Life Cycle Assessment of a 150 MW Offshore Wind Turbine Farm at Nysted/Roedsand, Denmark

(Presented at European Wind Energy Conference and Exhibition, Copenhagen, Denmark. 4 July 2001)

Scott Properzi , Helle Herk-Hansen

ENERGI E2

Lautruphøj 5, 2750 Ballerup, Denmark

E-mail: spx@e2.dk, hhg@e2.dk

Abstract:

The purpose of this life cycle assessment (LCA) was to illuminate and describe the potential environmental impacts caused by an offshore wind turbine farm (WTF) throughout its lifetime and use this knowledge in the planning and improvement of future WTFs. The LCA was based on experience from the LCA on Danish electricity and district heating [1] as well as the offshore WTF project at Middelgrunden which is in operation.

LCA of a wind turbine is not new, however, development in the area of wind turbines at sea and transmission of the electricity from the offshore WTF is new, and therefore, focus on the advantages and disadvantages in comparison to wind turbines on land is necessary. Data from the current wind turbine project, Middelgrunden, near Copenhagen, was collected from SEAS' wind energy center and the other participating organizations and extrapolated in order to reflect the offshore WTF at Nysted/Roedsand. Nysted/Roedsand is expected to be in operation by the year 2003.

All of the components of the WTF and transmission facilities have been examined and areas of environmental improvement have been identified. It was found that Nysted/Roedsand's offshore WTF and associated transmission facilities per produced kilowatt-hour have an improved environmental profile in comparison to a land wind turbine. Areas of improvement of an offshore WTF include the recycling of metals, recycling of the wings, minimizing resource consumption and increasing the life expectancy of the entire wind turbine.

The ISO 14040 standard on LCA was followed and the EDIP (Environmental Design of Industrial Products) method and modelling tool were used [2].

Keywords: offshore wind turbine farm, land-based wind turbine, life cycle assessment, recycling, Environmental design of industrial products (EDIP)

1 Introduction

In 1996 the Danish Government launched a new national action plan, Energy 21. One of the important targets set in Energy 21 was a reduction in emissions of CO_2. Among the methods stated in the action plan is that an energy system is developed which to a greater degree is based on sustainable energy sources. The development of sustainable energy in both the short and long term is expected to be realized through the use of domestic renewable energy sources and wind power [3].

ENERGI E2 takes this challenge seriously and are striving to ensure the best solution for the use of wind power with respect to the environment and the economic possibilities.

Today, the majority of wind turbines in Denmark and the world are erected on land. However, there are a few demonstration offshore wind turbines in Denmark namely Vindeby and Tunoe knob. These wind turbines were erected in the early 1990's. Since land resources in Denmark are limited and experiences with offshore wind turbines have been good, it is expected that future efforts will be concentrated on offshore wind turbine farms (WTF). In the "Wind turbines in Danish Coastal Waters" Action Plan initiated by the Danish Energy Agency and The Association of Danish Energy Companies, five areas at sea have been selected which are all suitable for the installation of wind turbines. Each of these sites including Roedsand, Horns Rev, Læsø, Omø Stålgrund and Gedser are all projected for an electrical effect of 150 MW in their first stage. By the year 2030 a capacity of approximately 4000 MW offshore wind power is expected [4].

As a part of the acceptance-in-principle of the offshore WTFs, the Ministry of Environment and Energy has required that a number of environmental investigations are to be carried out prior to, during and after establishment of the farms. These requirements include that an environmental impact assessment (EIA) is prepared. SEAS completed the EIA for Nysted/Roedsand (henceforth Nysted) in the summer of 2000. In connection with this, ENERGI E2 and SEAS initiated an LCA of the planned WTF at Nysted in order to supplement the EIA and enlighten other environmental impact areas, which an EIA is not designed to cover.

The work presented here is based on an extensive LCA of Danish electricity and district heating completed by ENERGI E2. It is also based on data collected from Middelgrund WTF near Copenhagen. The LCA is based on the scenario presented in the EIA of the Offshore WTF at Roedsand [5].

2 Purpose

The purpose of carrying out an LCA for Nysted's 150 MW offshore WTF prior to its actual design and construction is to describe the environmental impacts expected during the farm's lifetime. The knowledge gained through the LCA and its process in conjunction with other forms of evaluation such as the EIA of Nysted, will then be used in planning and evaluating future offshore WTF design.

