptions, and tests have been made. Moreover an extensive number of scenarios have been investigated by performing sensitivity analyses which have shown results deemed logical to hypothesis tested. As recommended by Jacobsen (2000) the results have been compared with expectations and experiences from experts within the industry which heightens the internal validity. The effectiveness of this method may be limited due to the risk that the opinions rendered are shared by many sources and constitute a paradigm for participants in the wind turbine industry. Since interviews were also conducted with representatives involved in decommissioning and demolition projects in other industries the probability of being affected by industry-specific assumptions was reduced.

The fact that two authors stand behind this thesis has also improved the possibility of questioning and discussion throughout the writing process. Moreover the work has been reviewed and discussed with supervisors from Lund University and Consortis Producentansvar AB as well as with peer students at Lund University.

2.3.3. External validity

According to Jacobssen (2000) external validity examines the extent to which the finding can be generalized. The aim of this thesis has been to develop a model that can be used to estimate decommissioning costs and revenues for wind turbines built today. The findings have been tested on a considerable number of cases and the results have been found to be reasonable. Unfortunately it has not been possible to test the predictions made by the model with live cases.

Researches wishing to perform similar studies in other industries may find use of the frameworks and methods developed in this study.

3. Theoretical discussion

In this chapter a theoretical discussion is held regarding the method that has been employed to develop a model that can estimate economic consequences of decommissioning. First a brief overview of existing theories will be presented. Thereafter the methodology will be described and discussed.

One of the objectives in this master thesis has been to develop a framework that can be used to estimate future decommissioning costs for technologies that are currently being implemented. The importance of this issue is augmented by increasing conciseness on behalf of politicians, general public, and enterprises. As the pace of technological development and change increases environmental consequences become evident and concerning. Shorter product life cycles impact the amount of waste being generated and there is increased interest in finding ways in which costs related to a product become explicit. Also, past experiences related to decommissioning costs have encouraged discussions as to who is to be held accountable.

The approval and implementation of the WEEE-directive in the European Union can be seen as an example of a step towards increased producer responsibility. With this policy producers of electric and electronic products are compelled to guarantee that there will be financial funds to cover waste-management costs related to their products. This is referred to as extended producer responsibility. The Organisation for Economic Co-operation and Development (OECD) defines Extended Producer Responsibility (EPR) as “an environmental policy approach under which the responsibility of producers for their products and product packaging is extended to include the social costs of waste management, including the environmental impact of waste disposal.” (OECD 2005, p. 7) It is designed to confront the producer with the whole cost of end of life and disposal of their product. Thereby it is anticipated that incentives are created for the producer to take account of these costs in the whole design process as well as the marketing of their product. (OECD 2005) Governments are becoming more concerned with ensuring that tax-payers are protected against decommissioning costs. Industries that have awoken concern about these issues are those engaged in nuclear energy generation, offshore oil retraction, and mining. In these cases previous experiences have created concerns about who will cover decommissioning costs or the risks are determined to be so significant they cannot be ignored. As these regulatory guidelines are approved and implemented paradigms shift towards a greater extent of social responsibility on behalf of enterprises engaged in other industries. Despite this there seem to be few theoretical frameworks or methodologies that can be used to help identify costs related to products end of life.

Two of the most influential theories regarding costs and revenues throughout the products life time are Life Cycle Costing (LCC) and Total Cost of Ownership (TCO). These methods commonly used to for supplier selection and are distinguished by that the procurement cost is seen as only a part of the entire cost for a product. Although acquisition costs remain an important decision factor economic consequences throughout the products life cycle have gained more attention.

Life Cycle Costing emerged in the United States Department of Defence as a method to calculate “all costs related to a product from its inception to its disposal” (Sherif & Kolarik 1981). Dhillon (1982) defines Life Cycle Costing as “The sum of all costs incurred during the life time of an item, i.e. the total of procurement and ownership costs.” The primary application has been to minimize costs when obtaining a certain level of output. TCO, on the other hand, was developed in 1987 by Gartner as a method to address the real costs attributed to owning and managing Information Technology in a business. In the same sense as LCC it has emerged as a valuable tool in other industries. (Gartner 2008-05-21)

A common characteristic for LCC and TCO is that the life cycle will be defined from the user's perspective. This implies that the scope of an LCC-analysis has changed. Initially in the Defence ministry LCC was used to account for costs related to all life-cycle phases; research and development, design, manufacture, installation, operation, maintenance, and salvage. As the model was employed in other industries the scope in most cases decreased and the model was used to analyze costs related to the user's specific phases of the life cycle. This is motivated by that the user controls only a particular part of the entire life cycle. In Figure 2 an example of how the product life cycle is defined by different users is shown. As can be seen both User 1 and User 2 will define the entire product life cycle as the proportion of the life cycle that affects them directly. (Sherif & Kolarik 1981) Compared with TCO the main difference is that LCC focuses mainly on capital or fixed assets and costs for supplier selection are included in the TCO. (Elram 1995)

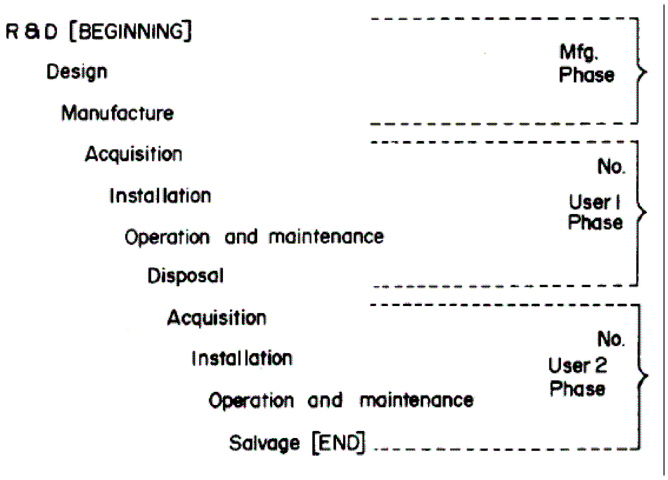

Figure 2 Users at different stages of the life cycle

Life cycle assessment (LCA) is a method used to assess environmental impacts of a product throughout its life cycle. This analysis is performed by focusing on raw material and resource consumption throughout lifecycle stages from acquisition, use, and disposal. A LCA is typically divided into four steps; goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation. LCA's have traditionally been used to assess energy and resources utilization and environmental consequences of products throughout their lifetime. LCA has been criticized for its failure to clarify economic consequences of environmental impact to decision makers. As LCA has gained ground efforts have been made to combine LCAs and LCCs in order to quantify environmental consequences in monetary terms. The interest for such initiatives have increased as legislation changes making producers cover "external" costs which are often related to environmental impact. (Steen 2005).

TCO, LCC, and LCA are valuable frameworks to expand the analysis of economic and environmental consequences of a product. However, since these frameworks consider the entire product life-cycle decommissioning costs are de-emphasized. Moreover many of these frameworks were developed before decommissioning and extended producer responsibility was considered of particular interest. For these reasons decommissioning costs are commonly ignored, estimated on questionable grounds, or assumed to be of limited economic consequence. A reason behind this may be that there is considerable uncertainty related to decommissioning and its economic consequences. The frameworks that have been developed are often intended for use on a particular product type. In other words very limited effort has been placed on developing methods that may assist in estimating decommissioning costs in a reliable manner regardless of industry. In the forthcoming section a methodology will be presented that can be valuable for many different products and industries. In this thesis the methodology is employed to reveal decommissioning costs for wind turbines.

The methodology that has been employed is presented in Figure 3.

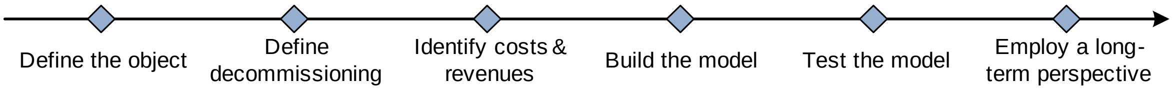

Figure 3 Method to estimate economic consequences of future decommissioning

The first two steps, aimed at defining the object and decommissioning, must be conducted before all other steps. Defining the object is important in order to set system boundaries. Depending on the object to be analysed this step can have a varying degree of complexity and difficulty. In literature one of the most important issues is the extent of ownership and allocation of costs Lenezna et al (2007) and Hanish (2000). However, these concerns are not to necessarily an issue in establishing costs related to decommissioning.

When defining the object to be decommissioned focus should be kept on the materials and components present. In other words, when defining the object an inventory of the product contents is conducted. This is important since the information will provide input to the third step - which is dedicated to establishing costs and revenues related to decommissioning. Special attention should be paid to substances present (solid, liquid, gases, and harmful substances).

The second step, which can be performed in parallel to or before the first step, is important in order to understand to what extent the product will be decommissioned. In this step it is important to consider legal requirements. In the case of Europe EU-directives, national laws in the environmental area, and other laws and regulations may be of consequence. As has been found in this thesis the extent of decommissioning can vary considerably depending on requirements posed by authorities. As will be proved this has important implications for forecasted economic consequences. In this thesis a number of different scenarios have been developed in order to account for uncertainties regarding the required extent of future decommissioning. Defining the object and the decommissioning bear resemblance to the first steps in an LCA where the goal and scope are defined and an inventory analysis is performed.

In the second step the economic implications of decommissioning are mapped out. It is important to organize costs and revenues in a logical and understandable manner. To do so an Activity Based Costing perspective was employed in this thesis. This economic framework is used since activities are linked to objects and cost drivers. By identifying these and relating them to specific decommissioning activities flexibility is built into the model. This flexibility is related to that activities can be ignored or taken into consideration as their importance changes in the future. In this sense it may be important to consider Activity Based Management as a framework when owners of the product perform similar analysis. This is due to that Activity Based Management is a more proactive framework where activities and processes are reviewed in order to improve productivity and efficiency. Since the aim of this thesis has not been to optimize the decommissioning process Activity Based Costing was considered more applicable.

By employing an Activity Based framework steps in the decommissioning process can be identified. In decommissioning projects these will commonly include preparations, dismantling, material sorting, transport, waste management (recycling/deposition), and restoration. Sub-activities for these activities also been identified, each bearing particular cost objects and cost drivers. The information in this step was gathered by conducting interviews with market participants and by using the information known today to forecast future events. The process developed is static, and reflects how these activities are performed and their economic effects under current circumstances. Since the process is aimed at estimating economic consequences of decommissioning taking place in the future it is important consider the effect of future events. This can be done in a number of different ways, which will be discussed more closely in step 5. However it is important to in this step identify which activities are uncertain or prone to change in the future. By considering and documenting such uncertainties the parties interested can review information and assess when changes are taking place towards new directions. Thus it is considered relevant to observe which activities and sub activities are currently of limited interest but could be have important economic consequences in the future. In the model this was done qualitatively, but other approaches could be used such as probability analyses.

The data gathered in the previous steps is used to build a model aimed at estimating economic consequences of future decommissioning. To do so the decommissioning activities must be reviewed and assessed as to their economic consequence. In this thesis a preference was made towards using costs and revenues as they are known today. Moreover a cautious approach was used when estimating economic consequences, meaning that qualitative analysis of the data was performed to determine its reliability. In cases where data was considered equally reliable data included had a tendency towards being cautious in minimizing costs and maximizing revenues. Although many activities are characterized by uncertainty it is considered preferable to include them instead of ignoring them altogether.

Another area of particular interest may be the valuation of components and materials. In the case where functioning markets exist for used equipment it may be reasonable to evaluate if the equipment can be sold once it is decommissioned. Here the time frame employed is of consequence. If market circumstances are stable it is reasonable to assume that as time progresses the value in the second hand products and components decreases. In the case of materials the revenues generated or costs incurred depend on market or regulatory circumstances at the time of decommissioning. These may be more difficult to forecast and have been handled in the fifth step of this method.

In order to document uncertainties regarding activities and their economic consequences a three-code system was developed. In the case where functioning markets exist and reliable information is found the cost object is characterized as an input parameter. For cost drivers or cost objects for which reliable information could not be found the parameter was tagged as an assumed parameter. For cases where information could be found but was considered as significantly uncertain the parameter was characterized as an input and assumed parameters. Having such an indexing of parameters enables sensibility analyzes since uncertainties can be identified. For actors wanting to develop these types of models it is also advised to build the model considering all activities that are considered likely become relevant at a future date. Cost and revenues should be kept separated as well as parameters that act as cost drivers. Doing so enables an update of the model as time passes and markets change.

Once the model has been built it is important to test its robustness and validity. Although there are many different ways in which to do this three are recommended due to their relative simplicity and effectiveness. Testing the models reaction to changes in parameters can reveal if the results presented by the model are logical. Should this not be the case the model must be revised as to confirm that revenue and cost objects and drivers have valid relations. It is also important to examine the effect of uncertainties built into the model. The effect of costs, revenues, and activities that are considered most uncertain must be tested. These are uncertainties related to the model itself – for example the time it takes to carry out a particular activity or the estimation of the content of a particular material in the product. Testing the effect of changes in these types of parameters will enable the user to identify the effect of erroneous assumptions. Thirdly a test can be conducted by comparing results to expectations. In this case the validity and reasonability of results is confirmed by comparing results with expectations on behalf of the authors of the model and industry experts. Such comparison, which is often done on qualitative bases, can be a good counter balance to the quantitative methodology employed. It is important to keep in mind that model in stage will only compute costs and revenues related to current conditions. Since decommissioning takes place in the future this must be accounted for.

The fifth and last step is focused on future developments. In this step thesis sensitivity analyses were performed in order to see how future events impact the economic consequences of decommissioning. This type of analysis is performed advantageously by first investigating which costs and revenues of most significance. This will enable the creator to focus the forthcoming tests on particular areas of interest. By conducting sensitivity analysis on each of these parameters their importance can be determined. Moreover the likeliness of particular changes taking place can be evaluated. This is particularly relevant if the costs and revenues are independent of each other. Risk categories that the model author may want to keep in mind are risks related to costs, revenues, and legal aspects.

Should relations exist between different parameters a scenario-planning approach may be more useful. In such case the author builds different scenarios where several parameters are altered simultaneously. In the case examined in this thesis the cost and revenue parameters were determined to be independent of each other. Moreover current market conditions were determined to be unlikely to continue once decommissioning takes place in the future. Microeconomic theories describing competition, technological change and long-term costs were therefore applied in order to predict how the markets may develop in the future. Since a there is very limited decommissioning of the particular product type examined learning effects were also deemed of importance. Learning effects may be the theoretical framework of most importance where there is a limited experience in decommissioning and room for a considerable cumulative output to develop. However it is important to assess how transferrable the learning is at within a particular company, industry, or geographical boundary.

The results presented by the model can be used proactively. By identifying which are the parameters that drive costs and increase difficulty in decommissioning and waste handling producers can act to change these circumstances. For example materials can be replaced or designs improved. Design for disassembly is a method or philosophy that is being employed in many industries. Also as has been pointed out an Activity Based Management perspective can be employed in order to improve processes. This means that the model can be used to assess which activities are most relevant and how these can be redesigned in the decommissioning process. One of the most important insights may relate to the financial risks present in the decommissioning of a product or a system. Identifying these risks may help actors reduce them or hedge against them. By identifying the costs, revenues and risks related to decommissioning market participants and regulatory entities are enabled to make more qualified assessments as to when decommissioning costs are of concern and how they should be handled.

4. Empirical findings regarding wind turbine decommissioning

In the first section of this chapter the scope of wind turbine decommissioning is described. This is done by examining laws regulating decommissioning and their application in the wind energy industry. In the second section of this chapter technical aspects of a wind turbine are presented. This will help the reader understand what components and materials are found in typical wind turbines. The scope of decommissioning and the characteristics of the turbines come together in the third section. In this section the decommissioning process is described using the framework of Activity Based Costing. Before presenting the decommissioning process the reader is therefore introduced to the theoretical framework of Activity Based Costing.

4.1. The scope of decommissioning

The aim of this thesis is to establish the economic implications of a future decommissioning of wind turbines. To accomplish this, an investigation was conducted to understand to what extent decommissioning is expected to take place in the future. Some of the questions to be answered included: Which parts of a wind power farm have to be removed? What laws and regulations control this process? The answers to these questions are important since they define the system boundaries and the extent in which decommissioning is expected to take place. In the process described in chapter three this corresponds to Define Decommissioning, marked in red in Figure 4.

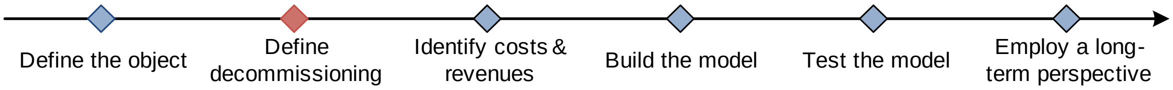

Figure 4 Process to estimate economic consequences of decommissioning

To understand laws governing wind turbine decommissioning and their application in the wind power industry representatives from several governmental entities were interviewed. Interviews were conducted with all of the environmental courts (Miljödomstolar) and the counties administrative boards (Länsstyrelser). Moreover, representatives from municipalities (kommuner) and the Swedish Environmental Protection Agency (Naturvårdsverket) were interviewed as well as two lawyers with expertise in the field. A list of the representatives from governmental entities interviewed and legal documents reviewed can be found in the reference section of this thesis (section 9.2). The portrait that emerged from these interviews is far from uniform and the lack of experience is evident. Moreover the opinions and interest in the matter on behalf of the interviewees was very diverse.

Findings

In order to erect and operate wind turbines in Sweden it is required to declare construction intentions to the appropriate municipality and county’s administrative board. If the wind power installation has a power below 25 MW, and thus is handled by the municipality as a declaration errand, no operation permit is required. Consequently the turbine can remain standing as long as the municipality does not see any motive for it to be taken down. Such reason could be that the municipality wishes to use the property other purposes such as housing. (Engzell 2008-02-07)

For installations with total power exceeding 25 MW a permit must be obtained. From the interviews with the environmental courts and the county's administrative boards it is concluded that the permit usually has no time limit. However the permit does specify a number of aspects such as height, rated power, noise and shadow effects for which the permit is granted. Should the permit holder want to replace the existing turbines it is almost certain that the new turbines will differ from the existing ones. Therefore a new permit will be required. The practical implication is that the permit applies only for the turbine for which it was granted.

The interviewees estimate the holder will exercise the permit during 20 to 30 years, with the highest estimate exceeding the expected life-time of a turbine which is often 25 years. The granting authority has the right to establish a time limit on the permit. If this takes place the permit usually expires after 20 to 30 years. A permit cannot be renewed; instead the establisher has to seek a new permit. Frequently it is stated that the turbine has to be decommissioned within a given time period after production has ceased. This time period is typically one or two years.

Conditions for decommissioning are usually stated in the permit. However, the conditions are typically stated in general terms. This is motivated by that the future use of the site is unclear. (Ryrbreg) From the interviews and reviewed documentation it is observed that there is always a requirement to dismantle the wings, nacelle, and tower. The requirements to remove concrete foundations and electrical cables, on the other hand, vary. There are no specifications regarding how to care for the turbine and other waste once it is dismantled. Some extracts regarding decommissioning conditions are presented below:

> Latest two years after the production of electricity has ceased the wind power turbines, the machine house, transformers, cables and other equipment shall have been removed. The foundations and wind power site shall have been adapted to natural surroundings. A dialogue shall be held with the property owner and the supervising authority during the process.[1]
> (Hammarström 2008-02-01)
>
> When activity fully or partially ceases the supervising authority shall be notified well in advance. How this is affected and conditions regarding the restoration of the site are to be obtained through a dialogue with the supervising authority.[2]
> (LänsstyrelsenVästernorrland 2006)
>
> Measures for restoration of the site are to be taken when the activity is closed down. The activity shall be regarded as closed-down if there has been no production of electricity within one year or if the permit has ceased to be valid. A written report comprising a work plan and a time plan shall be handed in to the supervising authority one month at the latest before the wind power turbine is permanently taken out of operation. In the report it shall be evident which measures will be taken to restore the site. Restoration measures shall be carried out in consultation with the municipal building board. At the latest two years after the dismantling of each wind power turbine the restoration shall be completed.[3]

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[1] Senast 2 år efter att elproduktionen har upphört skall vindkraftverken, maskinhus, transformatorer, ledningar och annan utrustning ha avlägsnats. Fundamenten och platserna för vindkraftverken skall ha anpassats till omgivande naturmiljö. Arbetet skall utföras i samråd med markägaren och tillsynsmyndigheten.

[2] När verksamheten i sin helhet eller någon del av denna upphör skall detta i god tid innan anmälas till tillsynsmyndigheten. Hur verksamheten ska avslutas samt området återställas skall ske i samråd med tillsynsmyndigheten.

[3] Åtgärder för återställande av området skall vidtas vid nedläggning av verksamheten. Verksamheten skall, utöver när tillståndet upphör att gälla, även anses som nedlagd om elproduktion inte har bedrivits under ett år. Skriftlig anmälan, omfattande en arbets- och tidsplan, skall göras till tillsynsmyndigheten senast en månad innan vindkraftverken permanent tas ur drift. Av anmälan skall framgå vilka åtgärder som avses vidtas för att återställa

> (Nacka Tingsrätt 2007)

Intentions to decommission turbines with a rated power over 125 kW have to be reported to the supervising authority. This applies whether or not decommissioning conditions were expressed by authorities when the turbine was erected. The notification is made by delivering a dismantling plan that must be approved by the authorities. In the plan the permit holder must describe how the dismantling will take place and how waste material is to be handled. (Plan- och bygglagen (1987:10) 1.4) In this stage final decisions are made regarding to what extent dismantling and restoration takes place. To exemplify the extent of detail with which decommissioning is described an extract is presented below:

> ...besides removal of the wind power turbine and its foundation the bottom shall be cleared from concrete scrap and other pollution. The stays for the tripod shall be cut at bottom level so that net or other fishing equipment will not get caught. The bottom shall be levelled out with existing macadam. The cable that connects the wind power turbine with land shall be removed from the power turbine and about 25 m on land. The shack in connection with the harbour parking shall be removed.[4]
> (Sölvesborgs kommun 2007)

The permit holder for the operation of the turbines is responsible for the decommissioning of the turbine. The responsibility also entails funding the decommissioning. To secure that financial funds will be available when the turbine is to be decommissioned the permit can be conditioned by a security. The security is a guarantee for that cost of environmental damage and restoration will be covered by the permit holder. Below is an example of how a permit can be conditioned with the requirement of a security:

> Validity of permit, approval or exemption in accordance with the code or in accordance with regulations communicated with support of the code, may be conditioned by that he who intends to run the operation provides a security to cover cost of relieving environmental damage or other restoration measures which the operations may cause. [5]
> (Miljöbalken (1998:808) 16.3)

The interviews conducted show that securities are only required occasionally and mostly when the permits are approved by the environmental courts. Only three counties have stated that they have conditioned permits in this way. (Fors 2008-02-06, Laurell 2008-02-01, Huss 2008-02-26) As for the municipalities interviewed it is found that none of them stated that they have conditioned a permit. For the permits that are conditioned the size of the financial guarantee required varies from 50 000 SEK up to 1.3 million SEK per installed turbine. The size of the security is found to be higher in the north of Sweden. (Fors 2008-02-06)

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området. Återställningsåtgärder skall genomföras i samråd med den kommunala byggnadsnämnden. Senast två år efter respektive vindkraftverks nedmontering skall återställningen vara utförd.

[4] …förutom borttagande av vindkraftverk med fundament skall botten rensas från betongskrot och annan förorening. Stagen till tripoden skall kapas vid bottennivån så att nät eller andra fiskeredskap inte kan fastna. Botten skall utjämnas med befintlig makadam. Kabeln som förbinder verket med land skall tas upp från verket och ca 25 m upp på land. Boden I anslutning till hamnens parkering skall borttransporteras.

[5] MB 16.3 Tillstånd, godkännande eller dispens enligt balken eller enligt föreskrifter meddelade med stöd av balken, får för sin giltighet göras beroende av att den som avser att bedriva verksamheten ställer säkerhet för kostnaderna för det avhjälpande av en miljöskada och de andra återställningsåtgärder som verksamheten kan föranleda.

Below extracts relating to the security are presented:

> The applicant shall provide a security of sixty-five thousand kr (65 000 SEK) thousand per wind power turbine to cover cost for dismantling and restoration of land etc. The security shall consist of an undertaking from a bank, a so-called bank guarantee. The county administrative board of Dalarna shall keep the security. The permit cannot be employed before the security is provided.[6]
> (Nacka Tingsrätt 2007)
>
> The Environmental Licensing Board decides that the permit's validity is dependent on that the company places a security in the form of a locked bank account. The security shall cover the cost for post treatment or other measures of restoration, which the operations may cause.
>
> Before a wind power turbine is taken in operation a sum of 300 000 SEK, in the money value of 2008, shall be placed in the locked bank account. A total of 3.6 million SEK provided that all the twelve wind power turbines will be constructed.
>
> Furthermore the company shall, for every wind power turbine taken into operation, allocate 100 000 SEK per year, in the money value of 2008, under ten years time starting on the eleventh year after each wind power turbine has been taken into operation. The company shall each year account for the transactions, which have been made to the supervising authority.
>
> ... The security shall be put out to the county administrative board and shall be kept with the county administrative board.[7]
> (Länsstyrelsen Norrbotten 2007)
>
> ...security should be provided where the company after the fifth year up until the fifteenth year places 150 000 SEK per year and turbine in a locked bank account.[8]
> (Svea Hovrätt 2007)

The size of the security is usually based on calculations made by the operator. These estimations are then examined and, if deemed necessary by the granting authority, adjusted. (Hansson 2008-02-14) The calculations made by the operator are for the most part not more than rough estimates. Interviews

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[6] Sökande skall ställa säkerhet om sextiofemtusen (65 000) kr per vindkraftverk för nedmonteringskostnader och återställande av markytor m.m. Säkerheten skall bestå av utfästelse från bank, s.k. bankgaranti. Säkerheten skall förvaras av Länsstyrelsen Dalarnas län. Tillståndet får inte tas i anspråk innan säkerhet ställs.

[7] Miljöprövningsdelegationen beslutar att tillståndets giltighet är beroende av att bolaget ställer säkerhet i form av ett spärrat bankkonto. Säkerheten ska täcka kostnaderna för efterbehandling eller andra återställningsåtgärder som verksamheten kan föranleda.

Innan dess att ett vindkraftverk tas i drift ska 300 000 kronor i 2008 års penningvärde sättas in på det spärrade bankkontot. Totalt 3,6 miljoner kronor under förutsättning att samtliga tolv verk anläggs.

Vidare ska bolaget för varje idrifttaget verk avsätta 100 000 kronor per år i 2008 års penningvärde under tio års tid med start det elfte året efter idrifttagandet av respektive verk. Bolaget ska årligen till tillsynsmyndigheten redovisa vilka avsättningar som har gjorts till det spärrade bankkontot.

Bolaget ska vid beräkningen av penningvärdet utgå från konsumentprisindex varvid år 2008 ska vara basår.

Säkerheten ska ställas till länsstyrelsen och förvaras hos länsstyrelsen.

[8] …säkerhet bör ställas på så sätt att bolaget efter det femte året fram till och med det femtonde året på ett spärrat konto avsätter 150 000 kr per år och verk.

held with operators makes apparent that there is a severe lack of practical experience within decommissioning. Moreover no one seems to know the costs related to the decommissioning of wind turbines. To a certain extent this is to be expected as few turbines have been decommissioned in Sweden. However there are additional uncertainty factors. The fact that there is vagueness regarding the extent to which dismantling and site restoration will be required increases the difficulty in predicting costs. The effect of time on decommissioning costs and potential revenues from sales of waste materials is also viewed as an important uncertainty factor.

Requiring a security increases the likelihood that there will be financial funds available to cover decommissioning costs in the future. If no guarantee is given the financing of decommissioning relies entirely on the funds available in the organization at the time of decommissioning. Since costs for environmental measures are claims against the bankruptcy estate itself they have priority over all other claims. (Adolfsson 2008-01-25) However, the course of action if there are not sufficient funds available in the company to cover decommissioning costs seems unclear.

From the interviews performed it is gathered that both the estate owner and the state are considered potential candidates to cover the decommissioning costs. Here it is worthwhile noting that the estate owner in many cases is a private person that rent out a piece of land where the turbine is located to the turbine owner and/or operator.

Many of the counties and municipalities interviewed, and particularly those wavering the right to demand a financial security, expect decommissioning costs to be covered by the turbines scrap value. The authors find it somewhat worrying that this assumption is made without any reliable bases. None of the interviewees could provide reference to studies conducted about this matter and none could appreciate the costs related to decommissioning.

4.1.1. Implications

The interviews performed with legal authorities show that there application of regulations related to decommissioning is far from clear and uniform in the wind power industry. This has may have considerable consequences, some of which are presented below.

The lack of a clear and consistent application of decommissioning requirements reduces predictability. At the time being it seems impossible for the establishers to foresee to what extent they will be required to dismantle and restore the site after operations. As mentioned previously this is clarified only when a decommissioning plan is approved by the supervising authority, which takes place shortly before the actual decommissioning. Consequently there is a large variation regarding the extent to which the permit holder may be required to decommission. Four scenarios have been identified which are presented in order of augmentation:

Scenario 1:	Only the turbine is decommissioned
Scenario 2:	The turbine and its foundation are decommissioned
Scenario 3:	The turbine its foundation, and internal cables are decommissioned
Scenario 4:	The turbine, its foundation, and both internal and external cables are decommissioned. This is also referred to as a full-scope scenario.

