Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines

Contents

Summary

This report makes up the final reporting on the life cycle assessment (LCA) of onshore sited wind power plants based on the Vestas V82-1.65 MW turbine. The LCA and the reporting have been prepared by Vestas Wind Systems A/S.

The purpose of the project is to carry out a life cycle assessment of an onshore wind power plant, as a basis for assessment of environmental improvement possibilities for wind power plants through their life cycles. Furthermore, Vestas Wind Systems A/S wishes to document the environmental performance of its wind turbines to supply customers, NGOs (non-governmental organisations), governments and other stakeholders with objective information on wind energy delivered by Vestas turbines.

Previously, similar LCA reports have been prepared for the V80-2.0 MW turbine in cooperation with Elsam Engineering A/S and most recently for the V90-3.0 MW turbine. The V90-3.0 MW report and this report have been prepared solely by Vestas Wind Systems A/S. However, data from the previous reports has been used where appropriate in the LCA of the V82-1.65 MW turbine. It has been a goal for this LCA project to improve the LCA model used in relation to the previous LCA models. The LCA has been submitted to an external expert review by Force Technology to ensure the quality of the LCA. The review by Force Technology can be seen in appendix 3.

The results of the LCA shows that the energy pay back time and of the environmental performance of the V82-1.65 MW wind turbines compared to V90-3.0 MW and V80-2.0 MW is almost similar, as the energy balance is 7.2 compared to from 7.7 months for a V80-2.0 onshore to 6.6 months for a V90-3.0 MW onshore.

Electricity generated from Vestas turbines results in considerably less environmental burdens compared with European average electricity, which is in accordance with common understanding.

Wind turbines generate sustainable energy, and hence no CO_2 is emitted during the production of electricity. However, seen from a life cycle perspective CO_2 is emitted during the various processes in the life cycle of a wind turbine. The LCA shows that 1 kWh electricity generated by a V82-1.65 MW onshore turbine has an impact of 6.6 grams of CO_2 during the life cycle. If this is compared to the CO_2 emission of 546 grams per kWh from European average electricity it is clear that the environmental burdens are significantly lower for electricity generated by wind turbines.

The most important aspects in a LCA perspective for electricity from wind power plants is the selection of a site with good wind conditions, the recycling of steel and the impacts when producing steel components, as steel is the most used material in a wind power plant.

Review summary

The study has been conducted in accordance with the ISO 14044 standard, with some minor deviations. It provides a representative picture of the environmental impacts associated with production of electricity at large scale wind power plants and is therefore suitable for external communication, e.g. in the form of an Environmental Product Declaration.

The study has a very broad scope, requiring many assumptions. All choices made are justified, and it is emphasized that they all - with a few minor exceptions – aim to give a conservative, but realistic picture. The exceptions – most notable the missing data for transportation of raw materials – are recommended to be amended in future LCA reporting from Vestas.

The calculations are based on detailed inventories from Vestas' and its suppliers production facilities, representing modern production technologies. In the detailed calculations, the most recent data from industrial organisations have been used, ensuring the best possible quality. It is, however, rightly acknowledged that the available data not necessarily are fully suited for the modelling approach and that possibilities for continuous improvements of the database should be examined.

The report is judged to be consistent, but some sections could be improved with respect to its transparency. Although some information is given with respect to the origin of the basic information, little detail is provided with respect to how the data are modelled in the PC-tool. It is therefore suggested that Vestas in future LCAs establish a more thorough (and modular) documentation which can be used in the reports.

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FORCE Technology
March, 2007

Introduction

Life cycle assessment (LCA) addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment recycling and final disposal (i.e. cradle-to grave).

The present report makes up the final reporting on the LCA of electricity produced from an onshore sited wind power plant based on the Vestas V82-1.65 MW turbine. Vestas Wind Systems A/S (hereafter called Vestas) has prepared the report and the underlying LCA model.

In the year 2001 Vestas and Elsam Engineering A/S completed a design scheme, in which a life cycle assessment was prepared for a Vestas V80-2.0 MW turbine. In 2004 Vestas and Elsam Engineering A/S furthermore completed a life cycle assessment in which the offshore and onshore version of the V80-2.0 turbine was compared. Energy balances for the two versions were also presented in the assessments. For the first time in 2005 Vestas solely prepared and conducted an LCA on respectively the onshore and offshore V90-3.0 MW turbine

This report is the fourth report from Vestas Wind Systems A/S. The three previous LCAs[i, ii & iii] of the V80-2.0 and the V90-3.0 MW turbine have been used as basis for this LCA.

Although LCA often is a comprehensive exercise – as is also the case for the present LCA – it can in general not stand alone in the assessment of technologies. Other environmental management techniques like risk assessment, environmental performance evaluation and environmental impact assessment are valuable supplementary tools in addressing other types of environmental aspects (e.g. noise and impacts on fauna). Likewise, other tools may be used to address social and economic aspects which are not included in environmental LCA.

The LCA has been prepared according to the principles of the standard ISO 14044 with the exception that a review by interested parties has not been carried out as required when comparative assertions are made. ISO 14044 allows for some flexibility, e.g. with respect to setting of system boundaries, which may influence the results. Throughout the work it has been the intention of Vestas to provide a representative picture of the environmental impacts from electricity produced from our wind turbines. The most important decisions in this context are discussed in the report, but it must be acknowledged that not all details included in the model are included in the report.

To ensure that the LCA has been established in accordance with the requirements in ISO 14044, a critical review has been conducted by FORCE Technology. The entire critical review can be found in appendix 3. During the critical review, FORCE Technology has had access to all data sources, giving the possibility to verify that both modelling and calculations have been done using best practice.

For modelling, the PC tool GaBi is used based on the EDIP methodology. EDIP is an abbreviation for Environmental Design of Industrial Products[iv].

Goal of the study

The goal of the present LCA of electricity delivered from an onshore power plant based on Vestas V82-1.65 MW turbines is threefold:

- To use LCA data to document the environmental performance of the V82-1.65 MW turbine. The present report provides the basic documentation and allows for preparation of an environmental declaration for electricity produced by the V82-1.65 MW turbine.
- To use results from the life cycle assessment for environmental improvement strategies in connection with product development
- To improve the existing LCA model for Vestas wind turbines.

This LCA is directed primarily towards four target groups:

- Customers of Vestas
- Vestas Wind Systems A/S
- Investors of Vestas Wind Systems A/S
- Other stakeholders, including energy authorities from countries with interest in renewable energy that should be able to use the overall results as part of an assessment of the environmental characteristics of Vestas turbines.

The LCA has been performed in a way that makes it possible to compare the impacts of electricity produced on a wind power plant with electricity produced on power plants based on different technologies. In the current study, a comparison with average electricity production in EU-25 in 2002 has been made to exemplify the possibility. Similar comparisons with specific technologies may be performed by relevant stakeholders, based on the results in the report.

Scope of the study

Electricity, generated by wind power is regarded sustainable electricity. However, in a life cycle perspective also wind turbines consume resources and cause emissions to air, water and soil, primarily during the production and disposal stages but also during its use. In order to determine the precise impacts from electricity produced by a wind turbine all components needed for the production of electricity based on wind has been included, from the wind turbines to the cables, transformer station and finally the connection to the existing grid, see figure 1. Each of the components in the wind power plant has been considered in the life cycle perspective, i.e. that all environmental exchanges related to their production, use and disposal have been included in the calculations. The wind power plant is capable of delivering 300 MW, making the wind power plant comparable with other electricity power plants as i.e. gas and coal power plants.

The 300 MW wind power plant, consists of 182 Vestas V82-1.65 MW turbines. The V82-1.65 is typically used as an onshore site wind turbine, and therefore only an onshore sited wind plant has been used in this LCA. Data regarding wind power plant configuration and electricity production for the wind power plant has been derived, not from actual sites, but from general project models used at Vestas, reflecting standard site data.

The scope of the study is in principle the entire world, which is the market for Vestas' products. This has been considered when finding data for transport, power production at the selected site and final disposal of the wind power plant. This very broad scope obviously means that some uncertainties are introduced when compared to conditions in specific countries. The general approach used in the study has been to provide a realistic, but conservative, estimate in those cases where differences were known or expected to occur.

Functional unit

The functional unit is selected as 1 kWh electricity generated at the wind power plants with the selected turbines. As all the impacts are balanced to this functional unit, the results are comparable with results from LCA's of other electricity production technologies.

Please note that this functional unit only includes electricity delivered to the electricity grid and not electricity delivered to the consumer. If this study should be used for comparison with electricity delivered to the customer, then the grid loss should be considered. Grid loss varies from country to country, in this study 10% grid loss is used, simulating the grid in EU-25.

General system boundaries

The system studied includes:

- 182 V82-1.65 MW turbines with the following main elements:
  - Tower
  - Nacelle

  - Rotor (consisting of three blades and a spinner)
  - Foundation for the wind turbine
  - Internal cables – connecting the individual wind turbines to the transformerstation
- Transformer station
- External cables – connecting the wind power plant to the existing grid

Figure 1 shows the elements included in the LCA project model for the onshore wind power plant. Each of the elements are described in some more detail in the subsequent sections.

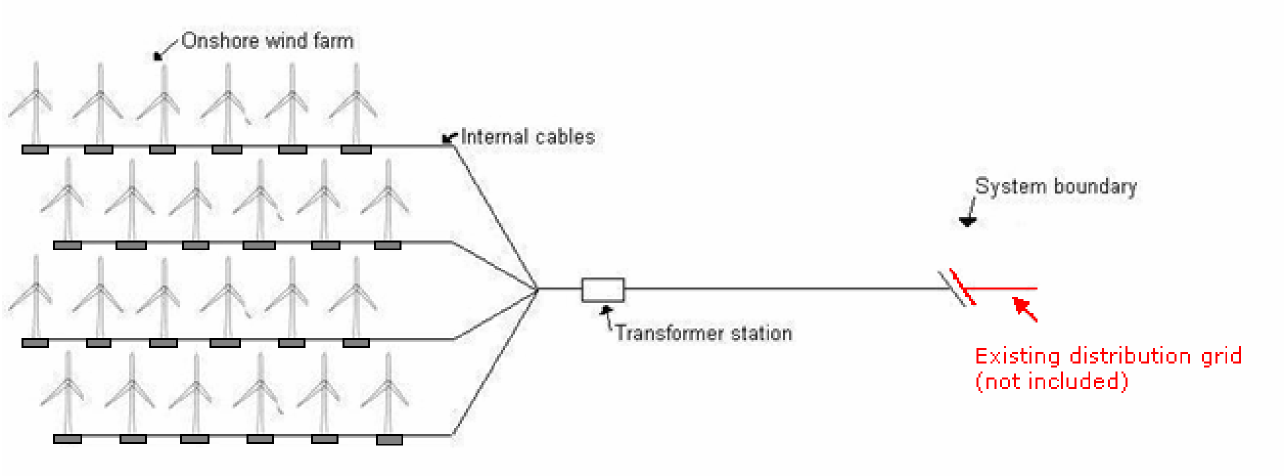

Figure 1: Scope of the LCA.

The assessment includes production, transport, erection, operation, dismantling and removal of turbines, foundations and transmission grid to the existing electricity grid. This is illustrated by figure 2 with an attendant explanation of the specific life stages.

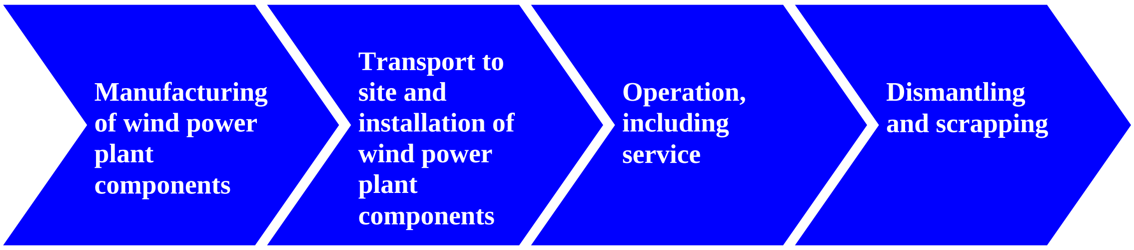

Figure 2: Life cycle stages.

Manufacturing of wind power plant components includes production of raw materials and manufacturing of foundations, towers, nacelles, blades, cables and transformer station. Transport of raw materials, e.g. steel, copper, epoxy etc. to the specific production sites are not included in the model.

Transport to site and installation of wind power plant components includes transport by truck and transport by vessel at sea. Furthermore, transport of certain large components from sub-suppliers to Vestas is included in the project model. As a worst case approach it has been assumed that the wind power plant is erected in a continent where Vestas does not have production facilities.

This means that all main components are transported by ship and truck over long distances to their final destination.

Erection includes cranage and other construction work at site. The turbines are erected on foundations. Each turbine foundation is established in connection to a road, working and turning area. Road, working area and turning area are not included in this study and are expected to be insignificant.

Transport of raw materials is not included in the study. The omission is addressed in a sensitivity analysis.

Operation, including service includes change of oil, lubrication and transport to and from the turbines is included in the stages of operation and maintenance. Furthermore, a worst-case scenario of renovation/replacement of gearbox and generator is included. Transport onshore is carried out by truck.

It is assumed that the lifetime of the wind power plant turbines and internal cables is 20 years, corresponding to the design life time of the V82-1.65 MW. Still, it is expected that the operation of the turbines will exceed 20 years, but there is no certainty for this..

Dismantling and scrapping includes cranage when dismantling, transport from erection place to the final disposal (by truck + escorting car(s), if necessary). Furthermore, final waste management of materials is included, either by recycling, incineration with energy recovery or by depositing at a landfill site.

In case of recycling of materials this is handled by system expansion. This means that the environmental exchanges from recycling (e.g. collection, scrapping and remelting) are allocated to the LCA system. The LCA system is on the other hand credited for the avoided production of (virgin) materials.

In case of incineration with energy recovery it has been assumed that 30% of the net calorific value of the materials is utilized in electricity production, substituting conventional production methodologies. These obviously differ from one region to another, and it has been chosen to use average electricity production in EU-25 in 2002 as the avoided production.

In case of landfilling, no other burdens than those related to the transportation of waste - and the actual amounts of different types of waste have been allocated to the LCA system. This is a realistic assumption within the 100 year time frame used to calculate potential environmental impacts, but on the longer term, the landfilled waste may degrade with increased impacts on waste and soil as a consequence. However, available LCA models are not yet operational for addressing such impacts.

A more detailed description of the life cycle of wind power plants and the included materials will appear from the following chapters.

Allocation

As turbines only produce electricity and e.g. no heat, there is no need to allocate between more products. This simplifies the inventory.

Quantification of material and energy exchanges

In relation to data collection, the target for including materials has been to cover 100% of the components for the wind power plant by weight, as it has previously been proven that production of raw materials and manufacturing processes causes the major part of environmental impacts in the whole life cycle of the wind power plant. [i, ii & iii].

As the wind power plant consists of more than 10.000 components, it has been a target to map at least 95% by weight of the components with respect to material type. For the remaining 5% of the components the material type has been estimated – assuming the same content as for the mapped materials.

Information regarding environmental exchanges in production of raw materials has primarily been taken from the GaBi-EDIP database, supplemented with a few datasets from the GaBi professional database and from industrial organisations as International Iron and Steel Institute (IISI), International Stainless Steel Forum (ISSF), International Copper Association (ICA), European Aluminium Association (EAA) and Association of Plastics Manufacturers (APME). Data for environmental exchanges on transportation has also been taken from the GaBi-EDIP database.

With respect to consumption of resources and emissions in various manufacturing proceses this has been addressed by using site specific data. All Vestas’ production sites prepares detailed environmental statements with precise accounts of all environmental exchanges. The environmental exchanges have been distributed to the LCA system by means of production output (i.e. weight, number of produced items). The most appropriate means of distribution has been selected in each case and is explained in more detail in the following chapter.

Similar information has been available from suppliers of the main components. From smaller suppliers, environmental exchanges have been estimated by analogy to comparable activities at Vestas or its main suppliers.

For electricity consumed at Vestas’ own production facilities, a specific scenario has been established (see the chapter “Vestas’ resource consumption and emissions”).

Since Vestas sources components from different suppliers and also has production facilities all over the world a general process for electricity production to Vestas’ suppliers has been chosen. The choice – “Power grid mix EU 25, 2002” – is for natural reasons not equally representative for all production sites, but it is assumed to provide a fair estimate because it includes a variety of production technologies used today. It is remarked that it is the same electricity scenario which is displaced when waste is incinerated in the life cycle of wind power plant.

Data requirements

Data for mapping the materials and components input in this study shall as far as possible be specific data from Vestas and suppliers of Vestas. This data should preferably be in form of technical specifications, and if this is not possible in the form of statements from experts.

Data for mapping the resource and energy consumption as well as emissions should as far as possible be based on site-specific information from Vestas' own production sites and relevant suppliers. Where this is not possible, data from similar known processes at suppliers, Vestas or from LCA databases such as GaBi EDIP shall be used.

For data on production of raw materials generic data is preferred from LCA databases such as:

- GaBi EDIP
- International Iron and Steel Institute (IISI)
- International Stainless Steel Forum (ISSF)
- International Copper Association (ICA)
- European Aluminium Association (EAA)
- Association of Plastics Manufacturers (APME)

The data used shall be for present technologies and should reflect processes in the industrialised parts of the world. This is also valid for the disposal stage even though this will take place in the future.

Life Cycle inventory analysis

Data collection

The collection of data has taken place in close co-operation with relevant functions at Vestas, technical specifications of the V82-1.65 MW turbine have been used and a number of suppliers have been involved. All assumptions of and approaches to materials and processes, which are new in relation to the previous LCA reports [i, ii & iii], have been evaluated and discussed by Vestas. New materials and processes in the study are:

- Data for cables
- Data for transformer
- Data from all suppliers of main components
- Data for all metals
- Data for concrete
- Data for power grid mix
- Data for production sites in Vestas
- Transport scenario

Concerning the turbines, the most significant environmental impacts will typically arise during manufacturing of the turbines and final disposal of the turbines. On the other hand, the operational stage does not contribute significantly to environmental impacts. Therefore, data collection has been focused on procuring as precise data as possible for the production and disposal stages. The turbine system is divided into the following component systems:

- Tower
- Nacelle
- Rotor (consisting of three blades, hub and spinner)
- Foundation
- Internal cables – connecting the individual wind turbines to the transformer station
- Transformer station
- External cables – connecting the wind power plant to the existing grid

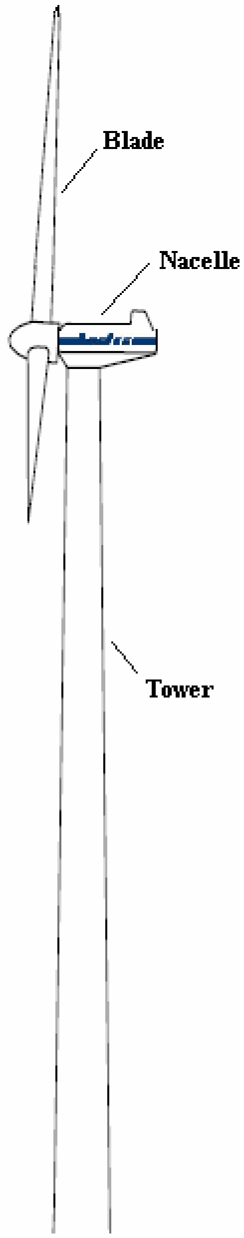

Figure 3: V82-1.65MW wind turbine

Procedures for data collection

Data collection has mainly been carried out on the basis of the item lists, technical drawings and specifications of various components for a wind power plant consisting of V82-1.65 MW wind turbines. The item lists are taken from Vestas' ERP system, which furthermore contains information about material type and weight of a very large part of incoming raw materials and semi-manufactured articles. As a starting point, all the item numbers on the item lists are included. As regards the items, where the information has not been immediately accessible it has been assessed in each case whether it would be relevant to search for further information about weight and material composition. This has resulted in an up scaling of some components by weight from the previous LCA of the V80-2.0 MW and V90-3.0 MW [i, ii & iii]. Although there are technological differences between the V80-2.0 MW, the V90-3.0 MW and the V82-1.65 MW turbines, the materials and processes used in the life cycle does not differ significantly. Items upscaled from previous LCA's are:

- Ground controller in tower
- Yaw system for nacelle
- Cable trace system
- Cable termination and signal cable

As regards to large items as e.g. transformer and generator, the information originates from the supplier.

