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RECYCLING AND REMOVAL OF OFFSHORE WIND TURBINES – AN INTERACTIVE METHOD FOR REDUCTION OF NEGATIVE ENVIRONMENTAL EFFECTS

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ABSTRACT: This paper describes a method for reduction of negative environmental impacts of wind turbines and an analysis of future removal and recycling processes of offshore wind turbines. The method is process-oriented and interactive with participation of the actors involved in the area. It recognizes the dynamic, uncertain and fast changing character of the wind energy area and deals systematically with the future removal and recycling of windmills and the future wind turbine technologies. The method is a combination of life cycle assessment and technology foresight methods and integrates the perspectives of the present and the future. [1]

1 INTRODUCTION

Wind turbines are one the most environmentally sound technologies for producing electricity. The removal phase of the life cycle of wind turbines has, however, been identified as a blind spot of analyses of environmental impacts of wind power systems. Most impact analyses carried out until now focus primarily on the operation phase of the wind turbine life cycle and in some cases also on the production and mounting phases. Only a very limited amount of practical experience from the removal and recycling of wind turbines exists, particularly when talking about offshore wind turbines which is a relatively recent phenomenon. It is likely to take more than 20 years before a substantial amount of practical experiences about dismounting, separation, recycling, disposal etc. is gained. Still, major parts of the definition and planning of the processes in the removal phase are implicitly made in the present years. The design of the offshore wind farms and turbines, and also the regulatory demands and organizational responsibilities, to a considerable extent determine the structure and processes of the removal phases many years ahead. A systematic combination of the present and the future perspective that reflects the fast development of the wind power area and the continuously changing character of the wind turbine technologies is necessary to deal with this. The research project reported here emphasizes the removal phase and novel aspects originating from offshore localization of wind turbines. The project develops an interactive and process-oriented method for investigation of the environmental impacts of wind turbines and for finding ways to reduction of negative impacts. It tries to establish an exchange of knowledge from the removal phases to the design phases of new wind turbines.

The approach of the project is an integration of the life cycle assessment method (LCA) with the method of technology foresight (TF). Life cycle assessment is a tool for analyzing the environmental impacts of a given product. Technology foresight is a tool for analysis and discussion of future technologies, their possible qualities, roles, and impacts. In particular, technology foresight is a method that deals with uncertainties of the future. The approach of the project is process-oriented and interactive. That is, the project sets up a process of interaction between different actors e.g. experts with different backgrounds, industry representatives, etc. The process is as important (or even more important) than the final results in a narrow sense, say, for example in the form of a set of numbers or similar simple conclusion.

The paper starts with a list of main conclusions about the environmental impacts of the wind turbines including an identification of important uncertainties appearing from the analysis. Then the hybrid method of the research process is presented and the different parts are described. First, the life cycle assessment perspective and the main conclusions from these processes. Second, the technology foresight interactions and the contents of these. Third, the processes and main results of an interactive workshop on the removal and recycling phase with participation of representatives of the dismounting, recycling and waste handling industry, of the wind turbine producers, etc. The paper ends with conclusions about the future handling of the environmental aspects of the wind turbines.

There are plans about offshore wind farms in many countries e.g. in northern Europe around the North Sea. Important parts of the developments in wind power systems and technologies are of cross-national character and it is our understanding that the method and the conclusions of the research project are of general relevance. However, it shall be noted that the research project is carried out primarily in the Danish context including the understandings of offshore wind turbines, wind power developments, and organizational and regulatory practices that are prevailing here.

2 PRELIMINARY RESULTS AND UNCERTAINTIES

The main conclusions about the environmental impact of the offshore wind turbines are these:

- Actors from the dismounting and recovery industry expect to be able to handle the removal and recycling without serious problems. However, it is needed to take a closer look at many of the concrete processes and methods employed. A considerable amount of uncertainty of the processes exists.
- Knowledge development is needed on the subject.
- The blades of fibre glass are an environment and recycling problem.
- Future blades of carbon fibre are, too.
- Cables constitute an important impact.
- The nacelle is, due to its' complex construction and the use of many special materials, a dismantling and recycling challenge and constitutes a potential problem.
- The institutional organization of the removal phases is uncertain. It is not clear which actors will be involved.
- A short cut between actors carrying out the removal and recycling processes and wind turbine designers is needed in order to secure the best environmental profile.