It recognized that it is difficult to be more precise at an early stage; however it would be interesting to know what this uncertainty will mean in financial terms. Considering the economic consequences of decommissioning are generally unknown they seem somewhat harder to predict considering the disparity between the different scenarios. Two important consequences are identified. The first is that the potential establishers may be stalled in their expansion plans. The second, which is more worrying, is that establishers may consider this to be a problem to deal with later. This is, of course, a correct evaluation. However it seems risky to postpone the issue. Once the economic consequences of decommissioning become apparent the establisher may wake up to an unwelcome surprise.

Another observation made during the interviews is the discrepancy in the opinions and attitudes towards decommissioning. Some interviewees were completely unconcerned with decommissioning – many of them wondered why this issue was relevant and one even stated that this would be a problem to be dealt with after his retirement. Others, on the other hand, regarded decommissioning as a very important issue requiring more attention. Diverging opinions are not a problem in themselves. However a problem does emerge if this affects the permit issuing process which as a consequence varies between different counties and municipalities.

Judging by the fact that some counties exercise their right to require a security, whereas others do not, seems to indicate the decommissioning issue is handled differently throughout the country. The differences may of course be explained by differing site conditions (logically an offshore turbine will be more costly to decommission than a land-based turbine). In such case the counties not requiring securities are those which, after thorough investigations, find it superfluous to require such security. It is also possible that the counties have not required a security in the particular cases where permits have been granted, but that there are intentions to do so in forthcoming cases. There is also a possibility that the differences can be attributed to coincidence. However, the interviews have shown that the most likely of all scenarios is that the issue of decommissioning is not being noted by many counties. The authors find that the implication is that regulations, are in fact, being applied in different manners. This is concerning since the consequences are that establishers will receive different indications depending on where their turbines are established. For the competitive landscape this means companies are competing under different conditions due to the interest that the authority representative places in the matter.

The fact that different forms of financial guarantees are accepted as securities is not viewed as a problem. It is suitable that the issuer of the guarantee can provide it in the most convenient form, as long as the required level of security is fulfilled. Another important consideration may be the effects on competition. If companies with great financial strength are presumed to be more reliable, and thereby not required to leave a guarantee, they will receive preference over smaller companies.

Overall it can be said that there is an arbitrary view on the importance of rules and regulations concerning decommissioning and how they should be applied. The authors’ believe that a thorough investigation of the financial implications of decommissioning can help to create a more stringent view. In order to enable an investigation of financial implications an overview of the wind turbines technical aspects follows.

4.2. Technical aspects of a wind turbine

The costs and revenues related to the decommissioning of wind turbines to a large extent depend on the processes employed when decommissioning, the components and materials present, and how these are handled. As has been explained in chapter three this information is necessary in order to define the system and to provide information for the forthcoming step, where costs and revenues will be identified. In this section information will be presented about the components and materials used in typical wind turbines erected in Sweden at the present time. As can be seen in Figure 5 below this correspond to the first step in the process to estimate economic consequences of decommissioning, described in chapter three.

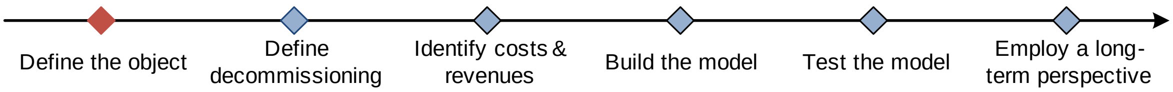


Figure 5 Process to estimate economic consequences of decommissioning

Information has been gathered from manufacturers with the largest market shares in Sweden; Vestas and Enercon. Approximately 45% of the wind turbines historically installed in Sweden are manufactured by Vestas. Enercon holds a second position as with a historical market share of 20%. In recent years Enercon has increased its market share and in 2007 Enercon turbines accounted for approximately 50% of all new installations (Carlsson 2008-04-01). Information about Nordex turbines has also been reviewed although the use of these turbines has been limited in Sweden.

4.2.1. Technical description of the turbines components and materials

In order to ease understanding the will be described in six different parts. Together these parts constitute a typical wind turbine. Each turbine requires a rotor, nacelle, tower and foundation. The transformer station and the cables, however, are shared by the turbines in the wind energy park. In the upcoming section the turbines will be described in the following parts:

- Rotor
- Nacelle
- Tower
- Foundation
- Cables
- Transformer station

The rotor

The blades together with the hub make up the rotor. (Wizelius 2002, p. 101)

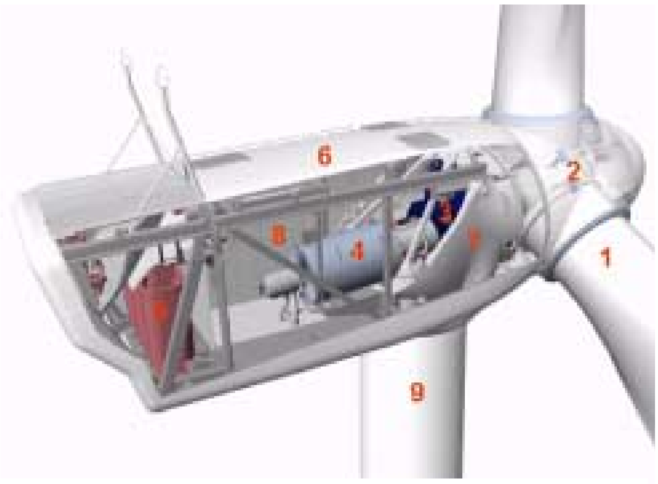
Blades

According to the Danish Wind Industry Association blades are usually made of glass fibre reinforced polyester, a material made of fibre glass mats impregnated with materials such as polyester or epoxy. In larger blades carbon fibre may be preferred over fibre glass due to its lighter weight and wood-epoxy laminates may also be used (Danish Wind Industry Association, 2008-03-25). Information from Vestas, Enercon and Nordex confirm fibre glass with epoxy resin and wood-epoxy as typical blade materials. Auxiliary materials include vacuum fleece and plastic films. The rotor also compromises nose cone supports, torque arm plates, torque arm shafts and torque arm blocks – all of which are also constructed in fibre glass reinforced polyester. (Vestas 2006, pp. 22-24)

The hub

The hub, to which the blades are fastened, is made normally made of cast steel or cast iron. (Danish Wind Industry Association, 2008-03-25)

The nacelle



1. Blade
2. Rotor
3. Gear
4. Generator
5. Transformer
6. Nacelle cover
7. Main foundation
8. Electric switchboard
9. Tower

Figure 6 Overview of the nacelle (Vestas 2006)

The rotor is attached to the nacelle in which several of the basic turbine components are found. These include the generator, the controller, and the shaft with gear. In Figure 6 an overview of a typical nacelle is presented. The nacelle is a cast iron chassis inside a cover typically made of composite material (Danish Wind Industry Association, 2008-03-25). Although the use of composite material is confirmed by Vestas, Enercon has developed a nacelle cover made of aluminium (Carlsson 2008-04-01).

The weight of the nacelle and the rotor combined is the top head mass (THM) and can vary from 200 to 400 tons for a large wind power turbine (5 MW). To reduce manufacturing and installation costs, manufacturers strive to keep THM low. (Patel 2006, p. 64)

The main foundation
The main foundation, which attaches the rotor to the nacelle, is made of cast iron. (Vestas 2006)

Electrical Generator
The generator produces electricity from the motion energy in the wind. (Patel 2006, p. 87) In most case these generators are of a standard make. (Patel 2006, p. 62) The generator consists of cast iron and various steel types including steel plates and copper. (Vestas 2004 and Vestas 2006)

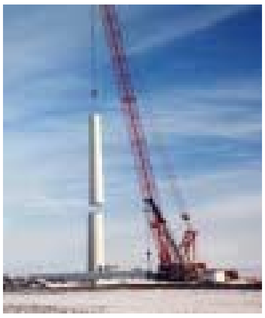
Shaft with mechanical gear
Wind power turbines have a low-speed and a high-speed shaft that guarantee that energy is produced efficiently in the generator. (Patel 2006, p. 62) Vestas reports the gear consists of 50% stainless steel and 50% cast iron. The main shaft is manufactured in steel assumed to have the same properties as stainless steel (Vestas 2006). Enercon has developed a turbine model without a mechanical gear. Therefore Enercon turbines have a larger generator compared with other manufacturers (Carlsson, 2008-04-01).

Sensors and Control
A wind power turbine requires a number of different sensors and controls, which makes up its control system. This provides operational and safety functions from a remote location. The control system placed in the nacelle consists of electricity switch boards and has an approximate weight of 1500 kg. (Vestas 2004 and Vestas 2006)

The Tower

The tower supports the nacelle and the rotor and it can have a tubular or lattice construction. The tower has to be at least 25-30 m high to avoid turbulence caused by buildings and trees. Wind turbines for commercial use typically have towers twice that height to take advantage of swifter winds that occur at higher heights. For wind turbines with a rated power of 600 kW and above the tower height (referred to as hub height) approximately equals the diameter of the rotor. The towers can be made in steel or concrete. (Patel 2006, p. 63) The tower is usually bolted onto the foundation to secure stability. (Danish Wind Industry Association, 2008-03-28)

Tubular steel towers



Currently most wind turbines are delivered with tubular steel towers (shown in the picture to the left). These towers are manufactured in section of 20-30 meters and bolted together to form a conical construction. The amount of steel required depends on the height of the tower. For towers exceeding 100 meters limitations arise. (Danish Wind Industry Association, 2008-03-28) In these towers the diameter of the lowest section exceeds 4 meters and thereby maximum restrictions on a low loader. Also, once the wall thickness exceeds 50 mm rolling and bolting together of sections becomes difficult. (The Concrete Centre, 2008-03-28)

Lattice towers

Lattice towers (in the picture to the right) require approximately half of the steel used to manufacture a tubular steel tower with similar stiffness. Despite the cost advantages of these towers their use is limited due to aesthetic reasons. (Danish Wind Industry Association, 2008-03-28)

Hybrid towers

The use of concrete in towers has gained attention as increasing turbine sizes creates difficulties in production and logistics related to tubular steel towers. The design for concrete towers vary, but the towers are usually made of pre-stressed concrete armoured with steel. The top sections of these towers are commonly made in steel. The hybrid tower used in Nordex 5 MW wind turbine employed approximately 800 m3 of concrete and 130 t of armour iron. (Nordex, 2008-03-29)

Foundation

Ground conditions at the site and the type of tower used determine the proper foundation type. The foundation is necessary to secure the stability of the wind turbine. Foundation piles weigh several hundred tones and are embedded into the ground. Only a small part of the foundation is actually visible above ground or sea level. (Vestas 2006, Vestas 2004, and Nordex 2008-03-28)

Onshore foundation

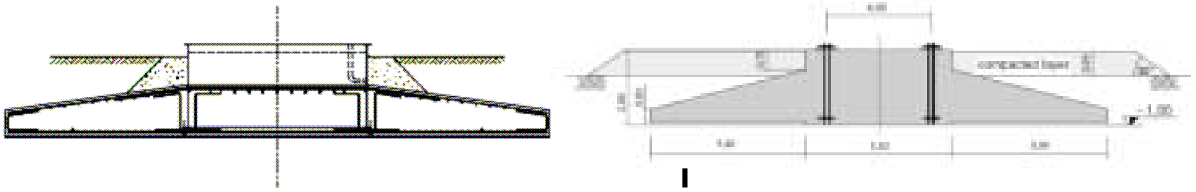


Figure 7 Examples of foundations for onshore turbines (Vestas 2008-02-20 and Nordes 2008-02-20)

Figure 7 shows two drawings of foundations used in land-based turbines. Regardless of the tower type chosen the foundation will usually have a similar shape. The size of the foundation, on the other hand, will vary. As hub height increases the size and amount of material in the foundation increase. Another significant difference arises depending on the type of tower.

For tubular towers (tubular steel towers or hybrid towers) a single foundation pile is put in place. Lattice towers, on the other hand, utilize four smaller foundation piles. The materials employed in the studied tubular towers varied between 27 tons and 66.5 tons reinforcement steel and between 330 cubic meters and 475 cubic meters of concrete. (Vestas 2006, Vestas 2004, and Nordex 2008-03-28) A lattice tower, with a hub height of 105 meters, uses four smaller foundation piles with a total of 26.5 tons of steel and 380 cubic meters of concrete. (Nordex 2008-03-28)

Offshore foundation

Offshore foundations are more complex due to that installation has takes place at sea. There are three different types of foundations piles; “mono pile”, “cassion” or “tripod”. In Figure 8 drawings of these are presented. Mono pile foundations are by far the most commonly used.

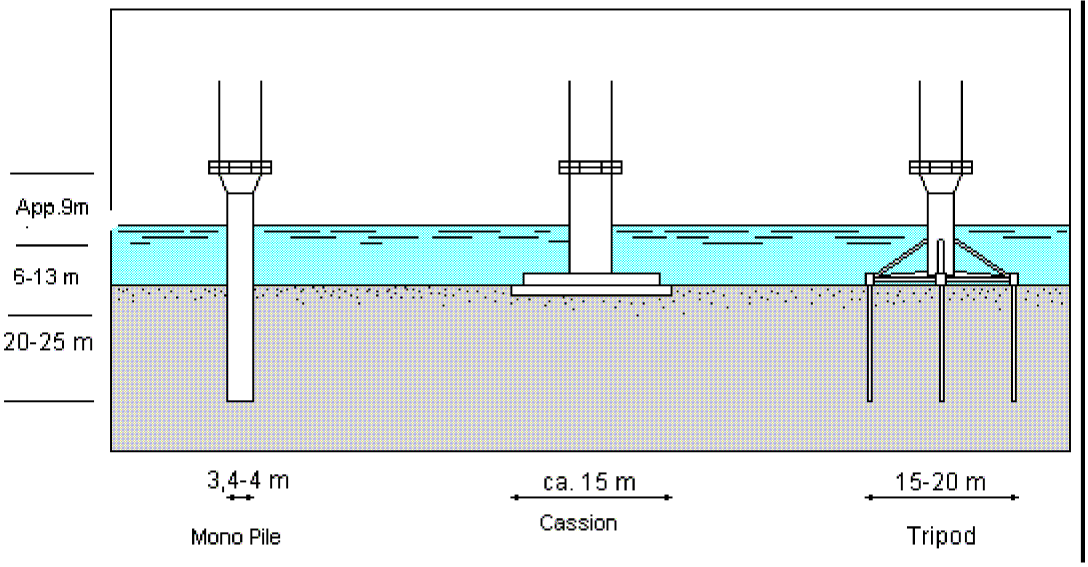


Figure 8 Examples of offshore foundations (Vestas 2006)

Mono piles

Mono piles are by far the most commonly used type of foundation. The preference to use mono piles is explained by that these foundations are the most cost effective at a depth less than 20 m. Mono pile foundations are constructed specifically for the turbines to be mounted which makes them difficult to reuse. (Offshore Wind Energy Europe, 2007-12-06) Basically the mono pile is a long steel rod which is hammered into the seabed (Offshore Centre Denmark, 2008). This foundation type commonly has a diameter of 4-6 meters and is thus marginally larger than the diameter of the tower. The embedded length of the foundation will depend on the depth and type of sea bed, but they are commonly rammed down 25-30 meters. (Scott & Downie 2003)

The characteristics described above are confirmed by information about Vestas offshore wind park at Horns Reef where 2MW turbines have been installed. With an average depth of 10 m the mono piles had a diameter of approximately 4 meters are rammed down 25 meters into the sea bed. The mono pile is made of high-strength steel and has a length of 29.7 m a diameter of 4 m and a thickness between 30 and 50 mm depending on the place measured. (Vestas 2006)

Caisson

For caisson foundations the weight of the mass in the foundation is used to stabilize the tower. There are two different types of caisson foundations; gravity foundations and suction caissons. With a gravity foundation a massive steel or concrete base is used to stabilize the turbine. Here the weight of the base itself ensures the stability of the turbine. The foundation often contains compartments which are filled with ballast material to increase weight. These foundations can weight 2000 t for a 2 MW turbine and 3500 t for a 5 MW turbine. (SETech, 2003)

A suction caisson is a hollow steel structure that is installed as water is pumped out and the foundation, forced by downward pressure, is sucked into the ocean bed. At the time being these foundations have not been used in the wind power industry and initial trials have pointed towards technical difficulties (Byrne & Houlsby 2003).

Tripod
The tripod construction is currently used in gas and oil installation and is considered an interesting foundation type for wind turbines. These foundations are similar to mono piles except that in this case there are an additional number of smaller mono piles. The total weight of this construction is approximately 30% less than for mono pile foundations. Depending on the number of legs these foundations can be referred to as tripod or quadpod foundations. (Strömberg, 2007)

The transition piece
The piece that joins the foundation and the tower is called the transition piece. The transition piece is constructed in steel. Onto the transition piece a boat platform is mounted which is also constructed in steel. (Vestas 2004, Vestas 2006)

The transformer station
The transformer transforms energy from one voltage to another. It consists primarily of tin, copper and steel. In offshore installations the transformer is placed on a platform which can measure approximately 20x28x7 meters. The foundation for the platform consists of three piles which are interconnected through a lattice girder construction. The foundation and the platform consist of steel, stainless steel, aluminium and reinforced concrete. (Vestas 2004, Vestas 2006)

Cables
At a wind farm there are internal and external cables. Internal cables are those which connect the turbines within the farm to the transformer station. Cables found after the transformer station, which transfer electricity to the electrical grid, are regarded as external cables. The external cables can be owned by the turbine owner or by the owner of the transmission grid such as Vattenfall or E.on.

The need for cables will depend on the number of turbines, the location of the turbines, and the distance to the electrical grid. The previously mentioned factors determine the weight of the cables - which can vary between 30-90 kg per meter. To exemplify: the weight for the cable installed in Lillgrund is 70 kg per meter and it consists of 15% copper, 30% lead, 27% steel and 22% plastic. Smaller cables used to between the turbines at an offshore farm can weight 15 kg per meter and where 19% of the weight constitutes copper, 43% steel, and 15% plastic. (Liffler, 2008-04-10)

Primary materials in cables are aluminium or copper, steel and plastic insulator. For onshore installations aluminium is usually used conductor material in Sweden. In such case the cables are much lighter and the plastic constitutes a significant proportion of the cable weight. At offshore installations in Sweden copper is usually used as conducing material. The weight of submarine cables exceeds the weight of cables used in land-based wind farms. (Liffler, 2008-04-10)

4.3. The decommissioning process

In this section the decommissioning process will be described. Costs and revenues related to different activities will also be presented. As can be seen in Figure 9 this corresponds to step three in the process to recognise the economic consequences of decommissioning.

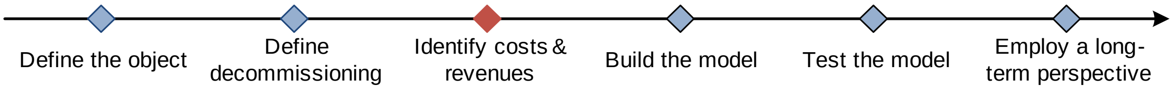


Figure 9 Process to recognize economic consequences of decommissioning

As information was gathered about the process it became apparent that Activity-Based Costing would prove to be a valuable framework to describe the process. To our research one of the most valuable advantages of ABC is that it enables the estimation of costs by identifying necessary activities. By inducing costs in this way a more accurate, useful, and comprehensible model could be developed.

This will also allow for a built-in flexibility in the model since activities can be excluded or replaced in the future as real conditions become apparent.

4.3.1. Activity-Based Costing

Activity Based Costing is a costing method that focuses on activities performed in the organization. The primary difference between ABC and traditional costing methods is that with ABC costs are allocated in a more direct fashion. Cause and effect between activities performed and costs incurred are investigated. As pointed out by Raz&Elnathan (1999) the advantages of ABC should not be underestimated in project organisations for the estimation of project costs. Although projects are often described as unique they are many times characterized by similar activities. By identifying these activities and related costs the costs of specific projects can be approximated.

Implementing Activity Based Costing

Activity Based Costing is process oriented and based upon activities, resources and cost objects. An activity represents physical work such as planning, sourcing, processing, etc and is by Emblemsvåg (2003) described as what is actually being done in the organisation. In order to perform these activities resources must be consumed such as man-hours, equipment, energy, etc. Activities and cost objects are linked by cost drivers. Cost drivers describe resource consumption for activities. When employing ABC costs are traced to activities that consume resources and the activity costs are traced to cost objects such as products or customers that consume activities.

Below a process to implement activity based costing is described. This process is based on the approaches presented by Kaplan and Cooper (1998) and Ax et al (2001). The process has been modified in order to suit a simpler environment where there is a restricted complexity regarding both activities and organizational considerations.

1. Develop the activity dictionary
2. Determine the cost of the activities.
3. Select cost drivers that link activity costs to cost objects.

1. Developing the activity dictionary

The first step aims at identifying the activities performed and that can be described by verbs and associated objects such as purchase of material, inspection of material, and transport of material. The number of activities should not exceed 10-30 but may vary considerably depending on the purpose of the model. This step in the implementation process culminates in a list or “activity dictionary” identifying every major activity performed. (Kaplan and Cooper 1998, pp. 85-86) According to Ax et al. (2001) it is essential to identify which activities are relevant for the calculation. An important criterion to distinguish these activities is their relative resource consumption. In order to identify activities interviews with personnel, process studies, or observations can be performed.

2. Determine the costs of the activities.

Once activities have been defined costs are allocated to them. The process of cost allocation begins with assigning specific costs to their activities. This entails understanding the resources involved in performing an activity and their cost (Kaplan & Cooper 1998, p. 89).Once this is done costs can be shared by several different activities are assigned to these activities.

Kaplan and Cooper (1998) recommend that activities are organized hierarchically. In its basic form the hierarchy has three levels: unit, batch and sustaining levels. The unit level activities are performed each time a unit is produced. Batch activities are those that have to be performed for each setup of work performed and are independent of the number of units in the batch. Sustaining activities are performed to enable the production. These can be traced to particular products, services or customers but are independent of the volume and mix of these. An alternative is to organize the activities as belonging to different processes. When doing this it is important to keep in mind that different activities in the process can require different cost drivers.

3. Selecting cost drivers that link activity costs to cost objects

Cost drivers can depend on transactions, duration, or intensity. Transaction based cost drivers are best suited when the cost objects have an equal resource consumption. Each activity, for example attending a customer order, will thus require the same amount of resources each time it is performed. A cost driver that relates to duration will focus on the time it takes to perform an activity. Assumption that the resource is always used with equal efficiency this cost driver is useful when the time it takes to perform an activity varies. For material movement the distance can be considered as a duration driver. Cost drivers related to the intensity of the resource consumption are appropriate to employ if the cost objects needed for specific activities vary. For example the involvement of experts may vary from one project to another. (Ax et. al 2001)

4.3.2. Applying Activity-Based Costing to the decommissioning process

In forthcoming sections the decommissioning process will be described as a series of activities and sub-activities. These activities have been identified by conducting interviews with experts in the field. These include entrepreneurs involved in turbine erection, demolition entrepreneurs, turbine farm projectors, as well as turbine owners and operators. Also interviews have been conducted with experts that have taken part in decommissioning projects in Sweden, Denmark, and Germany.

As data was collected an activity dictionary was developed. Following an analysis of these activities a process consisting of five steps emerged. In each of these steps a number of sub-activities were identified. As can be seen in the Figure 10 the number of activities is five and there are between three and six sub-activities in each activity. This is considered reasonable as the process described is relatively simple, but a thorough description is sought after.

Although certain evaluations could be made about the activities relative resources consumption it was necessary to perform additional interviews to establish costs. As explained by Kaplan and Cooper in this step it was important to understand when and how these costs take place, that is, if they are generated by for example every project or every turbine.

Once the activities and their costs were identified cost drivers were assigned. For most of the activities and sub-activities the cost drivers are related to transactions or duration. A transaction cost driver is interpreted as a cost that is related to the number of turbines. To clarify, the activity has to be performed and has the same cost or revenue effect for each unit of measure (such as turbine, ton or meter). Duration characterizes the sub-activities where costs depend on the durations of the activity. In some activities several types of cost driver are employed to describe different elements in the activity.

It is agreed that the Activity-Based Costing model should be kept as simple as possible, and that irrelevant costs should be excluded. However, an effort has been made to include activities that currently may have irrelevant economic consequences, but that in the future may prove important. The reasoning behind this is that the aim behind this study is to cast light upon the economic consequences of decommissioning in the future. In twenty years time, the estimated life time of a turbine, many changes can take place. Therefore the activity framework seeks to identify the activities that have the largest potential to imply economic consequences.

In the upcoming process description the costs and revenues related to the activities are stated in their current price levels. This entails that prices may fluctuate depending on market developments. This is not analysed in this chapter, but is considered in the last chapter of this thesis. Moreover the aim has not been to establish the exact prices related to the activities. The aspiration has been to understand which are the factors affecting the economic consequences of decommissioning and to generate an estimate of costs and revenues that can be expected.

As for the revenue generating activities it is important to point out that second hand value of turbines or its components is assumed to be negligible. This is due to that the market for second hand turbines is currently very underdeveloped which impedes gathering of reliable data. Moreover the experts in the market are doubtful that there will be economies in selling second hand turbines (Tschierschke 2008-03-14 and Lauritzen 2008-03-07).

Figure 10 shows an overview of the activities and sub-activities that characterize the decommissioning process. The two last activities, Treatment of foundation and treatment of cables, are those that may or may not be performed depending on the requirements posed by the county or commune at the time of decommissioning.

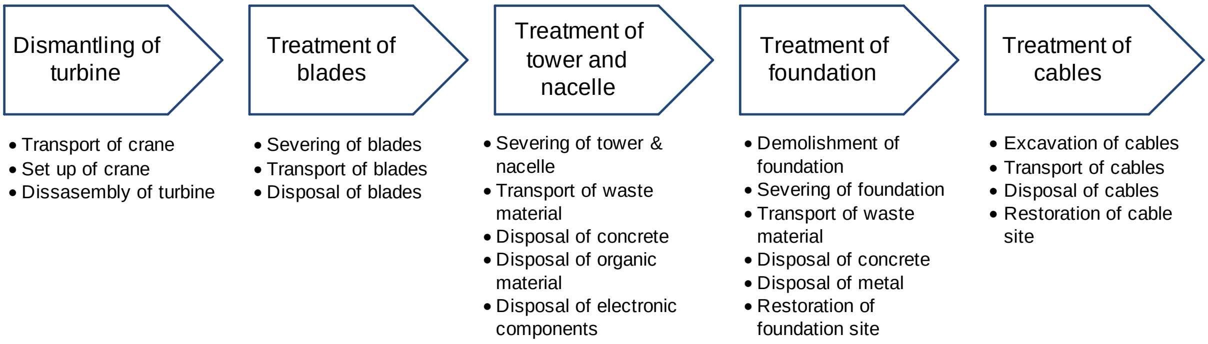


Figure 10 An overview of the decommissioning process.

Activity 1: Dismantling of turbine

Sub activity 1.1: Transport of crane

The dismantling of wind power turbines requires the use of a mobile crane, which has to be transported to the site. The costs depend on the crane required, how far it has to be transported to reach the site, and whether the turbines are land-based or located offshore.

<u>Land-based:</u> Mobile cranes for land-based dismantling involve the transportation of the crane itself and also a truck fleet needed to carry counterbalance and other equipment. A small crane only requires 3-5 tucks while a midsize to large crane requires 10-15 trucks. The price rate for trucks used is 300 SEK per 10 km. (Tunmats 2008-03-14 and Jakobsen 2008-03-17)

<u>Offshore:</u> For offshore sites the crane is mounted on a jack-up barge or a self-elevating crane ship. Globally there are five vessels that are specialised in working with offshore wind power turbine

installation. Three of these are owned by A2SEA from whom the information presented was gathered. (Nedergaard 2008-04-01)

Self-elevating crane ships are self-propelling, thus eliminating the need for additional transportation boats. In the case of jack-up barges there are both self-propelling and non-self-propelling barges. For non-self-propelling barges towboats must be used in order to transport the barge to the site. (Nedergaard 2008-04-01)

The cost for transportation depends on the vessel used and how long it takes to reach the site. The vessels travel at a speed of 4 to 8 knots. For a vessel with a smaller lifting capacity (approximately 120 tons at 80 meters height) the cost is currently 40 000 EUR per day. Vessel with a lifting capacity of 200 tons currently cost 120 000 EUR per day. Since market capacity is currently low the price trend points upwards. Between the first of January and the first of April of 2008 the prices increased with 10 to 15% due to high demand for these boats. However, there are currently plans to build five new vessels specialized in wind power installations. The construction of new vessels takes approximately three years. The new vessels will have increased capacity since wind turbines are generally becoming larger. This also means that the smaller vessels used today might be refurbished into service boats or sold off in the future. (Nedergaard 2008-04-01)

Sub activity 1.2.: Set up of crane

Once the crane has been transported to the site it is set up by the turbine to be dismantled. Consequently each turbine requires a set up.