Information about overall conditions for the wind power plants, transmission, foundations, electric power generation and installation, transport and service is collected from relevant departments in Vestas.

Where possible, the information about various materials is taken from sources specified under "Data requirements". In some cases, it has been necessary to make assumptions about the materials. These assumptions are described in the individual sections below.

Building the model in GaBi

The LCA tool GaBi has been used to model production of electricity from an onshore power plant based on Vestas V82-1.65 MW turbines.

Figure 4 shows simplified the structure in three plans, from the functional unit (delivery of 1 kwh electricity), to the content of the wind power plant (main components), to the life cycle of one of the components – a generator. Additional layers, addressing the single processes can be found underneath the general outline.

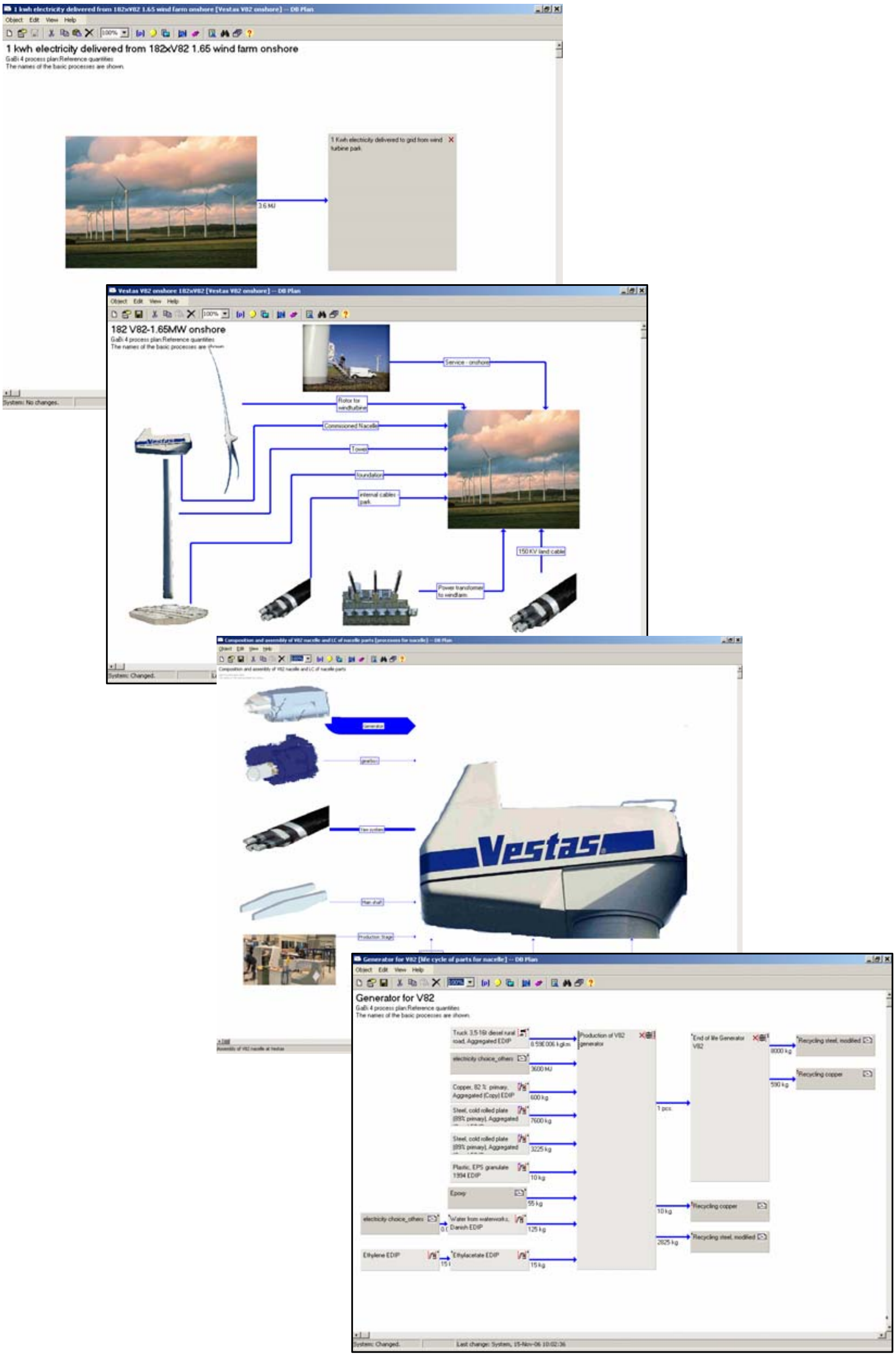

Figure 4: Building the model in GaBi

Inventory of onshore wind power plant

The onshore wind power plant in this LCA study is based on general project models used at Vestas.

The onshore wind power plant consists of 182 Vestas V82-1.65 MW turbines.

Main data for a V82-1.65 MW turbine can be seen in table 1.

Onshore turbine **78 meter hub height on concrete foundation**	
Tower	**136 ton**
Steel	126.1 ton
Aluminium	2.6 ton
Electronics	2.2 ton
Plastic	2.0 ton
Copper	1.3 ton
Oil	1.0 ton
Nacelle	**51 ton**
Cast iron	18.0 ton
Steel, engineering	13.0 ton
Stainless steel	7.8 ton
Steel	6.3 ton
Fibreglass	1.8 ton
Copper	1.6 ton
Plastic	1.0 ton
Aluminium	0.5 ton
Electronics	0.3 ton
Oil	0.3 ton
Rotor	**42.2 ton**
Cast iron	11.3 ton
Steel	4.2 ton
steel, engineering	1.5 ton
Rest: Epoxy, fibre glass, birchwood, balsawood etc.	25.2 ton
Foundation	**832 ton**
Concrete	805 ton
Steel	27 ton

Table 1: Main data for V82-1.65MW turbines for onshore sited wind power plant.

At the onshore wind power plant, there is a total of 95 km of 32 kV cables for connecting all 182 turbines to a 32/150 kV transformer station. It is assumed that the wind power plant is placed in 50 km distance from the existing distribution grid. For the connection of the transformer station, the existing distribution grid two 150 kV cables are used. The distance to the existing grid varies a lot from project to project as the length of the cables specific to the single wind turbine site. A sensitivity analysis has been carried out to show the significance of this parameter.

Internal cables, transformer station and external cables to a wind farm consisting of 182 V82-1.65 MW turbines	
Internal cables	**149.5 ton**
Aluminium	63.4 ton
Plastic	55.2 ton
Copper	30.9 ton
Transformer station	**174.3 ton**
Steel	91.8 ton
Copper	24.0 ton
Transformer oil	37.8
Rest: insulation, paint, wood, porcelain etc.	20.7 ton
External Cables	**2711.5 ton**
Plastic	1519.0 ton
Aluminium	953.0 ton
Copper	238.6 ton

Table 2: Main data for Internal cables, transformer station and external cables to a wind farm consisting of 182 V82-1.65 MW turbines.

Data sources

The following paragraphs provides an overview of the data sources used, together with a short discussion of their quality and representativity in relation to the present LCA.

Glass fibre

Data for glass fibre production have been aquired from PE International, the developer of the GaBi LCA software and the associated databases. According to the documentation the data are rather old, and interviews with PE indicates that they energy consumption may be overestimated with up to 10%. To Vestas knowledge no other datasets specifically addressing glass fibre production are available and the use of conservative estimates as is the case with glass fibres is in line with the general approach of the study.

Steel

Data have been provided by IISI, the International Iron and Steel Institute[v]. The data were specifically developed to meet Vestas' needs, including not only production of steel but also the credit that can be obtained through recycling. The data have been entered manually into the software as they are not present in any commercially available edition. The following dataset have been used from IISI:

- Plate (Heavy Steel Plate)
- Engineering Steel (Tool Steel)

Copper

Data for copper production have been taken from a report from ICA, the International Copper Association[vi]. The way the data are modelled in the ICA-study does not fit very well with the system expansion approach generally used in the present study, and it has therefore been chosen to make some changes.

The most important change is that all copper consumed is assumed to of a quality suitable for wire and cable production. This gives a conservative estimate, partly because the energy consumption is significantly higher (about 50%) for this quality, compared to the quality used in sheet production. Another main difference is that in the ICA-study of copper sheet about 50% of the raw material is assumed to be scrap, entering the system with no environmental burdens associated. This will give a significant underestimation of the consumption of non-renewable resources.

When recycled, a 10% loss during collection and refining processes is used as a conservative estimate in line with the recommendations from the recycling workshop held at Vestas. No information on energy consumption in recycling is available from the ICA-report. Instead, information from a US study (Jolly, 2001) is used, estimating an energy consumption of 1.81 MJ/kg in scrapping and 4.02, respectively 16.57 MJ/kg for remelting of wire and sheets.

The recycled copper is assumed to replace wire copper, i.e. that full credit is given to the recycled material. It is acknowledged that this may give an additional benefit from the recycling process because the copper cathode produced in recycling still needs to be shaped to wire in order to be fully comparable to the product it replaces. However, this error is judged to be of minor importance in relation to the overall picture.

It is remarked that Vestas is aware of the relatively poor data quality for copper. If and when better data becomes available, the life cycle model will be adjusted.

Plastics

Data for plastic materials, both thermoplastics resins like ABS and thermosetting resins like epoxy have been taken from the databases available at PlasticsEurope[vii]. The data are judged to be the best possible available, but it should be noted that they are not sufficiently detailed to be able to distinguish between different types of epoxy.

Concrete

Data for concrete production have been adapted from an environmental report published by Aalborg Portland cement factory in Denmark[viii]. The data presents an average for Danish cement production, and it is remarked that there may be significant differences in the environmental impacts from cement production related to material specifications as well as to national differences. The data used are, however, believed to give a representative picture of modern cement production.

Cast iron

Data for cast iron has been created from environmental site descriptions from Vestas' four casting factories[ix,x,xi]. The site descriptions comprises input of all relevant environmental ressources and materials as well as all relevant emissions. All iron has been calculated as virgin iron in the lack of data. This ensures that the conservative apporach is kept.

Aluminium

Aluminium has been included using data from EAA, the European Aluminium Association[xii]. The most recent update (from 2005) allows a distinction between primary production and recycling, i.e. that it has been possible to use the data for system expansion which is the general approach of the study. It is remarked that a 10% loss in the recycling process has been assumed, being in line with the recommendations from the workshop on end-of-life scenarios arranged by Vestas (see the chapter “End of life scenario”).

Electronics
Manufacturing of electronics components has been addressed using a process from the GaBi-EDIP database. This is in turn based on a report from the Danish EPA, establishing a general inventory for production of electronic components[xiii]. Energy consumption in production is not included in the inventory, and there is no possibility of assessing the representativity of the data in relation to electronics used in wind turbines. It is judged that refinement of the inventory, e.g. by adding supplier specific information, will be very demanding in terms of resources – without having a significant influence on the overall results.

Wood
Two types of wood are used in the blades, birch and balsa. The Birch wood is PEFC certified and produced in Finland. The Balsa wood comes from Ecuador. No information on production of balsa wood has been identified and it is therefore assumed that all wood is birch. Transport of the wood to Vestas’ factories is no included in the LCA study, as it is assumed to be insignificant.

Transformer
The transformer is modelled from an EPD from ABB on a Power transformer TrafoStar 500MVA[xiv]. The functional unit of the EPD, which is 1 MVA, has been used for scaling the environmental impacts to meet the actual performance of the transformer used in the wind power plant. Only little information is available regarding the approach used in the life cycle modelling of the transformer, except that the information given regards cradle to gate only. The content of materials is modelled further in the present project to include the end of life, using system expansion as for the other materials and components.

Operation

In connection with the operation of turbines, wear and tear will take place especially of rotating parts.

The turbines are dimensioned and constructed to a lifetime of minimum 20 years. To be on the safe side in this LCA, a conservative estimate of maintenance of the turbines is assumed. It is expected that during the lifetime of 20 years one reconditioning/renewal of half of either the gearboxes or the generators must be carried out which, as a minimum, is expected to comprise renewal of the bearings. To simplify the model of operation, only the gearboxes have been included in the model, but in return the project model comprises a total renewal of half of the gearboxes once in the turbine’s lifetime. Thus, the model is assumed to include a conservative estimate of the amount of materials used in operation and for maintenance, as several of the gearboxes and the generators will probably be repaired and not renewed. Moreover, the gearbox is 90% heavier than the generator.

In addition, materials for servicing of the turbines are included, i.e. change of oil and lubrication of gearbox, generator, etc.

Electric power generation

A standard site with an average wind of 7,38 m/s in hub height has been chosen, expressing a realistic site placement in for example Denmark. With an average wind speed the electric power generation from the wind power plant has been calculated to 1,025.9 GWh/year, i.e. each turbine produces 5,637 MWh/year, corresponding to a capacity factor of 40.8. For 20 years this equals 20,518 GWh.

For more information on how to calculate the electricity production of a wind turbine please refer to www.windpower.org

Losses in the cables and transformer station have been included and are calculated to approximately 5%.

As the amount of electricity produced in the life time of the wind mill park is a decisive factor in the environmental profile of 1 kWh produced, a sensitivity analysis has been applied, considering alternative scenarios (see page 46).

Transport

Since Vestas sources components from different suppliers and has production facilities all over the world general assumptions for the transport has been used. Transport of raw materials is not included in the LCA study, but a sensitivity analysis has been carried out to show the significance of the exclusion.

Transport of large components

For a number of large components covering above 90% of the weight of the wind turbine (ex. Foundation) 1000 km by truck has been assumed. This covers the transport of the components from the supplier to Vestas' factories.

The following dataset are contribute to the majority of the used materials and are used in the calculation of the environmental impacts for electricity from a wind power plant:

- Truck >16t diesel, motorway, Aggregated, EDIP, 1997
- Truck >16t diesel, rural road, Aggregated, EDIP, 1997
- Truck 3,5-16t diesel rural road, Aggregated, EDIP, 1997

Transport of wind turbine to erection site

The following transport distances for the single wind turbine components have been used:

- Nacelle, 8405 Nautical miles (15566km) with containership, and 1000 km with truck.
- Hub, 8405 Nautical miles (15566km) with containership, and 1000 km with truck.
- Blades, 8405 Nautical miles (15566km) with containership, and 1000 km with truck.
- Tower, 700 km with truck.
- Foundation, 200 km with truck.

The used distances are regarded as a worst case scenario, as they reflect a placement of the wind power plant in a continent without Vestas production facilities..

The following dataset are used in the calculations:

- Truck >16t diesel, rural road, Aggregated, EDIP, 1997
- Container ship, 2 stroke, 28000 DWT, Aggregated, EDIP, 1997

Erection, service and decommissioning of the wind turbine

Erection and decommissioning includes cranage and other construction work at site.

Twice a year, a technician must carry out inspection of each turbine. For an onshore wind power plant of this size a service crew has been assigned fulltime. The transport is therefore limited to the transport from the service building to the individual wind turbines. Transport of 180 km a year by car per turbine has been included in the project model.

The following dataset are used in the calculations of environmental impacts from raw material production:

- Van < 3,5 t diesel, rural road, Aggregated, EDIP, 1997
- Truck 3,5-16t diesel rural road, Aggregated, EDIP, 1997

End of life scenario

As regards the end of life scenario, the scenario used in the previous LCA report has been used in this study as well [i, ii & iii]. The scenario is based on a workshop held December 2001, where the dismantling of the turbines and removal of components/materials was discussed. Participants at the workshop were companies and institutions working with dismantling, scrapping and recycling. The following parties were represented:

- Vestas
- Elsam Engineering A/S
- H.J. Hansen Genvindingsindustri A/S (working with dismantling, recovery and electronic waste)
- Demex (working with dismantling)
- Waste Centre Denmark
- RISØ, who at that time was working on an assessment of future wind turbines in a life cycle perspective

Furthermore, input from H.J. Hansen about recent work with the recovery of turbine blades was used to develop the scenarios used in the calculations in the present LCA.

As the geographical scope of the study is the entire world, then a conservative assumption has been made regarding the disposal of plastics and composites. It has been assumed the plastics and composites are land filled. Previous LCA reports have however shown that the disposal scenario of composites does not affect the impact of the total LCA of electricity from a wind power plant.

The following removal scenario is used in this study:

Material	Scenario
Steel	90% recovery from recycling, 10% loss (to landfill)
Cast iron	90% recovery from recycling, 10% loss (to landfill)
Stainless steel	90% recovery from recycling, 10% loss (to landfill)
High-strength steel	90% recovery from recycling, 10% loss (to landfill)
Copper	90% recovery from recycling, 10% loss (to landfill)
Aluminium	90% recovery from recycling, 10% loss (to landfill)
Glass fibre components	100% Land filled
Plastic	100% Land filled
Plastic from cables connecting wind turbines and cables to existing grid	68% recovery of plastic and 32% incineration with energy recovery

Table 3: Removal scenario for materials

The above-mentioned scenarios of data regarding disposal derive from literature data and from the recycling workshop. However, some of the experts from the recycling industry expressed that the loss in recovery of steel and other metals is less than the 10% used in this study for all metals as presented in the table above. The 10% is maintained as there is much uncertainty about the figure and at the same time it is not known exactly if all materials can be disassembled totally in material fractions, i.e. there might be a loss, before the recycling process is started.

Data for processing of metal scrap into metal that can be used in the production of new components is furthermore included.

As the recovered metals are included in the production of new metal components, the LCA is credited for the recovered materials.

Datasets used for the recovery of metals are:

- Recovery of steel, International Iron and Steel institute, 2000
- Recovery of Aluminium, European Aluminium Association, 2002
- Recovery of Copper, ICA, 2000, supplemented with Jolly, 2001
- Scredding of steel, EDIP, 1997
- Recycling of cables at NKT cables, 2005[xv]

Incineration with energy recovery of materials with an energy content may be a viable future disposal option in many industrialised countries. A variety of technologies already exists, e.g. in Denmark, and the benefits that can be obtained differ significantly. Combined heat and power production is seen as the most benign technology, being in principle able to provide both electricity and district heating from the same process. Due to the complexity of local and regional energy systems, it is however not always possible to fully utilize the inherent calorific value, e.g. because waste heat has to be vented to air or water due to lack of demand.