It is important to notice that these main conclusions are not all of the same type or character. It is a quality of the employed approach that a number of heterogeneous aspects of the wind turbines' life cycles are analyzed. Some aspects concern technical elements and parts of the single wind turbine. Others are about organizational aspects or about the system of offshore wind farms. The time perspective and the degree of uncertainty concerning both technical and other issues also vary considerably. The list of conclusions shall not be considered a final end to analysis and discussion about environmental impacts in connection with removal and recycling of offshore wind turbines. Instead, it shall be seen as a part of an on-going process of experience building and development in direction of continuous reduction of the wind power systems' negative environmental effects.

3 THE INTERACTIVE APPROACH, OVERVIEW

Over the last 10 years lifecycle assessment has been established as a method for analyzing the environmental impacts of a product [for an introduction see 2]. The core of LCA is a detailed analysis of the processes of the entire lifecycle of the product from the early phases of the design process to the demolition and recycling of the product materials after end use. It is the assumption that the product is given and well-specified. In principle all materials and resource consumptions and all discharges and environmental impacts including all sub-processes shall be assessed. In practice, there is always a limit of how much information there is included and a focus on some parts and dimensions of the processes above others. The specific focus and limits reflect the purpose of the LCA and the perspective employed.

These limitations can become a devastating problem if the LCA is considered narrowly a question of getting the results and figures coming out of the process. If instead the LCA is considered a process of learning where the involved persons and organizations through the process gain knowledge about the product and its environmental impacts, the limitations will often appear less severe. Often one of the important outcomes of a LCA is the knowledge the actors obtain about which parts of the lifecycle processes that are uncertain; which parts there exist no precise information about. This point is supported by the observation that it usually is very difficult to understand the results from LCAs carried out by others. To make proper sense of the results it is needed to have an elaborated understanding of the background for the numbers.

The approach employed here is therefore process-oriented and sees the possibilities of reduction of hazardous environmental impacts from wind turbines to a considerable degree as a question of establishing an interaction between the relevant actors of the area. Other LCA studies also recognize that LCAs normally are part of decision and priority processes and carried out in order to not only document the present products and situation but to improve the products of the future. It is a part of change processes over time [3, 4, 5].

The methods of technology foresight have the time dimension and change processes as central elements. Through interaction with and between experts and other actors from different backgrounds, TF processes analyze the future technologies and their qualities and roles [6, 7]. TF discusses and deals with the uncertainties of the future and often scenario elements are included. TF analyses usually focus on the technology and its function. It has normally no special focus on environmental issues. It is focused on the functionality of the technology and does not include a the perspective of the different lifecycle phases of the technology. From the above considerations it can be seen that LCA and TF complement each other and an integration of the two approaches is fruitful in order to deal with environmental aspects of fast changing technology areas. In Figure 1 the different steps of the project is shown.

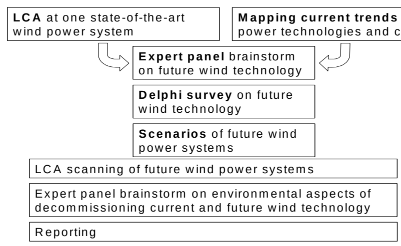

Figure 1 Project phases

4 LIFE CYCLE ASSESSMENTS

Several projects have shown that wind turbines are an environmentally sound technology for producing electricity. Wind energy has very low environmental effects [8, 9]. Other studies carry out LCA on offshore wind farms [10, 11, 12]. These studies conclude that the largest contributions come from three sources:

1. bulk waste from tower and foundation (e.g. from steel production) even though a high percentage of the steel is recycled
2. hazardous waste from components in nacelle (e.g. from steel alloys)
3. greenhouse effects (e.g. from steel production and surface treatment)

The results indicate that further analysis should take into account changes in materials in tower and foundations and changes of nacelle components (changes of overall concept, gearless designs, use of power electronics, etc). Comparing offshore and onshore wind farms, the role of the cables becomes central [13]. Many kilometres of sea cables shall be used and the cables are heavy and complex constructions resistant to the hard environment in the sea. There is a considerable environmental impact from the production of the cables and they consist of many different materials, which make them difficult to handle in the dismantling phase.

There are uncertainties and limitations of the LCA studies: The specific processes of e.g. the dismantling and recycling processes, which are crucial for the environmental profile, are not known. Many material recovery processes are not included in the analyses. Another example of the limitations is that the area use and the impacts on the landscape, which are often considered critical environmental impacts, are not included. In general, it is the experience of these LCA that it is difficult to obtain data for the analysis and difficult to delimit the data collection. It is concluded that it is important to make iterative data collection processes. Through the learning process of the iterative data collection, it is defined where to focus attention of the analysis. More reliable data and knowledge about the uncertainties of the analysis and of the wind turbines are developed. It is argued that a close co-operation with the wind turbine producer is necessary.