Land-based: For land-based turbines the set up cost can be divided into an initial set up cost and a variable set up cost if there is more than one turbine to be dismantled at the same site. The initial set up cost covers the cost of set up for the first turbine. The variable set up cost, which applies to each of the remaining turbines, corresponds to approximately two thirds of the initial set up. From the interviews it was deduced that the initial set up cost varies from 50 000 SEK to the tenfold amount depending on the size of the crane used. (Tunmats 2008-03-14 and Jakobsen 2008-03-17)

Offshore: The offshore set up cost depends on the time required for set up at each turbine, which is estimated to range between 1 and 2 hours per turbine. Despite this estimate the real set up time may vary considerably depending on site conditions such as weather, currents, and other site-specific conditions. In order to account for unforeseen conditions Nedergaard recommends that an additional 30% margin is added to the estimated durations. The daily rate is the same as for the transport of the vessel which is 40 000 EUR for a smaller vessel and 120 000 EUR for a lager vessel. (Nedergaard 2008-04-01)

Sub activity 1.3.: Disassembly of turbine

To avoid the risk of pollution caused by spill, it is important that oils and other environmentally harmful fluids are removed before the turbine structures are tampered with.

Land-based: For land-based turbines there are two plausible methods to bring down the tower. One of these is to use of lifting equipment, such as crane or a winch, to bring down the turbine. The turbine can also be toppled over without such equipment. To do so explosives can be employed to blast away the tower structure and bring the tower down. In the case of a hybrid tower explosives can be replaced by a hydraulic hammer that is used at the base of the tower.

Important considerations when deciding which method to employ are the material in which the tower is built and the surrounding areas that can be affected by vibrations due to the toppling or blasting of the tower. (Ardefors&Budzynsk 2006, Dressler 2008-04-14, Ahlström 2008-04-01)

When the turbine is disassembled with a crane the first step is to remove the blades, one at a time. After removing the blades the nacelle is lifted down. Once these parts have been removed the tower is cared for. (Andersson 2008-03-10) The price estimates for the cranes (expressed in rental rate per hour) vary between 5 000 SEK for the smallest cranes and 10 000 SEK for the largest crane. There is a linear variation for the sizes in between. The dismantling is estimated to take one day regardless of the size of the turbine. The make of the turbine, on the other hand, may have an effect on the disassembly time needed. (Juntti 2008-03-11 and Winberg 2008-03-17)

Offshore: The dismantling at offshore locations is expected to be a reversed assembly process. It is expected to take approximately 5-6 hours and a crane is required. The blades and nacelle are removed in the same manner as for land-based turbines. The tower is brought down by releasing it from the base and then lifting it down. Alternatively, the tower can first be divided into segments and then each segment is lifted down. Currently no hybrid towers have been raised at offshore locations; therefore the process employed is uncertain. (Nedergaard 2008-04-01)

The dismantling costs at offshore locations are defined by the duration and day rate for the vessels employed. As mentioned previously the rates are currently between 40 000 EUR and 120 000 EUR depending on the crane required. The boats have a limited load capacity and space, therefore several runs must be made to and from the harbour where the turbines can be unloaded. Since the boats can carry only four turbines at the time a number of tours might be necessary, adding costs to the project. Furthermore, it is not always possible to use the closest harbour since not all harbours have capacity to store wind power turbines. (Nedergaard 2008-04-01)

Summary of the dismantling of turbine activity

Table 2 Overview of the dismandling of turbine activity

Sub-activity	Cost object	Cost drivers	Level
Transport of crane	Logistics	Duration (distance), intensity (crane type)	Batch
Set up of crane	Crane	Duration (time), intensity (crane type)	Unit
Disassembly of turbine	Crane	Duration (time), intensity (crane type)	Unit

In Table 2 information about cost objects, cost drivers and the level at which costs are incurred is presented. The cost for transportation of the crane is independent of the number of turbines. Therefore it is established at a batch level. The cost drivers for this activity are duration and intensity since the costs will vary depending on the transportation distance and the crane required. The costs for set up and disassembly depend on the crane required and the time it takes to set up the crane and disassemble the turbine. This cost will depend directly on the number of turbines dismantled and is therefore incurred at a unit level.

Activity 2: Treatment of blades

Sub activity 2.1.: Severing of blades

When the blades have been removed they must be severed into smaller pieces in order to facilitate transportation and disposal. The severing cost is approximately 200 SEK per ton. (Ardefors & Budzynsk 2006)

Sub activity 2.2.: Transport of blades

The blades material must be transported to a disposal facility. Transportation is to some extent included in the price for severing but for long distances transportation costs will increase. (Ardefors&Budzynsk 2006) The trailers used for transportation of this type of material cost 300 SEK per 10 km and have a maximum load capacity of 25 tons. (Andersson 2008-03-10)

Sub activity 2.3.: Disposal of blades

According to the directive Förordningen (2001:512) om deponering av avfall § 9 and 10 in Sweden it is forbidden to use landfill as disposal method for flammable and/or organic waste. Glass fibre and carbon fibre are flammable. However combustion of these materials requires very high temperatures, which few incineration facilities can provide. This implicates that long transportations may take place if these materials are to be incinerated. (SITA 2008-04-03)

According to the Swedish Environmental Protection Agency it is environmentally motivated to transport the blades up to 300 - 500 kilometres in order to avoid landfill. It is unclear to what extent this is monitored. The fee for disposal of blades for incineration is 900 SEK per ton and the charge for landfill is 1 400 SEK per ton. If landfill is chosen as disposal method the costs for severing will be reduced since sizes up to 6 meters are accepted. (SITA 2008-04-03)

Two additional methods for handling of the waste material will be mentioned since they may become increasingly interesting in the future. One method is to fragment the material and then separate it so it can be used as filling material. (Bank 2008-03-14) Another more advanced method is to use pyrolyzes. In this case the plastic is gasified and burnt to produce energy whereas the glass fibre, metal, and fillers recovered and separated. The glass fibre can then be used as insulation material or as short fibre reinforcement for new plastic products or filler pastes. (ReFiber 2008-04-14) Currently these methods cannot compete economically with the other disposal methods. (Bank 2008-03-14)

Summary of the treatment of blades activity

Table 3 Overview of the treatment of blades activity

Sub-activity	Cost object	Cost drivers	Level
Severing of blades	Severing fee	Transaction (material weight)	Unit
Transport of waste material	Logistics	Duration (material weight, distance)	Unit/batch
Disposal of blades	Disposal fee	Transaction (material weight)	Unit

Table 3 summarises the costs objects, cost drivers and level at which costs arise in the treatment of blades activity. For the severing and disposal activities the cost driver is the number of transactions. This is due to that the cost will be the same for every ton of material. Thus the number of tons represents the number of transactions. The tonnage will depend on the number of turbines; therefore the cost will be incurred at the unit level.

The transportation cost depends on the transportation distance and the amount of material transported. Since the transportation distance is independent of the number of turbines this cost is established at the batch level. The number of trailers necessary, however, depends on the amount of material and therefore the number of turbines.

Activity 3: Treatment of tower and nacelle

Sub activity 3.1.: Severing of tower and nacelle

The cost for severing depends on the material to be treated. Concrete is crushed at a fee of approximately 400 SEK per cubic meter. (Ahlström 2008-04-01) Steel, on the other hand, is severed into pieces of 0.5x01.5 metres at a fee of 200 SEK per ton. (Ardefors&Budzynsk 2006)

Sub activity 3.2.: Transport of waste material

The transport of waste material to a disposal facility is normally included in the severing price (Ahlström 2008-04-01 and Ardefors&Budzynsk 2006). If exceptionally long transport distances are required the cost for trailers with a maximum capacity of 25 tons is currently 300 SEK per 10 km. (Andersson 2008-03-10)

Sub activity 3.3.: Disposal of metal

The metal material in the turbine has a second hand value and can be sold to a scrap dealer. The most common metal in wind turbines is steel and high-strength steel. High strength steel is ordinary steel that has been treated in order to make it more persistent. This has no effect on its scrap value, thus steel and high strength steel is sold at the same market price. The turbine also contains cast iron, which is sold at approximately the same price as steel. The steel price is adjusted on a monthly basis in accordance with Aktiebolaget Järnbruksförnödenheter (JBF) (Holm 2008-03-31). JBF is a limited company owned by Swedish steelworks that handles purchasing of scrap steel. (JBF 2008-03-31)

Stainless steel is more valuable than ordinary steel due to its content of nickel. It is the share of nickel content that determines the scrap value and the price is based on the London Metal Exchange (LME). Standard stainless steel has a nickel content of 8%. (Holm 2008-03-31)

Besides steel, iron, and stainless steel the turbine contains copper, aluminium and lead. The price for these metals is also based on the LME. Copper can be found both in the generator and in the electrical cables. Copper from the generator has a lower market value than the copper from cables. This is due to the pureness of the copper used. The copper in cable can be separated from other materials in the cables and sold for 47-48 SEK per kilo copper. Alternatively, the entire cable can be sold off at a price of 13-14 SEK per kilo of cable. (Holm 2008-03-31) The prices for the different metals are summarised in Table 4.

Table 4 Metal prices as of 31 march 2008 (Holm 2008-03-31)

Metal	**Price**
Steel and Cast Iron	1 500 SEK/ton
Stainless Steel (Ni 8%)	11 000 SEK/ton
Copper (generator)	28 000-30 000 SEK/ton
Copper (cable)	13 000-14 000 SEK/ton cable
Aluminium	13 000-15 000 SEK/ton
Lead	7 000-9 000 SEK/ton

Sub activity 3.4.: Disposal of concrete

Recovered concrete is used as filling material and is most commonly given away since it does not hold any significant second hand value. Transportation costs for concrete waste are usually included in the severing fee. A cost can be associated with the concrete disposal if the concrete is land filled. (Ahlström 2008-04-01)

Sub activity 3.5.: Disposal of organic material

Organic material is incinerated at the charge of 900 SEK per ton. (SYSAV 2008-04-03)

Sub activity 3.6.: Disposal of electronic components

Electronic components can be handed in to a recycler free of charge. (Bank 2008-03-14)

Summary of the treatment of tower and nacelle activity

Table 5 Overview of treatment of tower and nacelle activity

Sub-activity	**Cost object**	**Cost drivers**	**Level**
Severing of tower and nacelle	Severing fee	Transaction (material weight)	Unit
Transport of waste material	Logistics	Duration (material weight, distance)	Unit/batch
Disposal of metal	Revenues	Transaction (material weight)	Unit
Disposal of concrete	Disposal fee	Transaction (material weight)	Unit
Disposal of organic material	Disposal fee	Transaction (material weight)	Unit
Disposal of electronic components	Disposal fee	Transaction (material weight)	Unit

Table 5 summarises the cost objects, cost drivers and levels at which costs arise in the treatment of tower and nacelle activity. For severing and disposal activities the costs and revenues are transaction driven. This is due to that there is a fixed cost or revenue for each ton of material. The number of transactions is therefore defined by the total tonnage of each material type. With the exception of the transport activity all activities are defined by the number of turbines. This is due to that the number of turbines defines the total amount of material. The economic effects therefore arise at a unit level.

For transportation the distance is independent of the number of turbines and therefore arises at a batch level. The number of turbines, however, defines the number of trailers or runs required.

Activity 4: Treatment of foundation

This activity is not considered compulsory by all counties and communes, therefore it is uncertain whether or not it will be undertaken. A consideration regarding whether or not to remove a land-based concrete foundation is on what type of land it is placed. (Jönsson 2008-03-31)

The propensity to remove offshore foundations in the future is also uncertain. During the period of time from installation to decommissioning the foundations may have become a habitat for flora and fauna in the ocean, acting like an artificial reef (Öhman & Wilhelmsson, 2005). In such case a removal may cause more negative effects on the environment than leaving it behind. (Strömberg 2007) At the time being there is no experience in removing offshore foundations, therefore the process described is based on deductions, assumptions and to a certain extent speculation.

Sub activity 4.1.: Demolishment of foundation

Land-based: At land-based locations the concrete in the foundation can be removed using a hydraulic hammer on an excavator or by using concrete scissors. The process normally takes one hour per 10 cubic meters and costs 250-400 SEK per cubic meter. Some of the factors determining the costs are the properties of the concrete and the site location. In some cases there is also an establishment cost, which depends on the site location and which type of machinery is needed. This cost usually lies between 10 000 – 15 000 SEK. (Ahlström 2008-04-01 and Andersson 2008-04-02) The process and expenses where verified by another source that estimated the cost to 500 SEK per cubic meter, including establishment costs. (Segerström 2008-04-01)

Offshore: The removal of offshore foundations is expected to be considerably more expensive than the removal of land-based foundations. The methods employed will depend on the type of foundation in place. Consideration must also be taken to the surrounding maritime environment. (Petersen, 2008-04-18, Mygård 2008-04-19, and Christensen 2008-04-10)

In the case of mono pile foundations it is presumed that the foundation will be cut at its root with an underwater cutting tool or employing a small load of explosives. The mono pile can then be lifted onto a transport boat as a whole. It is not desirable to let the mono pile reach the ocean floor since make lifting more difficult. Petersen estimates the removal may take 1.5 days. Mygård, on the other hand, questions whether the removal is even possible and, if it is, estimates it will take three to seven days. (Petersen, 2008-04-18, Mygård 2008-04-19)

For gravity based foundations weight is a considerable issue. According to Petersen (2008-04-14) there are three viable methods to remove this type of foundation. One alternative is to employ underwater cutting tools to divide the construction into more manageable parts and thereafter remove these from the site. Segerström confirms this view and believes the offshore foundations can be removed using a hydraulic hammer or a concrete scissors. Segerström estimates that the costs to demolish concrete triple if the work is conducted offshore, amounting to approximately 1500 SEK per cubic meter at depths of 10-15 meters. In most cases it is probably necessary contract a diver costing 1000 SEK per hour. (Löfstrand 2008-05-16)

Petersen (2008-04-14) explains that another alternative is to employ explosives to induce a quiet blast. The remainders of the foundation can thereafter be removed. Segerstörm argues that at depths exceeding 10-15 m explosives will most likely be required increasing costs to 2500 SEK per cubic meter. (Segerström 2008-04-01)

The third alternative suggested by Petersen (2008-04-14) is to remove the ballast and then use a pump to replace water inside the foundation with air. The foundation can then be towed to land. The last proposal is considered less viable since gravity foundations are presently not designed to enable removal of ballast making this process quite difficult.

The costs for this sub-activity primarily depend on the boat required and the duration of the operation. Both Mygård (2008-04-19) and Petersen (2008-04-18) believe it will be necessary to use the same boats as when the foundations are installed. Access to these vessels is currently scarce and their prices amount to between 500 000 GBP to 1 000 000 GBP for mobilization. The day rate is currently between 8 000 and 15 000 GBP. As mentioned previously the time required to remove a foundation is estimated to between 1.5 to 7 days for a mono pile foundation and 3 days for a gravity foundation. To account for unfavourable weather conditions it is advised to add between 30% and 50% to the expected duration. (Petersen, 2008-04-18 and Mygård 2008-04-19)

Sub activity 4.2.: Severing of foundation material

After the initial demolishment the material still consists of large segments. Thus the material has to be fragmented in order to make it more manageable. For onshore foundations and offshore gravity foundations a hydraulic hammer is used that crushes concrete and removes armouring steel magnetically. For land-based foundations the severing fee is included in the demolition fee. For offshore foundations, on the other hand, the severing will take place when the foundation material reaches land. Costs for concrete demolition can be reviewed in the demolition of foundation activity. There cost increases if especially fine crushed concrete is requested. (Ahlström 2008-04-01)

In the case where mono pile foundations have been used it is most likely that the steel will be severed into smaller parts once the foundation reaches land. The cost and process should be similar to the severing of steel in the tower and nacelle and costs 200 SEK per ton. (Ardefors & Budzynsk 2006)

Sub activity 4.3.: Transport of waste material

Waste material from the foundation consists of concrete and steel. The transportation costs are normally included in the severing costs and therefore no cost is specified in this activity. However if the disposal implicates long transpirations additional costs may arise. Currently trailers with a capacity of 25 tons can be rented for 300 SEK per 10 km. (Ahlström 2008-04-01)

Sub activity 4.4.: Disposal of concrete

The concrete is used as filling material and is most commonly given away since it does not hold any significant second hand value. A cost can be associated with the concrete disposal if the concrete is land-filled and/or if long transportation distances are necessary. (Ahlström 2008-04-01)

Sub activity 4.5.: Disposal of steel

Steel from the mono pile foundations can be sold to scrap dealers. The market price per ton of scrap steel is currently 1 500 SEK. (Holm 2008-03-31)

Sub activity 4.6.: Restoration of foundation site

Land-based: The hole left once the foundation is removed must be filled with suitable material, which in most cases is humus. This cost approximately 50 000 SEK and is estimated to take one day. Restoration costs may increase considerably if there is an access road to the turbine that is no longer wanted and therefore must be “removed”. This means that the road area is restored by its location is matched to the surroundings (for example by planning trees if there is a forest surrounding the road). The costs will vary considerably depending on the road length and the degree of restoration necessary. For example restoration after a 250 meter long road with no exceptional characteristics costs approximately 150 000 SEK. (Jönsson 2008-03-31)

Offshore: No restoration is needed at offshore sites since the seabed is levelled over time by natural causes. (Nedergaard 2008-04-01)

Summary treatment of foundation

Table 6 Overview of treatment of foundation activity

Sub-activity	Cost object	Cost drivers	Level
Demolishment of foundation	Rental rate, Demolishment fee	Duration (no. of turbines) Transaction (material weight)	Unit/batch
Severing of foundation material	Severing fee	Duration (material weight)	Unit
Transport of waste material	Logistics	Duration (material weight, distance)	Unit/batch
Disposal of concrete	Disposal fee	Transaction (material weight)	Unit
Disposal of metal	Revenues	Transaction (material weight)	Unit
Restoration of foundation site	Restoration fee	Transaction (material weight)	Unit

In Table 6 information about the cost objects, cost drivers and levels of aggregation is presented for the treatment of foundation activity. The cost driver behind the demolishment activity depends on the location of the turbine. For offshore turbines duration is the cost driver and it is defined at a batch and unit level. The mobilization cost for the vessel is independent of the number of turbines and therefore incurred at the batch level. The total rental cost for the vessel, on the other hand, depends on the number of turbines and is therefore defined at the unit level. On land-based locations the cost driver is transaction based since the demolition fee is stated per ton. The total cost for this activity will therefore depend on the tonnage, which is interpreted as the number of transactions.

Transportation costs are, as previously has been explained, duration driven and incurred at a batch and unit level. The transportation distance is independent of the number of turbines and thereby defined at the batch level. The number of turbines, on the other hand, define the amount for material and thereby the number of runs.

For disposal and restoration there is a given fee per cubic meter. This activity is therefore transaction based, where the total dimensions defines the number of transactions. The number of turbines defines the total number of cubic meters; therefore the cost is incurred at a unit level.

Activity 5: Treatment of cables

Currently cables dug down in Sweden are usually left behind when they are rendered useless. As has been pointed out in the first section of this chapter, where legal aspects were covered, the requirement to dig up cables varies between different counties. Some companies within the recovery industry have expressed interest in digging up cables due the material value that can be retrieved. Nevertheless this currently does not take place at a considerable extent. (Wallerius 2005-08-31 and Forsgren 2008-03-20)

Sub-activity 5.1.: Excavation of cables

If the cables are to be removed there are standardized price approximations used in the industry to estimate removal costs. This cost varies between 183 and 185 SEK per meter of cable depending on the cable type. The job usually involves two persons and one excavating machine as well as a truck and a driver. The removal is not considered problematic since the ground was prepared when the cables were dug down. In other words the ground will easier to excavate when removing the cables since rocks, for instance, will already have been removed. (Nordgren 2008-03-22 and Karlström 2008-03-25). If the cables are airborne the costs are reduced considerably to between 13 to 18 SEK per meter of cable (Karlström 2008-03-25). It is assumed that the cables are always dug down since this scenario is always the case for internal cables. Moreover the cables at offshore sites are also dug down.

The cables at offshore locations are can be placed inside of tubes. In this case the cables can be removed by cutting them off at the turbine and then dragging them to land. (Holst, 2008-03-25) The cables can also be buried under stones or put down in the sea bead through other methods, depending on the surrounding conditions. (Löfstrand 2008-05-16) It has not been possible to find reliable pricing regarding the excavation of cables at sea. Therefore the cost is approximated to be the same as for onshore locations, which may imply an underestimation of actual costs.

Sub-activity 5.2.: Transport of cables

The transportation cost for cables is normally included in the removal fee. This may, however, vary depending on transportation distances and the amount of material to be transported. (Nordgren 2008-03-22 and Karlström 2008-03-25)

Sub-activity 5.3.: Disposal of cables

Once the cables have been dug up they are transported to a recovery station or exported to developing countries where the recovery process can be performed with cost advantages. Cables have a considerable material value due to their metal content. The materials in the cable and their share of cable weight vary depending on the conductor metal used and the type of cable. The aluminium and copper in the cables, which are the common conductor materials, have a high market value due to their high quality. (Jansson, 2008-03-15 and Jiffler, 2008-04-01)

StenaMetall has specialized in the recovery of metals and has a facility that handles used cables in Sweden. Since the metal in the cable is usually sold together with the entire cable its value is depreciated due to the costs incurred in recovering the metal. Compared with the market value of the metals this depreciation is about 70%.

Summary of the treatment of cables activity

Table 7 Overview of treatment of cables activity

Sub-activity	Cost object	Cost drivers	Level
Excavation of cables	Excavation fee	Transaction (cable length)	Unit/batch
Transport of cables	Logistics	Duration (material weight, distance)	Unit/batch
Disposal of cables	Revenues	Transaction (material weight)	Unit
Restoration of cables site	Restoration fee	Transaction (cable length)	Unit/batch

Table 7 summarises the cost objects, cost drivers and levels at which the costs are incurred for the treatment of cables activity. All sub-activities except transportation of cables have transaction based cost drivers. This is due to that fees are stated per unit (meters or tons). The number of meters define the excavation and restoration cost for internal cables. For external cables, on the other hand, these costs are shared by all turbines and thus incurred at a batch level.

As has been explained previously the transportation cost is defined by distance at the batch level and by the material which depends on the number of turbines. For disposal of cables the number of units defines the material weight and thereby the revenues generated.

5. Modelling economic consequences of wind turbine decommissioning

In this chapter the information presented in the previous chapter concerning the scope of decommissioning, the wind turbines technical characteristics, and the decommissioning process come together. The information is used to build a model that can help participants within the wind energy industry to predict costs for wind turbine decommissioning. The chapter begins with an introduction to modelling. Here modelling is described from a theoretical perspective and methodologies for creating models are presented. These frameworks are then used to build and describe a model aimed at estimating economic consequences of wind turbine decommissioning. The model is presented by describing its intended use, assumptions & limitations underlying the model, and parameters chosen. A detailed account is then given of how economic consequences of each sub-activity of the decommissioning process have been calculated.

Once the reader is familiarized with the models general characteristics it is applied to specific cases. With the intention to investigate how well the model estimates materials present in the turbine it is applied to a Vestas V82 1,65MW turbine. The model is then used to predict economic consequences for decommissioning of sixteen different types of turbines. In each of these cases the characteristics of the turbines and the extent of decommissioning vary. The chapter is concluded with a discussion of the economic consequences of decommissioning estimated by the model.

5.1. Modelling

A model is a something that mimics relevant features of the situation being studied. (Bender 1978, p.1). Dym (2004, p.4) sees modelling as an important part of our understanding of the “real world” where it is one of the three stages observation, modelling, and prediction. The modelling part is concerned with analysing our observations for at least one of three reasons; to describe the behaviour or result observed; to explain why that behaviour or result occurred as it did; to allow us to predict future behaviour or results that are yet unseen or unmeasured. (Dym 2004 p. 5)

5.1.1. The components of a model

According to Bender (1978, p .2) the world seen in the perspective of a model can be divided into three categories:

1. Things whose effects are neglected.
2. Things that affect the model but whose behaviour the model is not designed to study.
3. Things the model is designed to study the behaviour of.

The first category is completely ignored by the model. The second category is for example constants and functions. They are external and can be referred to as input. The third category, what the model seeks to explain, is referred to as output. These three categories (neglect, input and output) are important in modelling. If for example the wrong thing is neglected the model will be no good. If too many variables are taken into consideration the model will become too complex and difficult to use since it will probably require large amount of data. (Bender 1978, pp. 2-3)

Another important consideration is what variables to use in the model. For a variable to be useful it must be measurable, either directly or indirectly (Shier & Wallenius 1999, p. 30). However this does not mean that a variable can be neglected because it is difficult to handle since this might make the conclusions of the model invalid. Another thing to keep in mind is that different models make different types of simplifying assumptions. Thus there is usually no single best way of describing a situation. (Bender 1978, p .3) Levin (1968, p. 7) states, “it is not possible to maximize simultaneously generality, realism, and precision”. This means that tradeoffs between the three have to be made.

5.1.2. Building a model

Bender (1978, pp. 6-7) stresses that building a model requires imagination and skill. It is not something that can be taught trough a textbook or by listing rules. He does however present an outline of the modelling process consisting of four steps.

1. Formulate the problem
2. Outline the model
3. Examine its usefulness
4. Test the model

The first step is important since the nature of the model is chosen depending on how the model is to be used and what information is to be retrieved from it. In the second step information must be divided into one of the three categories mentioned earlier; neglect, input and output. The interrelations among variables must also be determined. In the third step the model author must question if the data required to make predictions can be obtained. If not, step two or even step one have to be revised. In the last step the model is tested. (Bender 1978, pp. 6-7) The ultimate test of a model is how well it performs when it is applied on the problem it was designed to handle. (Bender 1978, p .1) It advisable to start out with easy predictions, in order to minimize the time wasted on complicated calculations built on defective bases. If the predictions are wrong or unacceptable in some way and mathematical errors can be ruled out, the first steps have to be revised again. If the predictions are less accurate than anticipated, it is a good idea to try to understand why. This may uncover implicit or false assumptions. (Bender 1978, pp. 6-7)

It is important to remember not to go too far in the extent of applying the model. It is dangerous to use the model blindly on problems that differ greatly from those on which it was tested. Every application should be view as a test of the model. (Bender 1978, p. 7)

5.2. Modelling wind turbine decommissioning

Using the frameworks presented above, a model that will predict revenues and costs related to turbine decommissioning has been developed. In this section the models intended use is described, followed by a discussion about assumption and limitations underlying the model. After this, the calculations made in the model are described. Building the model corresponds to the fourth activity in the process to recognize economic consequences of decommissioning, as can be seen in Figure 11.

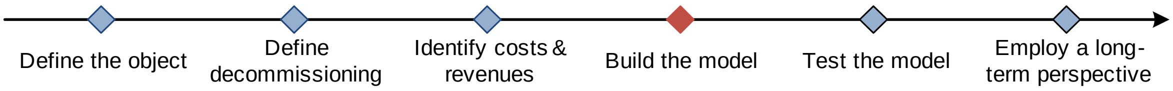


Figure 11 Process to estimate the economic consequences of decommissioning

5.2.1. Intended use

The aim of this thesis is to develop a model that can estimate the costs for decommissioning wind turbines that are currently being installed in Sweden. It is important to stress that the calculation will only give an indication of the economic effects. The validity of the results presented by the model will depend on market forces affecting costs and revenues related to decommissioning.

Moreover, the information reviewed about turbines has been based on information gathered about models from three manufacturers; Vestas, Enercon, and Nordex. Much of the information is considered to be applicable to other manufactures, but it is worthwhile noting that there may be differences which may not be considered in the model. Therefore this model is recommended to users that have turbines similar to those examined. The model may also be limited to calculate decommissioning costs for turbines ranging between 800 kW and 3000 kW, since information has been gathered relate to turbines within this range of rated power. Therefore the assumptions in the model may not be valid for turbines outside this interval of rated power.

Another important consideration the user must keep in mind is that the model approximates costs for a somewhat ideal decommissioning project. If the user finds that there are complications with the site or the turbines to be decommissioned the results presented by the model should be regarded as a very optimistic approximation.

Since the model has been constructed based on activities, there is a built in flexibility in the model. The users can choose to include or exclude activities that apply to their particular case. For example the need to remove foundations and cables has been questioned. Should the user find that these activities will not be performed the costs and revenues related to them can be ignored by excluding the parameters that define those costs. By using excel as programme software to build the model the user is also enabled to change parameters in order to better reflect current prices or considerations that have been ignored. With the intention of enabling the user to assess the validity of the calculations the results for all sub-activities are presented. The costs for some sub-activities have been ignored since they were considered to be negligible. These sub-activities are still included in the model since they may help the user to reflect on which costs and revenues should be considered.

The model does consider that decommissioning projects may encompass one or several turbines. This has been handled by managing fixed and variable cost components. The results are presented in a total cost and a cost per turbine. *Note that in the model costs and revenues have reversed signs; that is, costs are positive and revenues negative*.

5.2.2. Assumptions and limitations

The costs and process for dismantling and restoration have been described in the previous chapter. The input data for the model has been gathered by an extensive number of interviews with experts within the industry. Throughout the creation of the model a careful approach has been preferred when estimating revenues and costs. This means that if the information gathered on cost and revenues where stated as an interval, the high end of the interval was used in the case of costs and the low end of the interval was used in the case of revenues. Exceptions to this were made in cases where the approach was not deemed reasonable.

The model builds on the assumption that decommissioned turbines and/or their components will not be sold on the market. This is motivated by the fact that the progress in wind turbine technology is likely to slow in the future. As the marginal technological development in turbines slows the propensity to replace older turbines with new ones should also be restricted since their technological superiority will be limited. Another argument in favour of this proposition is that as the turbine sizes increase so do investment costs for the turbine and its installation and decommissioning processes. To justify incurring sunk costs for the investment in the turbine and installation and to justify additional costs for removal and replacement the requisite on technological superiority of new turbines increases. Therefore it is expected that the turbines installed today will be serve their economic lifetime of 20-25 years. The revenues are therefore calculated bases on the scrap value of materials in the turbine.

