ERGEBNISSE VON TA-PROJEKTEN – NEUE TA-PROJEKTE

Prospective Life-Cycle Assessment on Wind Power Technology by 2020[1]

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This paper reports on a case study on prospective Life Cycle Assessments (LCA) combining LCA methodologies and technology foresight or forecast (TF) methodologies. The case analysed in the article is wind power technology as it might appear by 2020.

1 Introduction

There is an increased focus on technologies' adverse effects on the environment. In many countries this has led to legislation, regulation and standardisation. A number of standards and guidelines have been issued, such as the ISO 14040 on Life Cycle Assessments (LCA), a guide (no. 109) of the International Electrotechnical Commission (IEC) on Environmental Impact Assessment (EIA) and guidelines of the European Committee for Standardisation (CEN).

Generally, the wind power industry welcomes this development. Wind energy is clean and safe and is generally recognised as one of the most environmentally sound technologies for producing electricity. Nevertheless, it is important to acknowledge that renewable energy technologies also are subject to assessments of their impact on the environment.

Wind power is the fastest growing energy industry with annual growth rates in the world market between 20 % - 40 %. If the expected future importance of wind power is going to be realised – resulting in two digit percentages of many countries' and regions' electricity supply – a lot of wind turbines are to be installed over the decades to come. This rapid growth in a long-term perspective is likely to affect the design of future wind turbines. The wind power technology installed 20 years from now might be radically different from the technology today. This change in technology is likely to happen not through radical changes but as a series of incremental changes (Dannemand Andersen and Hjuler Jensen 1998).

Looking 20 years ahead is not unknown in the energy sector. Several countries have carried out long-term energy planning for decades – especially since the oil embargo in the early 1970s. Furthermore, electricity-producing technologies have, traditionally, a long economic lifetime. Fossil based and nuclear power plants often have lifetimes of 20 to 30 years, and lots of hydro plants have been in operation even longer.

A challenge here is that most methodologies for assessing technology's environmental effects are based on historical data or on state-of-the-art of the technology. That is especially a challenge for technologies that are expected to change over a long planning period such as wind power technology (and PhotoVoltaics technology). Therefore, there is a need for developing LCA/EIA methodologies that include future changes in technology. This is the scope of the project reported in this article.

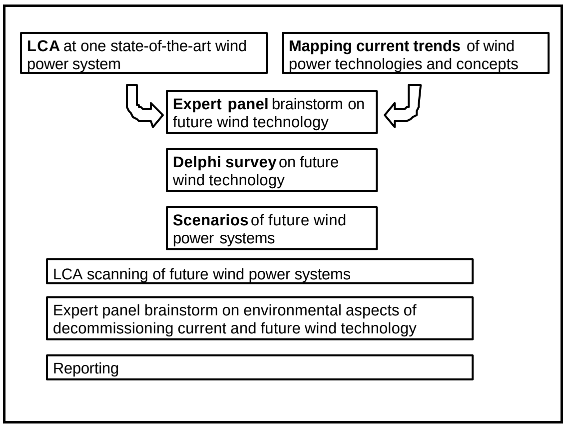
2 Aims and Approach of the Project

The project reported in this article has three aims. The first aim is to analyse the environmental effects of wind turbines during production and decommissioning of wind turbines in a long-term view. That is a time horizon of 2020-30 for the manufacturing of wind turbines and 2040-50 for dismantling. The second aim is to set up societal recommendations concerning decommissioning, recycling and handling of waste for existing and future wind turbine concepts and components. Finally, it is an aim of the project to contribute to the development of methodologies for using LCA as a tool for designation of experts and for making perspectives on a long-term.

The project is financed by the Danish Energy Agency and carried out in collaboration between Risø's Wind Energy Department and Systems Analysis Department.

The project is carried out in seven steps (cf. Fig. 1). Step 1 is an analysis of environmental effects of state-of-the-art wind turbines through a LCA with a focus on manufacturing and decommissioning. This project has not independently carried out LCA on state-of-the-art wind power systems but has relied on other studies on wind energy's environmental effects. The objective is to get an overview of the most important adverse effects on the environment from the manufacturing and decommissioning of wind power systems. Step 2 is a mapping of current trends of wind power technologies and concepts. The aim here is to get an overview of trends affecting how wind turbines will be designed in the future. Some trends can even be extrapolated for a longer period. Step 3 is an expert panel brainstorm on drivers for the development of wind turbine technology. The focus is set on factors that cannot easily be extrapolated. Step 4 is a Delphi survey on the future for wind energy technology with questions based on the first three phases. In step 5 a number of scenarios for future wind turbine technology (2020-2030) are drawn. In step 6 a LCA of future wind power systems is carried out as a desk study. Finally in step 7 a panel with experts on decommissioning, recycling, waste handling, etc. brainstorm on present and future (2050) environmental aspects after decommissioning the machines. This article reports on steps 1 to 4.