3 LCA of the Nysted Offshore WTF

3.1 Danish electricity and district heat – the first step

LCA is an important element in the Danish government's product oriented strategy, which calls for LCAs of individual products or product categories as the basis for setting priorities in the work for environmental improvements. This strategy along with an increasing interest from ENERGI E2's various stakeholders led us to initiate an LCA of electricity and district heating.

In 1998 a group of leading Danish power companies co-lead by ENERGI E2 undertook a collaborative LCA project – to carry out a comprehensive LCA of electricity and district heat produced and consumed in Denmark. At the time the project was initiated, existing data provided by the Danish EPA was over six years old and did not reflect the current energy production mix. The project provided new and improved data for the assessment of total environmental impacts of electricity and district heat delivered to the consumer. It provided production companies and electricity users with updated data that could be used in their own LCAs and environmental declarations. It also provided the power companies with an extensive database of the various production technologies, a more wide-spread knowledge of the life cycle train-of-thought and an in-depth description of where the environmental impacts were located and areas where improvements could be made. This detailed knowledge on the environmental aspects in the chain of production of Danish electricity and district heat supplied to the customer has provided ENERGI E2 with experience and an instrument to better prioritize its investments and resources in activities that will benefit the environment.

Some of the activities this LCA project has helped to initiate include:

- Environmental Product Declarations (EPD) - which many energy companies in the Nordic/Baltic region are preparing to market at the request of customers and other interested organizations.
- Design for Environment (DfE).
- Technology evaluation.

The LCA project was based on the internationally acknowledged, Danish developed EDIP [2] method (Environmental Design of Industrial Products). As well, the ISO 14040 series standard was followed and the project was subjected to a third party critical review.

3.1.1 Wind turbines on land

The LCA of Danish electricity and district heat considered all the production technologies used in Denmark including coal, Orimulsion, natural gas, oil, biomass, waste, wind and other smaller technologies.

Figure 1 below shows the normalized environmental impact potentials of three selected impact categories for some of the Danish electricity and district heat production technologies. For clarity purposes only selected environmental impacts are shown here. Global warming and acidification are shown since these are often used and are well known impacts. The hazardous waste category is shown since wind turbines have a large contribution to this category.

As is often the case, normalized LCA results are shown here in milli-person equivalents. A milli-person equivalent is 1/1000 th. of an average European's "environmental footprint" or allocated emission.

The results for wind turbines on land in this LCA showed, as expected, that electricity produced by wind had the smallest normalized environmental impacts in most categories. However, as mentioned above, wind turbines on land produced a large amount of hazardous waste per kWh electricity amongst the various production technologies. This is attributed to the fact that a wind turbine on land uses a relatively large amount of material (steel) per installed effect and has a relatively low number of operational hours in comparison to the other conventional production technologies. However, it should be noted here, that with the exception of the land-based wind technology, the other technologies' contribution to the hazardous waste category are over estimated. Discrepancies in allocation of hazardous waste between the technologies used in the Danish electricity and district heat project are the reason for this. The allocation principles used for land-based wind turbines will be applied for

Nysted and in future updates of Danish electricity and district heat in order to facilitate a more fair comparison.

The remaining categories are not shown here, however when considering the aggregated, weighted contributions in all categories, according to the EDIP method, the wind turbine has the least environmental impact contribution. It is important to note however, that this comparison is not completely valid since the wind turbine does not deliver the same security of supply, which is an integral part of conventional systems.

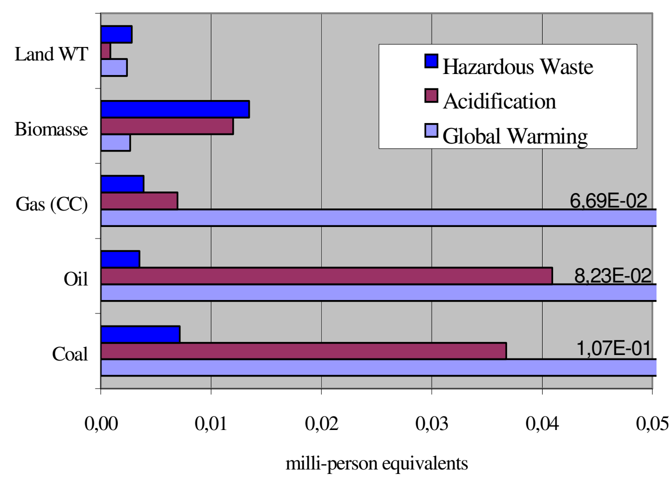

Figure 1. A comparison of three normalized environmental impact potentials for some production technologies in the Danish electricity and district heating mix per kWh. (Note: these technologies do not necessarily have the same functional unit with respect to the security of supply, especially wind, and therefore this comparison is for presentation purposes only. Not all environmental impacts are shown here for clarity).