As mentioned previously the model may be limited to predict costs and revenues for decommissioning wind turbines with rated powers between 800 kW and 3000 kW. This range of rated power was chosen since it represents the turbines being installed in Sweden today. For turbines outside of this range the predicted economic consequences may be erroneous since turbines with that rated power have not been examined. It has been observed that manufacturers often increase the models in scale when the rated power increases, which means that the descriptions and assumptions in the model may very well be valid for turbines with higher rated power. Despite this caution is advised.

Moreover there are many assumptions made about the materials in the turbine, which are specified in the upcoming sections. These assumptions are built on observation made about Vestas, Nordex, and Enercon models. Some significant differences where found between these models which have been used in order to establish which parameters are important to consider in the model. Due to time restraints all models and all manufacturers have not been examined which may pose a problem if the turbines on which the model is to be applied differ significantly from the turbines examined. For example there may be models that have an abnormal hub height or nacelle weight. In such cases the model may give erroneous estimates since the largest crane accounted for is a 600 ton lattice boom crane. For models that require a crane with a capacity exceeding this crane’s costs should be calculated with other methods.

The model takes into account that turbines can be located at onshore and offshore installations, but is restricted to predict costs for relatively easily accessible locations. This simplification is motivated by the difficulties in including extraordinary considerations in the model, while keeping it simple. Should the user want to predict costs for turbines at locations that are hard to access, this must be considered outside of the model.

The model also ignores costs related to planning and costs that may arise due to unforeseen difficulties during the decommissioning. This is motivated by that these costs can be hard to foresee and the validity and reliability in including them is questionable. Certain activities have also been excluded. For example there is no account for the costs and revenues associated with removing the transformer station. This is due to that the model is designed to account for the removal of turbines only.

The model is also limited to account for decommissioning that follows the process described in the previous chapter. Should other methods be employed the model will not anticipate costs accurately. It is assumed that all turbines will be dismantled with a crane since this method is applicable at all locations. For example, if dynamite is considered as an alternative to bring the tower down factors such as the effect of vibrations to the surroundings may restrict the viability of this alternative.

Although certain assumptions are made about the process to be followed there is a considerable flexibility built into the model. The user can choose to ignore costs or revenues that do not apply to the particular case examined. It is also important to note that some of the processes described have a considerable uncertainty related to them. In many cases there is no previous experience of certain activities such as the removal of offshore foundations. To minimize the risk of making wrong assumptions several sources have been interviewed.

5.2.3. Choice of parameters

The choice of parameters was made by reviewing the information about costs and revenues related to the expected decommissioning process for wind turbines. Identified costs and cost divers for different activities were related to characteristics that could vary between different turbines. The number of parameters have been restricted in the extent it is possible in order to keep the model simple and to guarantee ease of use. There is a total of thirteen parameters requested from the user, these are:

- *Location:* the user can only specify whether the turbines are land-based or offshore sites. This parameter defines the process employed in the decommissioning process. The variable is used in the following activities: dismantling of turbine and treatment of foundation.

- *Number of turbines*: the user establishes this variable by inserting a discrete number in the field. The number of turbines becomes a cost driver for all variable costs in the calculations. The variable is used in all the activities.

- *Nacelle weight*: the user establishes this variable by stating a discrete number, corresponding to the weight of the nacelle in tons. The nacelle weight is used to calculate the capacity required of the crane and the presence of different metals. The variable is used in the following activities: dismantling of turbine and treatment of tower and nacelle.

- *Gearbox*: the user can only specify whether or not a gearbox is included in the turbine. Together with the nacelle weight this parameter is used to calculate the distribution of weight between different materials in the nacelle. The variable is used the treatment of tower and nacelle activity.

- *Hub height:* the user defines this variable by stating a discrete number corresponding to the hub height, expressed in meters. The hub height is used to calculate the capacity required of the crane. The variable is used in the following activities: dismantling of turbine and treatment of tower and nacelle.

- *Tower type:* the user can only specify whether the tower is a hybrid tower or a tubular steel tower. This variable is used to determine the costs related to the treatment of the tower and the revenues related to the tower material. The variable is used in the treatment of tower and nacelle activity.

- *Tower weight:* the user states the tower weight expressed as a discrete number, specified in tons. Together with the tower type this information is used to calculate the costs and revenues related to the material in the tower. The variable is used in the treatment of tower and nacelle activity.

- *Blade weight:* the user defines this variable by stating a discrete number accounting for the total tonnage of blades per turbine. The information is used to calculate the material to be handled in the treatment of blades activity. The blade weight is also used to calculate the weight of steel in the rotor. The parameter is used in the following activities: treatment of blades and treatment of tower and nacelle.

- *Foundation weight or volume*: this variable must be expressed by the user as a discrete number. Depending on whether the turbine is land-based or offshore, and the type of foundation, the dimensions are specified in tons or cubic meters. For land-based foundations and gravity foundations offshore, the unit of measure is cubic meters. In the case of mono pile foundation the foundation weight, specified in tons, is necessary. This variable is used to define costs and revenues in the treatment of foundation activity. Removal of foundation is optional, therefore this parameter does not have to be stated if the foundation is left behind.

- *Foundation type:* the foundation type is automatically defined by the unit used to describe the foundation dimensions (tons or cubic meters) and the location of the turbine. This variable is used to define costs and revenues in the treatment of foundation activity. Removal of foundation is optional, therefore this parameter does not have to be stated if the foundation is left behind.

- *Distance to electrical grid:* this variable is specified in meters and should give an approximation of the distance to the electrical grid. The distance to the electrical grid is used to calculate the costs and revenues in the treatment of external cables activity. Removal of cables is optional, therefore this parameter does not have to be stated if the cables are left behind.

- *Type of external cable:* this variable is specified by stating the share of copper and aluminium in the conductor material. Conductor material can be composed of only copper, only aluminium, or a mix of both. The data is used to compute revenues in the treatment of cables activity.

- *Weight of external cable:* this variable is specified by stating a discrete number, corresponding to the cable weight per meter. Although there is a relation to the number of turbines and the cable weight per meter it is nearly impossible to foresee the figure. This is due to that the cable weight will vary depending on the location of the turbine, the number of turbines, and the conductor material. In order to ensure accuracy this parameter is therefore requested from the user. The information is used to calculate revenues in the treatment of cables activity.

In order to better understand how these parameters have been used the model will be described in view of the activities performed in the decommissioning process. For every sub-activity a table is presented that specifies all the parameters used in the calculation and how they have been specified. *Requested parameters* are the ten parameters that have been described above and that are specified by the user. *Assumed parameters* are those which have been specified by the creators of the model. *Input parameters* are parameters that have been specified by information gathered from interviews. In some cases a parameter is described as both an assumed and an input parameter, this means that the information has been gathered by interviews but that there is a considerable degree of uncertainty in the accuracy.

5.3. Calculations and formulas used in the model

Activity 1: Dismantling of turbine

According to the description in the previous chapter this activity consists of three sub-activities; transport of crane, set up of crane, and disassembly of turbine. Together they represent the total economic effect for the dismantling activity.

$$Dismantling\ of\ turbine = transport\ of crane + setup\ of crane + dissasembly\ of turbine$$

Throughout this activity the crane used is the most important cost driver. The crane required is defined by the hub height, the nacelle weight and the location of the turbines; therefore these three parameters are used in all three sub-activities. These parameters are required since the hub height can be chosen independent of the nacelle and both of these are independent of the turbine location. Information about hub height and nacelle weight has been clearly specified in all of the technical descriptions reviewed, therefore it is concluded that the user will have access to this information. When finding data about the nacelle weight it is recommended to observe that the rotor and blade weight is not included.

The required capacity is computed in a similar manner regardless of location. The primary difference lies in the types of cranes considered and the costs for the crane.

To find the capacity of crane needed, five different cranes where studied. Four of them were telescopic boom cranes at a tonnage of 250, 300, 350 and 500, and one was a lattice boom crane with a tonnage of 600. These cranes where chosen since they are the once that can be used for dismantling turbines of the sizes this model concern. It can also be mentioned that all of these cranes are available in Sweden.

For these five cranes load lists where studied to find out how their lifting capacities were affected at different heights. This was summarised in a table for each crane. To retrieve which crane capacity is needed for a specific turbine the model searches the tables to find the crane with the least capacity that can lift the weight of the nacelle at hub height. The number of turbines is also requested in the sub-activities. This is explained by that the cost for the crane is driven by duration, which in its turn depends on the number of turbines to be dismantled.

Sub-activity 1.1.: Transport of crane

	Onshore	**Offshore**
Requested parameters	*Location, hub height, nacelle weight*	*Location, number of turbines, hub height, nacelle weight*
Assumed parameters	*Transport distance in km*	*Duration of transport*
Input parameters	*Trailer cost*	*Vessel cost*

The user must specify if the turbine is located at an offshore or an onshore site since this parameter defines how the crane's transportation costs are calculated. As can be seen in the table above the rest of the parameters used to perform the calculations differ depending on the location.

For onshore locations the crane capacity required, defined by the hub height and the nacelle weight, defines transportation costs for the crane used to dismantle the turbines. This is due to that the crane capacity defines how many trailers are needed to transport the crane and the counter weight.

The formula used to calculate the number of trailers is shown below. The data collected showed that a linear approximation could be made regarding the number of trailers needed. The number of trailers needed increases by two as tonnage increases by fifty, starting at a tonnage of 250 where three trailers are needed.

$$Number\ of\ trailers = \left(\frac{crane\ capacity - 200}{50} x\, 2 + 1\right)$$

Once the number of trailers is determined it is used as input to estimate the transportation costs. In Sweden distances are commonly measured in tens of kilometres, therefore the transportation distance is divided by ten. Sweden measures 1 572 km in length and 500 km in width and the location of the turbines can vary considerably. Therefore this cost can become quite significant. In the model a default transport distance of 300 km is used. This is due to that once the transportation cost for the crane become excessive it is probable that other alternatives will be considered to bring down the structure, such as employing dynamite. Should this distance be very inaccurate the user can alter the transport distance to better reflect actual conditions. The formula below shows how the transportation costs are computed as a function of the number of trailers, the rental rate, and the distance.

$$Crane\ transportation\ cost\ onshore = \frac{sek}{10\ km} x \frac{km}{10}\ x\ number\ of\ trailers$$

For offshore turbines other calculations must be made. In the model it is assumed that mobilization of the vessel and the transportation of turbines from the site to an adequate harbour will take approximately 1.3 days per turbine. One day is considered to represent the actual transportation time and a 30% margin is added to account for unfavourable weather or current conditions, as has been advised by experts in the industry.

$$Crane\ transporation\ cost\ offshore = 1{,}3\ x\ daily\ rate\ x\ number\ of\ turbines$$

Sub-activity 1.2.: Set up of crane

	Onshore	**Offshore**
Requested parameters	*Location of turbine, hub height, nacelle weight, number of turbines*	*Location of turbine, hub height, nacelle weight, number of turbines*
Assumed parameters		*duration of set up*
Input parameters		*duration of set up*

Once the crane has been transported to the site there is an initial set up cost. The set up cost is defined by the crane required. With the hub height, the nacelle weight and the turbine location the model identifies the crane and the applicable cost.

For onshore locations there is an initial set up cost that is defined by the crane required. The model will automatically calculate this set up cost once the crane has been defined. Following this initial set up cost, there is a variable set up cost for each turbine. This variable cost is equal to the initial set up cost reduced by one third. The formula is presented below.

$$\begin{aligned} &\textit{Setup cost onshore crane} \\ &\quad = \textit{Initial set up cost} + \textit{Initial setup cost}\ x\frac{2}{3}x\ (\textit{number of turbines} - 1) \end{aligned}$$

Although duration is a cost driver, both for setting up the crane and the disassembly of the turbine for offshore locations, it was chosen to keep the posts separated. This is motivated by that the set up cost for an offshore crane can vary considerably due to conditions at the particular site. For instance currents which can make it difficult to anchor the vessel or the jack up barge. By keeping this cost post separated the cost remains visible and the user can determine how reasonable this cost is when considering the particular site.

In the model offshore dismantling is assumed to take a total of 1 day per turbine. Of this time approximately 25% is assumed to correspond to the set up. This duration is increased by 30% to account for unfavourable weather and current conditions at the site. The estimated duration is then multiplied by the daily rate and by the number of turbines, to arrive at the set up cost for an offshore crane.

$$\textit{Setup cost offshore crane} = \textit{daily rate}\ x\frac{0{,}25\ \textit{days}\ x\ 1{,}3}{\textit{turbine}}x\ \textit{number of turbines}$$

Sub-activity 1.3.: Disassembly of turbine

	Onshore	**Offshore**
Requested parameters	*Location, hub height, nacelle weight, number of turbines*	*Location, hub height, nacelle weight, number of turbines*
Assumed parameters	*Duration of disassembly*	*Duration of disassembly*
Input parameters	*Rental rate*	*Vessel cost*

Once the crane has been transported to the site and set up by the turbine the disassembly can begin. At onshore locations the total cost for this activity depends on the crane used, the dismantling duration for each turbine, and the number of turbines to be dismantled. The duration of dismantling is estimated to

8 hours per turbine. To establish the hourly rate the established required capacity is used. At the lowest capacity of 250 tons the hourly cost is 5000 SEK. The hourly rate then increases with 5 SEK per ton. The formula to calculate rental costs for an onshore crane is presented below.

$$Dissasembly\ cost\ onshore = (5 * (crane\ capacity - 250) + 5000)\ x \frac{8\ hours}{tubine}\ x\ number\ of\ turbines$$

Also in the case of offshore turbines the crane required to a large extent defines the cost associated with dismantling since it defines the daily rates for the crane. As mentioned previously in the case of offshore turbines the dismantling is assumed to take a total of 1 day per turbine. In the model it is estimated that 75% of this time corresponds to actual dismantling. The duration is increased by 30% to account for unfavourable weather and current conditions. For the dismantling activity the duration is considered to be more reliable than for setting up the crane since once the vessel or the jack up barge is in place the process is independent of site conditions. The estimated duration is multiplied by the daily rate and by the number of turbines to be dismantled to arrive at the total rental cost for the offshore crane.

$$Dissasembly\ cost\ offshore = daily\ rate\ for\ crane\ x \frac{0{,}75\ days\ x\ 1{,}3}{turbine}\ x\ number\ of\ turbines$$

Activity 2: Treatment of blades

The treatment of blades activity includes three sub-activities; severing of blades, transport of blades and disposal of blades. The economic effects of these three sub-activities are added together to represent the total cost for treatment of blades.

$$Treatment\ of\ blades = severing\ of\ blades + transport\ of\ blades + disposal\ of\ blades$$

The total blade weight is the cost driver behind all the activities related to the treatment of blades. This is due to that the costs of all sub-activities are a function of the weight of the material to be handled. As has been mentioned in the technical description of the turbine the blade length, from which weight can be calculated, is often related to the hub height. Using this logic would have eliminated the need to specify the blade weight. This option was not chosen since no constant relation could be found between the hub height and the blade length since the tower can be chosen independent of the blade length. The hub height only establishes a maximum length for the blade. Since the blade weight was specified in all technical descriptions for the turbines it was considered to be a good parameter. The user is reminded that the parameter required is the total blade weight, that is, the blade weight for each blade multiplied by the number of blades.

For the treatment of blade activity in this model the possibility to recover blade material is ignored. This is due to that there is currently no functioning market for these activities and it is uncertain whether they will actually be performed in the future. Only blade disposal by landfill and by incineration are thereby considered.

Sub-activity 2.1.: Severing of blades

Requested parameters	*Blade weight*
Assumed parameters	
Input parameters	*Severing cost*

As has been described in the decommissioning process there are four different disposal methods for the turbine blades of which two will be considered; landfill or incineration. In the model the costs for both methods are automatically computed. In both cases the blades must first be severed to reduce transportation and handling costs. The total blade weight per turbine is used in the model. The formula used to calculate the cost for severing is shown below. The severing cost used will differ depending on the disposal method. This is due to that material to be entered into an incinerator must be reduced to smaller pieces, which increases costs.

$$Severing\ of\ blades = total\ blade\ weight\ x \frac{severing\ cost}{ton} x\ number\ of\ turbines$$

Sub-activity 2.2.: Transport of blades

Requested parameters	*Blade weight*
Assumed parameters	*Transport distance*
Input parameters	*Trailer cost*

Since waste stations are found throughout the country transportation costs were assumed to be negligible if the blades are disposed of by land fill. In the case of incineration there are few facilities that can incinerate the blade material and transportation costs may become significant. The cost driver in this case is the number of trailers and the transportation distance. The number of trailers is defined by weight restrictions applied to trailers which is 25 tones. The number received when dividing the total weight by the weight restriction is rounded up to the next whole number since it is considered improbable that the last trailer will be rented partially.

$$Number\ of\ trailers = \frac{total\ blade\ weight\ x\ number\ of\ turbines}{25}$$

The model assumes a default transport distance of 300 km to the nearest incineration facility. This number was considered to be reasonable since authorities have specified that 300-500 km is a rational distance to transport this kind of material for incineration.

$$Transportation\ cost = number\ of\ trailers\ x \frac{cost}{10\ km} x \frac{km}{10}$$

Sub-activity 2.3.: Disposal of blades

Requested parameters	*Blade weight*
Assumed parameters	
Input parameters	*Incineration fee, landfill fee*

Once again blade weight is the cost driver for cost related to blade treatment. Depending on whether the blade material will be incinerated or disposed of in land fill the fee varies. In the model both alternatives are computed automatically by multiplying the total blade weight per turbine by the fee per ton and the number of turbines, as shown in the formula below.

$$Disposal\ of\ blades = total\ blade\ weight\ x\ \frac{fee}{ton}\ x\ number\ of\ turbines$$

Activity 3: Treatment of tower and nacelle

The treatment of tower and nacelle encompasses six sub-activities; severing of tower and nacelle, transport of waste material, disposal of metal, disposal of concrete, disposal of organic material and disposal of electronic material. Together the economic effects of these four activities represent the cost of the treatment of tower and nacelle.

$$\begin{aligned} &Treatment\ of\ tower\ and\ nacelle \\ &\qquad = severing\ of\ tower\ and\ nacelle + transport\ of\ waste\ material \\ &\qquad + disposal\ of\ metal + disposal\ of\ concrete + disposal\ of\ organic\ material \\ &\qquad + disposal\ of\ electronic\ material \end{aligned}$$

The cost drivers between the different sub-activities differ. In all activities the important issue is the amount of material to be handled. In order to account for different materials many simplifications have been made based on data reviewed about the turbines. To calculate the cost of severing and transport of waste material it is only important to account for the total amount of material and distinguish between two material types; concrete and metal. When it comes to disposal of metal, on the other hand, it is important to differ between different types of metals since they have different market values. Therefore in the disposal of metal sub-activity an extensive number of parameters have been used.

The most important difference between different models that affect this activity is the characteristics of tower. The tower type and tower weight are considered to be parameters that can easily be specified by the user. Also a significant difference has been found regarding the weight of the nacelle in Enercon models compared with other models due to the absence of a gearbox.

Sub-activity 3.1.: Severing of tower and nacelle

Requested parameters	*Tower type, tower weight, nacelle weight, number of turbines, blade weight*
Assumed parameters	*Material losses*
Input parameters	*Severing costs*

The type and weight of the tower define the cost for the severing of material since they indicate the amount and type of material to be handled. Depending on whether the tower is built in concrete or steel the cost associated with severing differs.

In the model steel corresponds to 100% of the tower weight in tubular steel towers and 7% of the tower weight for hybrid towers. These material distributions were found by reviewing information on different tower types. 100% of the nacelle weight is assumed to be metal or severed to the same cost as metal. The rotor is also made of steel, and its weight is approximated to be the same as the blade weight. This relation was found to be nearly accurate in all models examined.

Regardless of the tower type the weight of the nacelle and the rotor are added to the metal weight in the tower to arrive at a total tonnage of metal per turbine. To calculate the cost for severing this metal the tonnage per turbine is multiplied by the severing cost per ton and the number of turbines, shown in the formula below.

$$Tons\ of\ metal\ in\ turbine = metal\ weight\ in\ tower + nacelle\ weight + steel\ in\ rotor$$

$$Severing\ of\ metal = tons\ of\ metal\ in\ turbine\ x \frac{sek}{ton} x\ number\ of\ turbines$$

To sever concrete in the hybrid towers there is a fixed establishment cost and a variable cost per m3 of concrete. To calculate the weight of concrete in the tower seven percent of the tower weight is subtracted from tower weight since this share of the weight is steel. The variable cost is determined by the tons of concrete, the cost per ton, and the number of turbines. As can be seen below the establishment cost and the variable cost together constitute the total cost for severing of concrete in the tower.

$$Severing\ of concrete = establishment\ cost + tons\ of\ concrete\ x \frac{sek}{m3} x\ number\ of\ turbines$$

Sub-activity 3.2.: Transport of waste material

Transportation costs are ignored in the model since costs has been included in the severing fee by the entrepreneurs that were interviewed.

Sub-activity 3.3.: Disposal of metal

Requested parameters	*Tower type, hub height, tower weight, nacelle weight, number of turbines, gearbox, blade weight*
Assumed parameters	*Material shares and losses*
Input parameters	*Severing costs*

Since metals are valuable, and there are functioning markets for the sale of scrap metals, there is a substantial material value that must be considered. To explain assumptions and calculations underlying this sub-activity this section will be explained based on where in the turbine the material is located. In many cases an assumed material loss of 10% is applied. This is due to that a certain part of the metal can be expected to be lost during severing and handling. The percentage is also confirmed by Vestas Life Cycle Analysis (Vestas 2004, Vestas 2006). The revenues received from the sale of different materials are added together in the post “disposal of metal”. The posts will be negative since it represents revenue in a cost model.

The tower

As mentioned previously it is approximated that the steel tower is made of 100% steel and that steel tubes in the hybrid tower account for 7% of the total tower weight. In the model it is assumed that 90% of the steel from the tower can be recovered and sold to metal scrap dealers. The loss of 10% of the material is deduced from that there may be other materials in the tower. Also a loss of material will probably take place in the severing and handling of the metal. The assumed tonnage of steel per tower is multiplied by the steel price and the number of turbines to arrive at the revenue from steel in the tower.

$$Revenue\ steel\ in\ tower\ = 0{,}9\ x\ tons\ of\ steel\ in\ tower\ x\ steel\ price\ x\ number\ of\ turbines$$

The nacelle

The nacelle weight is used to estimate revenues from the sales of metals in the nacelle. In the nacelle three materials were considered of particular importance due to their high market value and presence in the nacelle; stainless steel, copper, and steel.

Data reviewed shows that approximately 10% of the nacelle weight in Vestas' turbines consists of stainless steel. In these models the gearbox accounts for a large part of this stainless steel. Such detailed information about metal contents in the nacelle could not be found about Enercon models, but it is clear that these models do not have a gearbox. Despite this difference the same approximation is used to find stainless steel in all turbines. This is explained by that the turbines are likely to have a similar share of precious metals. The amount of stainless steel is multiplied by the market value and the number of turbines to estimate the total revenue from stainless steel.

$$Revenue\ stainless\ steel\ in\ nacelle = nacelle\ weight\ x\ 0{,}1\ x \frac{stainless\ steel\ price}{ton} xnumber\ of\ turbines$$

In order to establish the amount of copper in the nacelle it is important to consider whether or not the model has a gearbox since this affects the size of the generator. In models with a gearbox the generator is smaller and thus constitutes approximately 10% of the nacelle weight. In models without a gearbox the generator accounts for approximately 45% of the nacelle weight. The copper found in the generator and is assumed to constitute approximately 20% of the generator weight. Once the weight of copper has been calculated it is multiplied by the copper price and the number of turbines to arrive at the revenue from copper in the generators. The first formula is for a generator with a gearbox and the second shows the formula for a generator without a gearbox.

$$Revenue\ copper\ in\ generator = nacelle\ weightx\ 0{,}1\ x\ 0{,}2\ x \frac{copper\ price}{ton} x\ number\ of\ turbines$$

$$Revenue\ copper\ in\ generator = nacelle\ weight\ x\ 0{,}45\ x\ 0{,}2\ x \frac{copper\ price}{ton} x\ number\ of\ turbines$$

The weight of steel in the nacelle is calculated by deducting the weight of copper and the weight of stainless steel. To account for other materials in the nacelle and the steel that may be lost in the dismantling and severing process this figure is reduced by 30%. The amount of steel computed is then multiplied by the price of steel per ton and the number of turbines to result in the revenue from steel in the nacelle.

$$\begin{aligned} &Revenue\ from\ steel\ in\ nacelle \\ &\quad = 0{,}7\ x\ (nacelle\ weight - copper\ weight\ nacelle \\ &\quad - stainless\ steel\ nacelle)\ x \frac{steel\ price}{ton} x\ number\ of\ turbines \end{aligned}$$

The rotor

Reviewing data about different wind turbines it was observed that the weight of steel in the rotor can be approximated by the total weight of the blades. The blade weight is therefore also used to establish the steel weight in the rotor. A material loss of ten percent is expected to take place. In order to calculate the revenue from the steel in the rotor the following formula is used:

$$Revenue\ from\ steel\ in\ rotor = total\ blade\ weight\ x\ 0{,}9\ x\ \frac{steel\ price}{ton}\ x\ number\ of\ turbines$$

Sub-activity 3.4.: Disposal of concrete

This cost is ignored since it is assumed that the concrete can be disposed of at construction site free of charge.

Sub-activity 3.5.: Disposal of organic materials

Requested parameters	*Tower weight*
Assumed parameters	*Material shares and losses*
Input parameters	*Incineration fee*

It is considered appropriate to assume that there will be a cost to handle and dispose of organic material and other rest materials. In Sweden organic materials are incinerated at a given expense per ton. The number of tones was estimated by assuming that organic material and rest materials will account for 10% of the metal weight in the tower. The metal weight of the tower, as opposed to the tower weight, is used since for hybrid towers the entire tower weight is considered to give an excessive approximation of the organic material.

$$Disposal\ of\ organic\ waste = metal\ weight\ in\ tower\ x\ 0{,}1\ x\ \frac{incineration\ fee}{ton}$$

Sub-activity 3.6.: Disposal of electronic material

The cost for disposing electronic material was found to be negligible. Therefore it was excluded from the calculation.

Activity 4: Treatment of foundation

The treatment of foundation is an optional activity. If this activity is exclude from the calculation the parameters defining the most important cost drivers – foundation weight or cubic meters – do not have to be stated. The activity consist of three sub-activities; demolishment of foundation, transportation of material, and waste disposal. Together these define the cost for economic consequences of treatment of foundation.

$$\begin{aligned} &Treatmentoffoundation \\ &\quad = demolishment\ of foundation + severing\ of\ material + waste\ disposal \\ &\quad + resotration\ of\ foundation\ site \end{aligned}$$

As mentioned previously the dimensions of the foundation are one of the most important parameters in the activities related to the treatment of the foundation. Data reviewed about the foundations show onshore and offshore foundations vary considerably. Factors affecting the foundation are the type of tower, the hub height, and considerations at the particular site such as the ground characteristics. Therefore it was considered necessary to ask the user to specify important characteristics of the foundation such as type, weight, and location. Only the most commonly used foundations are include in the model, which are; concrete foundations for onshore locations as well as gravity foundations and mono piles for offshore foundations.

For gravity foundations the model ignores the possibility of removing the ballast and then pumping air into the structure to float it and tow it to shore since this method is considered less viable. Empirical findings show that the water depth will affect the method employed. In the model this is ignored since it was considered more valuable to keep the number of parameters as few as possible.

Sub-activity 4.1.: Demolishment of foundation

Requested parameters	*Foundation weight or cubic meters, location, number of turbines*
Assumed parameters	
Input parameters	*Demolishment cost*

The foundation weight or volume is the cost driver for the handling of foundation material. For onshore foundations the size of the foundation should be specified in cubic meters. This data is then used to establish demolition costs which are calculated in the same way as costs for demolishing hybrid towers. Since the same equipment is used it can be argued that the establishment cost should only be accounted for once. Since the cost is relatively small and it is reasonable that more than one hydraulic hammer may be used due to the amount of material to be handled this cost was included anyways. The variable demolition cost is computed by multiplying the tons of concrete per turbine foundation by the fee per cubic meter and the number of turbines. To this cost the establishment cost is added to calculate the demolishment cost for an offshore foundation.

$$\begin{aligned}&Demolishment\ of\ onshore\ foundation\\&\quad = establishment\ cost + tons\ of\ concrete\ x\,\frac{sek}{m3}\,x\ number\ of\ turbines\end{aligned}$$

In the case of offshore foundations the cost driver is the duration for the demolishment. In the model it is assumed that only two foundation types are used; mono piles and gravity foundations. Regardless of the type of offshore foundation found the most important cost is attributed to the vessels that must be used to lift the foundation material from the sea bed. The same types of boats are used for mono piles and gravity based foundations but the duration of the operation varies depending on the foundation type. The duration is estimated to one and half day and three days per foundation for mono piles and gravity foundations respectively. Once again these durations are increased by 30% to account for weather and current conditions at the site. The vessel cost is composed of a mobilization cost and a variable day rate. The total cost will therefore depend on the duration of the operation which is defined by the foundation type and the number of turbines present. The formula used to calculate the demolishment cost for offshore foundations is shown below.

$$\begin{aligned}&Demolishment\ of\ foundation\\&\quad = mobilization\ cost + daily\,rate\ x\,\frac{duration\,x\ 1{,}3}{turbine}\ x\ number\ of\ turbines\end{aligned}$$

Sub-activity 4.2.: Severing of foundation material

Requested parameters	*Foundation weight or cubic meters, tower location, number of turbines*
Assumed parameters	
Input parameters	*Demolishment cost*

For land-based foundations the severing cost is assumed to be included in the demolition fee.