In many countries only electricity is generated, with widely differing efficiencies. In the calculations in the current LCA efficiency in electricity production of 30% has been assumed, without co-generation of heat. It is acknowledged that this approach can only provide a very crude estimate of the consequences, and that more considerations should be given to the issue, especially if it becomes technically possible to utilize the inherent energy in the blades (epoxy and wood).

Manufacturing of wind power plant components

Vestas' resource consumption and emissions

Vestas' resource consumption and emissions for manufacturing of turbines is reported in the Environmental Statement for 2005 and in a number of site descriptions for the separate factories. It has therefore been possible to assign the environmental aspects directly to each manufacturing process, from casting of iron, production of PCB (Printed Circuit Board) to assembly of the nacelle.

Vestas wish to contribute to the expansion of sustainable energy by purchasing electricity from sustainable sources for its activities. In 2005, sustainable electricity accounted for 75 per cent of Vestas' total electricity consumption.

The adoption of the Kyoto Protocol and the introduction of the European quota market have resulted in around 11,500 European energy utilities and companies incurring a financial cost for their emissions of CO_2. Companies that wish to emit more CO_2 than their quotas allow can purchase additional quotas on a quota exchange. The CO_2 quotes are purchased from companies that e.g. have reduced their CO_2 emission through investing in sustainable energy sources, cleaner technology etc.

The total emission of CO_2 in EU has to decrease with 8% compared to 1990 in the period of 2008-2012. The need for energy with less or no CO_2 emission is therefore evident. By freely buying sustainable electricity Vestas is reducing the current available sustainable energy and hence contributing to the expansion of sustainable energy.

The following has been used to model the electricity consumption on Vestas' factories.

Energy system	Share	Modelled as
- hydro power	70%	Norwegian electricity 1990 (99.7% hydro power + 0.4% conventional power plants), EDIP, 1997
- wind power	5%	Electricity from V90-3.0 MW based offshore wind farm, Vestas, 2005
- Other electricity	25%	Power grid mix EU 25, PE, 2002

Table 4: Vestas' electricity consumption 2005

Manufacturing of tower

The tower is 80 m high and is built for IEC IIA wind conditions. Other tower heights and tower for other wind conditions are available for the V82-1.65MW turbine, however the chosen model represents a conservative approach, as it is the heaviest realistic tower model available.

Towers for Vestas' turbines are to a minor extent manufactured at Vestas' own factories, the majority is purchased from sub-suppliers. In this project, data from towers manufactured by Vestas has been used. Considering the required technologies for producing towers, then data from Vestas' factory is representative for producing towers.

Towers are manufactured of steel. The steel is delivered to Vestas in steel plates. The steel plates are cut and the cut-off waste is recycled and modelled as such. The steel plates are then rolled and welded into tower sections. Subsequent treatment, i.e. sandblasting and surface treatment of towers is - depending on the manufacturing site - either performed at Vestas or at sub-suppliers.

In this project, manufacturing and the subsequent surface treatment has been included.

Following the surface treatment, the tower sections are fitted with "internals" such as: Platforms, ladders and fixtures for cables. Finally, the controller units in the bottom of the tower are installed.

Tower sections

The environmental site description from the tower factory in Varde, 2005 has been used and includes all processes from manufacturing of the tower to the fitting of internals[xvi]. The weight of the tower has been used to distribute the environmental aspects.

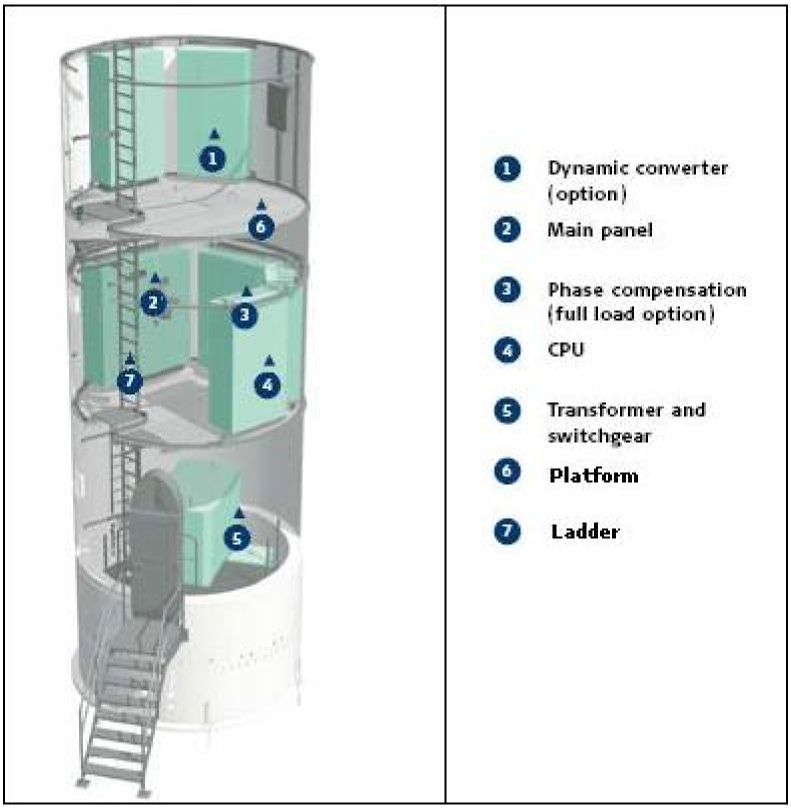

Figure 5: Bottom of tower for V82-1.65MW

Transformer

Data for the V82-1.65 MW transformer is based on supplier data. According to the supplier, the transformer mainly consists of steel, copper, aluminium and resin.

The manufacturer has informed of materials used, energy consumption used during the manufacturing process as well as waste generated.

Cables

Data for the cables in the tower is based on supplier statement. According to the supplier, the cables mainly consist of aluminium, copper and plastic (PE).

The manufacturer has informed of materials used, energy consumption used during the manufacturing process as well as waste generated[xvii].

Controller units

In this project, data from Electronic factory Aarhus, 2005[xviii], Controller factory Olvega, 2005[xix], Controller factory Hammel, 2005[xx] and Controller factory Lem, 2005[xxi] have been used. The environmental site descriptions covers the manufacture of all controller units in Vestas from the reception of electronic components to the final controller units. Distribution has been performed on the basis of the rated output of the turbine, i.e. 1.65 MW for the V82 turbine divided in the total production of Vestas in 2005, which was 3185 MW.

Resource consumptions and emissions regarding welding wire, welding powder, paint, metallizing agent, grit for shot blasting and switchgear originates from information from the sub-suppliers and experts at Vestas.

The following dataset are used in the calculations of environmental impacts from raw material production:

- Steel plate from International Iron and Steel institute, 2000
- Extruded aluminium from European Aluminium Association, 2002
- Electronics, from working report from the Danish Environmental protection agency, 2001
- Plastic, PE (high density) granulate, EDIP, 2000
- Copper wire from International Copper Association, 2000
- Oil, refined, (fuel), North sea, EDIP, 2001

Manufacturing of nacelle

The nacelle consists of the nacelle cover, main shaft, main bearing, gear, generator, foundation etc.

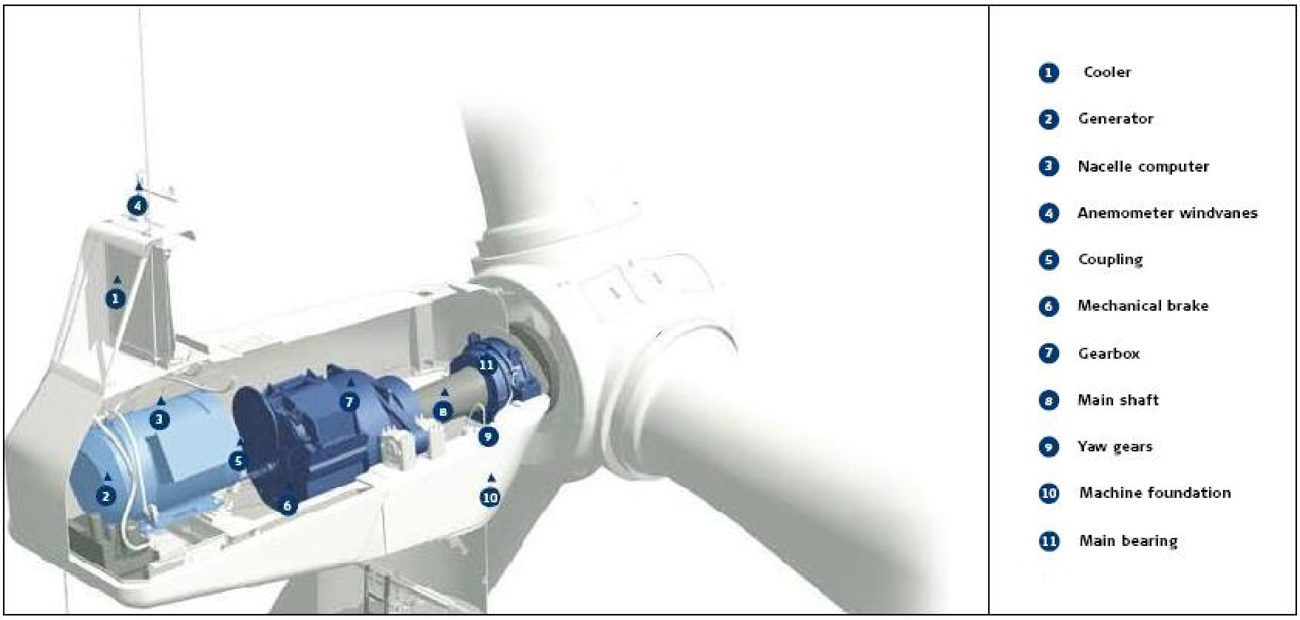

Figure 6: V82-1.65MW nacelle

Most of the individual components are not manufactured by Vestas, but are purchased from sub-suppliers. Final finishing (welding, metal cutting) and subsequent assembly takes place at Vestas' factories. The environmental site description from nacelle factory – Galicia, 2005[xxii] has been used and includes the assembly of all the components for the nacelle. Distribution has been done by dividing the environmental exchanges with the number of turbines produced in 2005.

The following description lists data on the most significant components:

Main shaft

The main shaft for the wind turbine is manufactured of high-strength steel. The main shaft is delivered to Vestas for CNC processing, and then assembled in the nacelle.

The environmental site description from machine factory - Lem, 2005 has been used and includes all CNC processes[xxiii]. The weight of produced components has been used to distribute the environmental aspects, i.e. by dividing the environmental exchanges with the total weight of the produced items in 2005.

Data on high-strength steel is based on "Engineering Steel (Tool Steel)" from International Iron and Steel Institute.

Main bearing

Data for the V82-1.65 MW main bearing is based on supplier statement. According to the supplier, the gear mainly consists of steel and high strength steel.

Gearbox
Data for the V82-1.65 MW gearbox is based on supplier statement. According to the supplier, the gear mainly consists of steel and cast iron.

The manufacturer has informed of materials used, energy consumption used during the manufacturing process as well as waste generated.

Generator
According to the supplier, the generator mainly consists of steel and copper.

The manufacturer has informed of materials used, energy consumption used during the manufacturing process as well as waste generated.

Machine foundation
The machine foundation is made of cast iron and produced at Vestas' casting facilities. The site descriptions from Vestas Castings Kristianssand, Guldsmedshyttan and Magdeburg have been used and include all process for casting of iron. The weight of produced components has been used to allocate the environmental aspects.

Nacelle cover
The nacelle cover is made of fibreglass. LCI information on fibreglass fibre for part of a nacelle cover for the V80 turbine has been used. The LCI information has been provided by the Danish Plastics Federation. Fibreglass consist of woven glass fibres, polyethylene (PET) and styrene.

Furthermore, the resource for the production of the nacelle cover has been stated by the Danish Plastics Federation.

Other parts in the nacelle
In addition to the above-mentioned components the nacelle also consists of a range of other components as i.e.:
- Yaw system
- Coupling
- Cooler
- Cables.

All parts mentioned above are also represented in this LCA, as data about the individual part's weight and materials and data for processing of steel, glass fibre, rubber and plastics is used.

The following datasets are used in the calculations:

- Cast Iron from information from internal Casting factories in Vestas Wind Systems A/S, 2005[ix,x,xi] **Error! Bookmark not defined.**.
- Engineering Steel (Tool Steel) from International Iron and Steel Institute, 2000
- Stainless steel from International Stainless Steel Forum, 2004
- Steel plate from International Iron and Steel institute, 2000
- Fibreglass from the Danish Plastics Federation, 2001[xxiv]

- Glass fibre, PE, 1997
- Copper wire from International Copper Association, 2000
- Plastic, PE (high density) granulate, EDIP, 2000
- Plastic, PET, EDIP, 2000
- Styrene, PE, 1997
- Extruded aluminium from European Aluminium Association, 2002
- Electronics, from working report from the Danish Environmental protection agency, 2001
- Oil, refined, (fuel), North sea, EDIP, 2001

Manufacturing of rotor

The blades are mainly produced at Vestas' blades factories.

Each blade is 40 meter long and comprises a web, which is glued between two blade shell sections. The main components of the blades are wood, carbon fibre and woven glass fibres infused with epoxy resin.

After the gluing process, the blades are ground and polished to ensure the correct finish.

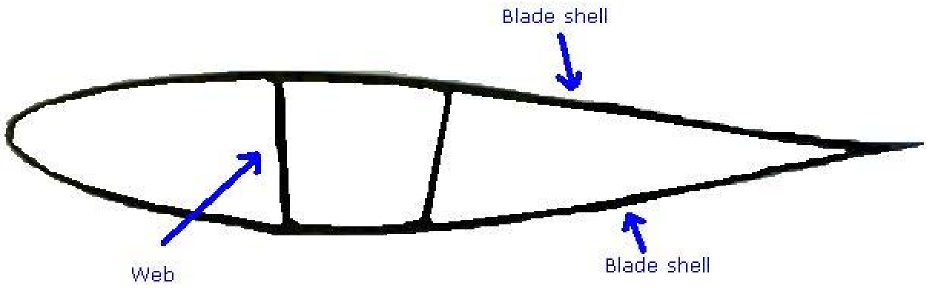

Figure 7: Rough sketch of a cross-section of a blade

Polyurethane (PUR) glue is the primary material used to assemble blade shells and web.

The site description from Vestas Blades - Isle of Wight[xxv] has been used and includes all processes for the production of the blade.

The hub and spinner is also a part of the rotor. Finished part components for the spinner are delivered to the Vestas factories where assembly is carried out. The spinner consists of a cover constructed of glass fibre-reinforced polyester, a blade hub made of cast iron and internals.

Information about all components, material types and weights of these has been found in technical specifications.

The blade hub has been modelled as described in the 'Machine foundation' section.
Apart from the above-mentioned materials auxiliary materials such as vacuum fleece and various plastic films are used in the production of the blades. These materials are included in this study.

The following dataset are used in the calculations of environmental impacts from raw material production:

- Cast Iron from information from internal Casting factories in Vestas Wind Systems A/S, 2005[ix,x,xi]
- Steel plate from International Iron and Steel institute, 2000
- Engineering Steel (Tool Steel) from International Iron and Steel Institute, 2000
- Epoxy, liquid from Association of Plastic Manufacturers, 2005
- Glass fibre, PE, 1997
- Birchwood from EDIP 1997
- Fibreglass from the Danish Plastics Federation, 2001

Manufacturing of onshore foundation

The turbines are erected on foundations. Each turbine foundation is established in connection with a road, working and turning area. Road, working area and turning area are not included in this study and are expected to be insignificant.

The foundation for the onshore turbine consists of plate foundations made with reinforced concrete. Typically, the size is 15 x 15 metres and 2 metres deep. The foundation is concreted in situ. After excavation the hole is filled with approx 400 m3 concrete with approx 27 tons of reinforcement.

The below figure shows a principle design of an onshore foundation

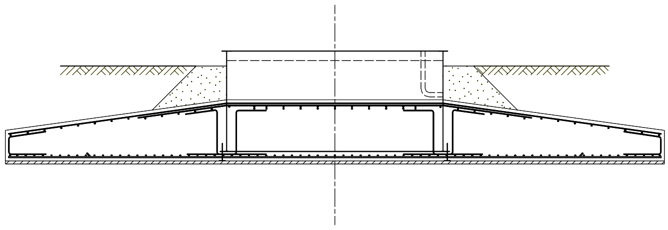

Figure 8: Principle sketch foundation for onshore turbines.

The following dataset are used in the calculations of environmental impacts from raw material production:

- Concrete, data from Aalborg Portland, Environmental statement, 2005
- Steel plate from International Iron and Steel institute, 2000

Manufacturing of cables to onshore wind power plant

32 kV PEX cables with an aluminium conductor are used as internal cables for the wind power plant, i.e. between the turbines and between the turbine plant and the 32/150 kV transformer. To connect the 182 turbines the following types and length of cables are used:

- 33.6 km of 1X95+25mm2 AL, 1500 kg/Km
- 33.6 km of 1X240+35mm2 AL, 2200 kg/Km
- 28.0 km of 1X500+35mm2 AL, 2500 kg/Km

According to the supplier, the cables mainly consist of aluminium, copper and plastic.

The manufacturer has informed of materials used, energy consumption used during the manufacturing process as well as waste generated.

150 kV PEX cables with an aluminium conductor is used from the 32/150kV transformer to the existing grid. The cable will be equipped with one-conductor PEX isolated cables with 1.200 mm^2. Each of the three one-conductor cables weighs approx 9 kilos/m and has a diameter of 90 mm. The primary materials in the cable are aluminium, cobber and plastic.

Resources and consumptions for the manufacture of the 150 kV cable have been scaled according the internal cables using the weight.

The following dataset are used in the calculations of environmental impacts from raw material production:

- Extruded aluminium from European Aluminium Association, 2002
- Copper wire from International Copper Association, 2000
- Plastic, PE (high density) granulate, EDIP, 2000

Manufacturing of 32/150 kV transformer to onshore wind power plant

A 32/150 kV transformer has been included in the wind plant. The transformer is modelled from an EPD from ABB on a Power transformer TrafoStar 500MVA[xxvi]. The functional unit of the EPD, which is 1 MVA, has been used for factoring the environmental aspects.

Resource consumption for the V82-1.65MW wind power plant

The largest quantities of materials used in the life cycle of the wind power plant are illustrated in the table 5 (including 182 wind turbines, internal cables, transformer station for the wind power plant and external cables).

	Materials for onshore wind power plant [kg]				
	Total	Production	Transport	Operation	Disposal, incl. recovery of metals
Water (fresh) [kg]	7.43E+08	1.32E+09	1.33E+06	2.60E+03	-5.81E+08
Stone [kg]	7.03E+07	7.03E+07	0.00E+00	3.14E-03	7.68E-06
Inert rock [kg]	4.08E+07	3.80E+07	0.00E+00	0.00E+00	2.80E+06
Hard coal [kg]	2.16E+07	4.33E+07	2.91E+04	3.55E+03	-2.17E+07
Iron [kg]	1.95E+07	7.85E+07	5.72E+02	4.68E+00	-5.91E+07
Crude oil [kg]	1.40E+07	1.06E+07	5.93E+06	1.98E+05	-2.75E+06
Natural gas [kg]	1.03E+07	9.55E+06	3.55E+05	2.79E+03	4.10E+05
Limestone [kg]	6.39E+06	6.44E+06	1.25E+03	8.29E+01	-4.62E+04
Lignite [kg]	4.40E+06	5.10E+06	5.22E+02	2.23E+01	-7.01E+05
Sodium chloride (rock salt) [kg]	2.72E+06	2.76E+06	8.20E+02	2.09E+00	-4.71E+04
Quartz sand [kg]	2.41E+06	2.42E+06	8.59E+00	2.45E+01	-1.09E+04
Soil [kg]	6.73E+05	6.71E+05	0.00E+00	0.00E+00	1.28E+03
Kaolin [kg]	3.88E+05	3.88E+05	0.00E+00	0.00E+00	8.09E-01
Gypsum [kg]	2.82E+05	2.82E+05	0.00E+00	0.00E+00	3.03E+01
Dolomite [kg]	2.17E+05	6.70E+05	0.00E+00	0.00E+00	-4.53E+05
Colemanite [kg]	2.16E+05	2.16E+05	0.00E+00	0.00E+00	4.51E-01
Aluminum [kg]	1.62E+05	1.74E+05	4.57E+02	1.87E+00	-1.28E+04

Table 5: Significant resource consumptions in the project model of onshore wind power plant. Note that statement of materials for the disposal is negative. This is because the recovered materials are credited.