Fig. 1: Project phases



3 Methodological Consideration

This study is based on combining established methodological frameworks of Life Cycle Assessments (LCA) and Technology Foresight (TF). The coupling of TF and LCA is related to how to handle the time horizon in a life cycle assessment of a product where new procedures or new materials may be introduced in the future. So far, only a few articles have been published on this area (Weidema 1998; Pesonen et al. 2000; Borch and Rasmusssen 2000).

The technical framework for the LCA methodology as it is defined in ISO 14040 consists of four phases: Goal and scope definition, life-cycle inventory (LCI) analysis, impact assessment and interpretation. The phases are not necessarily followed sequentially. It is an iterative process, which can be followed in different rounds achieving increasing levels of detail (from screening LCA to full LCA), or which may lead to changes in the first phase because of the results of the last phase. Obviously, LCA is a decision support tool that can be used by industry already in the development and design phases of new products. Especially when considering LCA on a product system and not just a product, LCA seems to be a suitable tool in the mapping of the product system and its potential impact (Weidema 1998). However, it might be difficult to balance the importance of the LCA results with non-environmental related issues. Therefore, it is recommended to use LCA as early as possible in the product development chain (Brohammer 1999). A LCA screening may be carried out in the pre-study phase in order to find suitable environmental criteria and in the project execution phase LCA may be used in the environmental decision process in relation to materials used, procedures, etc.

Technology Foresight is often defined as „*the process involved in systematically attempting to look into the longer-term future of science, technology, the economy and society with the aim of identifying the areas of strategic research and the emerging generic technologies likely to yield the greatest economical and social benefits*" (Martin 1995). The term Foresight is often affiliated with a societal process or dialog on priorisation of strategic, publicly financed research. Another related term is

Technology Forecasting. Technology Forecasting has been defined as *„an early recognition of technological developments and validation of their potential*", (Holtsmannspötter and Zweck 2001). Forecasting is often associated with monitoring of trends in technology and of break-throughs in natural sciences. Forecasting (or monitoring) is often carried out by governments for defence related reasons or by large enterprises for decision support or as strategic intelligence. Hence, dialogue between stakeholders is not a part of Technology Forecasting processes, but in both cases the same toolbox of methodologies can be utilised: expert panels, Delphi studies, scenarios, etc. In this project the focus is set mainly on technological issues. Prospective methodologies are used to get a broad base of knowledge to map wind energy's strategic environment with the aim of clarifying current or future practical problems in relation to the production and disposal of wind turbines. But the project is a little more than combining LCA with forecasts of the development of wind power technology. First, the project also contains a dialogue between central stakeholders. Representatives from the technology's main Danish stakeholders have been included in the process via an expert panel. Second, one of the objectives of the project is to give societal recommendations on recycling and disposal to the Danish Energy Agency.

As indicated above different sets of methodologies exist to introduce technological changes over time depending on the time horizon and the complexity of the studied system. For the short and medium term (1-5 years) and for forecasts for simple technologies and processes (low uncertainty and incremental changes), simple „econometric" methods can be used (e.g. extrapolation of trends and historical data, S-curves, experience curves, etc).

For the long term (5-25 years), for processes and systems characterised by high uncertainty, and more radical technological changes, it becomes increasingly relevant to use methodologies based on experts' judgements (e.g. expert panel, Delphi questionnaires, scenario building, etc.). This is often called judgemental methodologies.

For a discussion of combining methodologies of Technology Foresight (TF) and Technology Assessment (TA) see Loveridge (1996), Weidema (1998) and Holtmanspötter and Zweck (2001).

4 LCA on State-of-the-Art Wind Power Systems

Several projects have demonstrated that wind turbines are one of the most environmentally sound technologies for producing electricity. Wind energy has very low environmental effects. Other studies have carried out LCA on state-of-the-art offshore wind farms (Hassing and Varming 2001; Properzi, Hansen, Pedersen, Svensson 2001). These studies conclude that through the whole life cycle of state-of-the-art wind power technology the main adverse environmental effects are due to material utilisation and disposal from manufacturing processes and from decommissioning at the end of the lifetime of the wind turbines. During operation only negligible emissions will appear. However, through the whole life cycle of the technology there will be environmental effects due to material utilisation and disposal. The largest contributions come from three sources:

- Voluminous waste from tower and foundation (e.g. from steel production) even though 85 % of the steel is assumed recycled
- Hazardous waste from components in nacelle (e.g. from steel alloys)
- Greenhouse gas 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).