In the case of offshore foundations severing is expected to take place once the foundation material reaches land. Material weight is used to calculate the cost for severing the metal found in the foundation once it has reached land. Since the part of the mono pile that has been rammed into the sea bed will be left behind the total foundation weight is reduced by one third. This weight per turbine is then multiplied by the fee per ton and the number of turbines. The severing costs for gravity foundations are calculated in the same manner with the exception that dimensions are specified in cubic meters and the severing rate used is for concrete. In this case it is also an assumption that one third of the material weight is lost since a part the ballast will most likely be left at the sea bottom.

$$Severing\ of\ foundation = dimensions\ x\ \frac{sek}{ton}\ x\ number\ of\ turbines$$

Sub-activity 4.3.: Transport of waste material

In the model it is assumed that these costs will be included in the demolition and severing fees.

Sub-activity 4.4.: Disposal of concrete

Requested parameters	*Foundation weight or cubic meters, number of turbines*
Assumed parameters	
Input parameters	*Disposal fee*

As has been pointed out in the empirical findings the cost related to this activity are often included in the concrete demolition fee. If this is not the case costs incurred for disposal of concrete can be calculated with the formula below.

$$Disposal\ of\ concrete = cubic\ meters\ x\ \frac{sek}{ton}\ x\ number\ of\ turbines$$

Sub-activity 4.5.: Disposal of steel

Requested parameters	*Foundation weight or cubic meters, tower location, number of turbines*
Assumed parameters	
Input parameters	*Steel price*

Depending on the type of foundation it may be necessary to consider revenues from scrap steel. In the case of onshore foundations and gravity foundations the steel produces no revenue since this revenue is assumed to belong to the demolishment contractor. For mono piles, which are made of steel, there is a material value that must be considered. To calculate the weight of steel is multiplied by the sales price. To find the steel weight the total foundation weight is reduced by 1/3 since the part of the foundation that has been rammed into the sea bed is left behind.

$$\begin{aligned}&\mathit{Revenue\ from\ steel\ in\ steel\ foundation}\\&\qquad = \mathit{tons\ of\ steel\ in\ foundation\ x}\,\frac{2}{3}\,\mathit{x\ steel\ price\ x\ number\ of\ turbines}\end{aligned}$$

Sub-activity 4.6.: Restoration of foundation site

Requested parameters	*Foundation weight or cubic meters, tower location, number of turbines*
Assumed parameters	
Input parameters	*Restoration cost*

In the model restoration applies only to land-based turbines. Therefore it is necessary to consider where the turbine is located. The cost driver for the restoration activity is the cubic meters of foundation that have been removed leaving a hole in the ground. The cubic meters are multiplied by the restoration cost and the number of turbines to arrive at a total restoration cost, as shown below:

$$\mathit{Restoration\ cost} = \mathit{cubic\ meters\ of\ foundation\ x\ restoration\ cost\ x\ number\ of\ turbines}$$

Activity 5: Treatment of cables

The treatment of external cables is an optional activity. If the user chooses to exclude the activity, the distance to the electrical grid does not have to be stated. The activity consists of three sub-activities which are added together to arrive at the total costs for the treatment of cables.

$$\begin{aligned}&\mathit{Treatment\ of\ external\ cables}\\&\qquad = \mathit{excavation\ of\ cables} + \mathit{transport\ of\ cables} + \mathit{disposal\ of\ cables}\end{aligned}$$

As has been explained in the technical description of the wind turbine there are external and internal cables in a wind turbine. It is important to consider these cables in the model since the conductor material consists of valuable metals such as aluminium and copper. In the information reviewed it became apparent that the cables are a complex issue that is difficult to simplify without losing valuable information. Also tests showed that the external cables have a considerable impact on the results computed by the model. Therefore the user is requested to specify three parameters that are used to deal with external cables in the model.

In this activity three parameters are used to make calculations about costs and revenues for external cables, these are: distance to the electrical grid, the conductor material in the external cable, and the weight of the external cable per meter. The distance to the electrical grid is requested from the user since it is impossible to predict the distance to the electrical grid in a reliable manner. Also the characteristics of the cable, such as conductor material and cable weight per meter must be specified since these cannot be computed by the model in a reliable fashion. For internal cables, on the other hand, simplifications can be made. Therefore only one parameter, the number of turbines, is requested from the user.

Sub-activity 5.1.: Excavation of cables

Requested parameters	*Distance to electrical grid in meters, number of turbines*
Assumed parameters	*Distance between turbines*
Input parameters	*Cost for excavation of cables*

The cost driver behind the excavation of cables is the meters of cables to be excavated. The excavation fee per meter is multiplied by the meters of cables to be excavated to calculate the cost for excavation of turbines. Since the distance to the electrical rid can vary considerably depending on the location of the turbines this parameter is requested from the user to calculate the cost for excavating external cables. The distance between the turbines, on the other hand, can be approximated to 450 meters in the model. Although this distance can vary it has a very limited effect on the results. Additional parameters such as the cable type and weight are irrelevant to the excavation costs.

$$\begin{aligned}&\mathit{Excavation\ of\ cables}\\&\qquad = (\mathit{distance\ to\ electrical\ grid}\\&\qquad + 450\ m\ x\ \mathit{number\ of\ turbines})\ x\ \frac{\mathit{excavation\ cost}}{\mathit{meter}}\end{aligned}$$

Sub-activity 5.2.: Transport of cables

In the model the cost for transport is assumed to be included in the excavation fee.

Sub-activity 5.3.: Disposal of cables

Requested parameters	*Number of turbines, distance to electrical grid in meters, external cable type, external cable weight per meter*
Assumed parameters	*Depreciation of material value*
Input parameters	*Market value aluminium and copper, weight of internal cable per meter, depreciation of material value*

Cables have a considerable material value due to the presence of copper and aluminium. Since the distance to the electrical grid, the conductor material, and the weight of the cable can vary considerably the user must specify this information. This information is used when calculating the revenues for external cables. By multiplying the cable weight per meter by the distance to the grid a total external cable weight is found. The revenues are found by multiplying the share of the metal by the market price for the metal which is reduced by 70% to account for the presence of other materials such as plastics, insulators and other metals that have been disregarded in the model.

$$\begin{aligned}&\mathit{Revenue\ external\ cables}\\&\qquad = \mathit{weight\ per\ meter\ x\ distance\ to\ grid\ x}\ 0{,}3\ \ (\mathit{copper\ price\ x\ share\ of\ copper}\\&\qquad + \mathit{aluminum\ price\ x\ share\ of\ aluminum})\end{aligned}$$

To calculate the revenue from internal cables similar calculations are made. Since these cables are less valuable due to their lighter weight simplifications can be made. In the model the internal cables are expected to weigh 0,002 tons per meter. This figure is multiplied by an assumed distance of 450 m between each turbine to arrive at the total internal cable weight per turbine. The revenue per turbine from internal cables is computed by multiplying the internal cable weight per turbine by the share of metal and the metal price reduced by 70%. To arrive at the total revenue the revenue per turbine is multiplied by the number of turbines at the installation.

$$\begin{aligned} &\mathit{Revenue\ from\ interal\ cable\ cable} \\ &\quad = \frac{0{,}002\ t}{meter}\ x\ 450\ m\ x\ 0{,}3\ x\ (copper\ price\ x\ share\ of\ copper \\ &\quad + aluminum\ price\ x\ share\ of\ aluminum)\ x\ number\ of\ turbines \end{aligned}$$

Sub-activity 5.4: Restoration of cable site

Restoration costs for cable sites are assumed to be included in the excavation price.

5.4. Applying the model on specific cases

In this section the model will be applied to a number of different turbines in scenarios created by the authors. First a closer look will be taken at a case with ten Vestas V82 1.65 MW turbines. In this section modelled approximations of materials present in the turbine will be compared with specific data about the turbine. Once the results have been presented and analysed the model is used to estimate economic consequences of decommissioning for sixteen turbines with different characteristics. The aim is to identify how the characteristics of the turbines and thereby input parameters affect the results produced by the model. As can be seen in Figure 12 this corresponds to the fifth step in the process to recognize economic consequences of decommissioning.

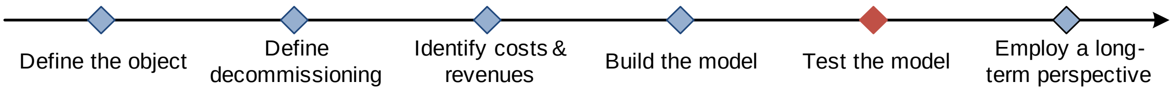


Figure 12 Process to recognize economic consequences of decommissioning

5.4.1. Presenting the case of Vestas V82 turbine

Table 8 Specifications Vestas V82 (Vestas 2006)

Specification of materials Vestas V82 1,65 MW		
Tower	**136,0**	T
Steel	126,1	T
Aluminium	2,6	T
Electronics	2,2	T
Plastic	2,0	T
Copper	1,3	T
Oil	1,0	T
Nacelle	**51,0**	T
Cast iron	18,0	T
Steel, engineering	13,0	T
Stainless steel	7,8	T
Fiberglas	1,8	T
Copper	1,6	T
Plastic	1,0	T
Aluminium	0,5	T
Electronics	0,3	T
Oil	0,3	T
Rotor	**42,2**	T
Cast iron	11,3	T
Steel	4,2	T
Steel, engineering	1,5	T
Rest: Epoxy, glass fibre, birch wood, balsawood, etc	25,2	T
Foundation	**832,0**	T
Concrete	805,0	T
Steel	27,0	T
Internal cables	**149,5**	T
Aluminium	63,4	T
Plastic	55,2	T
Copper	30,9	T
External Cables	**2711,5**	T
Plastic	1519,0	t
Aluminium	953,0	t
Copper	238,6	t

In order to assess how well the model estimates material contents in a turbine the model was applied to a Vestas V82 1.65 MW turbine. Since no actual decommissioning of this turbine takes place the validity of the activities and their economic consequences cannot be examined with reference to a live case. This example, on the other hand, can illustrate how well the model estimates material contents. The choice to analyse this turbine type was made due to that the turbine is representative for the turbines currently installed in Sweden. Moreover for this particular turbine more detailed information about material contents could be found. This information is presented in Table 8 and could be used to compare actual figures with the material contents estimated by the model. The economic effects of differences in real and estimated materials contents could also be examined.

In Table 8 the data about the tower, nacelle, rotor and foundation is expressed per turbine. Data about internal cables and external cables, on the other hand, is expressed for the entire wind farm which consists of 182 turbines. In the data used in the model information relating to internal and external cables was adjusted to better represent conditions that may be expected for a farm with only ten turbines.

In the case examined there will be 10 turbines to decommission. Calculations will be made for onshore and offshore locations. For the onshore locations all information in Table 8 has been used, as well as other technical data about the turbine. For the offshore case data about onshore foundations has been replaced by information about the mono pile foundations used in Vestas' offshore installations at Horns Rev. It is assumed that there are no particular complications at the site or regarding the turbines and the model will therefore be used without making alterations.

The results and the calculations made will be presented so that the model described above is applied to a case. The reader can thus interpret and evaluate the results. The most interesting insights and divergences concern the materials found in the turbine. The results obtained using more specific data about the turbine can be compared with the results obtained when using only the parameters in model developed. In order to ease understanding the results will once again be presented by following the decommissioning process.

Activity 1: Dismantling of turbine

The total costs for the dismantling activity, that is the sum of the costs for transport of crane, set up of crane and dismantling is presented below. After the brief overview presented below a more detailed account will be made of how the results were obtained.

Dismantling cost for an onshore turbines is estimated to be 2 367 000 SEK for the entire farm (or 236 700 SEK per turbine). The transport of the crane constitutes 117 000 SEK of the cost for the park disassembly. The set up is by far the largest cost post in the dismantling activity, reaching 1 750 000 SEK. For the disassembly sub-activity an additional 500 000 SEK are estimated.

Dismantling of turbines offshore is 9 536 800 SEK for the entire park (or 953 680 SEK per turbine). The transportation constitutes 4 768 400 SEK of the total cost, and is thereby the biggest cost post in the disassembly activity. This will always be the case since the duration is the cost driver behind all the activities and transportation is the sub-activity with the longest duration per turbine. The set up of the crane is approximated to cost 1 192 100 SEK. For the disassembly the model predicts that costs will amount to 3 576 300 SEK.

Sub-activity 1.1.: Transport of crane

In the onshore case the model accurately predicts that a 500 ton crane must be used to dismantle the turbine with a nacelle weight of 51 tons and a hub height of 78 meters. This crane capacity is then used as input in the formula to calculate the number of trailers required. The model predicts 13 trailers will be needed to transport the crane and its counter weight. To calculate the cost for transporting the crane the default transport distance of 300 km was used. The transport distance (divided by ten in order to match the measure used for the trailer cost) is multiplied by the number of trailers and the trailer cost per 10 km to arrive at the total transportation cost.

$$Number\ of\ trailers = 13 = \frac{500 - 200}{50} x\ 2 + 1$$

$$Transport\ cost\ onshore = 117\ 000\ SEK = 13\ trailers\ x \frac{300}{10} x\ 300\ SEK$$

For the offshore location the model accurately estimates that the smaller of the offshore cranes, with a capacity of 120 tons at 80 m height, can be used. To calculate the cost for transporting this crane to the offshore installation the estimated transport duration of one day is increased by 30% and then multiplied by the daily rate for the vessel and the number of turbines. Since the daily rates where specified in Euros the Forex exchange rate on the 14th of April 2008, which was 9.17 SEK/EUR, was used to convert the cost to SEK.

$$Transport\ cost\ offshore = 4\ 768\ 400\ SEK = 1{,}3\ days\ x\ 40\ 000\ EUR\ x\ 9{,}17 \frac{SEK}{EUR} x\ 10$$

Sub-activity 1.2.: Set up of crane

In the onshore case the model accurately uses the set up cost for the particular crane which amounts to 300 000 SEK. The variable cost is then calculated by diminishing the initial set up cost by one third and by multiplying by the number of remaining turbines to be dismantled (which is nine since the set up cost for the first turbine is covered by the initial set up cost).

$$Set\ up\ of\ crane\ onshore = 1\,750\,000\ SEK = 250\,000\ SEK + 250\,000\ SEK\ x\ \frac{2}{3} x\ 9$$

For the offshore example there are no specific site conditions to be considered, therefore the set up of the crane at the offshore location is assumed to take 0,25 days increased with a margin of 30%. The duration is multiplied by the day rate specified in EUR and converted to SEK by Forex exchange rate on the 14th of April 2008. This set up cost per turbine is multiplied by ten, the assumed number of turbines to be dismantled.

$$Setup\ offshore = 1\,192\,100\ SEK = 0{,}325\ days\ \ x\ 40\,000\ EUR\ x\ 9{,}17\ \frac{SEK}{EUR}\ x\ 10$$

Sub-activity 1.3.: Disassembly of turbine

To calculate the cost for turbine disassembly at an onshore location the hourly rental rate for the crane used is multiplied by the assumed duration per turbine and the number of turbines. The hourly rental rate is computed by using the formula presented in the previous section where the rental rate increases by 5 SEK/ton. The results of this calculation, 6 250 SEK/hour, accurately estimates the hourly cost for the 500 ton crane.

$$Rental\ rate\ 500\ ton\ crane = 6\,250\ SEK = (5 * (500 - 250) + 5000)$$

$$Disassembly\ onshore = 500\,000\ SEK = 8\ hours\ x\ 6250\ SEKx\ 10$$

For the offshore location the disassembly cost was calculated by increasing the expected dismantling duration of 0.75 days with a 30% margin. The estimated duration is then multiplied by the rental cost for the vessel. Since the costs were specified in Euro the Forex exchange rate of 9.17 SEK/EUR on the 14th of April 2008 was used to convert the figures to SEK.

$$Disassembly\ offshore = 3\,576\,300\ SEK\ = 0{,}975\ days\ x\ 40\,000\ EURx\ 9{,}17\ \frac{SEK}{EUR}\ x\ 10$$

Activity 2: Treatment of blades

As mentioned in the model description the model will compute the costs for landfill and incineration automatically. In the case examined the incineration will be the most economical alternative with a total cost of 312 000 SEK compared with 325 500 SEK for landfill. The same calculations are performed for the offshore and onshore example.

Due to that larger pieces are accepted severing costs 31 500 SEK if the blades are taken to landfill, compared with 41 000 SEK when incinerated. If incineration takes place transportation of the blade material is estimated to cost 81 000 SEK. This cost is ignored if the blades are taken to landfill since the transportation distance is expected to be shorter and thereby included in the severing cost. For the disposal of blades incineration is more cost effective with a total cost of 189 000 SEK compared with 294 000 SEK for landfill. Thus, in the example presented incineration is more inexpensive than landfill. Whether this holds true in other cases to a large extent depends on the transportation distance.

Sub-activity 2.1.: Severing of blades

The total material weight is the cost driver for this activity. To calculate the total material weight the total blade tonnage per turbine, which is 21, is multiplied by 10, the number of turbines, to arrive at the total blade material for the entire installation. The cost for severing of blades varies depending on the disposal method chosen since blades that are to be incinerated must be severed into smaller pieces increasing the severing cost per ton with 50 SEK.

$$Severing\ of\ blades\ incineration = \ 42\,000\ SEK = 21\ t\ x\ 10\ x\ 200\,\frac{SEK}{ton}$$

$$Severing\ of\ blades\ landfill = 31\,500\ SEK\ = 21\ t\ x\ 10\ x\ 150\,\frac{SEK}{ton}$$

Sub-activity 2.2.: Transportation of blades

When blades are incinerated the transportation distance is expected to be significant due to that there are few incineration facilities suitable for glass fibre in Sweden. To calculate the transportation costs the number of trailers required is established by dividing the total blade tonnage at the site (21 tons per turbine x 10 turbines) by the weight capacity of the trailers which is 25 tons per trailer. The number of trailers is rounded up to the next whole number and then multiplied by the trailer rental fee and the distance.

$$Transportation\ costs\ incineration = 81\,000\ SEK\ = \frac{21\ t\ x\ 10}{25}\ x\ 300\ SEK\ x\,\frac{300\ km}{10}$$

Sub-activity 2.3.: Disposal of blades

The disposal costs also differ depending on the chosen disposal method. If the blades are incinerated the disposal is fee is 900 SEK/ton compared with 1400 SEK/ton if landfill is chosen. In both cases the total tonnage is the cost driver which is multiplied by the disposal fee.

$$Disposal\ cost\ ineration = 189\,000\ SEK\ = 21\ t\ x\ 10\ x\,\frac{900\ SEK}{ton}$$

$$Disposal\ cost\ landfill = 294\,000\ SEK\ = \ 21\ t\ x\ 10\ x\,\frac{1400\ SEK}{ton}$$

Activity 3: Treatment of tower and nacelle

In this activity a large part of the revenues expected for the decommissioning are computed. The calculations are made in the same way for the offshore and the onshore case and the results are -

2 909 140 SEK. The post is negative since it represents revenue in a cost model. Severing of the towers and nacelles costs a total of 416 000 SEK. In the disposal of steel activity a revenue post of approximately 3 500 000 SEK is generated by the model. The cost for the disposal of organic materials amounts to 122 400 SEK.

In this activity important insights can be gathered about how well the model estimates material contents in the turbines since the figures can be compared with data about the V82 turbine. Therefore in the upcoming sub-activities the presence of different materials and their respective weights will be compared with the data found about the V82 turbine.

Sub-activity 3.1.: Severing of tower and nacelle

In order to calculate the amount of metal to be severed the tower weight (136 tons), the nacelle weight (51 tons), and the rotor weight (21 tons) are added together. The total amount of metal is then multiplied by the severing fee per ton, which is 200 SEK/ton to find the total cost for severing of metal in the turbine.

$$Material\ to\ be\ severed\ in\ the\ model = 208\ t\ = 136\ t + 51\ t + 21\ t$$

$$Severing\ cost\ model = 416\ 000\ SEK = 208\ t\ x\frac{200\ SEK}{ton}$$

Since data is provided about the V82 model the figure above can be compared to the actual materials in the turbine. As can be seen the difference is negligible, with a delta amounting to only 0.2 tons per turbine and a corresponding severing cost of 400 SEK for all ten turbines. In the data presented about the V82 model the weight specified in the rotor field includes the weight of the blades and amounts to 42.2 t. The weight of the blades is of course ignored in the calculation below calculations since it has been accounted for in the previous activity.

$$Material\ to\ be\ severed\ in\ V82 = 208.2\ t = 136\ t + 51\ t + 21.2\ t$$

$$Severing\ cost\ V82 = 416\ 400\ SEK = 208.2\ tx\frac{200\ SEK}{ton}$$

Sub-activity 3.2.: Transport of waste material

The cost for transporting waste material is ignored for both onshore and offshore cases. This is due to that the transport costs are included in the severing fee.

If these was not the case the cost for transportation would amount to 27 000 SEK assuming a 100 km distance to the nearest treatment facility. A total of nine trailers would be required, which is calculated by dividing the metal weight (208 or 204 tons) by the maximum weight capacity of the trailer (25 tons). The user is advice to confirm with the entrepreneur that is hired to perform the severing whether or not transportation is included.

Sub-activity 3.3.: Disposal of metal

In this sub-activity the revenues for sales of metals is accounted for. In the previous section, where the model was described, the reader was familiarized with the metals and where they were found in the turbine. In the forthcoming text the revenue will be presented depending on the material, regardless of where in the turbine the material is found.

Revenue from steel

In the model the tubular steel tower is assumed to consist of 100% steel. To the weight of the tower (136 tons) the steel in rotor (21 tons) is added. Of the weight from the tower and the rotor 90% is assumed to be revenue generating. The revenue from steel in the nacelle, on the other hand, is calculated by assuming that 70% of the nacelle weight remaining, once copper and stainless steel have been subtracted, corresponds to revenue generating steel. Thus the total of steel that generates revenues in the model is 172 tons (122.4 tons from the tower + 18.9 tons from the rotor + 31 tons from the nacelle). This figure is multiplied by the steel price per ton and the number of turbines to arrive at the total revenue from steel.

$$Revenue\ from\ steel\ in\ model = -2\,590\,740\ SEK = 172\ tx - 1500\frac{SEK}{ton}x\ 10$$

Using the data about the V82 model it is found that the steel in the tower, rotor and nacelle weighs 174 tons. This figure is found by adding together the weights of steel, engineering steel, and cast iron which are considered to hold a similar market value. The difference when compared with the models estimation is 2.1 tons more per turbine which accounts for approximately 1% of the material weight and 21 000 SEK. Thus, it is concluded that the model estimates the weight steel material accurately.

$$Revenue\ from\ steel\ in\ V82 = -2\,611\,500\ SEK = 174{,}1\ x\ 1500\frac{SEK}{ton}x\ 10$$

Revenue from stainless steel

In the model the content of stainless steel is approximated as ten percent of the nacelle weight. In the case examined this equals 5.1 tons of stainless steel. In the V82 specifications stainless steel in the turbine is found in the nacelle and weights for 7.8 tons. This means that the model underestimates the stainless steel content in comparison the turbine specifications.

A loss of stainless steel is explained by that some of the material may not be recyclable since it is mixed with other materials or lost during the recycling process. In the case of the nacelle it is proposed that this share exceeds 10% since stainless steel is used in various components and may therefore be more difficult to recover. Since stainless steel is a precious metal, currently valued at 11 000 SEK/ton the model ignores revenues amounting to 29 700 SEK per turbine, totalling at 297 000 SEK for the installation with ten turbines. This figure is considerable but the model was not adjusted since it was considered preferable to maintain a cautious approach to the revenues.

$$Revenue\ stainless\ steel\ model = -\ 561\,000\ SEK = 5{,}1\ x - 11\,000\frac{SEK}{ton}\ x\ 10$$

$$Revenue\ stainless\ steel\ V82 = -858\,000\ SEK = 7{,}8\ x - 11\,000\frac{SEK}{ton}\ x\ 10$$

Revenue from copper

According to specifications about the V82 turbine copper in the nacelle of the V82 weighs 1.6 tons. It is reasonable to presume that most of this copper is found in the generator. Since this model has a gearbox the model approximates the copper in the generator to 1.02 tons by assuming that the generator accounts for 10% of the nacelle weight and the copper in the generator is equal to 20% of the generator weight. The model thus slightly underestimates the copper in the nacelle. It is likely that a certain amount of the copper specified in the model is found in the electrical components of the nacelle. This copper is ignored in the model since it will probably be difficult to recover. Since the copper in the generator is likely to be relatively easy to recover the model assumes that no copper will be lot during the recovery process. The copper found in the nacelle is multiplied by the market price for copper of that quality and the number of turbines.

$$Revenue\ copper\ model = \ -295\,800\ SEK = 1{,}02\ t\ x - 29\,000\ SEK\ x\ 10$$

$$Revenue\ copper\ V82 = \ -464\,000\ SEK = 1{,}6\ t\ x - 29\,000\ SEK\ x\ 10$$

The difference between the revenues generated when using the model as compared to actual figures from the V82 is 168 200 SEK. Although this figure is considerable it is determined that it is reasonable to expect 0.04 tons of copper to be lost in the recovery process.

Sub-activity 3.4.: Disposal of concrete

This cost is ignored in the model since it is assumed that the concrete can be disposed of at construction sites free of charge.

Sub-activity 3.5.: Disposal of organic material

According to the V82 specifications there is a total of 6 t of organic material per turbine. In the model the weight of organic material and other waste treated as organic material is approximated to 10% of the metal weight in the tower. The approach used in the model increases the organic material by nearly 100%. This is motivated by that there has been a material loss in for example metals which will have to be handled and can be included in this post. The material weight is multiplied by the incineration fee and the number of turbines to arrive at the total cost.

$$Disposal\ organic\ material\ model = 122\,400\ SEK\ = 13{,}6\ t\ x\ 900\frac{SEK}{ton}x\ 10$$

$$Disposal\ organic\ material\ V82 = 54\,900\ SEK = 6{,}1\ t\ x\ 900\frac{SEK}{ton}x\ 10$$

Sub-activity 3.6: Disposal of electronic components

This cost is ignored in the model since it is considered to constitute a very small cost. It is worthwhile mentioning that this cost can increase in the future. Should legal requirements limit the possibilities of exporting electronic waste to developing nations or should the fees for handling this kind of waste in Sweden increase in the future the cost can become more significant.

Activity 4: Treatment of foundation

In the case examined it is assumed that the foundations will be removed for onshore and offshore sites. As has been pointed out in the finding about the legal scope of decommissioning the requirement to perform this activity varies. Many experts in the industry have a doubtful attitude towards performing this activity, which is not too strange since it is related to considerable costs. The model predicts that the cost for this activity in the example examined totals 1 585 000 SEK for onshore foundations and

6 079 867 for offshore foundations. The most important costs arise in the demolishment of foundation which costs a total of 1 410 000 SEK for onshore sites and 7 839 200 SEK at offshore sites. The offshore cost is reduced by the revenues generated by the sale of steel scrap from the mono pile in the disposal of steel activity.

Sub-activity 4.1.: Demolishment of foundation

The calculations for the demolishment of foundation material differ depending on the location of the turbine and the type of foundation. For the onshore turbine the foundation is a concrete foundation of 350 cubic meters according to the V82 specifications. This foundation material is demolished at a fee of 400 SEK per cubic meter, which is multiplied by the cubic meters per foundation and the number of turbines. To this variable cost a fixed installation cost of 10 000 SEK is added. Although there are 27 tons of steel detailed in the V82 specifications the revenue from selling this steel is not accounted for since the foundation material is taken by the contractor performing the demolishment. Since the user specifies the foundation weight there are no approximations made in this calculation.

$$Demolishment\ of\ foundation = 1\,410\,000\ SEK = 10\,000\ SEK + 350\ m3\ x\ 400\ SEK\ x\ 10$$

To calculate the demolishment cost for the offshore foundation the weight of the foundation is once again specified by the user. Since the V82 is located on an onshore location the offshore calculations are made using details from the foundations used in Vestas offshore installations at Horns Rev. These turbines have a mono pile foundation weighing 203 tons. In order to remove the foundation a vessel with capacity to carry very heavy loads is used. These vessels charge a fixed mobilization fee of 500 000 GBP and a variable rate of 8 000 GBP per day. As described in the previous section the job requires the vessel for an estimated 1.5 days per turbine increased by 30% to account for unfavourable weather conditions. The Forex exchange rate on the 14th of April 2008 of 11.95 SEK/GBP is used in the calculations.

$$Demolishment\ of\ foundation = 7\,839\,200\ SEK$$
$$= 500\,000\ GBPx\ 11{,}95\frac{SEK}{GBP} + 8\,000\ x\ 11{,}95\frac{SEK}{GBP}\ x\ 1{,}95\ x\ 10$$

Sub-activity 4.2.: Severing of foundation material

The severing of the onshore foundation is calculated in the previous activity and no additional severing is required. The steel in the mono piles present in the offshore case, on the other hand, must be severed once the foundations reach land. The severing is necessary to minimize handling costs and is performed at a fee of 200 SEK/ton of steel. The weight of the foundation in the example examined is as mentioned previously 203 tons. This figure is reduced by one third to account for that a part of the foundation, which has been rammed down into the sea bed, will be left behind. To calculate the total cost for this activity the weight of steel that reaches land is multiplied by the severing cost per ton and the number of turbines.

$$Severing\ of\ mono\ pile\ foundation = 270\,667\ SEK\ = 203\ t\ x\ \frac{2}{3}\ x\ 200\frac{SEK}{ton}x\ 10$$

Sub-activity 4.3.: Transport of waste material

In the case presented it is assumed that transport costs are included in the demolishment or severing fees.