Resource consumption for electricity delivered from a V82-1.65MW wind power plant

The life cycle inventory can be added up in a statement of resource consumption for the total lifetime of the wind power plant per kWh of produced electricity. The wind power plant has an annual electricity production of 1,072.9 GWh/year or 20493.36 GWh during the life time of 20 years.

	Input for 1 kwh electricity delivered from V82-1.65 based onshore wind power plant [kg/kWh]				
	Total	Production	Transport	Operation	Disposal, incl. recovery of metals
Water (fresh) [kg]	3.79E-02	6.76E-02	6.81E-05	1.32E-07	-2.97E-02
Stone [kg]	3.59E-03	3.59E-03	0.00E+00	1.60E-13	3.92E-16
Inert rock [kg]	2.08E-03	1.94E-03	0.00E+00	0.00E+00	1.43E-04
Hard coal [kg]	1.11E-03	2.21E-03	1.48E-06	1.81E-07	-1.11E-03
Iron [kg]	9.94E-04	4.01E-03	2.92E-08	2.39E-10	-3.01E-03
Crude oil [kg]	7.14E-04	5.41E-04	3.03E-04	1.01E-05	-1.40E-04
Natural gas [kg]	5.27E-04	4.87E-04	1.81E-05	1.42E-07	2.09E-05
Limestone [kg]	3.26E-04	3.29E-04	6.39E-08	4.23E-09	-2.36E-06
Lignite [kg]	2.25E-04	2.60E-04	2.66E-08	1.14E-09	-3.58E-05
Sodium chloride (rock salt) [kg]	1.39E-04	1.41E-04	4.18E-08	1.07E-10	-2.40E-06
Quartz sand [kg]	1.23E-04	1.23E-04	4.39E-10	1.25E-09	-5.55E-07
Soil [kg]	3.43E-05	3.43E-05	0.00E+00	0.00E+00	6.53E-08
Kaolin [kg]	1.98E-05	1.98E-05	0.00E+00	0.00E+00	4.13E-11
Gypsum [kg]	1.44E-05	1.44E-05	0.00E+00	0.00E+00	1.55E-09
Dolomite [kg]	1.11E-05	3.42E-05	0.00E+00	0.00E+00	-2.31E-05
Colemanite [kg]	1.10E-05	1.10E-05	0.00E+00	0.00E+00	2.30E-11
Aluminum [kg]	8.26E-06	8.89E-06	2.33E-08	9.54E-11	-6.54E-07

Table 6: Significant resource consumption of 1 kWh electricity from an onshore wind power plant.

Water is used in several production processes by sub-suppliers e.g. the manufacture of epoxy and in connection with the production of electricity at conventional power plants.

Hard coal, crude oil, lignite and natural gas are all energy resources used primarily in the production of the materials and components to the wind power plant. Crude oil – is furthermore used as transformer oil and as a component in the production of plastics here among epoxy for the blades. Stone in the form of broken granite and calcium are used for the concrete foundation of the onshore turbine and for the cable channels.

Iron is also one of the most used resources and is furthermore the most used metal. Iron is used to produce steel, which is applied in large quantities on the wind power plant.

Quartz sand is used in the production of cast iron components e.g. in the hub and the foundation in the nacelle.

Aluminium is beside iron the most used metals in the wind power plant. Aluminium is used in e.g. platforms and cables.

Energy consumption per kWh produced

From the resource statement of the wind power plant's life cycle, energy consumption per turbine including grid connection has been calculated, i.e. manufacturing, operation, transport, dismantling/disposal and transmission. In the statement, all energy resources have been included for the entire wind power plant's life cycle and related to the production of electricity from the wind power plant. These quantities are recalculated by means of gross calorific value to energy.

The calculations show that the energy consumption per onshore turbine is 3,392,042 kWh. In the section "Onshore wind power plant" it is established that one turbine generates 5,895,000 kWh/year.

Non-renewable fuels	kg	MJ/kg	MJ
Crude oil (resource)	7.14E-04	4.57E+01	3.26E-02
Hard coal (resource)	1.29E-03	2.52E+01	3.25E-02
Lignite (resource)	2.29E-04	9.58E+00	2.19E-03
Natural gas (resource)	5.22E-04	5.07E+01	2.65E-02
Uranium (resource)	9.98E-09	6.29E+05	6.27E-03
Renewable fuels	**kg**	MJ/kg	MJ
Biomass, dry matter, fuel	1.31E-04	2.25E+01	2.94E-03
Primary energy from wind power			1.21E-04
Primary energy from hydro power			5.09E-03
Primary energy from solar energy			9.87E-05
Primary energy from geothermics			3.09E-05
Total (MJ/kWh produced)			1.08E-01
Total (kWh/kWh produced)			3.01E-02
Total (kWh/turbine) in the lifetime			3,392,042

Table 7: Consumption of energy resources for the production of 1 kWh electricity from an onshore V82-1.65 MW based wind power plant.

Energy balance

One of the most significant aspects of the assessment of wind turbines is the product's energy balance. The energy balance is an assessment of the relation between the energy consumption of the product and the energy production throughout the lifetime.

Put in simple words: The energy balance expresses the period a wind turbine has to operate before it has produced as much energy as it consumes in its total life cycle.

The energy balance has been calculated as the relation between the turbine's energy consumption for manufacturing, operation, transport, dismantling, disposal and the expected average energy production. See table 6 for the total energy consumption of the onshore wind power plant.

Energy balance for the V82-1.65 MW turbine:

$$\frac{3{,}392{,}042\,[\mathrm{kWh/turbine}]}{5{,}637{,}000\,[kWh/turbine\cdot year]} = 0.60\,years \approx 7.2\,months$$

Emissions to air and water per kWh produced

The table below shows the most significant emissions to air and water for the onshore wind power plant.

Emissions to air	kg/kWh produced
Carbon dioxide	6.59E-03
Exhaust	3.13E-03
Steam	1.79E-03
Nitrogen oxides	2.94E-05
Carbon monoxide	2.66E-05
Used air	1.98E-05
Sulphur dioxide	1.94E-05
Methane	1.12E-05
Particles to air	5.91E-06
Group NMVOC to air	4.83E-06
VOC (unspecified)	7.33E-07
VOC from surface coating	5.17E-07
Nitrate	4.12E-07
Nitrous oxide (laughing gas)	3.52E-07
Emissions to water	kg/kWh produced
Water	7.74E-04
Chloride	7.30E-05
Sodium	2.62E-05
Particles	6.32E-06
Solids (suspended)	6.28E-06
Chemical oxygen demand (COD)	4.04E-06
Calcium	4.02E-06
Sulphate	2.61E-06
Solids (dissolved)	1.54E-06
Carbonate	1.08E-06
Total dissolved organic bounded carbon	8.34E-07
Substance (unspecified)	4.07E-07
Organic compounds (unspecified)	3.68E-07
Iron	3.52E-07

Table 8: significant emissions to air and water for 1 kwh electricity delivered from wind power plant

Life cycle impact assessment

This section presents the main result of the LCA on electricity delivered from a V82-1.65 MW based onshore wind power plant.

Where data from components or materials are missing, the rest of the materials have been assumed base on the already mapped materials. Hereby, it is ensured that 100% of the actual weight of the wind system is included in the LCA.

Life Cycle Impact Assessment methodology and types of impact

The EDIP methodology is used for the impact assessment of 1 kWh of electricity delivered from a V82-1.65MW onshore wind power plant. All calculations have been performed in the LCA tool GaBi.

Environmental impacts

The potential environmental impacts included in this study are:

- Global warming
- Ozone-depletion
- Acidification
- Nutrient enrichment (eutrophication)
- Photochemical ozone formation (smog)
- Human toxicity
- Eco-toxicity
- Bulk waste
- Slags and ashes
- Hazardous waste
- Radioactive waste

Global warming is the atmosphere’s ability to reflect a part of the heat radiation to the earth. Global warming is increased by the atmosphere’s content of carbon diode, CFC, laughing gas and methane, among others. Increased emission of these substances might impact the heat balance of the earth and over the next decades this may result in a warmer climate.

Ozone depletion: Formation and depletion of ozone is naturally in balance in the earth’s stratosphere 15-40km up in the atmosphere. However, the depletion will increase due to the emission of halocarbons, i.e. organic compounds, which contain chlorine or bromine and which are persistent enough to reach the stratosphere. The reduced amount of ozone in the stratosphere means that more harmful UV-rays in the sunlight will reach the surface of the earth. These UV-rays can for example cause skin cancer and have a negative effect on crop yields.

Acidification means that acids and compounds, which can be transformed into acids are emitted into the atmosphere and subsequently deposited in water and soil environments, which means that the admission of hydrogen ions decline (pH decline), e.g. the degree of acidity will be increased. This will for example result in negative consequences for coniferous trees and fish by way of forest die-back and death of fish, and furthermore this will result in corrosion damages on buildings, metals, etc.

Nutrient enrichment is an impact on eco systems with substances, which especially contains nitrogen (N) or phosphorus (P). The consequence might be a disturbed biological balance, where growth of some organisms takes place at the expense of other life forms. Oxygen depletion is a known consequence of nutrient enrichment, but also reduction in moor lands and other nutrient-poor ecosystems is seen due to nutrient enrichment.

Photochemical ozone formation (smog) is caused by degradation of organic compounds (VOC) in the presence of light and nitrogen oxide (NOx). Exposure of plants to ozone may result in damage of the leaf surface, leading to damage of the photosynthetic function, discolouring of leaves, dieback of leaves and finally the whole plant. Exposure of humans to ozone may result in eye irritation, respiratory problems, and chronic damage of the respiratory system.

Human and Eco-toxicity: Some substances can cause toxic effects on humans or on eco systems in various places in the environment both in the soil- water and air compartment. Assessment of toxicity in a LCA is very difficult because of the complexity of chemicals in the environment. There is no international consensus on how to do this, and the results are very uncertain. However, in this study it has been chosen to include impacts from chemicals – even though the results regarding this shall be interpreted as indicative.

Eco-toxicity: see above.

Bulk waste is construction waste and similar waste, which is deposited at controlled waste deposits. This waste is characterised by the fact that it does not contain environmentally hazardous substances.

Slag and ashes is the by-product of incineration processes. Slag and ashes is usually disposed of at special waste disposal sites.

Hazardous waste is waste, which must be brought to special processing plants or to a special deposit for hazardous waste. This waste is characterised by the fact that it contains environmentally hazardous substances, which may be released during the handling of the waste.

Radioactive waste is waste of low radiation intensity from nuclear power plants. One of the major problems associated with radioactive waste is the fact that much of it will be radioactive for hundreds of thousands, if not millions, of years, and thus will require isolation from the human environment.

For further descriptions we kindly refer to the documentation for the EDIP methodology.

Calculation method

By means of the GaBi pc-tool a characterisation is performed, i.e. all flows are related to the environmental impacts selected in the Chapter “Environmental impacts” above. This means that all flows contributing to e.g. global warming is reported in CO_2-equivalents, where e.g. the CO_2 equivalent for CO_2 is 1, for CO the CO_2 equivalent is 2.

Following the characterisation a normalisation of environmental impacts has been made. I.e. environmental impacts are stated in person equivalents (PE). The person equivalent is the contribution to a given category from an average citizen per. This means that environmental impacts of power from the wind power plant are related to a average citizen’s annual contribution to the individual environmental impacts.

By normalising environmental impacts it is possible to assess the relative importance of different environmental impacts from the production of electricity from wind turbines. However, a weighing of the different environmental impacts against each other is not performed, since no consensus for a weighing system exists. Weighing environmental impacts will thus be a subjective evaluation.

The characterisation and normalisation carried out is based on EDIP 1997. The normalisation is typically described as PE_{xxyy}, where xx describes the group of the average citizen (Denmark [DK], EU-15 [EU] or world [W]) and YY describes the reference year.

The normalisation references are:

- Ozone depletion potential: PE_{W94}
- Global warming potential (GWP 100 years): PE_{W94}
- Acidification potential (AP): PE_{W94}
- Nutrient enrichment potential: PE_{W94}
- Photochemical oxidant potential (low NOx): PE_{W94}
- Photochemical oxidant potential (high NOx): PE_{W94}
- Human toxicity water: PE_{EU94}
- Human toxicity air: PE_{EU94}
- Human toxicity soil: PE_{EU94}
- Ecotoxicity water chronic: PE_{EU94}
- Ecotoxicity water acute: PE_{EU94}
- Ecotoxicity soil chronic: PE_{EU94}
- Bulk waste: PE_{DK90}
- Hazardous waste: PE_{DK90}
- Slag and ashes: PE_{DK90}
- Nuclear waste: PE_{DK90}

Environmental impacts of 1 kWh

The main result of this LCA is the environmental impacts of 1 kWh electricity from the onshore wind power plant. These are characterised in the table below, furthermore the environmental impacts are normalised in table 10. The normalised impacts can be seen in figure 9.

Charaterised environmental impacts, EDIP 1997	
Acidification potential (AP) [kg SO2-Equiv.]	4.20E-05
Global warming potential (GWP 100 years) [kg CO2-Equiv.]	7.05E-03
Nutrient enrichment potential [kg NO3-Equiv.]	4.24E-05
Ozone depletion potential [kg R11-Equiv.]	1.49E-10
Photochemical oxidant potential (high NOx) [kg Ethene-Equiv.]	4.00E-06
Photochemical oxidant potential (low NOx) [kg Ethene-Equiv.]	3.74E-06
Ecotoxicity soil chronic [m3 soil]	7.11E-04
Ecotoxicity water acute [m3 water]	6.46E-03
Ecotoxicity water chronic [m3 water]	7.29E-02
Human toxicity air [m3 air]	1.41E+04
Human toxicity soil [m3 soil]	1.41E-04
Human toxicity water [m3 water]	3.45E-02
Bulk waste [kg]	1.48E-03
Hazardous waste [kg]	4.85E-05
Nuclear waste [kg]	2.27E-09
Slag and ashes [kg]	2.39E-05
Acidification potential (AP) [kg SO2-Equiv.]	4.20E-05

Table 9: Characterised environmental impacts, EDIP 1997 for 1 kwh electricity delivered from wind power plant.

The normalised environmental impacts of 1 kWh is shown in the table and figure below:

Normalised environmental impacts, EDIP 1997	Person Equivalents (PE)
Acidification potential (AP)	5.67E-07
Global warming potential (GWP 100 years)	8.10E-07
Nutrient enrichment potential	3.56E-07
Ozone depletion potential	1.45E-09
Photochemical oxidant potential (high NOx)	1.60E-07
Photochemical oxidant potential (low NOx)	1.50E-07
Ecotoxicity soil chronic	7.37E-10
Ecotoxicity water acute	2.22E-07
Ecotoxicity water chronic	2.07E-07
Human toxicity air	2.32E-07
Human toxicity soil	1.11E-06
Human toxicity water	6.61E-07
Bulk waste	1.09E-06
Hazardous waste	2.34E-06
Nuclear waste	6.48E-08
Slag and ashes	6.84E-08

Table 10: Normalised environmental impacts, EDIP 1997 for 1 kwh electricity delivered from wind power plant

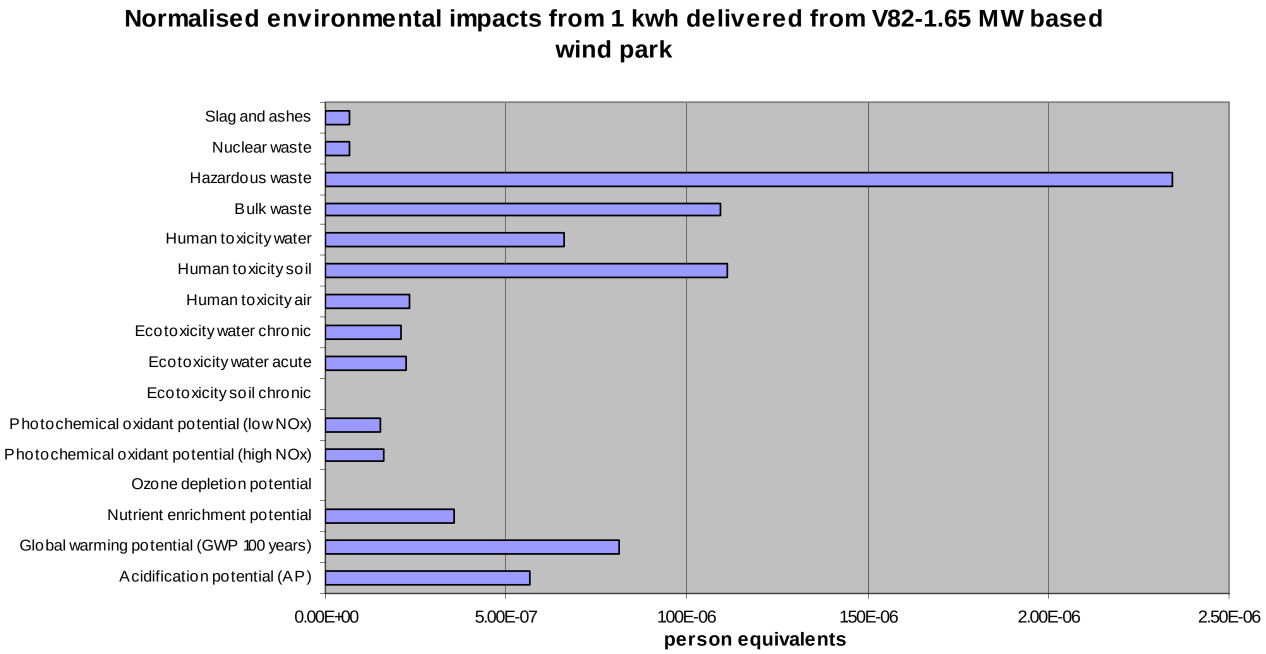

Figure 9: Environmental profiles of 1 kWh electricity from an onshore wind power plant.

Hazardous waste is mainly caused by the disposal of electronic components as these have been classified as hazardous waste. Furthermore hazardous waste is produced in the surface treatment of the tower section by both metallization and sand blasting.

Human toxicity soil is caused by the production of steel plates for the tower sections and foundation and stainless steel mainly for the main shaft.

The most significant contributor to bulk waste is also the production steel plates for the tower sections and foundation.

Global warming is mainly caused by production of steel plates for tower sections and foundation along with the production of cement for the concrete foundation.

Environmental impacts divided into life cycle stages

A division of environmental impacts on the life cycle stages can be seen from the following figure.