3.2 An LCA of the offshore WTF at Nysted – the second step

As mentioned in the first step, experiences from the LCA project on Danish electricity and district heating has helped to initiate projects for technology evaluation and implementing design for environment using LCA. An LCA of the offshore WTF at Nysted prior to its actual design and construction gives ENERGI E2 the ability to environmentally evaluate the farm and find potential environmental improvements and implement these in the actual farm or in future offshore WTFs.

3.2.1 Functional unit

The LCA has been carried out for 1 kWh of electricity delivered from the Nysted WTF to the existing transmission net at the Radsted station near Sakskøbing. Production of electricity from wind turbines is of course variable and therefore production of 500 GWh has been estimated per year based on wind studies in the area. Losses in transmission are included up to the station at Radsted.

The expected lifetime of the WTF has been set to 20 years. Certain components in the WTF have estimated life times of up to 50 years, including the foundation and transmission cables. However, considering technology improvements and other maintenance and replacement related factors, a 20 year lifetime is reasonable.

3.2.2 System boundaries

All of the primary processes in the manufacturing, use and decommissioning of the WTF are considered in the LCA. This includes such processes as steel production and the transport of components. The secondary processes such as the manufacture of the mode of transport are not included here as documented experience has shown that these contributions are insignificant. The project has assumed that the WTF will be decommissioned at the end of its 20 year lifetime as mentioned above. However, studies have shown that the wind turbines can continue to economically produce electricity in so-called developing countries and this will likely reduce the environmental impact even further.

The flow diagram below shows the major components included in the life cycle assessment as well as the life cycle phases. Data has not been gathered for the boxes that are shown dashed. This is partly due to the limited access entrepreneurs have allowed, as well as the fact that experience from previous LCA work has shown these areas to be of little consequence in the overall environmental picture.

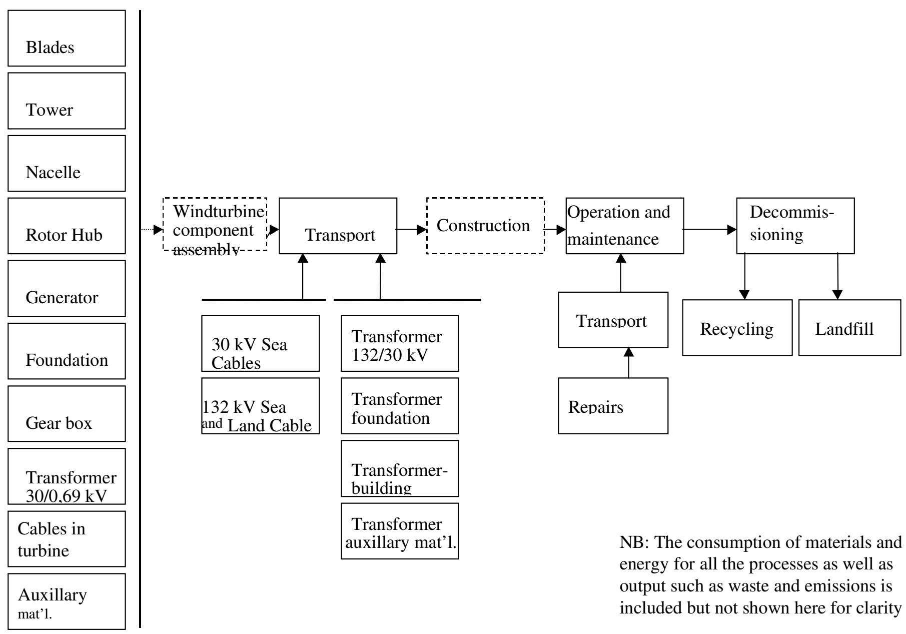

Figure 2. Flow diagram including the major components of an offshore wind turbine and the phases of the life cycle. Environmental exchanges from raw material extraction for and manufacturing of the various components is included but not shown in figure.