Sub-activity 4.4.: Disposal of concrete

In the model it is assumed that the concrete in the land-based turbine foundation will be deposited free of charge at construction sites where the concrete can be used as filling material. The handling costs are covered by the entrepreneur that demolishes the concrete.

Sub-activity 4.5.: Disposal of steel

Since the mono piles used in the offshore case are made of steel and weigh 203 tons there is a considerable steel value that must be accounted for. The steel is reduced by one third since a part of the foundation will be left behind. The steel per turbine is multiplied by the number of turbines to arrive at the total of steel to be sold. The steel is sold off to scrap dealers at the current market price of 1 500 SEK per ton.

$$Disposal\ of\ steel = -2\,030\,000\ SEK = 203\ t\ x\,\frac{2}{3}\,x - 1500\,\frac{sek}{ton}\,x\ 10$$

Sub-activity 4.6.: Restoration of foundation site

For onshore foundations the model computes a cost for site restoration. The cost for this is 50 SEK/m3 and in the model the space to be restored is assumed to equal the size of the foundation that has been removed. Since restoration has to take place after the removal of each foundation the figure must be multiplied by ten which is the number of turbines in the example presented.

$$Restoration\ of\ foundation\ site = 175\,000\ SEK = 350\ m3\ x\ 50\,\frac{SEK}{m3}\,x\ 10$$

Activity 5: Treatment of cables

As has been mentioned in previous sections the turbines have internal and external cables. The data specified by the user is related to the external cables since these have a much larger impact in the calculations due to their heavier weight. The results of this calculation show that with current price conditions the economic effects of performing this activity are quite limited. This is due to that high prices for metals compensate for the costs related to the excavation of cables. The results from the model estimate that this net effect of this activity will be -247 280 SEK. Using figures from the V82 installation which have been adjusted to a ten turbine case the net effect is estimated to -264 038 SEK.

Sub-activity 5.1.: Excavation of cables

The important parameter to calculate excavation costs is the length of cable to be excavated. The model assumes that there will be a distance of 450 m between the turbines for internal cables. The length of external cables, on the other hand, is specified by the user. In the example examined the distance to the electrical grid is estimated to be 50 km and all cables are assumed to be dug down. The excavation costs are calculated by multiplying the distance between the turbines with the number of turbines, adding the distance to the electrical grid and multiplying this figure by the excavation fee which is 185 SEK per meter.

$$Excavation\ of\ cables\ model = 10\,082\,500 = (450\ m\ x\ 10 + 50\,000\ m)\ x\ 185\ SEK$$

In the details of the V82 model the kilometres of internal cables is specified to 92 km for 182 turbines. This would give a cable length of 505 meters between the turbines. Since the kilometres to the electrical grid are specified by the user there is no need to compare this digit to the actual conditions in the V82 installation. Using the actual length between the turbines would give an excavation cost of 10 184 250, approximately 100 000 SEK above the cost estimated by the model. Although the cost is slightly underestimated the model gives a fairly accurate figure. Moreover the underestimated costs are partially compensated by slightly underestimated revenues since cable 55 meter of cable per turbine is ignored. Should the distance between the turbines considerably exceed 450 m it is recommended that the user adjusts this figure.

$$Excavation\ of\ cables\ V82 = 10\,184\,250\ SEK = (505\ m\ x\ 10 + 50\,000\ m)\ x\ 185\ SEK$$

Sub-activity 5.2.: Transport of cables

In the model the transportation costs are assumed to be included in the excavation fee.

Activity 5.3.: Disposal of cables

The important diver behind revenues for cables is the weight of cable to be sold. The model assumes that there are 450 m between the 10 turbines in the example and that these cables weigh 0.002 tons per meter, giving a total of 0.9 tons of internal cable per turbine. To calculate the weight of external cables the user specifies the length and weight of the cable, which in the case examined is 50 km and 0,032 tons per meter. This gives a total of 1600 tons of external cable for the case examined.

In the model examined the conductor material is composed of both aluminium and copper. The details about the turbine show that the material shares differ a bit between internal and external cables. In the case of internal cables the share of aluminium accounts for approximately 70% and copper 30% of the metal weight and the weight of the internal cable would be 1.01 tons per turbine. For external cables, on the other hand, the share of aluminium is 80% and copper 20%. Since the user specifies the material weights for external cables only the model assumes that all cables have the latter conductor material shares. The revenues generated are calculated by multiplying the weight by the material value depreciated by 70% to account for other materials in the cables. As can be seen below the effect of these assumptions on the revenue from internal cables is quite limited, underestimating the revenues with only 16 758 SEK for the ten turbines.

$$\begin{aligned}Revenue\ internal\ cables\ \ model &= -57\,780\ SEK\\ &= 0{,}9\ t\ x\ 10\ x\ (\ 0{,}8\ x - 4\,500\ SEK + 0{,}2\ x - 14\,100\ SEK)\end{aligned}$$

$$\begin{aligned}Revenue\ internal\ cables\ V82 &= -74\,538\ SEK\\ &= 1{,}01\ t\ x\ 10\ x\ (0{,}7\ x\ 4\,500\ SEK + 0{,}3\ x\ 14\,100\ SEK)\end{aligned}$$

Since the external cables are much more significant and affected by a number of parameters that are difficult to foresee, the user specifies the distance to the electrical grid which in the example is 50 km, the weight of cable per meter which is 0,032 tons, and the conductor material shares which are 80% aluminium and 20% copper. The revenues generated by the external cables are calculated below and do not differ between the model and the real case since all parameters are specified.

$$
\begin{aligned}
Revenue\ external\ cables &= -10\,272\,000\ SEK \\
&= 50\,000\ m\ x\ 0{,}032\ x\ (0{,}8\ x - 4\,500\ SEK + 0{,}2\ x - 14\,100\ SEK)
\end{aligned}
$$

In the model the revenue from the disposal of cables is presented in a single post. The results for the modelled case are -10 329 780 SEK and -10 338 420 SEK when using specific data for the V82 turbine.

Sub-activity 5.4.: Restoration of cable site

The model assumes that the cable site restoration is included in the excavation fee.

Results

The model estimates the decommissioning will cost approximately 1 110 000 SEK (110 000 SEK per turbine) for a land-based installation of ten turbines V82 1.65 MW turbines. The costs to decommission an installation with the same characteristics but at an offshore location would be 12 800 000 SEK (1 280 000 SEK per turbine). Compared with the figures generated when using more detailed information about the turbines there is a difference of approximately 570 000 SEK. The delta is equal in both onshore and offshore cases since the only parameters that differ between the modelled scenario and the V82 case are the amounts of materials in the turbine (primarily metals). The results can be reviewed in Table 9.

In order to understand what the effect of these costs, that will be incurred twenty years from now, will have on turbine owners today, discount principles have been applied. For theoretical information discounting principles, methods, and formulas the reader is referred to appendix 1.

To find a suitable discount rate a ten-year government bond issued by the Swedish National Debt Office is used. This bond was chosen since it is one of the safest investments available on the market. It is important to place the money required for decommissioning in risky-free assets since turbine operators must be able to access the money once decommissioning takes place.

The discount rate was calculated by removing inflation effects from the interest rates of the bond. The nominal return on this bond is currently 4.12% (Swedish Central Bank 2008-05-07). With the current inflation of 3.4% (Official Statistics of Sweden 2008-05-07) this gives a real rate of return 1.17%. To assess if this rate can be expected to stay constant in the future the return of the ten year government bond was examined over a ten year period. This analysis showed that the average real interest rate has been 2.11% during the past ten years. The real interest rate of 2% was chosen since the inflation in Sweden is currently at a fourteen year high. This may explain why current real rates are lower than average.

The present value of the decommissioning costs estimated by the model are approximately 745 000 SEK for an onshore installation of ten turbines (74 500 SEK per turbine) and 8 600 000 SEK for an offshore installation of ten turbines (860 000 SEK per turbine). To clarify, this is the sum that would have to be reserved and placed in a risk-free investment today to pay decommissioning costs in twenty years. This figure can be compared with the investment cost for a 2 MW turbine. The cost for an operational land-based 2 MW turbine approximately 22 000 000 SEK of which 20 000 000 are attributed to the purchasing cost of the turbine. For turbines located at an offshore sites costs increase with approximately 50%. For the 2 MW turbine this would mean an operational offshore turbine has an investment cost of approximately 33 000 000 SEK. The cost increase is attributed to increased costs for foundations and installation. Generally wind turbines are expected to have a payback time of approximately ten years. (Wizelius 2008-05-21)

A turbine with a rated power of 1.65 MW, which has been the case examined with the Vestas V82 turbine, can be expected to produce 3795 kWh of electricity per year[9]. With this electricity production a reservation of 0.0077 SEK per kWh would have to be made for onshore turbines throughout the turbines life time. Assuming the same production for offshore turbines the figure would be 0.0899 SEK per KWh.

Although the calculations explained above may give the reader the impression that the figures presented are exact this is not the case. The results are only an estimation which is based on data gathered through interviews. Market conditions determine costs and revenues; therefore these may change considerably in the future. Moreover many simplifications and assumptions underlie the model, as has been explained in previous sections. In order to determine which factors are of most importance, determined by their effect on the results computed by the model, sensitivity analyses have been performed. These will be presented in the forthcoming sections. First, however, results will be presented of the models estimated decommissioning costs for sixteen turbines with different characteristics.

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[9] The Danish Wind Power Association estimates that on average the kWh of electricity a turbine produces can be approximated by the following formula kWh=2,3 x rated power. The factor may slightly overestimate average production in Swedish land-based turbines. Moreover the factor will probably increase at offshore conditions. No alterations have been made to account for these considerations since the calculation is only intended to give the reader a notion of the costs per kWh.

Table 9 Estimated economic consequences of for decommissioning of a V82 turbine

	Vestas V82		Model calcualtions	
	ONSHORE	OFFSHORE	ONSHORE	OFFSHORE
Dismantling of turbine	**2 367 000 kr**	**9 536 800 kr**	**2 367 000 kr**	**9 536 800 kr**
Transport of crane	117 000 kr	4 768 400 kr	117 000 kr	4 768 400 kr
Set up of crane	1 750 000 kr	1 192 100 kr	1 750 000 kr	1 192 100 kr
Dissasembly of turbine	500 000 kr	3 576 300 kr	500 000 kr	3 576 300 kr
Treatment of blades	**312 000 kr**	**312 000 kr**	**312 000 kr**	**312 000 kr**
Severing of blades	42 000 kr	42 000 kr	42 000 kr	42 000 kr
Transport of blades	81 000 kr	81 000 kr	81 000 kr	81 000 kr
Disposal of blades	189 000 kr	189 000 kr	189 000 kr	189 000 kr
Treatment of tower and nacelle	**- 3 462 200 kr**	**- 3 462 200 kr**	**- 2 909 140 kr**	**- 2 909 140 kr**
Severing of tower and nacelle	416 400 kr	416 400 kr	416 000 kr	416 000 kr
Transport of waste material	- kr	- kr	- kr	- kr
Disposal of metal	- 3 933 500 kr	- 3 933 500 kr	- 3 447 540 kr	- 3 447 540 kr
Steel	- 2 611 500 kr	- 2 611 500 kr	- 2 590 740 kr	- 2 590 740 kr
Stainless steel	- 858 000 kr	- 858 000 kr	- 561 000 kr	- 561 000 kr
Copper	- 464 000 kr	- 464 000 kr	- 295 800 kr	- 295 800 kr
Disposal of concrete	- kr	- kr	- kr	- kr
Disposal of organic material	54 900 kr	54 900 kr	122 400 kr	122 400 kr
Disposal of electronic components	- kr	- kr	- kr	- kr
Treatment of foundation	**1 585 000 kr**	**6 079 867 kr**	**1 585 000 kr**	**6 079 867 kr**
Demolishment of foundation	1 410 000 kr	7 839 200 kr	1 410 000 kr	7 839 200 kr
Severing of foundation material	- kr	270 667 kr	- kr	270 667 kr
Transport of waste material	- kr	- kr	- kr	- kr
Disposal of concrete	- kr	- kr	- kr	- kr
Disposal of metal	- kr	- 2 030 000 kr	- kr	- 2 030 000 kr
Restoration of foundation site	175 000 kr	- kr	175 000 kr	- kr
Treatment of cables	**- 264 038**	**- 264 038**	**- 247 280**	**- 247 280**

	kr	kr	kr	kr
Excavation of internal cables	832 500 kr	832 500 kr	832 500 kr	832 500 kr
Excavation of external cables	9 250 000 kr	9 250 000 kr	9 250 000 kr	9 250 000 kr
Transport of cables	- kr	- kr	- kr	- kr
Disposal of internal cables	- 74 538 kr	- 74 538 kr	- 57 780 kr	- 57 780 kr
Disposal of external cables	- 10 272 000 kr	- 10 272 000 kr	- 10 272 000 kr	- 10 272 000 kr
Restoration of cable site	- kr	- kr	- kr	- kr
TOTAL COST	**537 762 kr**	**12 202 429 kr**	**1 107 580 kr**	**12 772 247 kr**
Delta			- 569 818 kr	- 569 818 kr
COST PER TUBINE	**53 776 kr**	**1 220 243 kr**	**110 758 kr**	**1 277 225 kr**
Yearly cost per KWh	**0,0037 kr**	**0,0850 kr**	**0,0077 kr**	**0,0890 kr**
Present value total cost	361 898 kr	8 211 885 kr	745 370 kr	8 595 356 kr
Present value cost per turbine	36 190 kr	821 188 kr	74 537 kr	859 536 kr
Yearly cost per KWh (as annuity)	0,0031 kr	0,0700 kr	0,0064 kr	0,0733 kr

5.4.2. Comparing decommissioning cost for different turbines

In this section the model is applied on sixteen different wind power turbines in order to verify that the estimates made by the model are acceptable and logical. The different parameters effect on the results is also examined.

General characteristics of the turbines on to which the model was applied can be viewed in Table 10. More specific details about the turbines can be found in Appendix 2. The selection was made to guarantee a spread of different turbines currently being erected in Sweden. There are three different makes represented and rated powers ranging from 800 kW to 3000 kW. Towers with different materials and heights are also included in order to make comparisons possible.

The tests are made by inserting the requested parameters into the model. In some cases assumptions have been made, for example when determining the distance to the electrical grid and characteristics of the cables. In those cases the assumptions are the same for all sixteen turbines. Four different scenarios representing the decommissioning scope are represented in Table 10. They are:

Scenario 1: Only the turbine is decommissioned.
Scenario 2: The turbine and its foundation are decommissioned.
Scenario 3: The turbine, its foundation, and internal cables are decommissioned.
Scenario 4: The turbine, its foundation, and both internal and external cables are decommissioned. This is also called the full-scope scenario.

Table 10 Comparison of decommissioning costs for sixteen different turbines.

Make	Location	Rated power	Tower type	Hub height	Nacelle weight	Scenario 1	Scenario 2	Scenario 3	Scenario 4

		(kW)		(m)	(t)				
EnerconE82	Onshore	2000	Steel	78	91	-166 000 kr	-7 000 kr	70 000 kr	- 32 000 kr
Vestas V90	Onshore	2000	Steel	78	61	-125 000 kr	73 000 kr	150 000 kr	48 000 kr
Vestas V90	Onshore	1800	Steel	80	68	- 86 000 kr	75 000 kr	153 000 kr	50 000 kr
EnerconE53	Onshore	800	Steel	60	38,5	- 83 000 kr	97 000 kr	175 000 kr	72 000 kr
Nordex N90	Onshore	2500	Steel	100	91	- 61 000 kr	101 000 kr	179 000 kr	77 000 kr
Vestas V82	Onshore	1650	Steel	78	51	- 30 000 kr	128 000 kr	206 000 kr	103 000 kr
EnerconE53	Onshore	800	Steel	73	38,5	- 4 000 kr	154 000 kr	232 000 kr	129 000 kr
Vestas V52	Onshore	850	Steel	74	22	- 2 000 kr	160 000 kr	237 000 kr	135 000 kr
Vestas V90	Onshore	1800	Steel	105	68	1 000 kr	167 000 kr	244 000 kr	142 000 kr
Nordex N90	Onshore	2500	Steel	80	91	6 000 kr	224 000 kr	302 000 kr	200 000 kr
Vestas V90	Onshore	3000	Steel	105	68	8 000 kr	232 000 kr	309 000 kr	207 000 kr
Nordex N80	Onshore		Steel	70	91	48 000 kr	274 000 kr	352 000 kr	250 000 kr
EnerconE82	Onshore	2000	Hybrid	98	91	285 000 kr	444 000 kr	521 000 kr	419 000 kr
EnerconE82	Onshore	2000	Hybrid	138	91	545 000 kr	704 000 kr	781 000 kr	679 000 kr
Vestas V90	Offshore	3000	Steel	80	68	624 000 kr	1 144 000 kr	1 222 000 kr	1 119 000 kr
Vestas V90	Offshore	2000	Steel	60	64	651 000 kr	1 171 000 kr	1 248 000 kr	1 146 000 kr

The decommissioning cost predicted by the model for each of the sixteen turbines in four different scenarios can be seen in Table 10. The impact of the different decommissioning scenarios and parameters on the estimated decommissioning costs are discussed below.

The first scenario, where only the turbine is removed, has the least negative economic consequence among the four scenarios. In half of the cases the result is actually a net positive. The positive results are explained by the revenues generated by the sale of scrap metals. A large part of these revenues are generated by the steel located in the tower. As can be seen in Table 10 the costs exceed revenues significantly when the turbines have hybrid towers or are located at offshore locations. This is explained by the fact that a hybrid tower reduces the amount of steel in the turbine and an offshore location increases dismantling costs.

The second scenario involves the removal of the turbine and its foundation. In the land-based case this is a large cost with no revenues since the foundations to a large extent are made of concrete. In the offshore case on the other hand removing the foundation implicates revenues. Despite the positive effects of this revenue the net effect is negative due to the larger costs related to the foundation removal. As a result the decommissioning of the foundation adds a net cost in all sixteen cases and therefore this scenario is more expensive.

In the third scenario decommissioning of the turbine, foundation, and internal cables takes place. Internal cables do contribute to the revenues due to metal found in the cables. However the excavation costs are larger than the metal value of the cables. Since the same assumptions are made regarding the characteristics of the cables the costs increase by approximately the same amount (77 000 or 78 000 SEK) in all cases. Divergence is explained by the rounding of numbers. It is concluded that in this scenario the economic consequences for decommissioning are once again affected negatively by an increased scope of decommissioning.

In the fourth scenario a full-scope decommissioning takes place. This involves the removal of the turbines, foundations, internal and of external cables. In difference to the internal cables, the metal value in external cables exceeds their decommissioning cost. This is explained by the fact that the cost for removing the internal and external cables is the same. However, external cables are heavier and have a higher content of metals which entails more revenue. Hence the economic consequence of decommissioning is affected positively. It is noteworthy that in the cases examined the metal content in the cables is assumed to be 80% aluminium and 20% copper. Should the copper content increase the revenues will be affected positively since copper is heavier and has a higher market value.

An analysis of the effect of the models parameters will now be conducted. In order to analyze all parameters the full-scope scenario is used. By examining Table 10 it can be observed that it is difficult to make a prediction of the economic consequences of decommissioning based on the turbine's rated power. This is explained by the fact that it is not the rated power that determines the equipment used when dismantling a turbine or the revenues generated. The rated power does usually implicate a heavier nacelle, however, this is only one of the factor determining the crane used when dismantling. Other important parameters are the hub height and the location of the turbine.

The effect of rated power on revenues can be clarified by examining the two cases involving Vestas turbines with a hub height of 78 meters and a nacelle weight. These have a rated power of 2 MW and 1.65 MW and similar nacelle weights thus requiring the same dismantling equipment. However these turbines differ in the weight of the tower with the 2 MW turbine having a heavier tower and nacelle. The metal value in the 2 MW turbine exceeds that of the 1.65 MW turbine due to a 10 ton heavier nacelle and a 29 ton heavier tower. This generates higher revenues and lowers the net costs when decommissioning the 2MW turbine. Enercon's E53 and Vestas V52 turbines can also exemplify how turbines with a relatively low rated power (800 and 850 kW respectively) but with relatively high towers (73 and 74 meters respectively) are expensive to decommission. Both these turbine require expensive equipment while their scrap metal value is quite low, resulting in a relatively expensive decommissioning.

As for the manufacturer (make of the turbine) one interesting observation can be made regarding the Enercon turbines. Enercon turbines do not have gearboxes, instead they have larger generators. This implies that the amount of copper is much larger in these turbines. Therefore the metal value is higher, increasing revenues and lowering net costs. The effect is most visible on the larger turbines where the copper amount differs greatly between a turbine with a gearbox and one without. For example, the model predicts that the Enercon E82 2MW turbine with tubular steel tower will be decommissioned with a positive balance of 32 000 SEK. For the Vestas V90 2MW, on the other hand, the model estimates a cost of 48 000 SEK for a full-scope decommissioning. The difference is smaller between Enercon's E53 800 kW turbine (hub height 73 meters) and Vestas's V52 850 kW turbine (hub height 74 meters) since the weight of copper differs less between turbines with lower rated power. However, the E52 turbine is still 6 000 SEK less expensive to decommission.

In Table 10 two Enercon E82 turbines are notably expensive to decommission, with costs reaching 420 000 SEK and 680 000 SEK respectively. This is due to that these turbines have hybrid towers. In hybrid towers there is a limited amount of steel that can be sold which reduces the revenues generated when decommissioning the turbine. Instead, a large amount of concrete has to be treated at a considerable cost. This increases the net costs, resulting in the most expensive type of land-based turbines to decommission.

As a final observation it is noted that offshore turbines are much more expensive to decommission. This is explained by the large difference in equipment costs. The revenues generated by the sales of scrap metals found in the mono pile foundations are offset by increased costs for the dismantling of the turbine and the treatment of the foundation.

The results presented in Table 10 show that the parameters requested in the model do have an impact on the estimated decommissioning costs. Important findings are:

- The rated power of a turbine does not determine its decommissioning costs.
- The net cost for decommissioning turbines with hybrid towers are higher than those for decommissioning of turbines with steel towers.
- Turbines with a gearbox are expected to be more expensive to decommission than those without a gearbox.
- Turbines located at offshore locations are significantly more expensive to decommission.
- The scope of decommissioning affects the economic effects of decommissioning.

The results are also deemed both logical and acceptable.

6. Validating the model and investigating long-term perspectives

In the previous chapter the model constructed to predict economic consequences of wind turbine decommissioning has been described and tested on different turbines. To gain a better understanding of the model, and particularly its validity, the properties of the model must be examined more closely. One of the most important aspects examined are the effects of uncertainties in the model. Uncertainties are present in the models parameters and in future events that may affect the economic consequences of decommissioning. In order to handle these uncertainties sensitivity analyses have been performed.

In the first section of this chapter sensitivity analysis is described from a theoretical perspective. Sensitivity analyses are then performed by examining the most important uncertainties regarding parameters in the model. The findings will enable a validation of the model and its robustness can be determined.

Once the robustness in the model is confirmed long-term effects on predicted economic consequences of decommissioning are examined. This is necessary since costs and revenues will take place in the future. To understand the effect of future developments on decommissioning costs three theories will be presented; competition in the long run, flexibility and technological progress, and learning curves. The theories will then be used to predict the economic consequences of wind turbine decommissioning in the future. Since developments in costs and revenues in the decommissioning process are judged to be independent of each other they are examined separately.

6.1. A theoretical introduction to sensitivity analysis

When building a model input is subject to many sources of uncertainty. These include errors of measurement, absence of information, and poor or partial understanding of the driving forces and mechanisms. This imposes a limit on the confidence that can be placed on the output of the model. Furthermore, models may have to cope with the natural intrinsic variability of the system, such as the occurrence of stochastic events. Good modelling practice requires the modeller to provide an evaluation of the confidence in the model. This involves assessing the uncertainties associated with the modelling process itself and with the outcome of the model. Sensitivity analysis can be a valuable tool for characterizing the uncertainty associated with a model. (JRC 2008-04-15)

Cullen and Frey (1999, p 315) define sensitivity analysis as an assessment of the impact of changes in input values on model outputs. Sensitivity analyses are useful since they can provide insight regarding model verification and regarding the robustness of model results. Sensitivity analysis can also be used a method to assess key sources of variability and uncertainty in a model. Such data can then be used as a basis for prioritizing additional data collection or research. (Cullen and Frey, 1999)

There are several procedures to perform sensitivity analysis. The most commonly used is sampling-based. Using this method the model is executed repeatedly with combinations of values sampled from the distribution (assumed or known) of the input factors. A sensitivity analysis is generally performed by carrying out the model repeatedly with different factor values, which are sampled with some probability distribution. The following steps are recommended when performing this type of analysis (JRC 2008-04-15):

1. Specify the target function and select the input of interest
2. Assign a distribution function to the selected factors
3. Generate a matrix of inputs with that distribution(s) through an appropriate design
4. Valuate the model and compute the distribution of the target function
5. Select a method for assessing the influence or relative importance of each input factor on the target function.

6.2. Assessing the robustness of the model

In this section the assumptions made in the model are tested and the robustness of the results is verified. The tests have been performed on an offshore example involving ten V82 1.65 MW turbines. The offshore case was considered suitable to examine more closely since there are more uncertainty factors affecting this scenario. The uncertainties regarded as unique and significant are fewer for the onshore case. Therefore many of the significant assumptions for this case will be tested indirectly by examining the offshore case. Thus conclusions from the offshore case can be transferred to the land-based case when the assumptions tested are analogous.

The analyses have been performed using the computer software MatLab. MatLab is a programme developed for technical computing. Below an account is made for each step in the sensitivity analysis so that the reader is familiarized with the procedure. The same steps are followed in each of the forthcoming sensitivity analyses.

1. Specify the target function and select the input of interest

The target functions and inputs of interest are specified in the section “Developing a model for wind power turbines”. When conducting the sensitivity analyses to establish the robustness of the model focus is placed on the parameters that have been listed as assumed parameters in that section. These will not be listed here. Instead the reader is recommended to review the model, activity, and calculation descriptions presented in the second section of chapter five.

2. Assign a distribution function to the selected factors

The assigned distribution function is a normal distribution with the standard deviance selected as a percentage of the nominal value for each factor. The percentages were selected based upon empirical findings and/or logical reasoning. The selection of normal distribution is motivated by the central limit theorem (for reference se any textbook on mathematical statistics for example Knight 2000).

3. Generate a matrix of inputs with the assigned distribution(s) through an appropriate design

The matrix of inputs where generated by drawing pseudo-random values from a normal distribution.

4. Evaluate the model and compute the distribution of the target function

The parameters in the model that were based on assumptions where evaluated one by one by generating a distribution with a 90% confidence interval for the target function. To make the factors comparable the standard deviation was set at ten percent of each factors nominal value. The results are presented in Table 11.

5. Select a method for assessing the influence or relative importance of each input factor on the target function.

The influence of each of the tested factors was checked for relative importance. This was completed by comparing the result of the above computed distributions and then relating them to the uncertainty of the collected data. Using the deviations selected in the second step of this process the impact of the factors deemed most important where simulated.

6.2.1. Results of model robustness analysis

Based on the evaluation in step four, the factor that by far has the largest impact is the duration of the turbine dismantling at offshore locations, which can be seen in Table 11. This is explained by the high day rate of the vessel used for dismantling. The uncertainty of this factor is regarded a low, despite the fact that there is very limited experience in offshore dismantling. This is due to that the process itself is regarded as very similar to the installation process where a satisfactory level of experience has been attained.

Table 11 also shows that the second largest impact is caused by the weight of steel in the turbine. In this case the uncertainty is also regarded as low. The predominant amount of steel in the turbine is found in the tower. As the reader may remember this is one of the input variables requested from the model user. The amount of steel in the nacelle is, on the other hand, is estimated based on data about the nacelle weight which is also provided by the user.

The duration of foundation demolishment, with a delta of over 60 000 SEK, also has a relatively high impact on the estimates made by the model. In this case the uncertainty is considered to be higher. The process of foundation demolishment at offshore locations is rather uncertain and no previous experience can be referred to. Moreover the activity is not expected to be similar to the installation, as is the case with turbine dismantling.

Remaining factors have a low impact on the model, as can be seen in Table 11, and will not affect the models robustness to an extent worth considering.

Table 11 Impact of the different assumption-based factors. Cost low indicates the 0.05-quatile and cost high indicates the 0.95-quatile. Delta is the difference between cost high and cost low.

Factor	Cost low	Cost high	Delta
Turbine dismantling duration	1 178 700 kr	1 378 300 kr	199 600 kr
Foundation demolishment duration	1 245 300 kr	1 307 900 kr	62 600 kr
Weight of Steel	1 234 700 kr	1 318 400 kr	83 700 kr
Weight of Stainless steel	1 267 500 kr	1 285 000 kr	17 600 kr
Weight of Generator copper	1 271 800 kr	1 281 000 kr	9 200 kr
Weight of organic material	1 274 300 kr	1 278 400 kr	4 100 kr
Length between turbines	1 263 800 kr	1 288 800 kr	25 000 kr
Weight of internal cables	1 275 300 kr	1 277 500 kr	2 200 kr

After examining the impact and uncertainty of the factors presented in Table 11, two factors where to chosen for the simulation of robustness. These are the weight of steel and the duration of the foundation demolishment. The standard deviations for these factors were set at 5% and 10% respectively as can be seen in Table 12. The weight of steel was chosen since, as mentioned previously, assumptions have been made regarding the steel content in the nacelle. However, the effects of these assumptions were not considered large enough to account for a standard deviation of 10%. Therefore the standard deviation was adjusted to 5%, which is deemed more reasonable.