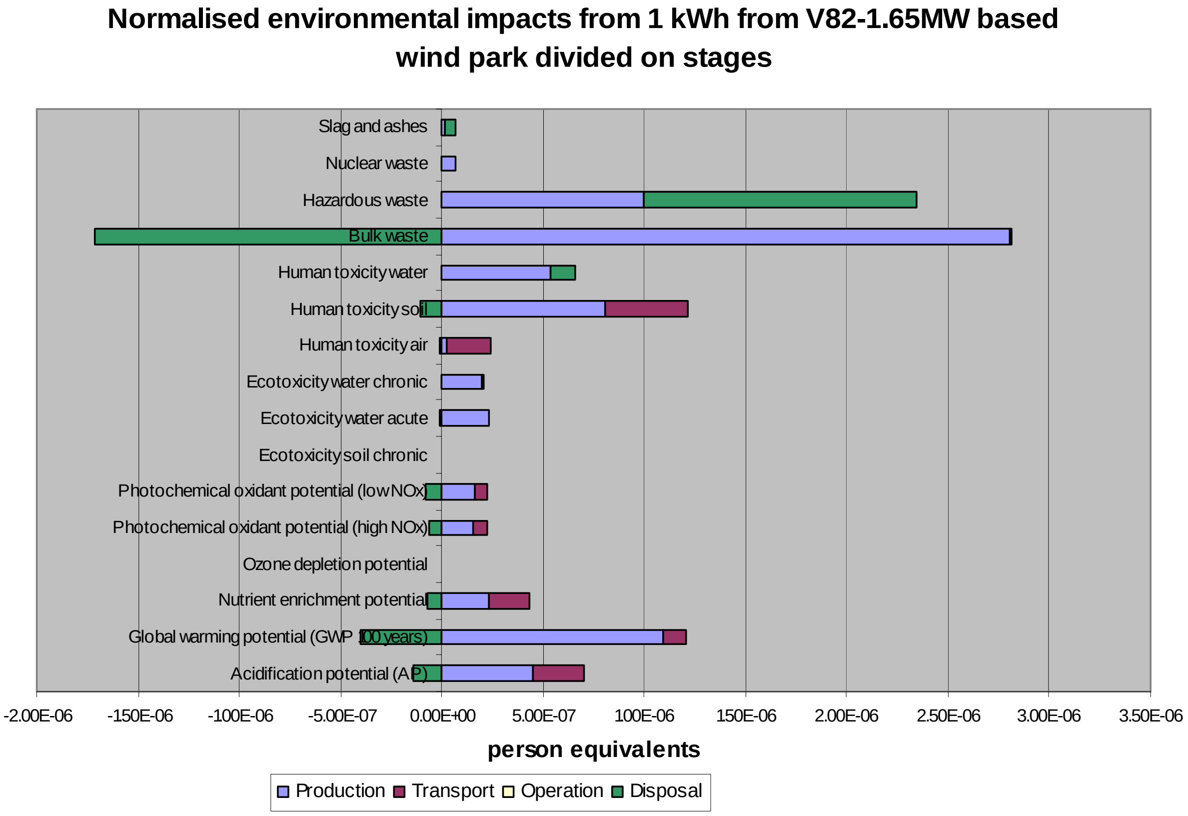

Figure 10: 1 kWh electricity from an onshore wind power plant divided into life stages.

A positive as well as a negative scale can be read in the figure. This means that dismantling and removal show a negative result which must be deducted from the positive column. Subsequently, the final, normalised potential environmental impact (as seen in figure 10) can be obtained. The reason why dismantling and removal give cause for reductions in impacts is that recycling is used to a high degree. I.e. the quantity of materials is credited and returned to the technosphere by means of recycling. Included in dismantling and removal is the environmental burdens of dismantling, transport and processing of materials so that the materials are ready for new use.

Not surprisingly, the manufacturing stage is significant for the environmental impacts of electricity generated by turbines. At the same time it is important to conclude that disposal of materials is important for the environmental profile of electricity generated from a wind power plant. Environmental impacts will change if less recycling is assumed.

Environmental impacts from the operational stage are insignificant, and not visible on the figure at all.

Transport covers approximately 7% of the total inverted global warming environmental inputs.

Comparison with European electricity

In order to relate the environmental impacts to the average European electricity generation we have decided to compare 1kWh electricity from the V82-1.65 MW based wind power plant with Power grid mix for EU 25, 2002 found in the GaBi professional database.

Data for European electricity presented in the figure has been modified in such a way that an estimated grid loss of 10% electricity is not included. This has been done to standardise functional units to be able to make equal comparisons.

As the above figure shows, environmental impacts of electricity from a V82-1.65 MW based wind power plant is considerably lower than from the power grid mix for EU 25, 2002.

The conclusion can also be seen by comparing emission of CO_2, which is one of the most important issues regarding generation of electricity presently. In terms of CO_2 emitted, then electricity from the wind power plant generates 6.6 g/kwh whereas the European grid mix generates 546 g/kwh.

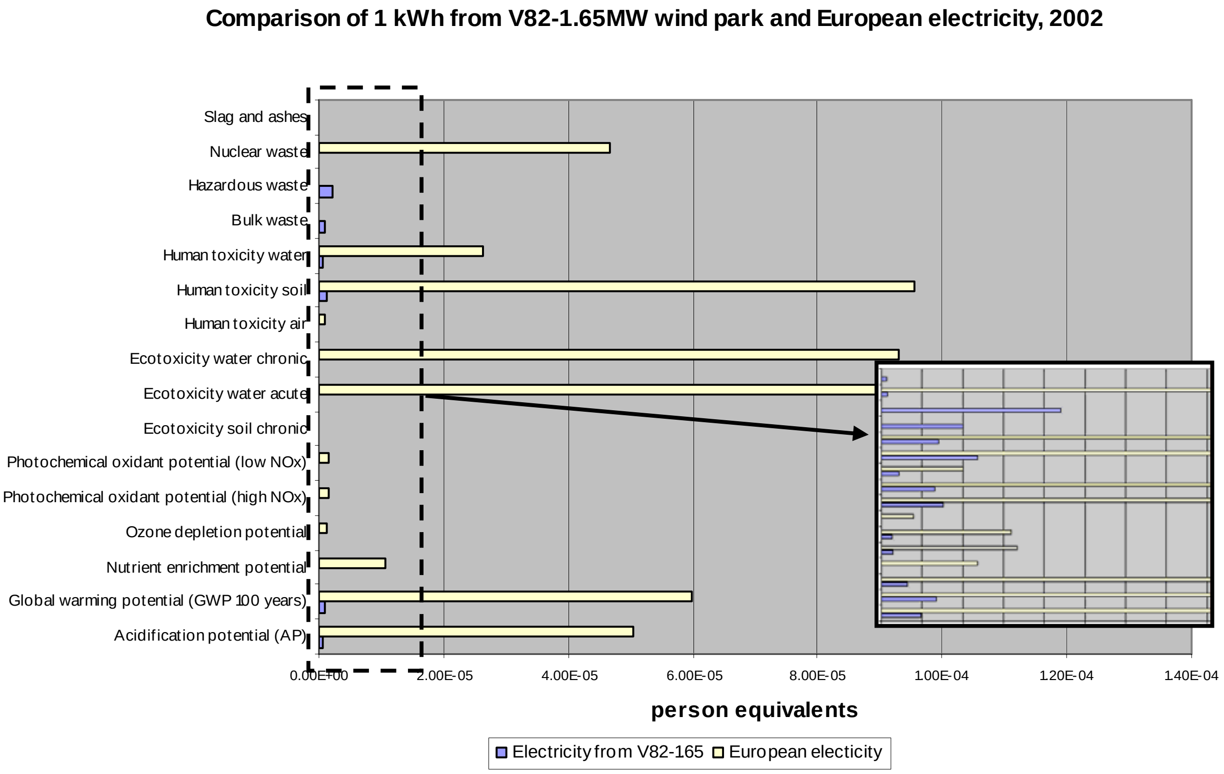

Figure 11: comparison of 1 kwh electricity delivered to grid for a V82-1.65MW based wind power plant and EU 25 electricity from 2002.

Life cycle interpretation

The goal of the LCA study was:

- To use LCA data to document the environmental performance of the V82-1.65 MW turbine. The present report provides the basic documentation and allows for preparation of an environmental declaration for electricity produced by the V82-1.65 MW turbine.
- To use results from the life cycle assessment for environmental improvement strategies in connection with product development
- To improve the existing LCA model for Vestas wind turbines.

The report will be made public for the target groups, however for internal Vestas target groups specific material will be drafted. It is the view of Vestas that the existing LCA model is significantly improved compared to the previous LCA model. Based on the review comments an update of all existing LCA's from Vestas will be performed.

The data is perceived to be valid and the LCA study can be regarded as representative for V82-1.65MW based wind power plants. The study is based on a standard choice of site for the wind power plant, which represents the average site where wind power plants are being set up. The size of the wind power plant has been chosen as it is of equal size of other power plants, i.e. coal and gas power plants.

To prove the representative ness the essential assumptions related to the standard site made during the study that will be subject to a sensitivity assessment. The essential assumptions are:

- **The electricity production of the chosen site for the wind power plant.** The electricity production reflects a standard site in i.e. Denmark, but will the results be affected by the choice of another site with different wind conditions. The sensitivity assessment will investigate if the production of more or less electricity have a significant impact on the results of this study.

- **The size of the wind power plant.** The size of the wind power plant is among the largest wind power plants currently sold by Vestas. The sensitivity assessment will investigate how the results of the study will be affected by selecting a different setup of the wind power plant by having significantly fewer wind turbines, e.g. 30 V82-1.65MW wind turbines.

- **The length of cables to the wind power plant.** Wind power plant are often placed in remote areas, to avoid impacts on neighbours, this implies that the length of the cables from the wind power plant to the existing grid can be very long. The current setup in the study is perceived as conservative. The sensitivity assessment will investigate how will a four doubling the length of the cables to the existing grid affect the results.

In the study some assumptions have been, in order to show the significance of these assumptions sensitivity assessments on each of the significant assumptions will be performed. The most significant assumptions are:

- **The life time of the wind power plant.** The wind power plant has been given a life time of 20 years. This life time equals the design life time of wind power plants, and also the experience for the first turbines built 20 years ago. The sensitivity assessment will investigate how the result will be affected if modern technology has enabled the turbines to function for 10 more years.

- **The disposal scenario for composites.** As the scope of the study is the entire world, then a conservative assumption has been made regarding the disposal of composites, as land filling has been used in the study. However currently in Denmark it is possible today to incinerate the blades, with recovery of the energy content with electricity and heat production. Furthermore intensive study is performed to enable the recovery of the glass content in the blades, for i.e. insulation material. In 20 years time it can be assumed that this technology or an improved technology is widely used in the entire world. The sensitivity assessment will investigate how will the results of this study be affected by using a different disposal scenario.

- **Transport scenario for raw materials.** In the study transport of components to Vestas, transport of the wind power plant components to the sites and transport of the wind power plant components to the disposal has been included. Transport of raw materials has not been included as it is regarded as insignificant. The sensitivity assessment will investigate how will the results of the study be affected if 500 km transport of all raw materials was included in the study.

- **Four doubling of replacement of main components.** In the current study replacement of half the gearboxes has been included. However history has shown that some types of gearboxes has caused problems and a higher rate of replacement could therefore become necessary. The sensitivity assessment will investigate how will the results of the study be affected by a four doubling of the replacement ratio to two replacement of gearboxes.

- **Data for processing steel.** For some components it has not been possible to attain data regarding the processing from raw materials to components. Instead standard data from either Vestas, other suppliers or EDIP has been used. The most used metal in the wind power plant is steel. The sensitivity assessment will investigate how the results of the study will be affected if the environmental exchanges for steel components are halved or doubled.

- **Change of the disposal scenario for steel.** Steel is the most used material in the wind power plant, and the results of the study is benefited by the recycling of steel. Currently a conservative recovery ratio of 90% has been used in the study. IISI has indicated that a recycling ratio of 96% can be assumed for most steel products. The sensitivity assessment will investigate how the results of the study will be affected be a change to 96% recovery ratio.

Data quality assessment

The data quality of the data, which has been used in the present LCA, have reached the targets set.

The targets were:

- Inclusion of 100% of the weight of the components, based on technical specifications or statements from experts.
- 95% mapping of the materials type of each component. The remaining 5% can be assuming to have the same content as the mapped materials. Data should be based on technical specifications or statements from experts.
- Inclusion of 100% of processing of the components. Data should be based on input from suppliers or Vestas, where this is not possible, then processing data from similar known processes at suppliers or Vestas can be used or data from LCA databases as GaBi EDIP
- Data for raw materials should be based on generic data, be updated, reflect processes in the industrialised parts of the world.

The most important dataset have been assessed critically to ensure that the data requirements are met. Previous reports have shown that the production is the most critical phase and therefore the production of steel and aluminium has been assessed. Furthermore the Electricity grid mix has been assessed since it is widely used in the LCA model.

Steel	Steel plate from International Iron and Steel institute, 2000	Comparing the same factors with data from the GaBi EDIP database of “Steel, cold rolled plate (89% primary), Aggregated”, they don’t differ that much. However, the GaBi EDIP data looks to have less impacts than the used data from IISI. Steel is important, and the data used can probably be seen as a conservative estimate.
Aluminium	Extruded aluminium from European Aluminium Association, 2002	This has been compared with data on Al (primary) I, Aggregated from the GaBi EDIP database and does not differ significantly on the compared parameters.
Electricity	Power grid mix EU 25, 2002 from PE	This has been compared with data on Electricity, EU 1990 from the GaBi EDIP database and does not differ significantly on the compared parameters. The EU 25 grid mix has a little less impact, however this seems reasonable as the data based on technology that is 12 years newer.

During the modelling is has been discovered that data regarding radioactive waste was too high in relation to the normalisation reference of the used EDIP methodology. Waste flows regarding radioactive waste have instead been scaled on the basis of an environmental product declaration for Nuclear power[xxvii].

Sensitivity analysis

The data is perceived to be valid, however some essential assumptions (see chapters “Representative ness of the study” and “Significant assumptions”) have been made and some processes may have a significant impact of the results of the LCA. To assess the sensitivity of the results the following will be subjects a sensitivity assessment:

- The electricity production of the chosen site for the wind power plant
- The size of the wind power plant
- The length of cables to the wind power plant
- The life time of the wind power plant
- The disposal scenario for composites
- Transport scenario for raw materials
- Four doubling of replacement of main components
- Data for processing steel
- Change of the disposal scenario for steel

The electricity production of the chosen site for the wind power plant

The electricity production reflects a standard site in i.e. Denmark, but will the results be affected by the choice of another site with different wind conditions. The sensitivity assessment will investigate if the production of more or less electricity have a significant impact on the results of this study.

Figure 12 shows global warming in relation to energy production. I.e. it is possible to see the variation of environmental impacts within the normal production frames for the wind power plant.

Global warming has been singled out to be looked at as global warming represents the energy consumption.

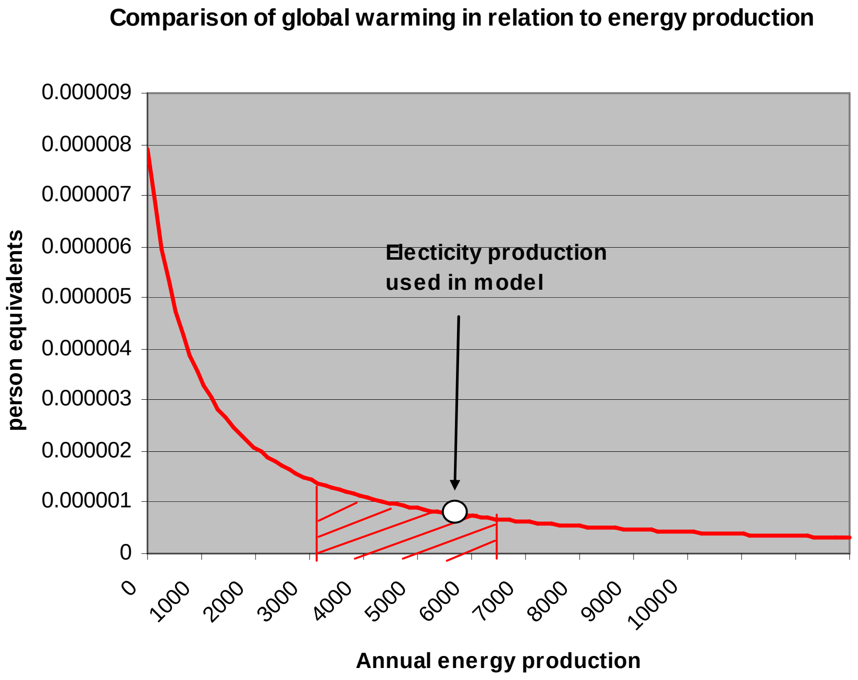

Figure 12: Comparison of global warming in relation to energy production. The annual production of the onshore wind turbine is 5,637 MWh. Besides electric power generation everything else is kept invariable.

The figure shows that production is important for the environmental impacts stated per kWh. The calculation presumes that all factors except electric power generation are equal. I.e. no considerations have been made for a better wind location, which could require increased material consumption in connection with construction, longer cables, other foundations, etc.

Experience show that it is realistic if a V82-1.65 MW based onshore wind power plant's annual production area is between approximately 3000 MWh/turbine and 6500 MWh/turbine depending on the siting of the wind power plant. This reflects that the onshore wind power plant has been sited in realistic locations. It should, however, be noted that wind power plants are also placed at sites outside the mentioned intervals.

The size of the wind power plant

The size of the wind power plant is among the largest wind power plants currently sold by Vestas. The sensitivity assessment will investigate how the results of the study will be affected by selecting a different setup of the wind power plant by having significantly fewer wind turbines, e.g. 30 V82-1.65MW wind turbines.

As almost all parameters are directly linked to the single turbine or its output, then only the cable from the wind power plant to the existing grid is almost fixed. However as the wind power plant is significantly smaller than the wind power plant used in the study then only one cable is used to connect the wind power plant to the existing grid.