5 TECHNOLOGY FORESIGHT STUDY

As part of the foresight activities in the project, a two-step process on future developments of wind power technology and their environmental impacts was carried out in interaction with experts of the wind energy area. For a more elaborated description see [5]. The first part was an expert panel brainstorm on driving factors for the development of wind turbine technologies. This was carried out as a workshop with 10 participants representing academic research, industry, power grid operators, wind farm operators, LCA consultants etc. Emphasis was on technological factors. The second part of the foresight process was a questionnaire with 24 statements building on the experience of the expert panel brainstorm. The 45 respondents were participants of the European Wind Energy Conference in Copenhagen 2001. They were asked to indicate when they expect the single statement will first occur (if ever) and whether it will be of benefit or harmful with respect to the cost competitiveness of wind power and to the environmental impact from manufacturing and decommissioning processes. Selected results from the questionnaire are shown in Figure 2 (below). Only answers from persons claiming to be knowledgeable on the statement subject are included.

None of the statements are by the experts from the wind energy area perceived to have particular harmful effects on the environments. Only the statements on replacing steel as tower material and on using foam to prevent buckling have an average score a little more harmful than neutral. Use of plant fibres instead of fibreglass in blades and use of new environmentally neutral surface treatment are judged environmentally beneficial. Also changes in the electrical components namely the use of high voltage frequency converters and super conducting cables for power transmission are considered of environmentally benefit by a majority of the respondents. Most of them expect these changes to occur in the period from 2006-2015. The results indicated that the respondents expect that steel based offshore foundations will be dominating in the future. These results from the wind energy experts on the future of wind turbines were used as input for a workshop on removal and recycling of wind turbines.

6 REMOVAL AND RECYCLING WORKSHOP

A workshop exclusively on the topic of future removal and recycling of wind turbines was held [14]. The participants were representatives of removal/recovery companies, of a wind turbine producer, of consultants and knowledge institutions on dismantling/waste handling and on wind power plants respectively. In addition we participated (researchers). The number of participants was 11. This is a good size for getting the workshop interactions going. The workshop included discussions concerning today's new wind turbines, concerning the wind turbines of the future (with input from the LCA and the foresight studies), and a questionnaire on problems and uncertainties in handling and reuse of the different parts of the wind turbines. In order to give also the participants coming from outside the wind power area an understanding of the wind turbines, the workshop started with a visit in a wind turbine production plant including a closer look at the construction of a nacelle.

The removal and recovery industry and the waste management companies often have considerable competences on environmental impacts of materials and processes. However, it is clear that their perspective is not always identical with the perspective of protecting the environment. There can be more or less significant deviations between on the one hand to get rid of waste materials and reuse them in an efficient manner and on the other hand to reduce the environmental impacts of the wind turbines as much as possible. E.g. some materials are considered no problem by the recovery industry actors because the materials can be sold to reuse e.g. as cheap filling material in concrete or asphalt. A recycling of the material to its original use or an avoidance of using the material at first hand, which might be the best environmental solution, is not necessarily in the interest of the recovery industry.

The answers of the questionnaire of the workshop are summarized in Figure 3. The questionnaire consisted of 33 questions grouped in 9 groups (N is between 7 and 9). Each point on the figure represents up till six questions concerning the topic. Most of the questions concerned the different parts of the wind turbines (e.g. the foundations) and some specific aspects of the removal and recycling processes of these (e.g. the material waste during the dismounting and removal of the foundations, or the junction between the foundations and the tower). In these questions the respondents were asked to indicate the extent of the environmental problems connected to the specific topic (on a scale from 1 to 5) and how much uncertainty there is with respect to the handling processes and the recycling degree that can be obtained. Other questions concerned organizational aspects and knowledge issues in connection with the removal and recycling of the wind turbines e.g. the potentials of incorporating experiences from the existing offshore industries or of systematic dismounting analyses. On these questions the participants were asked to assess the potentials for obtaining environmental improvements by the topic in case.

The questionnaire built upon the life cycle assessments, the foresights, etc. carried out earlier. It was an interactive part of the workshop and incorporated additional questions and issues identified in the first half of the workshop. The method combination of the oral discussions at the workshop and the written questionnaires is a way of getting an indication of the weighting of the different subtopics treated. E.g. can the written answers catch up on some topics which accidentally or due to strong rhetoric from one side are treated too superficially in the oral discussions.