The duration of the foundation demolishment activity was considered to be significantly uncertain and is consequently this factor is included in the simulation. In this case the standard deviation of 10% is considered reasonable. As has been explained there are considerable uncertainties affecting the process due to lacking experience. Additionally, the duration is difficult to foresee due to weather and current conditions at the site. These circumstances motivate the choice of a higher standard deviation.

Despite the fact that Table 11 shows that the duration of turbine dismantling has largest impact this factor is excluded in the simulation. This is due to that the uncertainty regarding turbine dismantling is considered low enough to leave it entirely out of the simulation.

Table 12 Factors used in the simulation to establish robustness.

Factor	Standard deviation
Weight of Steel	5% of nominal value
Foundation demolishment duration	10% of nominal value

With the factors presented in Table 12 the robustness of the model can be determined. The value of these two factors is varied around their nominal value in a normal distribution with the presented deviations. Through the tests decommission cost are calculated repeatedly using different values. The result of the simulation can be viewed in Figure 13.

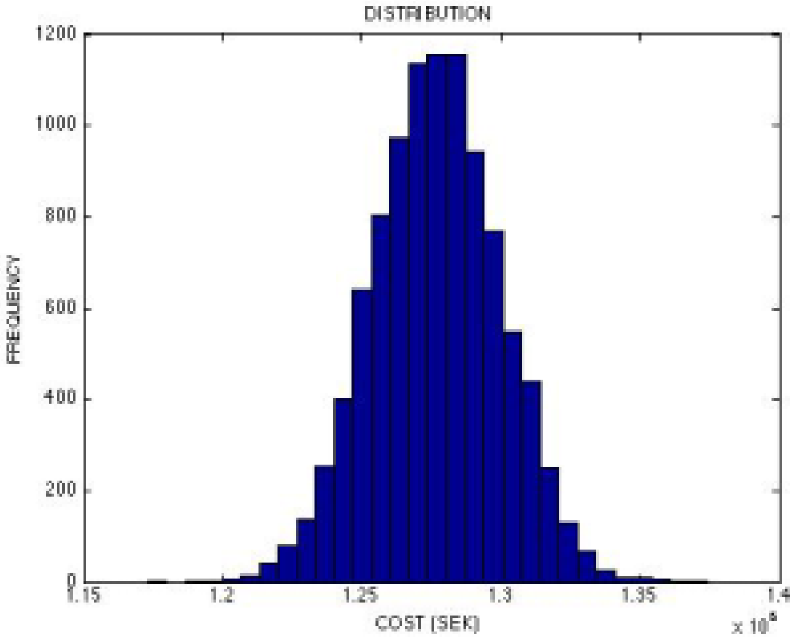

Figure 13 The distribution of predicted economic consequences for decommissioning for an offshore Vestas V82 1.65 MW turbine with variations according to Table 12. The cost at the 0.05-quantile is 1 239 300 and the cost at the 0.95-quantile is 1 314 000 creating a delta of 74 700.

The results demonstrate a delta of approximately 75 000 SEK. This relatively low delta conforms the model has a satisfactory level of robustness. However, it is important to remember that model is limited to compute the “ideal” decommissioning case. This case involves no complications or unexpected events. Any projector will attest to that there are no projects where these assumptions hold true. Consequently the variation of costs in a real example can - and probably will - diverge to a greater extent from the nominal value than simulated in this analysis.

6.3. Theoretical frameworks explaining long-term effects

In this section the effects of future developments affecting decommissioning costs and revenues are examined. In micro economical theory it is common to mention three factors that affect long term production costs. These are competition in the long run, flexibility and technical progress, and learning by doing (Perloff 2004, p. 220). Before analysing what effects these factors may have on the economic consequences predicted by the model their theoretical bases are described. Thereafter the effects of competition in the long run, flexibility and technical progress, and learning by doing on the costs and revenues related to wind turbine decommissioning will be examined. As can be seen in Figure 14 this is the last step in the process developed to estimate the economic consequences of decommissioning.

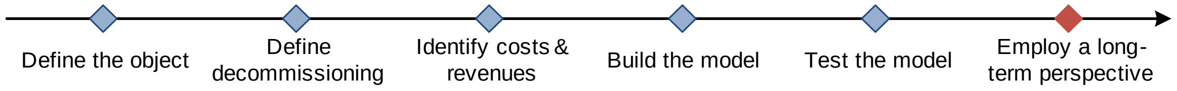

Figure 14 Process for recognizing economic consequences of decommissioning

6.3.1. Competition in the long run

In the short term the only way to affect supply is for existing firms to produce more. In the long run, however, firms can enter and leave markets. The decision to do so is based on a firm's ability to enter or exit the market - which is often limited by barriers to entry or exit. These barriers are often composed of large fixed costs. Theoretically, in a market characterized by perfect competition and no entry barriers, firms will continue to enter the market until the last firm to enter makes zero long-term economic profit. If there are substantial barriers to entry, however, firms will enter the market only if the long run economic profit exceeds the costs of entering. The ease of entry and exit varies considerable between different industries. (Perloff 2004)

In markets with supply shortages and barriers to entry demand can drive up costs in the short term. If competitors are scarce and their entry can be limited the firm(s) on the market will have considerable market power. The firm(s) will be a price setter rather than a price taker and maximize profits by setting the price above marginal costs. In the long term, however, other firms will be attracted by these profits and may enter the market. The entry of new market participants will continue as long as entry costs can be covered by profits in the long term. As the number of competitors increase competitive forces will drive down prices and profits. (Perloff 2004)

6.3.2. Flexibility and technical progress

Micro economical theory may also be useful to understand how technological progress and time affect a firm's cost conditions and productivity. In micro economics it is generally accepted that technology and/or production processes transform factors of production into outputs. The factors of production are capital which encompasses for example equipment, labour defined as human services, and materials. The production function defines the relationship between quantities of input and the maximum of output that can be produced. (Perloff 2004)

The short term is defined as a time period during which at least on factor of production cannot be varied, called fixed input. The long run is a time period long enough for all factors of production to be changed. There is no general length of time that characterizes long run and short run, but in the long run firms will adjust inputs so that production costs are as low as possible. Since capital cannot be varied in the short term, the short term costs will always be at least as high as the long-run costs. This also means that long term costs are always equal to or lower than short term costs. In the long-run ineffective combinations of inputs can be altered. (Perloff 2004)

Technical progress is defined as advances in technology that allow more output to be produced by the same level of input. These improvements in productivity are explained by better management or better organization of the production process. Technological progress will thus also lead to that long-run costs can be expected to decrease. The amount of technological progress does vary significantly between different industries. A longer time-frame does, however, increase the possibility of technical progress taking place regardless of industry. (Perloff 2004)

6.3.3. Learning curves

Learning curves describe the relationship between the consecutive number of units produced (x-axis) and the time per unit produced (y-axis). It is based on the statistical findings that as the cumulative output doubles; the cumulative average labour input time/cost required per unit will decrease by a constant percentage. This percentage is usually referred to as the Progress Rate (PR). (Siegel & Shim 2000, p. 252)

Learning functions are expressed by the following function (Stewart et al 1995, pp. 170-192):

$$Y = AX^b$$

where Y = time or cost per cycle or unit
A = time or cost for the first unit or cycle
X = number of cycles or units
b = constant for a given set of conditions

A typical learning curve has a downward sloping curve that flattens out as can be seen by the example presented in Figure 15.

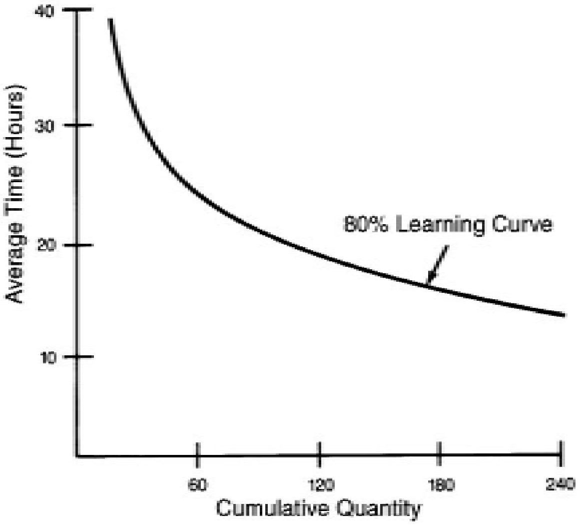

Figure 15 An example of learning curve with a PR of 80%. This illustrates that as production quantities double, the average time per unit decreases by 20% of its immediate previous time. (Siegel & Shim 2000, p. 253)

An 80 percent progress rate is common for many activities. Therefore it is sometimes used as an average expected PR in cost forecasting and production planning. As output doubles from one unit to two units to four units, etc., the learning curve descends quite sharply and costs decrease dramatically. As output increases and it consequently takes longer to double previous output, and the learning curve flattens out. Thus, costs decrease at a slower pace when cumulative output is high. (Hillstrom&Hillstrom 1998) The learning principle can be applied liberally on different situations in the real world; ranging from simple tasks to complicated processes. The same mathematical equation applies for learning processes of individuals as well as for larger production-oriented organizations. (Stewart et al 1995, pp. 170-192)

The shape of the learning curve depends on the tasks involved in the process. If a process is automated to a great extent or involves a lot of machining the curve slope will be flatter, thus signifying a lower degree of learning. If the process involves a lot of handwork and/or elements that are repetitive in their nature the curve slope will be steeper, thus signifying a higher degree of learning. (Stewart et al 1995, pp. 170-192)

In the case of the wind power industry research has been conducted to find progress rates for different areas. No research concerning progress rates for decommissioning has been found, which is not unexpected due to the overall lack of experience in this field. However, progress rates have been found for installation of both land-based and offshore wind turbines. In Denmark a study been conducted for land-based wind turbines. This study found that as the cumulated installation (measured in MW) doubled the investment costs decreased by 10%. Thus a progress rate of 90% was established. However, when determining the progress rate of ex-works costs for the wind turbine, it was found that these were 91%. This means that the PR for the installation related work was only 1%. (Andersen 2003)

For offshore turbines the progress rates that have been found are higher. The duration of installation has been estimated to have a PR of 77%, compared with 95% for other installation costs. These findings are also been based on experiences from Denmark. (Junginger et al 2004)

6.4. Using the model to analyse long term effects

In this section an analysis will be performed to investigate the effect of time on the results presented by the model. The theories presented above will be applied to answer the following question: how may the predicted economic consequences of wind turbine decommissioning be affected by the passage of twenty years?

The analysis will be divided up into two parts. The first part focuses on the revenue parameters whereas the second part focuses on the cost parameters. In the case of revenues, the parameters that will be analysed are metal prices and the analysis will be performed using historical pricing data. For parameters concerning costs the analyses will be based on theories on competition, long-term costs and learning curves. Either costs or revenues are manipulated, keeping the other fixed. This is done in order to isolate the effects of price changes on the cost or revenue side of the equation. In order to demonstrate how the result is affected depending on the scope of decommissioning four scenarios are analysed.

Scenario 1: Only the turbine is decommissioned.
Scenario 2: The turbine and its foundation are decommissioned.
Scenario 3: The turbine, its foundation, and internal cables are decommissioned.
Scenario 4: The turbine, its foundation, and both internal and external cables are decommissioned. This is also called the full-scope scenario.

6.4.1. Analysing revenue parameters

All the revenue in the model is generated by the sales of scrap metal. Therefore the most important parameter to consider when analysing the revenue parameters is the value of the turbines' metals in the future. In an attempt to understand how metal prices can be expected to develop in the future an analysis of historical data has been performed.

Before reading this analysis the reader is advised to keep in mind that it is an analysis the effect of metal prices on estimated decommissioning costs for wind turbines. It is not in any way an attempt to predict metal prices at the time of decommissioning. However, in order to estimate and vary future prices in a reasonable way historical metal price data is analysed.

The historical price data used has been documented by the U.S. Geological Survey. This institute has compiled data about metal prices in the United States of America dating to the beginning of the twentieth century. In the data provided by this institute the prices are expressed in both nominal money values and in the money value of 1998. In order make the figures more accessible to the reader the price figures were manipulated as to be expressed in the money value of year 2007 in U.S. dollars.

Since metals are a commodity traded on a global market where prices are determined at financial centres the data used was considered to accurately represent global price developments. The Swedish prices will of course be affected by exchange rates. This was not taken into consideration since the analysis is aimed at establishing only the variations in metal prices over time.

Historical pricing dated from 1950 to 2006 was analysed for copper, aluminium, and scrap steel. It was preferred to exclude information dating back to the beginning of the twentieth century since production methods and global trade have changed the markets considerably since then. Moreover the prices at the beginning of the century were significantly higher, which would increase the risk of overestimating the downward slope of the trend line. Year 1950 was chosen as a suitable base since the Second World War had by this time finished and global trade could once again take place.

The parameters that are analysed are the steel price, the aluminium price and the copper price. The choice of parameters was based on the first part of the sensitivity analysis. There it was established that the economic consequences of decommissioning are greatly affected by revenue produced by the sales of steel and external cables. The value of the cables is dependent on the price of aluminium and copper.

Data about historical prices was analysed by finding a trend with linear regression and calculating the standard deviance from that trend. The results are presented in Figure 16 to Figure 18.

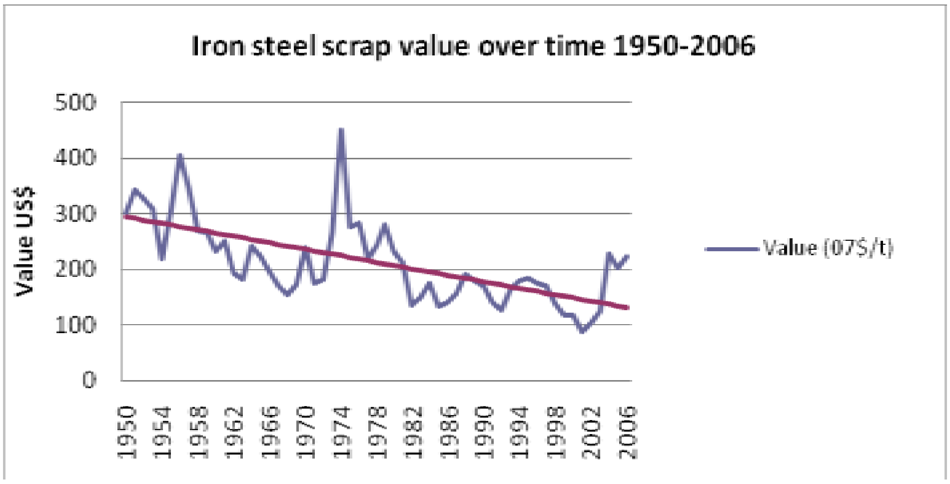

Figure 16 The value of iron steel scrap in 2007 US dollars per ton from 1950 to 2006. The trend line is described by the function y=-2.93x+6 009 and the standard deviation from the trend line is 57.23.

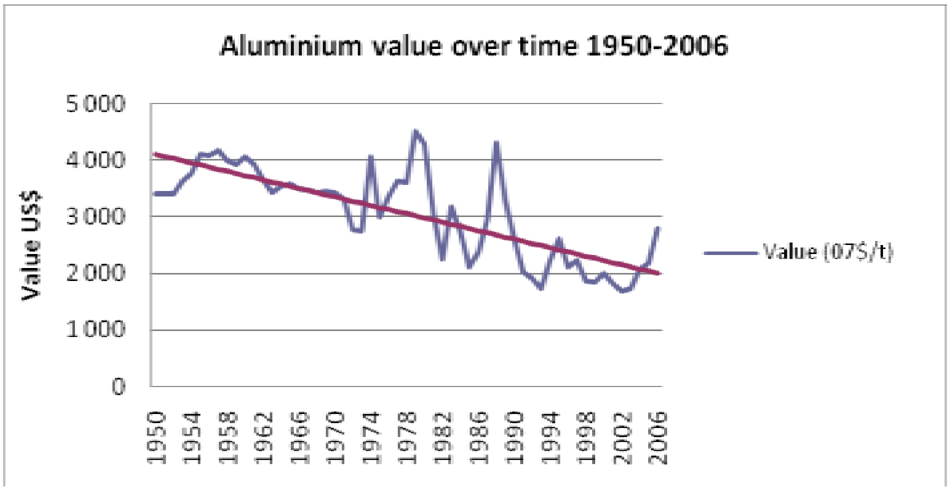

Figure 17 The value of aluminium in 2007 US dollar per ton from 1950 to 2006. The trend line is described by the function y=-38x+77 737 and the standard deviation from the trend line is 521.23.

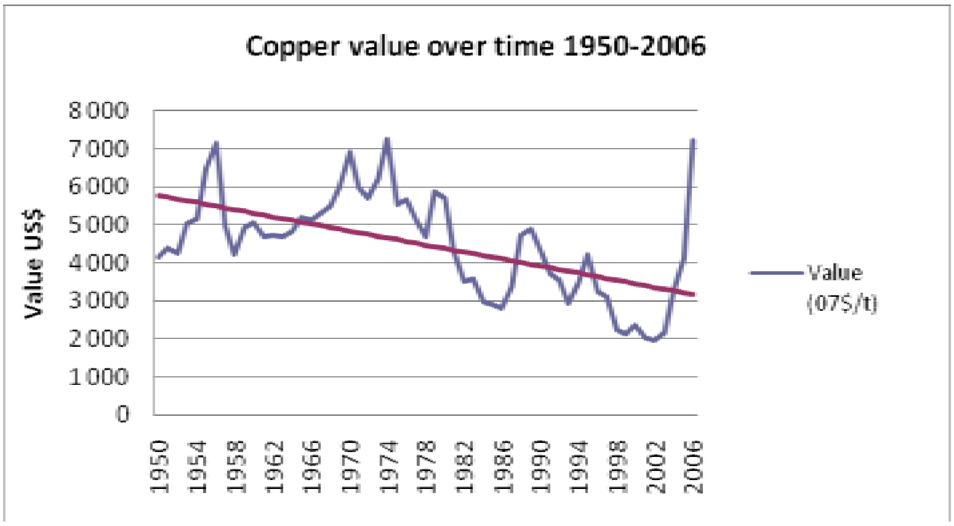

Figure 18 The value of iron steel scrap in 2007 US dollar per ton from 1950 to 2006. The trend line is described by the function y=-46x+95 351 and the standard deviation from the trend line is 1 041.66.

The trend lines presented above were used to estimate metal prices for the year 2028 expressed in the U.S. dollars in the money value of 2007. As the reader may understand, in twenty years time (year 2028) the turbines erected today will have served their economic lifetime and decommissioning may begin. Therefore the metal prices at that time will be of great significance for the economic effects of turbine decommissioning.

The sensitivity analysis was performed using the same methodology described in the first section of this chapter. The metal prices for 2028 where extrapolated by using linear regression of the historical data. The standard deviance for each metal was calculated using the deviation from the linear regression. The extrapolated prices along with their standard deviances where used to compute a normal distribution. In this way the standard deviation creates a fluctuation around the extrapolated price. The result can be seen in Table 13.

Table 13 Current metal prices as per March 2008-03-31 and extrapolated prices for 2028 calculated with linear regression of historic price data. Standard deviance is deviance from the linear regression.

Metal	Current price (SEK/ton)	Extrapolated price (SEK/ton)	Standard deviance (SEK)
Steel	1 500	400	340
Aluminium	15 000	6900	3130
Copper	47 000	12900	6250

Previously no correlations have been taken into account between the parameters analysed since it is reasonable to assume the parameters analysed are independent. This is not the case for metal prices. Therefore correlations between metal prices were taken into account when performing the analysis.

As stated previously this is not an attempt to forecast metal prices, it is merely a manner to extract figures for use in further analysis. However, before an analysis is performed using the figures presented in Table 13 a brief discussion of these figures is justified. As shown by the trend lines in Figure 16 to Figure 18, historically there has been a tendency towards decreasing metal prices. Given recent developments with increasing metal prices this may be surprising which justifies a brief discussion of the trend lines despite that this subject falls out of the scope of this study.

Some of the factors affecting metal prices are briefly discussed to gain a better understanding of the development of metal prices. Production improvements and trade developments that have taken place in the past will probably continue in the future, which can contribute to a further decrease in prices. Some factors causing this development are competitive forces, long-term costs, and technological progress presented in which have theoretically been presented in the first section of this chapter. Other sources confirm that this holds true, stating that with time the price of raw materials tend to approach the marginal cost of extraction (Dagens Industri 2008-05-19). However, the continued effect of cost decreases may be limited due to increasing demand of raw materials from developing nations. This development has already been observed by Chinas impact to the global market prices for metals. These are just some aspects that can be expected to affect future metal prices. As the marginal return on production improvements reach a limit and developing nations increase global demand for metals some speculate as to whether the long term decreasing trend that have been observed is about to change. (Melander 2008-05-19) This issue will not be examined more closely since it falls out of the scope of this study, but the reader has hopefully been convinced that future metal prices are difficult - if not impossible - to predict.

There are means to hedge against the uncertainty of future metal prices, for example by buying futures. The trading of steel futures is a new phenomenon, which started in the spring of 2008. Pricing statistics for these futures are therefore limited. The trading of copper futures has existed for a longer time period. The cash mean of copper in April 2008 was 8684 USD/ton whilst a 27-month mean was 7705. (LME 2008-05-19) This indicates that the market believes in a decrease in copper price over the coming 27 months. However, 27 months is a short-term view compared with the 20 years, which has the time frame employed in this analysis. As can be seen in Figure 16 to Figure 18 the prices can swing violently over a short term. Therefore no conclusions can be drawn by looking at the prices of futures.

These results are obtained by using extrapolation over a long period. Extrapolation should be done with great caution. In this case 50 years of data have been used to extrapolate the result 20 years from now. An extrapolation to this extent is very unreliable. The trend line computed would eventually lead to negative metal prices. This is, of course, unfeasible. Nevertheless, to a certain extent result can be said to represents a pessimistic view on the future development of steel prices. It is difficult, not to say impossible, to establish how unreliable the trend line is. However it can be noted that the lowest prices, or nearly lowest in the case of aluminium, were noted around year 2002. Since then the prices for all three metals have increased.

Despite the uncertainty regarding metal prices the analysis is found useful since it gives understanding of the financial risk that the decommissioning cost constitutes. Based on this analysis the assumption within the industry - that metal prices will cover decommissioning costs - can definitely be questioned. Due to the large variation in metal price it is difficult to predict the future metal prices at the time of decommissioning even if a reliable trend is found.

Result from analysis of revenue parameters

In this analysis it is interesting to regard three different factors and how they are affected by different scenarios. The factors are:

1. The economic consequences of decommissioning.
2. The revenue that arises from decommissioning.
3. The fluctuation of the economic consequences of decommissioning.

The effects on four different scenarios corresponding to the scopes of decommissioning are examined. Furthermore the analysis is performed on onshore and offshore cases for Vestas V82 1.65 MW turbines. It is only the revenues that are altered in this part of the analysis. The costs are kept at the current level (the same level that has been presented previously in this study). The results are presented in Table 14 and Table 15 and stated in costs per turbine. The reader is therefore reminded that revenues are presented with a negative sign.

Table 14 Expected costs when analysing the effect of extrapolated metal prices in 2028 for four different decommissioning scenarios based on a land-based Vestas V82 1.65 MW turbine.

Scenario	**1**	**2**	**3**	**4**
Result with current metal prices	-23 000	135 000	213 000	111 000
Result with extrapolated prices and no fluctuation	189 000	347 000	428 000	964 000
Revenue with current metal prices	-345 000	-345 000	-350 000	-1 377 000
Revenue with extrapolated prices and no fluctuation	-133 000	-133 000	-135 000	-524 000
Result at 0.05-quantile with extrapolated prices	90 000	250 000	330 000	662 000
Result at 0.95-quantile with extrapolated prices	260 000	419 000	501 000	1 256 000

Table 15 Expected costs when analysing the effect of extrapolated metal prices in 2028 for four different decommissioning scenarios based on an offshore Vestas V82 1.65 MW turbine.

Scenario	**1**	**2**	**3**	**4**
Result with current metal prices	694 000	1 302 000	1 379 000	1 277 000
Result with extrapolated prices and no fluctuation	906 000	1 662 000	1 744 000	2 280 000
Revenue with current metal prices	-345 000	-548 000	-554 000	-1 581 000
Revenue with extrapolated prices and no fluctuation	-133 000	-187 000	-189 000	-578 000
Result at 0.05-quantile with extrapolated prices	805 000	1 490 000	1 572 000	1 912 000
Result at 0.95-quantile with extrapolated prices	977 000	1 788 000	1 870 000	2 601 000

The economic consequences of decommissioning

The effect of metal prices on economic consequences of decommissioning can be observed when comparing “result with extrapolated prices and no fluctuation” with “result with current metal prices” in Table 14 and Table 15. Since the trend line predicts that metal prices decrease over time the economic consequences of decommissioning are affected negatively. Therefore the net cost for decommissioning will be higher with extrapolated metal prices than with current metal prices in all four scenarios.

The percentage increases in net costs for decommissioning will differ in the four scenarios. This can be seen when comparing the third and the forth scenario in Table 14. In the third scenario the net cost is approximately doubled, going from 213 000 SEK to 428 000 SEK. In the forth scenario the net cost is increased almost nine times, going from 111 000 SEK to 964 000 SEK. This is explained by the fact that the fourth scenario involves higher costs for the handling of cables which are not offset by revenues generated by the sale of metal. In difference to the third scenario, the fourth scenario considers the metal in the external cables. This means that the forth scenario is more sensitive to changes in metal prices, hence the large effect on the costs of decommissioning.

The percentage changes in economic consequences for decommissioning will also depend on how close the costs and revenues are to equilibrium. If the costs and revenues are roughly the same size effects in terms of percentages will be very large. This can be observed by comparing the results of scenario four in Table 14 and Table 15. In Table 14, which represents land-based results, net costs increase from 111 000 SEK to 964 000 SEK. This constitutes an 864% increase. In Table 15, which represents offshore results, net costs increase from 1 277 000 SEK to 2 280 000 SEK. This constitutes a 179% increase. In absolute terms, however, net costs increase with a similar amount, 853 000 SEK in the onshore case and with 1003 000 SEK in the offshore case. (The difference is explained by a somewhat higher metal content in the offshore case due to the mono pile foundation.) Similar lever effects will be observed in other parts of the analysis. Therefore it can generally be said that scenarios where the cost and revenues are close to equilibrium will be more sensitive, resulting in relatively large percentage changes.

The revenue that arises from decommissioning

The effects of price changes on the revenue related to decommissioning can be observed when comparing “revenue with extrapolated prices and no fluctuation” with “revenue with current metal prices” in Table 14 and Table 15. Since the trend line shows that metal prices decrease over time the revenues are affected negatively. Therefore the revenues that arise from decommissioning will be lower with extrapolated metal prices than with current metal prices in all four scenarios. The revenues will decrease with the same percentage in all four scenarios. In the land-based case the decreases in revenue is 62% and in the offshore case the decrease in revenue is 65%. The decrease is larger in the offshore case since this case involves more metal. As mentioned previously this is due to that the foundation in the offshore case is made of steel and in the land-based case the foundation is made of concrete.

The fluctuation of the economic consequences of decommissioning

The effect of variances in the metal prices can be observed in Table 14 and Table 15. The fluctuation is seen by comparing “result at the 0.05-quantile” and “result at the 0.95-quantile”. The fluctuation represents the difference between these and increases as the difference increases.

As may be expected the fluctuation increases if the scenario involves more metal. For example, when comparing the first scenario with the forth scenario it is observed that fluctuation is always greater in the forth scenario. This is because it involves metal from the turbine as well as internal and external cables. The first scenario only involves metal from the turbine. The effects of the metal content can also be observed when comparing the first and second scenarios. For the onshore case the fluctuation remains the same since both scenarios involve the same amount of metal, that from the turbine. The foundation is in this case made of concrete. In the offshore case, however, fluctuation increases between these scenario one and two since the metal from the foundation is included in the second case.

As for the total economic consequences the level of fluctuation will also depend on how close cost and revenues are to equilibrium. The percentage of fluctuation will be large the closer the cost and revenues are to equilibrium. The effect of the fluctuation creates a distribution of the result. This distribution is illustrated for the full-scope scenario in Figure 19 and Figure 20.