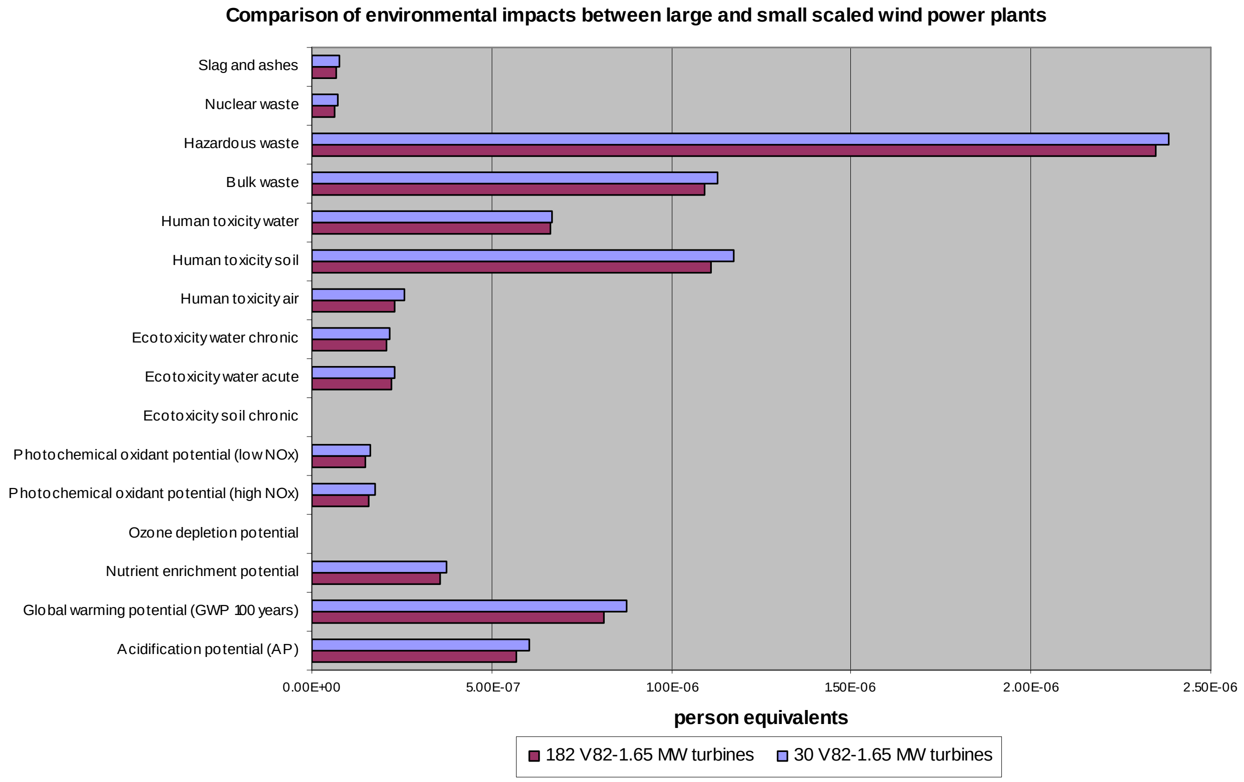

Figure 13: Comparison of environmental impacts for small and large scaled wind power plants based on the V82-1.65MW wind turbine.

As the figure shows, then the environmental impacts due not change significantly, when changing the size of the wind power plant from 182 turbines to 30 turbines. If the system is analysed in terms of gross energy, then the small wind power plant consisting of 30 turbines has an increased energy consumption of 5%, giving an energy balance of 7.8 months. Comparing the used scenario of the study with an energy balance of 7.2 months, it can be concluded that the size of the wind power plant does not have significant influence on the results of the study.

The length of cables to the wind power plant

If you imagine similar wind power plants erected in other locations, the conditions in some areas would be very different. Some onshore sited wind power plants will only be sited at a short distance from the existing electricity grid other at long distances from grid connection. For this LCA 50 km distance from the existing power grid has been used. To illustrate the importance of this factor on the LCA model, the result of the onshore wind power plant has been compared with a calculation where it has been assumed that the turbines have been placed further away from the electricity grid, and therefore 200 km of cables is required. In below calculation the electricity production has been assumed to remain the same and no grid loss has been included in either scenarios.

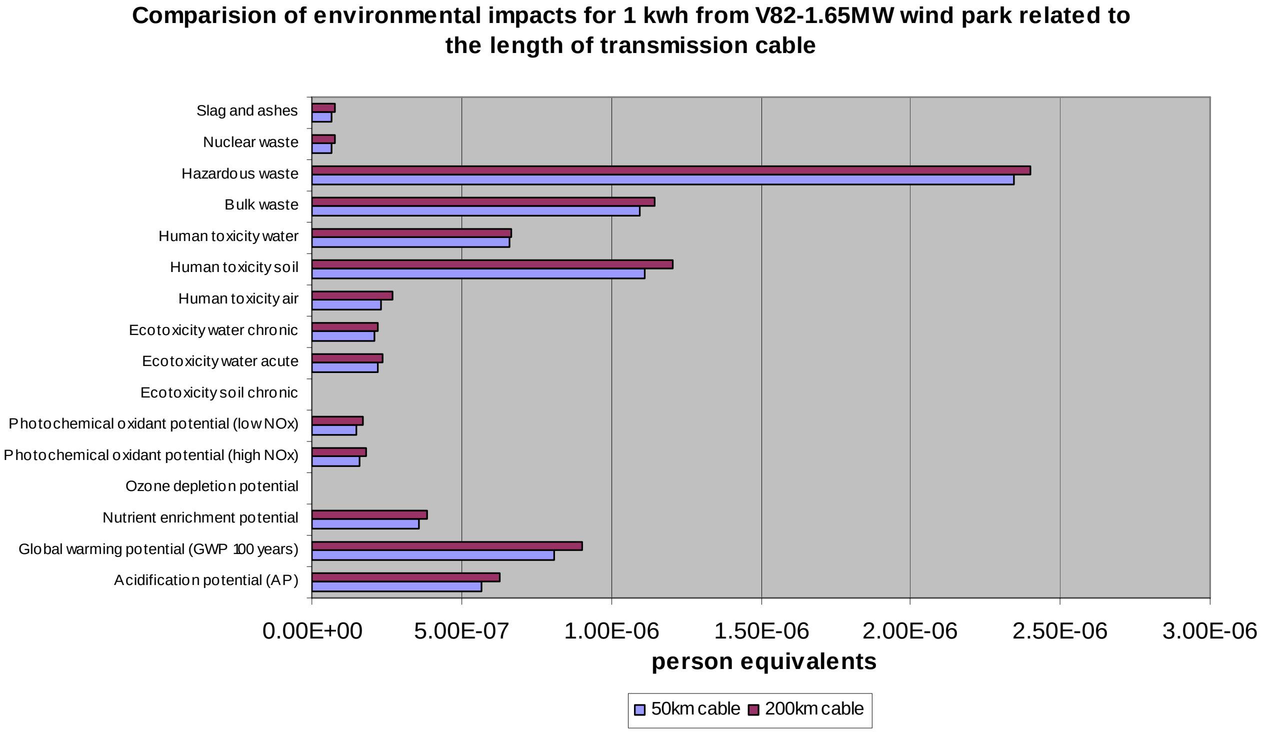

Figure 14: Comparison of environmental impacts of onshore sited wind power plant with various distances to the electrical grid.

Under the very simple assumptions regarding the changes, which take place in connection with alternative locations of a wind power plant, it has been found that there is some impact of the location but no significant changes.

Again, it has been concluded that energy production is one of the most significant parameters of the environmental impacts generated by an onshore wind power plant during its lifetime.

The life time of the wind power plant

The wind power plant has been given a life time of 20 years. This life time equals the design life time of wind power plants, and also the experience for the first turbines built 20 years ago.

The lifetime of the total wind power plant will have a proportional impact on the result. In the figure below a 30-year lifetime has been calculated for the turbines. Aspects regarding operation, i.e. servicing, are not taken into account in this calculation as it is assumed that these are insignificant.

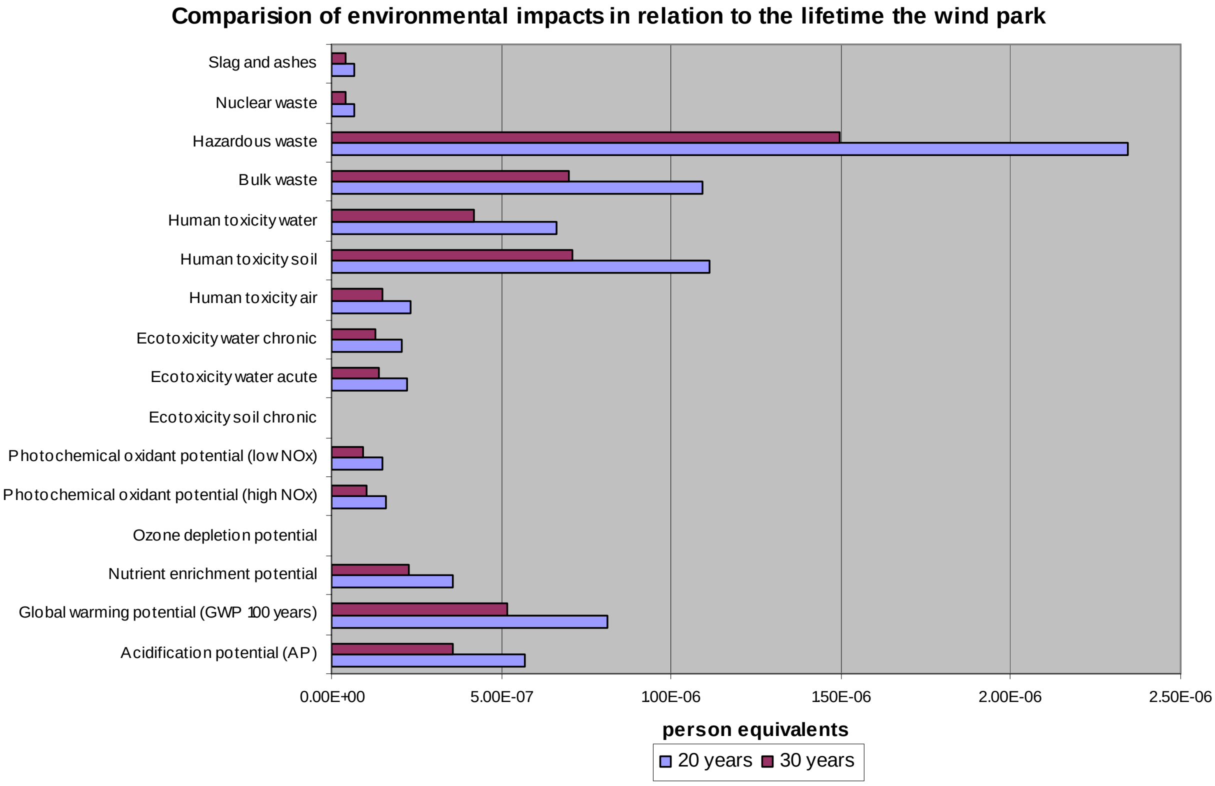

Figure 15: The lifetime's influence on environmental impacts.

The figure above shows that the total lifetime of the wind power plant is decisive for the environmental impacts of 1 kWh electricity generated from the wind power plant. The figure also shows that the lifetime is just as important as the production of the wind power plants as both result in direct linear changes of the environmental impacts, calculated per kWh generated by the wind power plant. At a lifetime of thirty years for the onshore turbines the environmental impacts are decreased by approximately 36% compared with the 20-year lifetime of the turbines.

It should, however, be noted that wind power plants occupy areas which cannot be used for other purposes. This means that if the wind power plant continues to operate for 30 years the wind power plant will occupy potential attractive space for a longer period, which could have been used for other purposes.

The disposal scenario for composites

Recently progress has been made regarding the disposal of composites especially blades. Previously, the only option was to deliver the blades to a waste disposal site for landfill, simply because no recycling methods were available.

However, due to a project Vestas has participated in along with among others H.J. Hansen Genvindingsindustri A/S, it is now possible to make use of energy content in the blades by incineration with heat recovery.

This study has however still calculated to waste disposal as landfill to be on the safe side.

It has furthermore been possible to find theoretical recycling options for the glass fraction in the blades. However, since no practical solutions for the glass fractions have been implemented landfill of the glass content (after incineration) has been used in the baseline model as a conservative estimate.

In order to estimate the importance of depositing blades we have made calculations of three various scenarios on how to dispose of the blades:

- 100% depositing of blades – current scenario
- Incineration of blades without the possibility of recycling the glass fraction. However, steel content in the blade is recycled.
- Incineration of blades with 100% recycling of the glass fraction (recovery of 90%, the rest is disposed of as landfill). Resources for processing of the glass fraction are not included.

Calculations have been made for the 1 kwh of electricity delivered from the wind power plant.

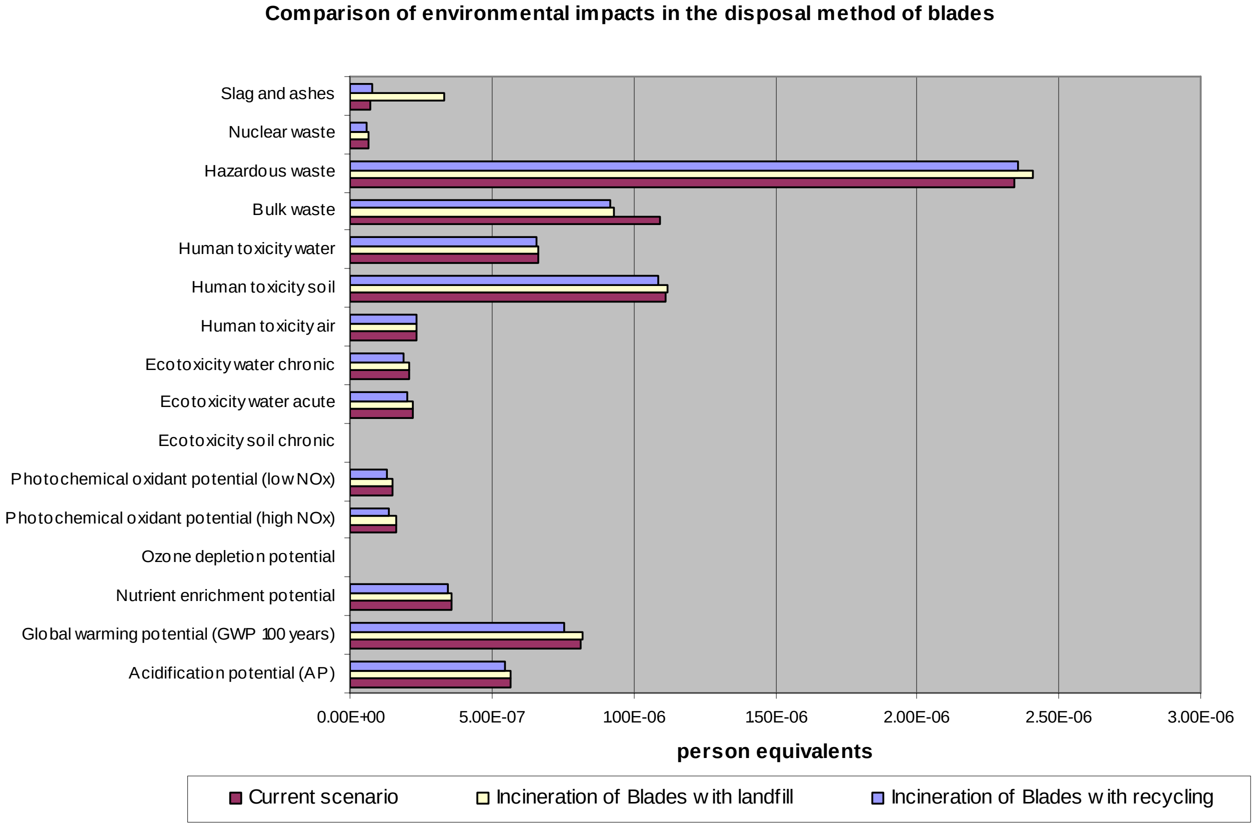

Figure 16: Environmental impacts of various scenarios for disposal of blades.

The comparison of the three disposal scenarios shows that there are only minor differences regarding environmental impacts, apart from the category ‘bulk waste’. Bulk waste is of course significantly larger when the blades are deposited. Incineration of blades also generates a very large quantity of waste, as the fibreglass in the blades is not combustible and therefore ends as a residual product from the incineration procedure. This residual product is defined as slag and ashes.

If the energy gross for the three scenarios are calculated the improvement from landfill to incineration and recycling is approximately 1% and 6% respectively for the rotor. This implies, seen from a life cycle perspective, that energy consumption is approximately 6% lower when recycling the materials in blades in relation to landfill of the entire rotor.

Transport scenario for raw materials

In the study transport of components to Vestas, transport of the wind power plant components to the sites and transport of the wind power plant components to the disposal has been included. Transport of raw materials has not been included as it is regarded as insignificant. The sensitivity assessment will investigate how will the results of the study be affected if 500 km transport of all raw materials was included in the study.

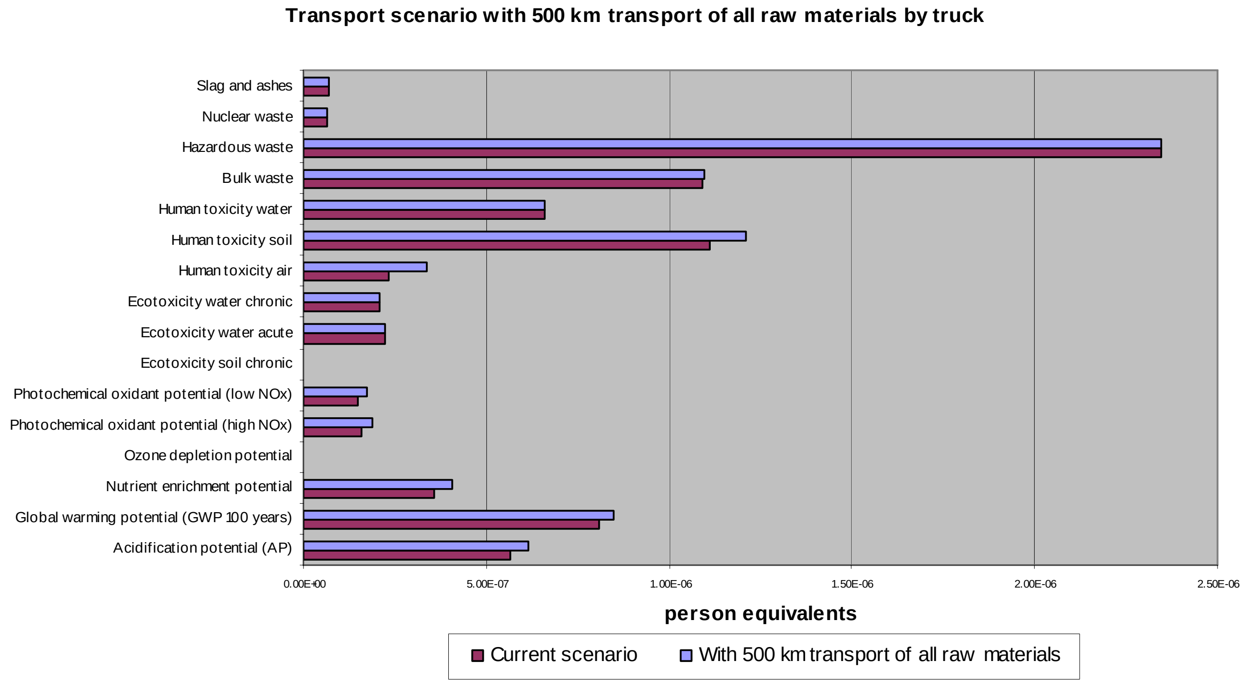

Figure 17: Environmental impacts of a transport scenario with 500 km transport of all raw materials.

The comparison of the current scenario and the scenario with 500 km transport of all raw materials shows that there are only minor differences regarding environmental impacts.

If the global warming for the two scenarios are calculated then the transport of all raw materials means an increase of global warming of 4%. It can be concluded that transport of all raw materials can be regarded as having a small impact.

Four doubling of replacement of main components

In the current study replacement of half the gearboxes has been included. However history has shown that some types of gearboxes has caused problems and a higher rate of replacement could therefore become necessary. The sensitivity assessment will investigate how will the results of the study be affected by a four doubling of the replacement ratio to two replacement of gearboxes.