3.2.3 Data Colection

Data for the Nysted WTF is based in part on existing data from ENERGI E2's recently completed project "LCA of Danish electricity and district heating". Data on the land-based wind turbines, which were collected during the above-mentioned project, were supplemented with current data collected from the Middelgrunden Project (20 – 2 MW offshore wind turbines). As well, other wind turbine suppliers and entrepreneurs in Denmark and Germany who were involved in the tendering phase of Middelgrunden supplied data.

Nysted is expected to be on-line in the summer of 2003, therefore data gathered from suppliers is expected to be reflective of that time period. All data collected have been catalogued with a description such that they can be confirmed and quality assured.

3.2.4 Results

The results are normalized in accordance with the EDIP method. The collected data is divided into impact categories and then in reference to an average person's contribution to that category, the data is normalized. The unit used here is given in milli-person equivalents, as described previously.

The overall normalized result for Nysted's 150 MW offshore WTF is shown below in figure 3 with the normalized result for a land-based wind turbine as taken from the LCA of Danish electricity and district heating. This has been done in order to facilitate a comparison between the current land-based wind turbines in use in Denmark and the Nysted offshore WTF.

There is a clear improvement in all categories with the largest improvement occurring for hazardous waste, even despite the fact that the offshore WTF includes transmission to the net. This improvement can be explained in part by the extra production capacity expected due to better wind conditions at sea, as well as electronic regulation and control of the offshore wind turbine facilitating better use of high wind speeds. This is a very significant improvement reducing the impact in most categories 4 fold. However, improvements in the actual physical design of the wind turbines have also reduced the impact potentials particularly in the hazardous waste category. These improvements include: tower design and shape - reducing the amount of steel used; foundation type – reducing the amount of concrete and reinforcing steel required; and an increased wing span and refined aerodynamic shape – utilizing more of the wind load.

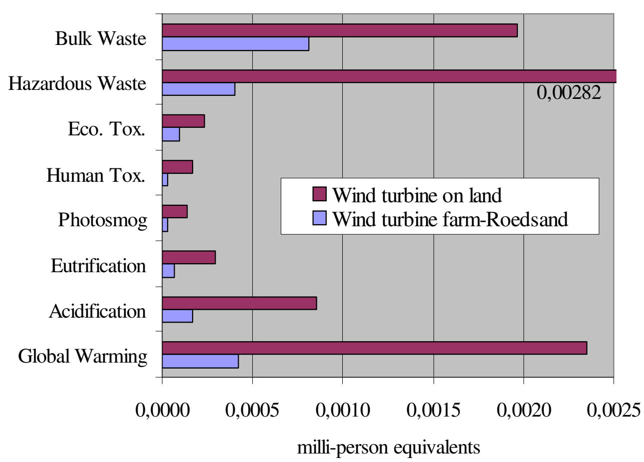

Figure 3. A comparison of the environmental effect potentials caused by 1 kWh of electricity production delivered to the transmission net from a 600 kW wind turbine on land and Nysted's 150 MW offshore WTF.

The transmission system that is included for the proposed placement at Nysted accounts for approximately 30 percent of the global warming contribution and between 15 and 20 percent for the other environmental categories. This is obviously valid only for the proposed offshore as described in the EIA [5].

3.2.5 Sensitivity analysis

A sensitivity analysis examines the significance of choices and/or assumptions made in the LCA in order to identify important impact areas.

Many scenarios were considered in the sensitivity analysis including the farms distance from shore, lifetime of the farm, foundation type, cable type, degree of recycling, disposal method for blades, etc. The most important results from the sensitivity analysis are given here.
In the sensitivity analysis, the distance of the farm from shore was increased 2 and 4 fold. The results of this scenario showed that doubling the farm's distance from shore made the transmission system responsible for over 40 percent of the majority of the environmental impact and a quadrupling over 50 percent (in effect, doubling the total environmental impact for the offshore WTF). These situations are not unlikely in that the Danish community has expressed that offshore wind turbines must not blemish their ocean vistas or result in a decrease in tourism.