5 Expert Panel on Future Wind Power Technology

A lot of information on future wind power technology can be determined from analysing current trends in the wind industry. In this study a number of earlier studies and available international statistics have been revisited with the scope of this study in mind (Dannemand Andersen 1999; Aubrey 1999; Hansen and Dannemand Andersen 1999; Dannemand Andersen and Hjuler Jensen 1998). This has given a clear idea about future market volumes for wind turbines and trends for technical data such as masses of main components, sizes, cost of energy, etc.

An expert panel was established with 10 persons representing academic research, industry, power grid operators (utilities), wind farm operators, LCA-consultants, etc.

Usually literature recommends that expert panels meet several times over some month to arrive at robust conclusions and to secure a fruitful dialog. But in this study it was not realistic to hope for attendance of the experts for more than one day. A meeting was held with the objective to agree on the most important factors determining future wind power technology (wind turbines and farms) and their environmental effects. A total of 158 statements about technological, economic, cultural, and environmental factors influencing the future of wind power technology were first formulated by the panel members in several rounds. Emphasis (2/3 of the time) was allocated to technological factors and the rest (1/3 of the time) allocated to other factors.

Furthermore, the participants were asked to evaluate the impact as well as the uncertainty pertaining to the statements on the 1-5 scale. With a total of more than 150 statements, the interest was primarily directed to the statements, which embodied a high potential impact and at the same time exhibited a high uncertainty. Statements reflecting issues with a low potential impact on the future of wind power were of limited interest in this study. Statements reflecting trends and issues with low uncertainty were also excluded from further discussion in the panel as they where better analysed through trend extrapolation and other „econometric“ tools.

As many factors cover similar issues (in some cases even identical issues), the factors were grouped by the participants and placed under a number of headlines. Among these groups the participants were asked to identify those groups of the highest importance for the future development of wind power technology.

Important *political and legal factors* were identified such as implementation of the Kyoto protocol, energy sector deregulation, internalisation of externalities, and EU's increased dependency on imported energy.

Important *economic factors* were identified such as increasing energy prices, public expenditures on R&D, and the appearance of other competitive renewable energy technologies.

Important *socio-cultural factors* were identified such as public acceptance of wind turbines in the landscape, general environmental awareness, increased energy consumption and rural electrification in developing areas.

As mentioned emphasis was on *technological factors*. Here a total of 95 statements/ factors were identified and grouped in 11 groups (in order of average impact score in each group): energy storage technologies, installation concepts, control and regulation, scientific computing, components, grid and power transmission, blade materials, other materials, new concepts and up-scaling, transport, and finally towers.

The panel was then asked to select the two most important factors (or groups of factors) influencing the appearance of future wind power systems. The idea was to construct four „scenarios“ on how wind turbines would be designed in 2020-2030. That showed to be impossible, either because of the time allowed during the meeting or because of the complexity of the technology. Instead the panel agreed on six important factors.

Three groups of factors were identified to affect the future market volume for wind turbines – and consequently the total amount of material utilised:

- National climate and energy policies (Kyoto, safety of supply, etc.)
- Conditions of future power markets (deregulation, decentralisation, etc.)
- R&D expenditures (public and industrial).

Also, three groups of factors were identified affecting the design of future wind technology – and consequently the types of material utilised:

- New materials (replacement of steel, new composites, super conducting materials, etc.)
- Concepts and main components (power electronics, control strategies, super conducting materials, etc.)
- Grid conditions (grid structure, power quality, etc.).

6 Delphi Study

On the basis of the results from the earlier phases in the project 24 statements were formulated in a questionnaire. The first 8 statements concerned market issues (political, economical and societal driving factors) and the remaining 16 statements were on technological issues (cf. Table 1).

The questionnaire was distributed to attendants at the European Wind Energy Conference, which took place on July 2-7, 2001 at Bella Centre, Copenhagen. In the questionnaire the respondents were asked for each statement to answer four questions: their level of expertise on the field of the statement; period in which the statement will have first occurred; impact on wind power's cost competitiveness; and environmental effects due to manufacturing and decommissioning. Often Delphi surveys are made in two rounds giving the respondents the results of the first round as inspiration in the second round. The intention is to create a larger consensus on the results. This study, however, only comprised one round due to the experimental nature of the project. Our primary interest was to demonstrate that a Delphi study could be useful and the focus of the project was on the expert panels and the scenario techniques.

Approximately 200 questionnaires were distributed during the conference and 45 were filled in and returned. Respondents represented 12 countries, with the majority from Denmark, Spain and Germany. Respondents were asked about their organisational affiliation. Most respondents belonged to one of the following three groups: industry, university or other research organisation, and consultancy or self-employed. The profile of the respondents was by and large similar to the attendents of the conference, but the response rate was less than anticipated. Furthermore, in a number of cases the questionnaire was only partly answered. Almost all answered the statements related to market issues (economical, societal, and political factors) whereas the technological statements were only partly answered. Based on the respondents' comments, we have concluded that our technological statements might have been too specific for the audience.