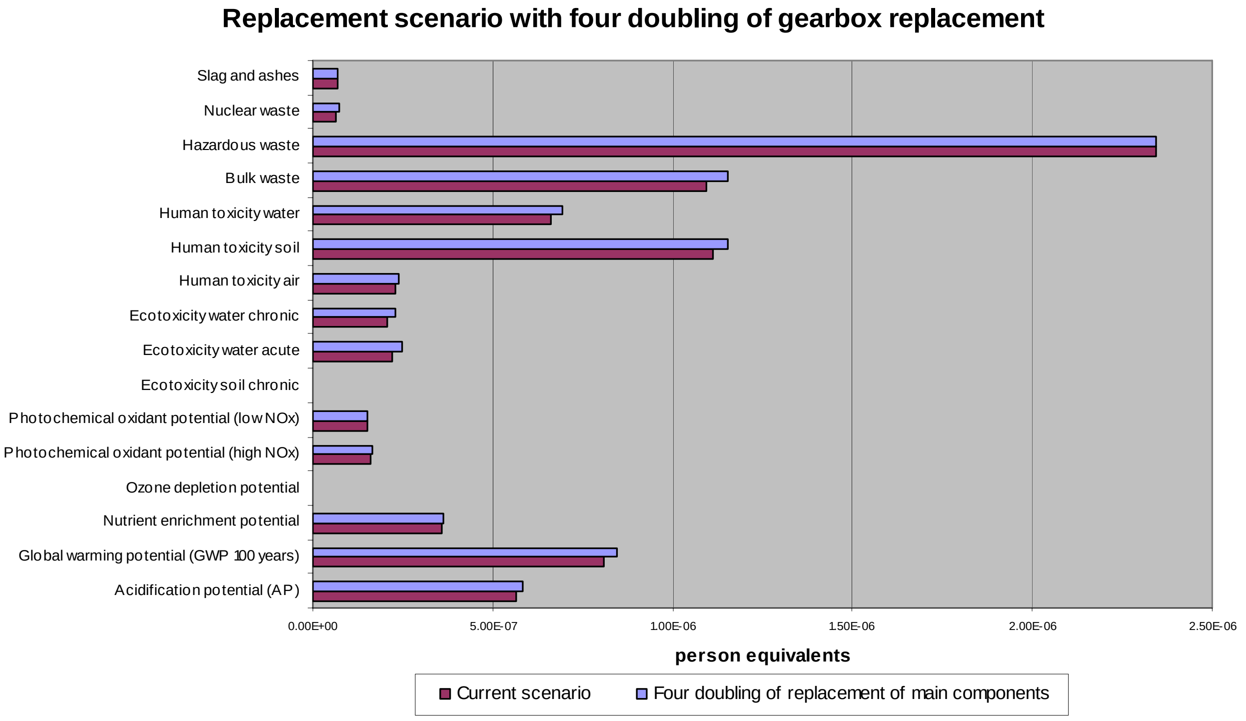

Figure 18: Environmental impacts of a replacement scenario with four doubling of the replacement ratio.

The comparison of the current scenario and the scenario with a four doubling of the replacement ratio shows that there are only minor differences regarding environmental impacts.

As an alternative replacement scenario, then the replacement of one blade has been analysed. Replacement of one blade gives an increased energy consumption of 5%, giving an energy balance of 7.6 months. Comparing the used scenario of the study with an energy balance of 7.2 months, it can be concluded that the replacement of one blade does not have significant influence on the results of the study.

Data for processing steel

A lot of efforts have been used to obtain energy consumption data from sub-suppliers. However, data for processing is still missing from some sub-contactors, i.e. the production of steel plates for tower sections, the manufacture of various other components. In the case of steel components general data for the manufacture of steel profiles have been used. A sensitivity analyses has been prepared for the steel manufacturing assumptions.

The below figure shows the three scenarios for the wind power plant, where the input and output for the processing of steel components have been altered:

- Half input and output in the processing of steel components
- Current scenario
- Double input and output in the processing of steel components

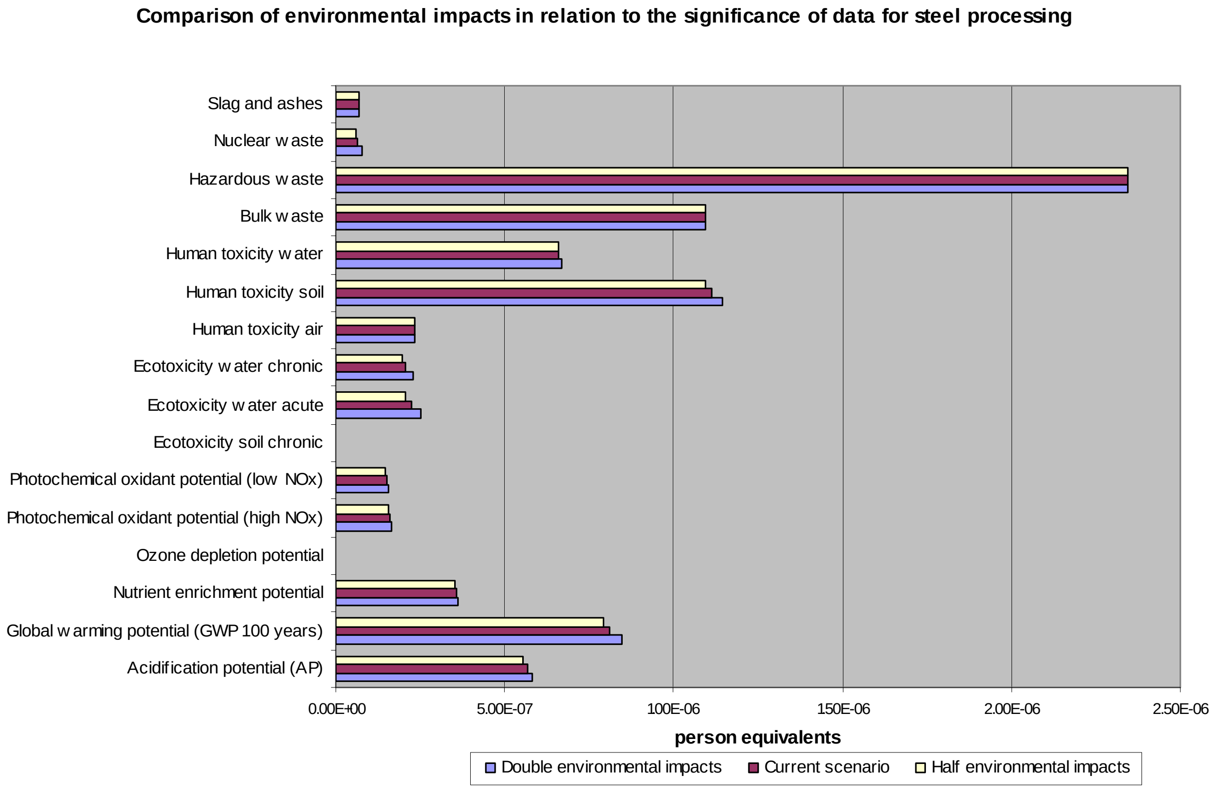

Figure 19: Comparison of environmental impacts in relation to the resource consumption for processing steel components.

The above figure shows that the data for processing steel has a minor impact on some environmental categories. The environmental impact of global warming increases by approximately 4% when resource consumption for processing steel components is doubled and decreases by approximately 2% when resource consumption for processing steel components is halved. As such it can be said that data for processing of steel does not have a significant impact of the results.

Change of the disposal scenario for steel

The selected scenario for recycling of materials has proved to be important for the total environmental impacts as it has been found that the used materials are decisive for the environment profile regarding electricity generated by wind power plants. Without the reutilisation scenario, the environmental impacts would be significantly higher.

As large quantities of metals are used for wind power plant. A sensitivity analysis has been prepared regarding the recycling of metals used for the wind power plant.

At the workshop where dismantling and disposal of turbines was discussed, the actual recycling scenario was discussed and it was observed that many metals could have a higher recovery rate than 90% if the materials were separated. Furthermore IISI indicate that a recovery ratio of 96% is reasonable. Therefore, in this case we have made calculations based on the assumption that total separation of materials is carried out and that the recovery rate of steel is 96%.

The following scenarios for recycling of metals have been estimated:

- The actual scenario, as described in table 2
- 96% recovery of steel

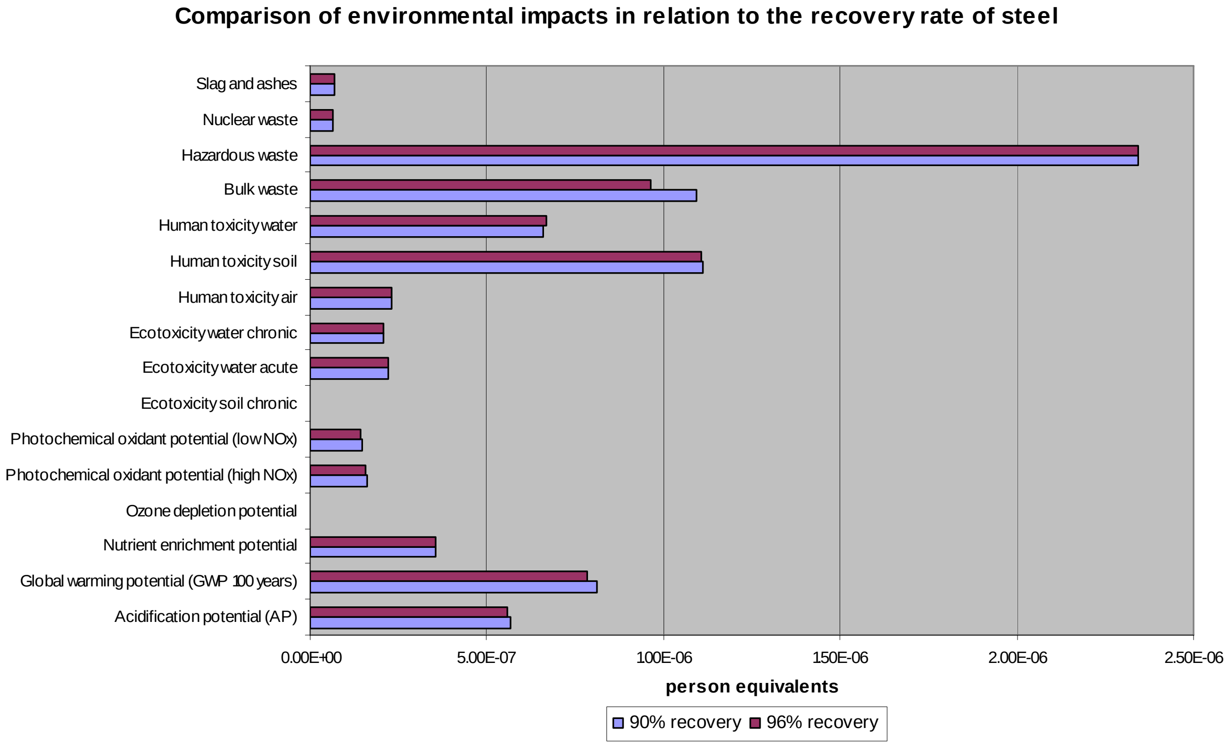

Figure 20: The total environmental profile for the V82-1.65 onshore wind power plant with various recycling scenarios for metals.

The above figure shows that recycling of metals is very import for the total environmental profile regarding 1 kWh electricity generated by the wind power plant. I.e. a 6% increase in recovery results in a reduction of global warming of approximately 3%.

Limitations

All incoming substances and materials for the turbines and transmissions have been included in present LCA. However, since it has been difficult to obtain LCA data on some components, it has been necessary to make certain assumptions. This applies to electronic components, among other things. For each of these materials we have been made assumptions and simplifications as described in the chapter “Procedures for data collection”. Vestas will continue to focus on collecting data from the entire life cycle based on the significance of the data.

Sub-suppliers’ resource consumption has not been stated in all cases. When data has been missing assumptions of resource consumption for the production. A sensitivity analysis on data for processing of steel (see chapter “Sensitivity analysis”) has proved the processing of steel does not significantly impact the results of the LCA.

Conclusions

The goal of the LCA study was:

- To use LCA data to document the environmental performance of the V82-1.65 MW turbine. The present report provides the basic documentation and allows for preparation of an environmental declaration for electricity produced by the V82-1.65 MW turbine.
- To use results from the life cycle assessment for environmental improvement strategies in connection with product development
- To improve the existing LCA model for Vestas wind turbines.

The report will be made public for the target groups, however for internal Vestas target groups specific material will be drafted. It is the view of Vestas that the existing LCA model is significantly improved compared to the previous LCA's of the V90-3.0 MW and V80-2.0 MW turbines.

Based on the review comments an update of all existing LCA's from Vestas will be performed.

The data is perceived to be valid and the LCA study can be regarded as representative for V82-1.65MW based wind power plants. The study is based on a standard choice of site for the wind power plant, which represents the average site where wind power plants are being set up. The size of the wind power plant has been chosen as it is of equal size of other power plants, i.e. coal and gas power plants.

In this project an LCA has been prepared for a V82-1.65 MW onshore wind power plant including grid connection. This life cycle assessment has shown that if environmental impacts per kWh electricity generated by the wind power plant are compared to average European electricity generation, then the environmental impacts for wind turbines are hardly noticeable.

Furthermore, the energy balance for a V82-1.65 MW onshore turbine is 7.2 months, which is close to the previous LCA's with 6.6 months for the V90-3.0 MW onshore turbine and 7.7 months for the V80-2.0MW onshore turbine.

Electricity from V82.1.65MW based wind power plant emits appr. 6.6 g CO_2 per produced kWh seen in a life cycle perspective. The CO_2 emission comes from all the processes in the life cycle of the wind power plant where sustainable energy sources are not used, e.g. in the manufacture of steel products.

Electricity production in relation to resource consumption is seen as the most important aspect of the onshore wind power plant. I.e. a 50% increase of the electricity production will result in a 50% decrease of the energy balance. Furthermore, the disposal stage and especially the recycling of metals are also contributing to the environmental profile. Environmental impacts from the transport stage and the operation stage are not considered significant in relation to the total environmental impacts of the onshore wind power plant.

Appendix 1

The following table shows the total inventory for electricity from V82-1.65 MW onshore based wind power plants.

Ressource input

Input for 1 kwh electricity delivered from V82-1.65 based onshore wind power plant [kg/kWh]	[kg]
Water (fresh) [kg]	3.79E-02
Stone [kg]	3.59E-03
Inert rock [kg]	2.08E-03
Hard coal [kg]	1.11E-03
Iron [kg]	9.94E-04
Crude oil [kg]	7.14E-04
Natural gas [kg]	5.27E-04
Limestone [kg]	3.26E-04
Lignite [kg]	2.25E-04
Sodium chloride (rock salt) [kg]	1.39E-04
Quartz sand [kg]	1.23E-04
Soil [kg]	3.43E-05
Kaolin [kg]	1.98E-05
Gypsum [kg]	1.44E-05
Dolomite [kg]	1.11E-05
Colemanite [kg]	1.10E-05
Aluminum [kg]	8.26E-06
Zinc [kg]	8.11E-06
Chromium [kg]	3.56E-06
Peat [kg]	2.76E-06
Copper [kg]	1.23E-06
Salt [kg]	6.79E-07
Potassium chloride [kg]	3.42E-07
Heavy spar [kg]	3.40E-07
Lead [kg]	2.02E-07
Antimony [kg]	1.99E-07
Wood [m3]	1.84E-07
Clay [kg]	5.45E-08
Sulphur [kg]	4.99E-08
Manganese [kg]	4.48E-08
Talc [kg]	1.35E-08
Barium sulphate [kg]	9.44E-09

Phosphorus [kg]	8.41E-09
Tin [kg]	4.28E-09
Mercury [kg]	3.68E-09
Shale [kg]	3.18E-09
Fluorspar [kg]	2.82E-09
Olivine [kg]	1.54E-09
Bentonit clay [kg]	6.22E-10
Gravel [kg]	6.02E-10
Nickel [kg]	2.59E-10
Magnesium [kg]	7.90E-11
Uranium [kg]	6.93E-12
Calcium chloride [kg]	5.71E-15
Feldspar [kg]	1.22E-15
Slate [kg]	5.04E-18
Titanium [kg]	8.47E-19

Emission to air

Heavy metals to air		Inorganic emissions to air	
Antimony	5.00E-12	Ammonia	5.26E-09
Arsenic	4.22E-11	Ammonium	7.31E-15
Arsenic trioxide	1.04E-17	Ammonium (total N)	3.58E-14
Cadmium	9.89E-11	Ammonium nitrate	1.40E-14
Chromium (unspecified)	8.90E-09	Barium	3.72E-10
Chromium +III	2.25E-14	Beryllium	9.39E-13
Chromium +VI	1.31E-09	Boron compounds (unspecified)	1.40E-09
Cobalt	5.58E-12	Bromine	5.98E-10
Copper	2.94E-11	Calcium	7.78E-13
Heavy metals to air (unspecified)	3.44E-12	Carbon dioxide	6.59E-03
Hydrogen arsenic (arsine)	8.66E-16	Carbon disulphide	1.11E-14
Iron	1.33E-11	Carbon monoxide	2.66E-05
Iron oxide	4.48E-13	Chloride (unspecified)	7.12E-08
Lanthanides	9.40E-15	Chlorine	3.42E-13
Lead	3.20E-09	Cyanide (unspecified)	1.49E-12
Manganese	1.61E-10	Fluoride	3.45E-12
Mercury	3.01E-10	Fluoride (unspecified)	3.96E-09
Molybdenum	7.09E-11	Fluorides	1.61E-11
Nickel	7.14E-10	Fluorine	2.24E-14
Palladium	1.58E-19	Helium	2.43E-10
Rhodium	1.53E-19	Hydrogen	3.26E-07
Selenium	1.25E-10	Hydrogen bromine (hydrobromic acid)	1.45E-12
Silver	1.75E-16	Hydrogen chloride	2.01E-07
Tellurium	2.09E-15	Hydrogen cyanide (prussic acid)	7.82E-13
Thallium	1.72E-14	Hydrogen fluoride	1.14E-08
Tin	4.30E-11	Hydrogen phosphorous	2.17E-16
Titanium	5.51E-13	Hydrogen sulphide	1.12E-07

Vanadium	9.01E-10	Na+ (sodium ion)	1.94E-17
Zinc	1.96E-08	Nitrogen (N2)	4.61E-12
Organic emissions to air (group VOC)		Nitrogen dioxide	2.81E-16
Group NMVOC to air	4.83E-06	Nitrogen monoxide	5.71E-15
Methane	1.12E-05	Nitrogen oxides	2.94E-05
Organic chlorine compounds	9.14E-10	Nitrous oxide (laughing gas)	3.52E-07
VOC (unspecified)	7.33E-07	Oxygen	3.06E-07
VOC for heating with coal	9.39E-11	Phosphorus	7.70E-15
VOC from diesel engine, pre EURO	1.16E-09	Scandium	4.79E-15
VOC from diesel engines	2.84E-07	Steam	1.79E-03
VOC from heating with natural gas	8.28E-08	Strontium	1.94E-13
VOC from heating with oil	1.36E-08	Sulphur dioxide	1.94E-05
VOC from surface coating	5.17E-07	Sulphur hexafluoride	-3.27E-13
Other emissions to air		Sulphuric acid	-3.29E-07
Exhaust	3.13E-03	Sulphuric acid aerosol	2.00E-14
Unspecified substance	9.03E-11	Tin oxide	2.20E-17
Used air	1.98E-05	Water	6.31E-08
Particles to air	5.91E-06	Zinc oxide	4.40E-17
Radioactive emissions to air		Zinc sulphate	2.13E-14
Thorium	1.89E-16	Nitrate	4.12E-07
Uranium (mass)	1.81E-16		
Uranium (total)	7.66E-11		