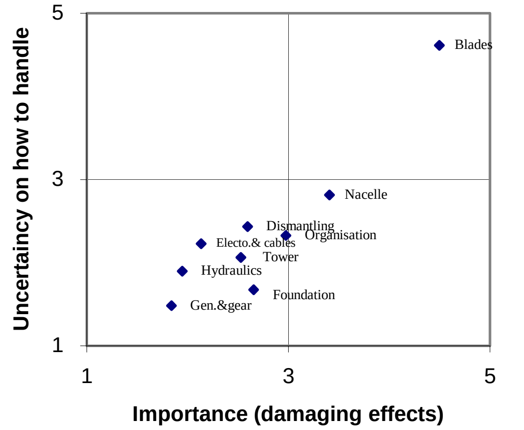

Figure 3

The figure reflects important conclusions from the workshop: The blades are a major problem in the removal and recycling phase of wind turbines and there is much uncertainty concerning how to get rid of them in a proper and safe way. It is the glass fiber material of the blades that constitutes the problem. The fiber dust that is produced when cutting in the blades is hazardous also for the working environment during the demolition processes. Depositing, which is the normal procedure today, is not considered a realistic possibility in the future and it is expected that it will prohibited. Carbon fibre which is likely to become a normal material in wind turbine blades in the future, has the same problematic characteristics. Investments and experiments in finding a solution to the problem of the blades are needed. An example of on-going activities on the subject is [15]. The nacelle is also an environmental and recycling problem due to its content of glass fiber materials. In addition, the PVC foam which is used in some parts of nacelles constitutes a problem. The removal of the foundations is not in general considered a problem. However there can be hazardous material wastes during the demolition and dismantling. In the approved plans for e.g. the new offshore wind farm at Horns Rev in the North Sea it is decided that the parts of the foundation over the seabed shall be removed when the wind farm is decommissioned while the foundation parts in the seabed can be left [16]. The workshop interactions pointed out that removal of the entire foundation will cause increased environmental impacts from the dismounting processes. Although major parts of the cable materials can be recycled e.g. most of the metals there can be problems with some of the special plastic materials. Today it is normal to deposit plastic parts from cables. It is needed to find solutions to this problem. Cables with oil in the construction can be hazardous to the sea environment in the dismantling phase and are in many cases avoided.

Another main conclusion from this workshop is that in general the dismantling and the dismounting of offshore wind turbines seem to be manageable. Most parts can be recycled and reused for other purposes. Direct reuse of components in new wind turbines, e.g. reuse of old foundations for new wind turbines, is not mentioned as a realistic opportunity. However, there are different judgments from the different experts and significant uncertainties concerning many parts of the wind turbines. This is reflected in the fact that in most questions in the questionnaire a large part of the scale from 1 to 5 is used by the respondents. E.g. this is the case concerning the painting of the towers. The painting used offshore is tough but there is disagreement between the experts whether it constitutes a significant problem or not in connection with recycling of the tower materials. Some experts pointed out that waste material from cutting processes in connection with the dismounting of the tower at sea can constitute a problem on the location.

The workshop interactions pointed out that much more and precise information about the specific materials and compositions of the different parts of the wind turbines is needed in order to carry out the dismantling and recycling. Despite the information already gathered in the life cycle assessments etc., there can be hidden environmental hazards in many of the wind turbine components. It is the experience of the recovery industry that e.g. in electronics components often contain special and hazardous materials which need to be treated specially. Also metals e.g. heavy metals or special alloys in gear, generator or other of the components can constitute a ‘hidden’ problem. This points to the importance of knowledge exchange and knowledge development in interaction between the design and mounting phases and the removal and recycling phases of the wind turbines.

The institutional and organizational structure of the dismantling and recycling of offshore wind turbines is not certain. Three models have been identified:

1. Existing removal/recovery companies do the work
2. Specialized companies
3. Strategic collaboration between wind turbine producers and removal companies

In the first model, the existing industrial set up prevails. The companies in the removal and recovery sector will take care of the dismantling and recycling of the wind turbines. It will be a ‘simple’ extension of their work area. From the point of view of the removal and recovery industry, the extension will be relatively small compared to their other fields of work. The methods of removal will to a large extent build on existing experiences from these other fields and follow the changes of the removal and recycling area in general. Only smaller developments and new procedures specifically concerning offshore wind turbines will appear. The first model is in a sense a status quo model. In the second model the major parts of the removal of the wind turbines will be carried out by companies (or sub division of companies) specialized exclusively in offshore wind turbines and their dismounting and recycling. The companies will built up and develop new, highly specialized knowledge particularly on this subject. Apart from knowledge from the wind turbine area, the competences will probably also build on knowledge and experiences from the offshore industry, oil rigs etc. A number of consultancy companies are at present creating new, more or less separate divisions with the purpose of engaging in the handling of offshore wind turbines. There are indications that this model for the organization of the removal/recycling of wind turbines by some actors is considered to be integrated with handling, maintenance etc. of the wind turbines during the operation phase. The third model consists of a collaboration and strategic alliance between the wind turbine producers and actors from the removal and recovery industry. Through close and formal collaboration an extensive information exchange and construction of new knowledge and procedures will take place. This model has been suggested in light of the expected regulatory changes in general in direction of an extended product liability and responsibility of the product producer.