Only results from people claiming to be knowledgeable or experts were chosen to ensure a satisfactory level of reliability. For some of the statements the number of respondents declaring „no knowledge“ on different statements was unfortunately quite high ranging from 5 % to 70 %. It is quite clear that no robust conclusions can be based on a limited sample size of say 12 respondents.

None of the statements have been perceived to have particular harmful effects on the environment. Only the statements on replacing steel in towers (#15) and using foam to prevent buckling in blades and towers (#18) have an average score a little more harmful than neutral.

The respondents by and large agreed that 10% of Europe's electricity will come from wind power at some point between 2011 and 2020, and that this will have a positive impact on wind power's competitiveness. Along with this a reduction of wind power's costs are expected approximately in the same time-frame.

As mentioned there are a few clear signals on the design of future wind turbines. The results indicated that the respondents expect replacement of steel in towers and that steel-based offshore foundations will be dominating. Also the results suggest that flexible two-bladed concepts will never have a radical break-through on the market place. Furthermore, a change of design of lifetime to 40 years seems less likely.

Together with the outcome of the expert panel meeting these observations can be used to construct a number of scenarios for wind power technology by 2020. These scenarios are technical scenarios: description of possible designs of wind turbines with lists of materials and their masses. Based on these scenarios an LCA scanning can reveal potential environmental advantages and adverse effects of the designs and, hopefully, give industry and public authorities advice on future developments.

Tab. 1: Results from Delphi questionnaire collected at the EWEC 2001 conference

		Your level of expertise 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*
1	10 % of Europe's electricity from wind power	14	28	2		8	28	11	5		15	19	4			7	15	12	3	
2	More than half of all new turbines in Europe are placed offshore	11	29	4		6	10	10	8	6	5	17	8	7		4	11	15	5	
3	40 % cost reduction of wind produced electricity relative to 2001	13	24	7	1	10	7	12	3	4	26	5	1			7	9	11	4	
4	Global implementation of Kyoto targets	5	30	9	1	8	9	3	10	5	13	18	2			10	19	12	1	
5	50 % increase in EU and European national expenditure on wind power related research	13	21	12	7	8	9			11	7	17	6	3		6	13	9	5	1
6	Other renewable source of energy (other than hydro) becomes fully competitive with wind	7	20	8	1	7	8	9	10	2	3	11	11	6		4	10	15	1	
7	Competitive concept for storage of wind energy (e.g. based on hydrogen)	5	26	15		10	5	9	9		11	14	3			6	9	10	4	
8	Significant global market for small (<50 kW) turbines for stand-alone and hybrid systems	6	29	9	2	12	7	4	2	9	5	11	11		2	8	6	11	2	1
9	More than 75 % of all wind turbines are of a two-bladed highly flexible design	9	21	14			5	6	2	18	1	9	14	3		1	6	15	2	
10	More than 75 % of all new turbines are without gearboxes	10	19	15		8	5	7	2	7	2	11	11	1		2	9	13	1	
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	
12	Design life-time of 40 years for most new turbines	9	24	10		6	5	6	3	15	7	14	2	7	1	9	14	6	2	
13	Commercially competitive hydraulic drive-train (e.g. based on synthetic oil or water)	2	11	31		3	6		1	6		4	7	2		1	2	8	2	
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
16	Losses in powerelectronic equipment are reduced by a factor of 10 due to new materials (e.g. siliciumcarbide)		15	29		4	6	4		1	4	8	2			2	5	7		
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		
20	Multipole generators with permanent magnets in half of all new turbines	7	16	21	1	5	7	6	2	5	1	9	7	1	1		7	11	1	
21	Introduction of high voltage generators (20-60 kV)	3	19	22	4	6	7	4		2	1	14	4		1		9	11	1	
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	
24	Noise emission from new turbines reduced by 50 % compared to 2001 levels	7	23	13	2	3	7	8	2	9	2	7	18	2		8	8	13		

7 Conclusions

This study has demonstrated that judgemental technology foresight methodologies can be applied to estimate future technological characteristics to be used in prospective LCA studies. The study has also indicated, that extracting exact data and information from foresight studies and applying them in LCA studies is a very difficult and time consuming task. Judgemental methodologies depend entirely on external experts' willingness to participate – in expert panel meetings as well as in Delphi surveys. In this study we were not able to compensate these experts and this lowered the rate of participation and the value of especially the Delphi survey. A lot of further methodological investigations and theory building are needed on this subject in the future.

Note

1) The article is based on the conference presentation: Dannemand Andersen, P.; Bjerregaard, E.; Schleisner, S., 2001: Driving factors for environmental sound design and recycling of future wind power systems. 2001 European wind energy conference and exhibition, Copenhagen (DK), 2-6 July

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