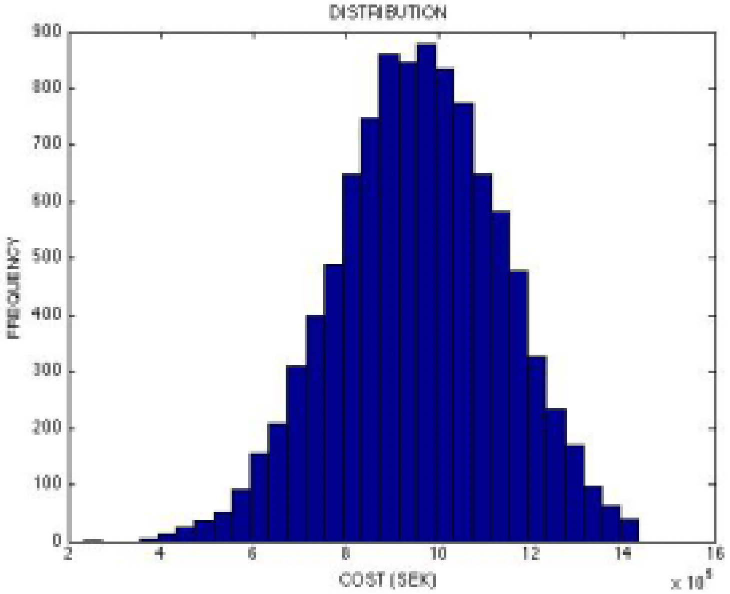

Figure 19 The distribution of the cost of decommissioning a land-based Vestas V82 1.65 MW with extrapolated metal prices of 2028. The figure shows the full-scope scenario. The cost at the 0.05-quantile is 662 000 and the cost at the 0.95-quantile is 1 256 000. 0 being the lowest value for the metal prices causes the asymmetry of the distribution.

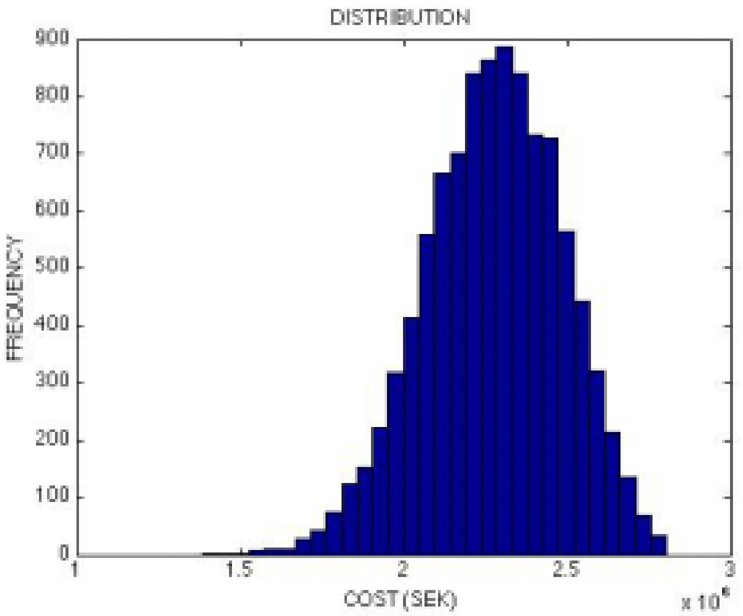

Figure 20 The distribution of the costs for decommissioning an offshore Vestas V82 1.65 MW with extrapolated metal prices of 2028. The figure shows the full-scope scenario. The cost at the 0.05-quantile is 1 912 000 and the cost at the 0.95-quantile is 2 601 000. 0 being the lowest value for the metal prices causes the asymmetry of the distribution.

As a complement to this analysis Figure 21 and Figure 22 illustrate how the financial results of decommissioning are affected by changes in metal price. The illustration is for the full-scope scenario showing the effect of percentage changes in prices for steel scrap, aluminium, and copper.

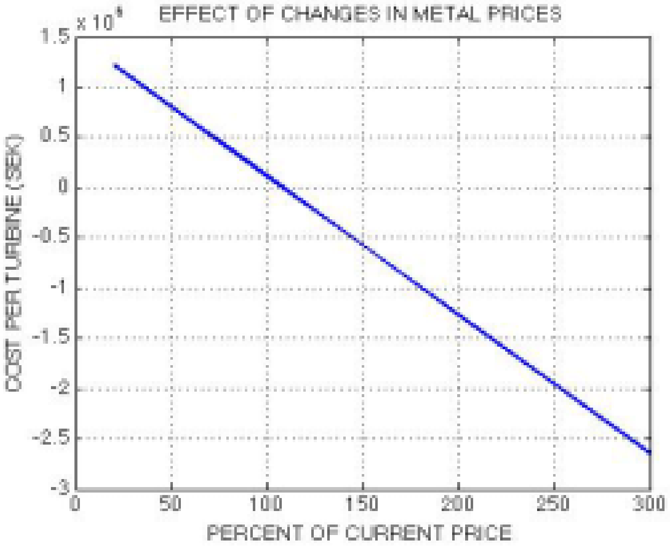

Figure 21 The effect of changing metal prices on economic consequences of decommissioning for a land-based Vestas V82 1.65 MW turbine. The figure shows the full-scope scenario.

Figure 21 shows that in the scenario of today, the cost and revenues are almost at equilibrium. With only a small percentage increase, for example 10%, in metal prices the cost and revenues would balance each other out. The figure also shows that there is a large difference in the possible outcomes. If the metal prices triple the decommissioning would result in net revenues of over two and half million SEK per turbine, whilst prices decreasing to a third of their value would lead to net cost of around one million SEK.

In Figure 22 the effect of changes in metal prices are shown for the offshore location. In this case it can be seen that the metal prices must almost double if equilibrium between cost and revenues is to be attained. Here the outcomes range from a net cost of around 2.5 million SEK if prices decrease to a third to net revenue of almost 2 million if prices triple. Although this may seem extreme it should be kept in mind that over a three year period (2002-2006) aluminium prices have increased by 1,7 multiple, the price of steel scrap has doubled, and the price of copper has quadrupled. Historically, the same drastic developments over similarly short periods of time can also be seen in the *opposite* direction.

Figure 22 The effect of changing metal prices on economic consequences of decommissioning for an offshore Vestas V82 1.65 MW turbine. The figure shows the full-scope scenario.

For both the land-based and offshore case the divergence in possible outcomes would be smaller for the first three scenarios. This is because the first three scenarios involve less metal. Therefore they are less sensitive to changes in metal prices, as is shown in previous analyses.

6.4.2. Analysing cost parameters

As has been described in the theoretical part of this section there are three different factors considered relevant when considering long-term cost conditions. These are the competitive landscape, long-term cost developments, and learning curves. In studies performed about learning curves and progress rates in the wind turbine industry no distinction is made between the sources of cost decreases. To find the progress rates the authors of the reviewed studies have compared costs at one point in time with costs at another point in time. Although these three sources depend on different factors in the quantitative analysis that follows all three will be included in the progress rate and related to as learning effects.

The effects of competition and the ability to decrease costs in the long term are considered to be limited in the case of land-based turbines. This is due to that the techniques and equipment used are standardized and there is a competitive environment that ensures costs are not excessive. In the case of offshore wind turbines, on the other hand, it is probable that costs will decrease in the future.

Currently the number of vessels and barges available to the wind power industry is quite limited. This is explained by that it is a relatively young industry and that there are considerable barriers of entry. These consist of high investment costs and prolonged building time for vessels. Despite this, in the next few years the number of vessels available will double. The theories of micro economics lead to the analysis that as capacity and competition increases in this industry the prices for services provided by these vessels will probably decrease. Although the offshore wind energy industry is gaining momentum, and is expected to grow considerably over the coming years, this growth will probably have decreased in twenty years time. This leads to the conclusion that capacity problems present today may be overcome when the turbines currently erected are to be decommissioned. Due to these factors the progress rate for offshore installations has been established at 95%, four points above the land-based progress rate of 99%.

A global approach is taken on the cost parameters in this analysis; the decrease used is an average instead of a specific progress rate for each of the cost parameters. The only exception is for the set up and disassembly offshore turbines where the progress rate is estimated to 77%. This figure is preferred since other studies conducted on learning curves in the wind power industry have found that this progress rate differed greatly from the average.

Since the progress rates used are based on studies performed on installation processes it is arguable whether or not they can be applied to decommissioning. In this case it is deemed reasonable on the account that the installation and decommissioning processes are regarded as rather similar. The learning curve theory holds that learning will be most dramatic and the progress rate high initially due to limited previous experience. Therefore it could be argued that the learning effects from decommissioning should be higher since the experience is very limited. Despite this the progress rates have not been adjusted mainly for two reasons.

The first is consistency, meaning that no such adjustments have been made when comparing installation and dismantling in other parts of the study. For example the duration of the dismantling activity is based on the duration for installation. The second reason is that even if the progress rate used is for installation the effect of learning will be greater for dismantling since the cumulative output doubles at a higher rate. This is easily understood by comparing figures. Experience of decommissioning in Sweden consists of 11 wind turbines that have been dismantled, of which one was located offshore. As for instalments approximately 900 have been made of which approximately 50 at offshore locations. (Driftuppföljning Vindkraftverk 2008-04-29) The first learning effect for dismantling will occur when 11 is doubled to 22, whereas the number of installations must increase to 1800 for the same effect to take place.

To calculate the cumulative output of decommissioning that will have been reached by the industry in twenty years time it is assumed that all turbines currently existing will have been dismantled. By considering the number of turbines that have been dismantled presently, which are 11 at onshore locations and 1 at an offshore location the progress ratio will have had an effect six times during the twenty year period.

Although the progress rates used have been gathered from empirical findings it is certain their accuracy can be questioned. In order to account for this uncertainty a standard deviance of 10% of is used and tested.

Findings from the analysis of cost parameters

In this analysis it is interesting to regard three different factors and how they are affected by different scenarios. The factors are:

1. The economic consequences of decommissioning
2. The costs that arises from decommissioning.
3. The fluctuation of the economic consequences of decommissioning.

The effects on the four different scenarios, representing the extent of decommissioning, are examined. Furthermore the analysis is performed on onshore and offshore cases for Vestas V82 1.65 MW turbines. It is only the costs that are altered in this part of the analysis. The revenues are kept at the current level (with metal prices retrieved from the empirical findings). The results are presented in

Table 16 and Table 17, stated in economic consequences per turbine. Since a cost model has been developed the reader is reminded that revenues are presented with a negative sign.

Table 16 Results when analyzing the effect of extrapolated progress rates for four different decommissioning scenarios on a land-based Vestas V82 1.65 MW.

Scenario	**1**	**2**	**3**	**4**
Result with no learning effects	-23 000	135 000	213 000	111 000
Result with learning effects and no fluctuation	-40 000	109 000	181 000	25 000
Cost with no learning effects	322 000	480 000	563 000	1 488 000
Cost with learning effects and no fluctuation	304 000	454 000	523 000	1 403 000
Result at 0.05-quantile with learning effects	-43 000	105 000	176 000	12 000
Result at 0.95-quantile with learning effects	-38 000	113 000	187 000	39 000

Table 17 Results when analyzing the effect of extrapolated progress rates for four different decommissioning scenarios on an offshore Vestas V82 1.65 MW.

Scenario	**1**	**2**	**3**	**4**
Result with no learning effects	694 000	1 302 000	1 379 000	1 277 000
Result with learning effects and no fluctuation	105 000	498 000	553 000	206 000
Cost with no learning effects	1 034 000	1 850 000	1 933 000	2 858 000
Cost with learning effects and no fluctuation	450 000	1 046 000	1 107 000	1 787 000
Result at 0.05-quantile learning effects	68 000	441 000	493 000	116 000
Result at 0.95-quantile learning effects	149 000	562 000	619 000	304 000

The economic consequences of decommissioning

The effect of learning curves on the economic consequences of decommissioning can be observed when comparing “result with learning effects and no fluctuation” with “result with no learning effects” in Table 16 and Table 17. Since learning effects implicate that costs decrease over time the economic consequence of decommissioning is affected positively. Therefore the cost for decommissioning will be lower with learning effects than without learning effects in all four scenarios.

Analogous to the results from analysing the revenue parameters the percentage decrease in net cost for decommissioning will differ in the four scenarios. This can be seen when comparing the third and the forth scenario Table 16. In the third scenario the costs decreases with, 15 % going from 213 000 SEK to 181 000 SEK. In the forth scenario the result decreases with 77%, going from 111 000 SEK to 25 000 SEK. The large decrease in costs in the fourth scenario is explained by that this scenario implies higher costs. The fourth scenario includes costs related to the excavation of external cables, which increases the total costs greatly. Therefore, the forth scenario is more sensitive to changes in costs. Hence the large effect on the expected decommissioning costs. The percentage decrease in decommissioning costs also depends on how close cost and revenues are to equilibrium, as was observed when analysing the revenue parameters.

The costs that arises from decommissioning

The effect on the cost that arises due to decommissioning can be observed when comparing “cost with learning effects and no fluctuation” with “cost with no learning effects” in Table 16 and Table 17. Learning effects will, as expected, implicate that the costs decrease. Therefore the costs that arise from decommissioning will be lower with learning effect compared to the case where no learning effects are accounted for. This applies for all four scenarios. The cost will decrease with the same percentage in all four scenarios. In the land-based case the decrease in costs is 6% and in the offshore case the decrease in costs is 37%. The decrease is larger in the offshore case since the progress rates used are higher.

The fluctuation of the economic consequences of decommissioning

The effect of fluctuations on the economic consequences of decommissioning can be observed when comparing “result at the 0.05-quantile” and “result at the 0.95-quantile” in Table 16 and Table 17. Fluctuation is identified by the difference between the result at the 0.05-quantile and the 0.95-quantile. The larger this difference is the greater is the fluctuation. As may be expected the fluctuation increases if the scenario involves more cost. This is coherent with the result obtained in the analysis of revenue parameters. For example, when comparing the first scenario with the forth scenario it can be observed that the fluctuation is greater in the forth scenario. This is because it involves cost from decommissioning the turbine, the foundation, and the internal and external cables, whereas the first scenario only involves decommissioning the turbine.

As for the economic consequence of the level of fluctuation this will depend on how close cost and revenues are to equilibrium. The percentage fluctuation will be large the closer the cost and revenues are to equilibrium. The effect of the fluctuation creates a distribution of the result illustrated for the full-scope scenario in Figure 23 and Figure 24.

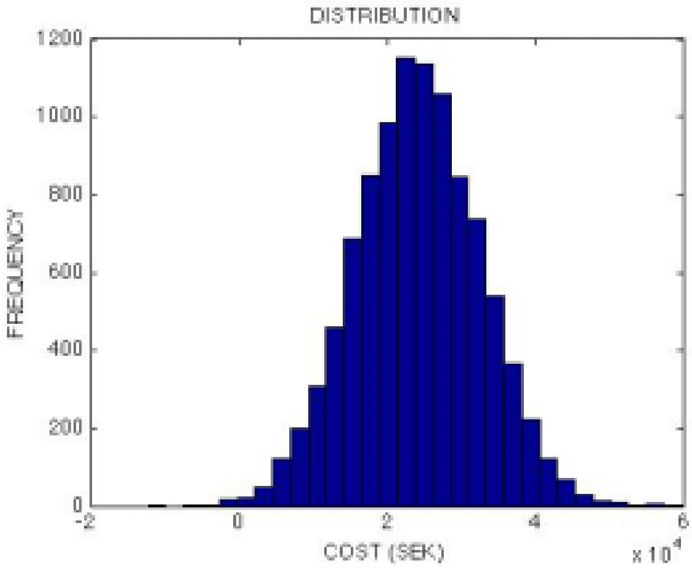

Figure 23 The distribution of predicted economic consequences for decommissioning of a land-based Vestas V82 1.65 MW with extrapolated learning effect over twenty years. The full-scope scenario is illustrated. The cost at the 0.05-quantile is 12 000 and the cost at the 0.95-quantile is 39 000.

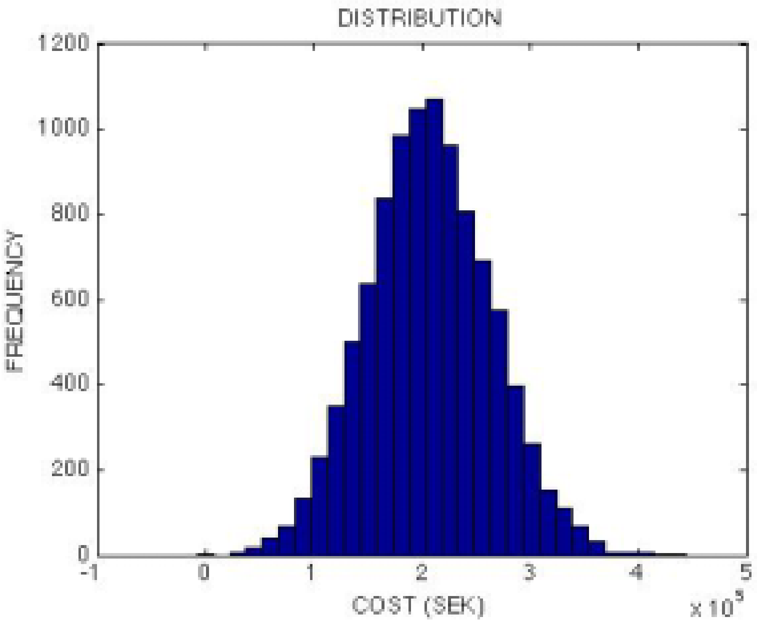

Figure 24 The distribution of predicted economic consequences for decommissioning of an offshore Vestas V82 1.65 MW with extrapolated learning effect over twenty years. The full-scope scenario is illustrated. The cost at the 0.05-quantile is 116 000 and the cost at the 0.95-quantile is 304 000.

Summary of the analysis of long-term effects

The percentage effect of change in revenues respective costs on the result of decommissioning will depend on the amount of revenues respective costs and how close cost and revenues are to equilibrium. The level of fluctuation will depend on the same factors.

To summarise the analysis the best case and the worst case is presented for each scenario. The result for the land-based location is presented in Table 18 and the result for the offshore location is presented inTable 19. For figures calculated as best case current metal prices were used to calculate revenues and earlier used progress rates were used to calculate costs. For figures calculated as worst case extrapolated metal prices were used and no progress rate were used to calculate costs.

Table 18 Best case and worst case for the decommissioning of a land-based Vestas V82 1.65 MW turbine

Scenario	**1**		**2**		**3**		**4**	
Case	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**
Revenue	-345 000	-133 000	-345 000	-133 000	-351 000	-135 000	-1 378 000	-524 000
Cost	304 000	322 000	454 000	480 000	532 000	563 000	1 403 000	1 488 000
Result	-41 000	189 000	109 000	347 000	181 000	428 000	25 000	964 000

Table 19 Best case and worst case for decommissioning of an offshore Vestas V82 1.65 MW turbine

Scenario	**1**		**2**		**3**		**4**	
Case	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**	**Best**	**Worst**
Revenue	-345 000	-133 000	-548 000	-187 000	-555 000	-189 000	-1 581 000	-578 000
Cost	450 000	1 039 000	1 046 000	1 850 000	1 107 000	1 933 000	1 787 000	2 858 000
Result	105 000	906 000	498 000	1 662 000	553 000	1 744 000	206 000	2 280 000

Critical examination of the long-term analysis

The method use to calculate new figures for cost and revenues in the long-term can be questioned. This has already been discussed to some extent in the analysis. Since the main issue of this analysis is to see the effect of these changes in general terms and not in a specific case these methods are not regarded as interesting to examine. Instead an examination will be done of the factors that can affect the compression itself.

Firstly some parts of the comparison are affected by the assumptions made or the specific case examined. For example, in the forth scenario a fictive figure of 50 km of external cable is used to perform computations. If this parameter were different the percentage change would also differ. However the analysis is not dependent on the exact figures. It is only interesting to illustrate general effects and the conclusions that can be drawn. These conclusions would be the same, even if they would be more or less evident depending on the assumptions made.

Regarding the analysis of fluctuation in the results one thing should be mentioned. Some of the parameters will reach their maximum respectively minimum value when fluctuation is added. Regarding revenues the lowest price for metal is regarded as zero, meaning that in those cases where the fluctuation leads to a negative price the price is set to zero. The same goes for the progress rate. In the case of the progress rate being over one, meaning an increase in cost the progress rate is set to one. This causes an uneven distribution, meaning that the simulation has favoured higher revenues and larger cost reductions. This is to such a small extent that the effect on the total result is deemed negligible.

7. Conclusions

7.1. Conclusions from this study

In this thesis, a process to estimate the economic consequences of a future decommissioning as been applied to the wind energy industry. The process can be seen in Figure 25.

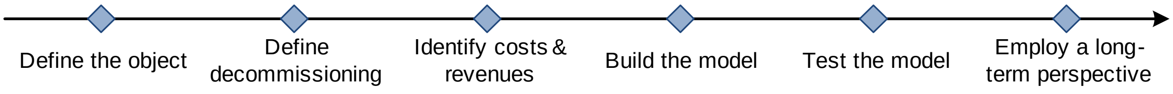

Figure 25 Process for estimating economic consequences of decommissioning

From the interviews performed with industry participants five initial conclusions can be drawn. The first is that in Sweden there is very limited experience within the area of wind turbine decommissioning. The second is that there is very limited knowledge regarding the economic consequences of future decommissioning. The third is that existing rules and regulations regarding decommissioning of wind power turbines are not applied uniformly. The forth is that, despite limited experience and knowledge, there is uniform expectation on the decommissioning process. The process is described as a reversed turbine erection process and the most significant uncertainty relates to the removal of offshore foundations. A full scope decommissioning involves removing the turbine, foundations, internal and external cables. The fifth conclusion drawn from the interviews is that most respondents expect the turbine scrap value to cover its decommissioning expense. This conclusion is drawn despite lacking experience, knowledge, and studies of the matter.

Table 20 Turbine characteristics affecting cost & revenue

Model parameters	
Location	Number of turbines
Hub height	Nacelle weight
Presence of gearbox	Tower type
Tower weight	Blade weight
Type of foundation	Foundation weight
Distance to electrical grid	Type of external cables
Weight of external cables	

In the model developed to estimate economic consequences of decommissioning, thirteen turbine characteristics determining costs and revenues have been identified. These are presented in Table 1Table 20. Tests performed have shown that these parameters do have significant effects on expected costs and revenues for turbine decommissioning. Assuming constant costs and revenues location, scope of decommissioning, and type of tower are the three factors with the largest impact on decommissioning costs.

Applying the model to a number of different turbines has showed that the economic consequences of decommissioning cannot be predicted from the rated power. For a full scope land-based decommissioning scenario, the results range from a revenue of 32 000 SEK to a cost of 679 000 SEK per turbine. In these cases the decommissioning of different 2 MW models was examined. For offshore turbines the economic consequence was a cost of slightly over one million SEK. This shows that it cannot be predicted generally whether or not the scrap value covers decommissioning expenses.

The most interesting findings surfaced when sensitivity analyses were performed. The decommissioning process balances large costs against large revenues. Therefore, considerable effects take place with relatively small changes in price levels. For example, changes in the price of metals found in the turbine have very large impact on the expected decommissioning costs. Doubtlessly metal prices will change over the twenty years left before decommissioning takes place. Metal prices can change dramatically over relatively short time periods. Consequently decommissioning could constitute a considerable economic risk.

As wind energy expands it is important to consider economic effects, not only presently, but also in the future. The trend towards building larger turbines in concrete and locating turbines at offshore sites has a very large impact on the costs for decommissioning. These factors increase decommissioning costs drastically. Ironically these are also the most important developments taking place in the wind energy industry. Therefore, the economic effects of decommissioning are more important to consider now than they ever have been in the past.

7.2. Recommended further studies

This study has only begun to scratch the surface regarding the economic consequences, and particularly the financial risks associated with wind turbine decommissioning. As has been shown in the sensitivity analyses presented it is very important to clarify what risks underlie the financial implications of decommissioning. It lies in the interest of wind turbine operators to uncover these risks and to the extent it is possible minimize them. In order to do this properly the authors would recommend that the costs presented in this thesis are reviewed thoroughly.

The authors hope that this study will awaken the interest for examining decommissioning costs for different types of industries. This field has many points of interest such as handling of financial risks, sustainable environmentally sound strategies.

8. Appendix 1: Discounted cash flows

In economics it is recognized that money has a time value – put simply a euro today is worth more than a euro tomorrow. The difference between the value of a euro today and the value of a euro in the future is referred to as the time value of money and depends on three factors. Since individuals have a predisposition towards impatience to consume *time* becomes an important factor. *Inflation* relates to the loss of purchasing power over time. Due to the fact that future events are unknown in the present there is a *risk* factor that must be compensated for. In order to account for the time value of money different discount methods have been developed. As can be seen below discounting relies on a variant of the formula used for compounding. (Arnold, G., 1998 pp. 64-68)

Compounding: $F = P(1+i)^n$ => Discounting: $P = F/(1+i)^n$

Where
F = future value
P = present value
I = interest rate
n = number of years over which compounding takes place

To calculate reoccurring cash-flows the annuity formula is employed, shown below.

$$Annuity = F\,x\,\frac{i}{(1+i)^n}$$

By discounting all monetary consequences to the present all cash flows are expressed in a common currency at time zero. This formula helps us calculate the economic consequences of future decommissioning in the present. In order to adjust for inflation two methods can be used: cash flows can be estimated in real or money terms. Money cash flows are expressed in prices expected to rule when the cash flow occurs whereas real cash flows are expressed in terms of constant purchasing power. Depending on which of these is chosen a money or real rate of return will be used to discount the cash flows. The relation between these is quite simple and is explained by Fisher's equation (1930): $(1 + money\ rate\ of\ return) = (1 + real\ rate\ of\ return)x(1 + anticipated\ rate\ of\ inflation)$.

In the calculation performed all costs and revenues have been estimated in real terms therefore the real rate of interest has been used. Below the formulas used are presented to calculate present values and yearly costs. To ease understanding an example is made of the costs to decommission a V82 turbine as estimated by the model.

$$Time\ in\ years\ (turbine\ lifetime) = n = 20$$

$$Interest\ rate\ = r = 0{,}02$$

$$Total\ Cost\ per\ turbine\ = TK = 110\ 758$$

$$Yearly\ Cost\ = YK = \frac{TC}{n} = \frac{110\ 758}{20} = 5\ 538\ SEK$$

$$Present\ value\ total\ cost\ = \frac{TK}{1+r^n}$$

$$Present\ value\ total\ cost\ V82 = \frac{110\ 758}{1+0{,}02^{20}} = 74\ 537\ SEK$$

$$Yearly\ cost\ per\ KWh = YK\ x\ rated\ power\ x\ 2{,}3\ x\ 10^{-3}$$

$$Yearly\ cost\ per\ KWh\ V82 = (\frac{5\ 538}{1650\ x\ 2{,}3})\ x\ 10^{-3} = 0{,}0077\ SEK/KWh$$

$$Yearly\ cost/KWh\ (based\ on\ annuity) = (TK\ x\frac{\frac{r}{(1+r)^{n-1}}}{rated\ powerx\ 2{,}3})\ x\ 10^{-3}$$

$$Yearly\ cost/KWh\ (based\ on\ annuity)\ V82 = \left(110\ 758\ x\frac{\frac{0{,}02}{(1+0{,}02)^{20-1}}}{1650\ x\ 2{,}3}\right)x\ 10^{-3} = 0{,}0064\ SEK/KWh$$

Manufacturer	Enercon E53	Enercon E53	Vestas V82	Vestas V90	Vestas V90	Enercon E82	Enercon E82	Enercon E82	Vestas	Vestas	Nordex N80	Nordex N90	Nordex N90	Vestas V90	Vestas V90
Type	Onshore	Onshore	Onshore	Onshore	Onshore	Onshore	Onshore	Onshore	Offshore	Onshore	Onshore	Onshore	Onshore	Offshore	Onshore
Rated power	800 kW	800 kW	1650 kW	1800 kW	1800 kW	2000 kW	2000 kW	2000 kW	2000 kW	2000 kW		2500 kW	2500 kW	3000 kW	3000 kW
Hub height	60 m	73 m	78 m	80 m	105 m	78 m	98 m	138 m	60 m	78 m	70 m	80 m	100 m	80 m	105 m
Tower type	Tubular steel	Tubular steel	Tubular steel	Tubular steel	Tubular steel	Tubular Steel	Hybrid	Hybrid	Tubular steel	Tubular steel		Tubular steel	Tubular steel	Tubular steel	Tubular steel
Total tower weight	62 t	85 t	136 t	147 t	233 t	214 t	781 t	1686 t	140 t	165 t	142,8 t	190 t	306 t	156 t	235 t
Steel	62 t	85 t	136 t	147 t	233 t	214 t	54 t	123 t	140 t	165 t	142,8 t	190 t	306 t	156 t	235 t
Concrete							727 t	1563 t							
Nacelle weight	38,5 t	38,5 t	51 t	68 t	68 t	120.5 t	91 t excl. Rotor	120.5 t	64 t	61 t	91 t excl. Rotor	91 t excl. Rotor	91 t excl. Rotor	68 t	68 t
Hub weight	8.4 t	8.4 t				23.5 t	23.5 t	23.5 t			23 t	23 t	23 t	8.85 t	8.85 t
Gearbox														22.8 t	22.8 t
Generator	17 t	17 t				54 t	54 t	54 t						8.6 t	8.6 t
Nacelle other	6 t	6 t				21 t	21 t	21 t							
Control cabinet											2.7 t	2,7 t	2,7 t		
Rotor weight	8,5 t excl. blades	8,5 t excl. Blades	42.2 t	38 t	38 t	23,5 t excl. blades	23,5 t excl. blades	23,5 t excl. blades	38 t	37 t	33 t excl. Blades	23 t excl. Blades	23 t excl. blades	40 t	40 t
Rotor diameter	53 m	53 m		90 m	90 m	82 m	82 m	82 m				90 m		90 m	90 m
Blade weight	2,7 t	2,7 t		6,7 t	6,7 t	8 t	8 t	8 t			9 t	10.2 t	10.2 t	6,7 t	6,7 t
Foundation weight			832 t						203 t	832 t		415 t		203 t	1 200 t
Steel			27 t									20,1 t	28,6 t		
Concrete			805 t									395	366 m3		

9. Appendix 2 Overview of turbines

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