In Denmark, spent transmission cables are sent to dedicated recycling plants where the degree of recycling of the metals is close to 100 percent. The decommissioned wind turbine and its components are sent to scrap metal dealers where the degree of recycling is also very high. In the Nysted project a conservative estimate of 90 percent recycling of metals was assumed. In the sensitivity analysis a recycling of 95 percent was considered. This is not unlikely in that the majority of the components are easily gathered and dismantled for recycling and the market for recycled metals in Denmark is very attractive. The results of the increase in recycling showed a reduction of approximately 50 percent in the amount of hazardous waste generated, as well as smaller reductions for global warming and bulk waste produced. This is reflective of a reduced need for primary metals.

Disposal of the wind turbine blades has not been a relevant topic until recently where many older wind turbines in Denmark are now being replaced by new, larger turbines. Disposal is facilitated by either granulation and landfilling or incineration. This project has assumed landfilling as the method of disposal. In Denmark, however, there is a great deal of focus on reusing the blade material and although no uses exist currently a great number of resources are being used to find methods of recycling the blade material. In the sensitivity analysis granulation for the purpose of recycling has been considered. The results when focussing on the entire system reveal a reduction in bulk waste generated of almost 20 percent with an insignificant increase in the global warming category.

Transport in general for the Nysted project was found to be insignificant. Transport systems considered here included lorries, ships, cranes and barges. Even with transport distances 5 times larger than the expected scenario, the environmental impacts were insignificant.

Wind conditions at sea have yet to be tested with large wind turbines and have therefore been conservative. It is estimated that a variation upwards of 10 percent can be expected and thereby reduce environmental impacts per kWh proportionally.

4 Conclusion and Outlook

All of the components of the WTF and transmission facilities have been examined and areas of environmental improvement have been identified. It was found that Nysted's offshore WTF and associated transmission facilities per produced kWh have an improved environmental profile in comparison to a land-based wind turbine.

The manufacturing and decommissioning phases for both land-based wind turbines and the offshore WTF at Nysted have the largest environmental impact, while transport and use have little or insignificant impact.

The largest environmental impact potentials from the offshore WTF at Nysted are bulk waste, global warming and hazardous waste. Bulk waste is mainly generated in connection with coal extraction for electricity generation used primarily in steel production for the tower, foundation and transmission cable. Landfilling of spent wind turbine blades also contribute considerably to this category as well as other processes. Global warming stems primarily from fossil fuel based electricity production used in the manufacture of the components in the WTF, especially the blades, tower and foundation. Hazardous waste is primarily generated in the production of steel for the tower, foundation and transmission cables, where various metal-rich slag fractions can only be disposed of at special hazardous depots.

The LCA has been carried out at an early stage in the planning of the offshore WTF at Nysted. Therefore, the results are representative of the scenario that is given in the EIA, Offshore WTF at Nysted [5]. However, it can be expected that many changes may occur in relation to the given scenario. Despite this, the LCA gives an overview of which parameters are of environmental interest at an early stage. As well, in the sensitivity analysis, a number of variables in the design of Nysted have been focussed upon in order to illustrate their environmental consequences.

Based on the experiences gained from the LCA of Danish electricity and district heating and the LCA of Nysted, ENERGI E2 now has the tools and knowledge-base to evaluate the environmental consequences of future projects and instigate design changes for environmental improvements while still in the design stage.

The information that this LCA has provided us with will allow us to set environmental demands on offshore WTF design and to suppliers and sub-suppliers in the same fashion that we set technical and economic demands. Numerous offshore WTFs will be built within the next 30 years in Denmark. In relation to this, ENERGI E2 will continue to further improve the environmental evaluation criteria in order to ensure environmental optimization of the planned offshore WTFs.

5 References

[1] LCA of Danish electricity and district heating – summary, ENERGI E2 A/S, Elsam A/S, Ekraft System, Eltra System.

[2] Wenzel, Henrik; Hauschild, Michael and Alting, Leo (1997): Environmental Assessment of Products, Volume 1: Methodology, tools and case studies in product development.

[3] Wind power in Denmark. Technology, policies and results. Danish Energy Agency (1999).

[4] Action plan for wind turbines in Danish coastal waters, Danish Energy Agency and The Association of Danish Energy Companies (June, 1997).

[5] Offshore WTF at Roedsand – an Environmental Impact Assessment, SEAS Wind Energy Centre, (July, 2000).