For the moment it is unclear which of these models will be the dominating and normal. It is likely that a combination of the different organizational forms will exist for a longer or shorter period of time. It shall be noted that these organizational issues also include material aspects of great importance for the environmental impacts from the offshore wind turbines. The organizational solutions to the removal and recycling challenge are reflected in the consumption of resources and materials and the possibilities of making improvements in these. For example the organizational structure will probably be directly related to the special ships developed for the handling of the offshore wind turbines. The way these ships are designed, owned, and used, and the environmentally efficiency of this, will be closely connected to the organization form. Model three is the model that most directly and explicitly facilitates and supports a connection of design phases and removal/recycling phases of the lifecycles of the wind turbines. A close formal collaboration between recycling actors and design actors will support the integration of knowledge from the different lifecycle phases and contribute to a comprehensive development of the wind energy technologies. However, the connection between design and removal phases can also be established in relation to Model 2 and 1.

7 CONCLUSIONS

An integration of knowledge and experiences from the removal and recycling phases of offshore wind turbines' lifecycles in the design and development phases is needed in order to secure environmentally sound design of wind turbines and wind power systems of the future. There are no traditions and routines for making this short cut between the dismounting and design phases. No fixed form of organization of the removal and recycling exists and the experiences from actual removal processes are very limited. As the wind power industry, the wind turbines and the wind turbine companies are fast changing and becoming large and complex systems, it is increasingly difficult to maintain an overview over the wind turbine technology and its environmental impacts. A systematic and standardized approach by the actors of the wind turbine area is needed to deal with this.

The method presented here offers a solution to this complex of problems and it is recommended that the wind turbine producers and other actors in the wind energy area take up the method. The fundamental elements of the method are the perspective of the lifecycles of wind turbines, the strategic and dynamic perspective of foresight processes, and the mutual and systematic integration of these two aspects. It is not needed to carry out every detail of the method exactly as we have done it. The process should be adapted to the application context. However, the interactive and process-oriented character and the integration of knowledge from the different areas of expertise are essential aspects of the method.

[1] This paper is part of the of the research project 'Environmentally sound design and recycling of wind turbines' funded by the Danish national Energy Research Program and Risø National Laboratory. We would like to thank Henriette Hassing, Tech-wise for valuable inputs and comments.

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		Your level of exper-tise on the field of the statement			Period in which the statement will have first occurred						Impact on wind power's cost competitiveness					Environmental effects due to manufacturing and decommissioning of wind technology				
Statement No.	Statements about future wind power technology	Own field of work	Knowledgeable	No knowledge	Before 2005	2006 – 2010	2011 – 2015	2016 – 2020	After 2021	Never	Highly beneficial	Beneficial	Neutral	Harmful	Highly harmful	Highly beneficial	Beneficial	Neutral	Harmful	Highly harmful
11	More than 50% of all new offshore turbines are 10 MW or larger	9	28	7	1	3	11	1	9	12	3	19	8	3	1	3	15	9	6	
14	More steel based than concrete based foundations for new offshore turbines	3	20	21	8	8	4	1	1	2		10	9	2			8	11	3	
15	Steel is replaced by other materials for towers in more than 25% of all new turbines	7	18	19	1	3	7	2	4	8		13	6	3		2	5	6	8	1
17	Commercial use of new environmentally neutral surface treatment for major steel parts (e.g. towers)	1	15	28	3	6	3	1	4	1		5	8	3		2	12	2		
18	Widespread use of foam materials to prevent buckling in blades and towers	4	15	26	7	4	5		3	1	2	8	6	1			4	7	6	
19	Plant (or cellulose) fibres are used instead of fibreglass in blades	2	23	19	3	4	5	5	4	5	1	7	11	3		9	12	2		
22	High voltage frequency converters in more than half of all new turbines	2	18	23		6	8	3	2	1	2	11	2	2			10	7	1	
23	Commercial use of super conducting cables for power transmission from wind farms	4	15	25		3	7	2	4	3	1	10	2	2		2	8	5	1	

Figure 2: Selected results from the technology foresight delphi questionnaire [5].