Emission to water

Analytical measures		Inorganic emissions	
Adsorbable organic halogen compounds (AOX)	3.79E-07	Acid (calculated as H+)	2.45E-08
Biological oxygen demand (BOD)	3.38E-07	Aluminum	5.95E-09
Chemical oxygen demand (COD)	4.10E-06	Aluminum ions (Al+++)	4.59E-10
Solids (dissolved)	1.51E-06	Ammonia	9.29E-08
Total dissolved organic bounded carbon	8.35E-07	Ammonium (total N)	2.90E-09
Total organic bounded carbon	7.18E-09	Ammonium / ammonia	3.91E-09
Heavy metals		Barium	1.46E-10
Antimony	4.18E-17	Beryllium	3.34E-13
Arsenic	1.90E-11	Boron	5.53E-10
Cadmium	1.13E-10	Bromate	1.41E-11
Chromium (unspecified)	1.16E-09	Bromine	8.94E-15
Chromium +III	2.86E-11	Calcium	3.97E-06
Chromium +VI	2.62E-10	Calcium chlorid (CaCl2)	1.78E-10
Cobalt	1.85E-12	Carbonate	1.08E-06
Copper	9.62E-11	Chlorate	5.98E-12
Heavy metals to water (unspecified)	4.04E-12	Chloride	7.21E-05
Iron	3.24E-07	Chlorine (dissolved)	8.29E-09
Iron oxides	5.47E-10	Copper ion (Cu++/Cu+++)	4.16E-12

Lead	1.05E-09	Cyanide	6.40E-12
Manganese	9.32E-10	Fluoride	2.60E-07
Mercury	4.70E-12	Fluorine	2.78E-12
Molybdenum	2.12E-10	Hydrogen chloride	3.18E-12
Nickel	2.94E-10	Hydrogen cyanide (prussic acid)	1.36E-15
Selenium	2.90E-11	Hydrogen fluoride (hydrofluoric acid)	1.27E-11
Silver	4.06E-13	Hydrogen sulphide	1.39E-19
Strontium	1.26E-09	Hydroxide	1.15E-12
Thallium	8.29E-16	Inorganic salts and acids (unspecified)	-1.15E-11
Tin	2.78E-12	Iron ion (Fe++/Fe+++)	2.20E-09
Titanium	1.97E-11	Magnesium	2.01E-08
Vanadium	5.85E-11	Magnesium chloride	4.30E-14
Zinc	5.10E-10	Metal ions (unspecific)	1.84E-08
Organic emissions		Neutral salts	4.32E-10
Halogenated organic emissions		Nitrate	2.22E-07
1,2-Dibromoethane	4.38E-17	Nitrate (as total N)	5.63E-09
Chlorinated hydrocarbons (unspecified)	3.28E-13	Nitrogen	4.09E-09
Chloromethane (methyl chloride)	1.99E-11	Nitrogen (as total N)	3.47E-08
Dichloroethane (ethylene dichloride)	3.29E-16	Nitrogen (N2)	8.69E-10
Dichloropropane	3.41E-19	Nitrogen organic bounded	1.73E-10
Polychlorinated dibenzo-p-dioxins (2,3,7,8 - TCDD)	5.29E-24	Nitrogen oxides	3.43E-11
Vinyl chloride (VCM; chloroethene)	4.78E-15	Oxides (unspecified)	4.55E-10
Hydrocarbons		Phosphate	6.42E-09
Acenaphthene	9.75E-14	Phosphorus	1.27E-08
Acenaphthylene	3.70E-14	Potassium	1.08E-08
Acetic acid	3.87E-11	Potassium hydroxide (KOH)	2.08E-11
Acrylonitrile	2.49E-14	Salt (unspecified)	2.00E-09
Anthracene	4.59E-14	Silicate ion (SiO3-)	6.14E-13
Aromatic hydrocarbons (unspecified)	2.92E-12	Silicate particles	1.45E-15
Benzene	8.94E-11	Silicon (Si)	5.13E-17
Benzo{a}anthracene	2.02E-14	Sodium	2.60E-05
Benzofluoranthene	2.14E-14	Sodium chloride (rock salt)	1.08E-13
Butylene glycol (butane diol)	6.39E-11	Sodium hypochlorite	1.07E-14
C9-C10 aromates	-2.51E-14	Sulphate	2.40E-06
Chrysene	1.12E-13	Sulphide	1.45E-09
Cresol (methyl phenol)	7.82E-16	Sulphite	4.78E-10
Ethyl benzene	1.32E-11	Sulphur	2.76E-08
Fluoranthene	2.61E-14	Sulphuric acid	2.40E-12
Hexane (isomers)	1.01E-16	Water	6.98E-04
Hydrocarbons (unspecified)	1.83E-08	Zinc ions (Zn++)	5.54E-11
Methanol	3.90E-10	Other emissions	
Oil (unspecified)	3.03E-08	Carbofuran	2.01E-17

Phenol (hydroxy benzene)	8.57E-10	Detergent (unspecified)	2.74E-11
Polycyclic aromatic hydrocarbons (PAH, unspec.)	2.81E-10	Salts, organic acids and fosphates - anodizing	1.10E-08
Toluene (methyl benzene)	8.00E-11	Substance (unspecified)	3.99E-07
VOC (unspecified)	1.18E-09	Unspecified anionic detergent	9.25E-14
Xylene (isomers; dimethyl benzene)	3.95E-10	Unspecified nonionic detergent	1.17E-15
Carbon, organically bound	2.01E-10	Waste water	1.14E-03
Dibutyltin oxide	2.51E-17	Particles (unspecified)	6.06E-08
Naphthalene	3.35E-12	Metals (unspecified)	2.11E-08
Organic chlorine compounds (unspecified)	5.26E-09	Soil loss by erosion into water	1.91E-13
Organic compounds (dissolved)	9.02E-16	Solids (suspended)	6.96E-06
Organic compounds (unspecified)	3.68E-07		
Organic Nitrogene Compounds	-2.92E-15		

Waste and emission to soil

Heavy metals to industrial soil		Hazardous waste for disposal	
Arsenic	2.29E-15	Chromium containing slag	9.15E-10
Cadmium	2.23E-14	Lead dross	4.32E-13
Chromium (unspecified)	5.22E-12	Sodium hydroxide (NaOH)	2.11E-11
Chromium +III	2.54E-16	Soil and sand containing heavy metals	1.65E-11
Cobalt	8.59E-14	Hazardous waste for recovery	
Copper	5.00E-14	Oil sludge	2.07E-10
Iron	7.24E-12	Waste water processing residue	3.32E-21
Lead	1.74E-15	Waste for disposal	
Manganese	1.58E-12	Incineration good	9.51E-15
Mercury	9.95E-17	Waste for recovery	
Nickel	3.37E-12	Aluminum chips	8.57E-17
Strontium	1.58E-09	Blast furnace slag	3.51E-14
Zinc	6.36E-13	Boiler ash (unspecified)	3.23E-07
Inorganic emissions to industrial soil		Chemicals (unspecified)	7.30E-13
Ammonia	2.51E-09	Cooling water	4.55E-04
Fluoride	2.45E-11	Filter dust (heavy fuel oil power plant)	1.56E-12
Nitrogen dioxide and other NOx	6.14E-09	Fly ash (unspecified)	9.84E-07
Phosphorus	2.57E-10	Glass	1.04E-11
Organic emissions to industrial soil		Gypsum	1.32E-08
Oil (unspecified)	5.92E-10	Gypsum (FDI)	5.50E-07
		Paper and board scrap	3.19E-10
		Scrap waste	1.35E-08
		Slag	5.49E-18
		Slag (Iron plate production)	2.30E-18
		Unspecified material	2.13E-09
		Unspecified plastic, pure	2.69E-09
		Unspecified recycling	1.79E-10

		Wood	2.95E-09
		Waste paper	6.79E-08

Appendix 2

The following data set have been used in the LCA model:

Dataset	Source	Year
Transport		
Van < 3,5 t diesel, rural road, Aggregated	EDIP	1997
Truck 3,5-16t diesel rural road, Aggregated	EDIP	1997
Truck >16t diesel, motorway, Aggregated	EDIP	1997
Truck >16t diesel, rural road, Aggregated	EDIP	1997
Container ship, 2 stroke, 28000 DWT, Aggregated	EDIP	1997
Electricity		
Norwegian electricity 1990 (99.7% hydro power + 0.4% conventional power plants)	EDIP	1997
Electricity from V90-3.0 MW based offshore wind farm	Vestas Wind Systems A/S	2005
Power grid mix EU 25	PE	2002
Materials		
Steel plate	International Iron and Steel institute	2000
Engineering Steel (Tool Steel)	International Iron and Steel institute	2000
Stainless steel	International Stainless Steel Forum	2004
Extruded aluminium	European Aluminium Association	2002
Copper wire	International Copper Association	2000
Copper sheet	International Copper Association	2000
Cast Iron	Vestas Wind Systems A/S	2005
Concrete	Aalborg Portland	2005
Electronics	Danish Environmental protection agency	2001
Fibreglass	the Danish Plastics Federation	2001
Glass fibres	PE	1997
Styrene	PE	1997
Plastic, PET	EDIP	1996
Plastic, PE (high density) granulate	EDIP	2000
Epoxy, liquid	Association of Plastic	2005

	Manufacturers	
Oil, refined, (fuel), North sea	EDIP	2001
Birchwood	EDIP	1997
Recycling		
Recovery of steel	International Iron and Steel institute	2000
Recovery of Aluminium	European Aluminium Association	2002
Recovery of Copper	EDIP	1997
Scredding of steel	EDIP	1997
Recycling of cables	NKT cables	2005

Appendix 3

Critical review of the report

”Life cycle assessment of electricity produced from onshore sited wind power plants based on Vestas V82-1.65 MW turbines”.

Anders Schmidt, Ph.D.
FORCE Technology
March, 2007

Review summary

The study has been conducted in accordance with the ISO 14044 standard, with some minor deviations. It provides a representative picture of the environmental impacts associated with production of electricity at large scale wind power plants and is therefore suitable for external communication, e.g. in the form of an Environmental Product Declaration.

The study has a very broad scope, requiring many assumptions. All choices made are justified, and it is emphasized that they all - with a few minor exceptions – aim to give a conservative, but realistic picture. The exceptions – most notable the missing data for transportation of raw materials – are recommended to be amended in future LCA reporting from Vestas.

The calculations are based on detailed inventories from Vestas' and its suppliers production facilities, representing modern production technologies. In the detailed calculations, the most recent data from industrial organisations have been used, ensuring the best possible quality. It is, however, rightly acknowledged that the available data not necessarily are fully suited for the modelling approach and that possibilities for continuous improvements of the database should be examined.

The report is judged to be consistent, but some sections could be improved with respect to its transparency. Although some information is given with respect to the origin of the basic information, little detail is provided with respect to how the data are modelled in the PC-tool. It is therefore suggested that Vestas in future LCAs establish a more thorough (and modular) documentation which can be used in the reports.

Introduction

According to ISO 14044 the scope and type of critical review shall be defined in the scope phase of an LCA, and the decision on the type of critical review shall be recorded. In order to decrease the likelihood of misunderstandings or negative effects on external interested parties, a panel of interested parties shall conduct critical reviews where the results are intended to be used to support a comparative assertion intended to be disclosed to the public.

ISO 14044 specifies that the critical review shall ensure that

- The methods used to carry out the LCA are consistent with the international standard
- The methods used to carry out the LCA are scientifically and technically valid
- The data used are appropriate and reasonable in relation to the goal of the study
- The interpretations reflect the limitations identified and the goal of the study, and
- The study report is transparent and consistent

Review process

The reviewer was engaged at an early stage of reporting, i.e. at a time where the calculation model was judged by Vestas to be almost fully established, while the reporting was in an early stage. This approach gave some possibilities to improve model as well as reporting, based on a dialogue between Vestas and the reviewer. However, it also gave rise to discussions about the level of detail and how the final report should be structured in order to fulfil the requirements in ISO 14044. In practice, the dialogue continued throughout the project and had as a consequence that FORCE Technology (Jan Poulsen) became engaged in amendments to the model.

It is mentioned that the approach for the critical review is not fully in line with ISO 14044. Firstly, a clear definition of the review process is missing in the Goal and Scope Definition. Secondly, it can be argued that because the LCA includes a comparison with another product (average electricity produced in EU in 2002) a review panel should have been used instead of a single reviewer. These are, however, judged to be minor flaws in the LCA as a more sophisticated review process most probably would not have changed the results or conclusions of the study.

Issues addressed in the review process

The review process was initiated on an early draft. This fact was stressed by Vestas, their main wish being an identification of where future efforts should be devoted with respect to reporting.

The draft showed that the methods used in the LCA were consistent with the ISO 14044 standard and were scientifically and technically valid. It was, however, the judgment of the reviewer that the data used in the study were not fully appropriate and reasonable in relation to the goal of the study and/or that the data and their treatment in the calculations were not described in sufficient detail. Finally, the review pointed to some basic elements which should be improved in order to make the report transparent and consistent, concerning e.g. the definition of the functional unit and the description of the system boundaries.

The findings of the initial readings were not presented in a formal report, but were discussed at telephone and face-to-face meetings with Vestas. As mentioned, the dialogue continued throughout the process, establishing a mutual understanding of how the available data could be used to produce a reliable result as well as a transparent and consistent report. The most important issues are presented in the following paragraphs.

Description of data sources

The draft report provided a good overview of the data sources used to assess the manufacturing steps. Internal data were available from relevant Vestas' production facilities and from suppliers of large components. Based on a short discussion the information was judged to be consistent with the data quality aims for the manufacturing stage.

Very little information on data sources for raw material production was given in the draft report. It was suggested to give a summary of the main data sources, focusing on their representativity for Vestas' products. The discussions between Vestas and FORCE Technology showed that except for copper, the data sources used were relevant and adequate in the present context. The copper data, however, did not fit very well into the system expansion approach applied in the model and were amended as a consequence of this observation, e.g. taking into consideration that copper scrap for recycling does carry some environmental burdens. The revised model adds some impacts to Vestas' products, but it is acknowledged by both Vestas and the reviewer that modelling of copper in the life cycle of Vestas' products shall be subjected to changes if and when better suited data becomes available.

Transportation

The transportation scenario is described as a conservative estimate, based on the fact that all components are transported long-distance to a continent where Vestas does not have production facilities. As such, the reviewer agrees that this will give a conservative picture of the impacts from transportation.

However, no transportation is included with respect to the raw materials. Given the large amounts of raw materials to be transported by truck or boat within the EU this omission may be visible in the final result, although it is not deemed decisive for the results. Irrespective of whether this type of transport is important or not in the overall picture it is strongly recommended to include the processes as soon as possible in order to have full credibility.

As an intermediate solution it was suggested to perform a sensitivity analysis in which the full amount of raw materials is transported 500 km by truck. This is assumed to give a good estimate of the associated impacts (e.g. concrete for the foundations will often be transported much shorter distances while other raw materials are transported longer distances) and as such it will provide an indication of the relative importance of this type of activity. The suggestion was accepted by Vestas and included in the final report.

Electricity scenarios

The choice of a specific "Vestas-scenario" for electricity used at their own production plants is questioned by the reviewer. Vestas has chosen to purchase a large share of its electricity from renewable sources. The purchase of renewable electricity is used in the model. This approach is not inconsistent with ISO 14044, but an international consensus has still not been established in this area. For example an analysis performed in the Danish EPD-project (www.mvd.dk) allegedly concludes that the purchase of additional electricity in Denmark should be included in an LCA by assuming that the technology used for production is modern coal-fired power plants. It is recommended by the reviewer to keep a close eye on the development within the area and if necessary adjust the model if international consensus emerges. A specific suggestion is to present the Vestas LCA at the next SETAC case study symposium in Gothenburg in December, 2007, including not only the results from the present LCA but also the specific choices made.

Other reporting issues

The description of allocation in the final report can be improved. It can be described in some detail that the general approach has been to avoid allocation by system expansion and how this is done in practice. The term allocation is, however, used several places in the report, but it is uncertain what it actually covers in the given context. The report will improve from being made consistent on this point. This has not been amended in the final report.

The draft report included only a fragmentary chapter on "Life Cycle Interpretation". According to ISO 14044, the following aspects should be addressed under this heading:

- Identification of significant issues, based on the LCI and LCA phases of LCA
- An evaluation that considers completeness, sensitivity and consistency checks
- Conclusions, limitations and recommendations
- Appropriateness of the definitions of system function, the functional unit and system boundary
- Limitations identified by the data quality assessment and the sensitivity analysis

The final report does not specifically address all of the above headings. However, a commendable range of issues have been handled by sensitivity analysis, each of these providing valuable information about their importance in relation to the system examined. In combination, they ensure a high credibility that important issues have not been overlooked. It should, however, be considered in future LCAs to establish a coherent summary of the findings in the sensitivity analysis, bringing LCA fully in line with the reporting requirements in ISO 14044.

A number of possible, minor errors and inconsistencies in the calculation and presentation of results were identified during the review. Most of these were amended as appropriate; the few remaining issues will be addressed in future LCAs from Vestas.

None of the remaining issues are judged to be of importance for the overall results, but are interesting in relation to focusing future recycling efforts. It is suggested that the incineration model used in this sensitivity analysis is described in some detail, as it is different from the general incineration model otherwise applied in the study. It is also suggested that the results are discussed in some more detail, e.g. addressing the finding that incineration will decrease the energy consumption but increase the GWP

Final review

Following the above iterations, the draft final report was reviewed in January, 2007. It is noticed in general that all apparent errors have been corrected and that most of the suggestions and recommendations given during the review process have been followed. The reviewer has examined both the final calculations in the GaBi4 LCA-tool and the further spreadsheet processing without finding inconsistencies other than those outlined in the following paragraphs.

General impression

The overall impression is that the report and the results provide a valid picture of the environmental impacts associated with production of wind power in large on-shore wind power plants. It is evident from the calculation model that large efforts have been devoted to include all components in the wind turbines at a reasonable level of detail, and it is understandable that the report does not provide all details with respect to data collection and data handling.

Consistency with the International Standard ISO 14044

The study claims to be performed according to ISO 14044. This claim is judged to be justified with respect to most essential elements, one formal exception being that the comparison with average European electricity in principle requires that a review panel – and not a single reviewer – is employed in the review process. However, it is not possible to identify particular stakeholders affected by the comparison.

It is also noticed that not all headings in the ISO 14044 standard are addressed. This is judged to be a minor flaw, because almost all important issues are discussed at some point in the report. As indicated previously there are many possibilities for increasing the level of detail and changing the structure in future reports, demonstrating an improved understanding of the environmental interventions caused by wind power plants.

System boundaries and functional unit

The choice of system boundaries is well founded. It is acknowledged throughout the study that site-specific conditions may cause relatively large variations, and the most important aspects are addressed in an exemplary way in the broad sensitivity analysis. It is therefore concluded by the reviewer that the calculations gives a representative overview of the impacts associated with wind power production. Furthermore, the level of detail in the reporting of the results allows for some recalculations if more precise information on actual production becomes available. The LCA thus fulfils on its most important aims, to provide the basis for development of Environmental Product Declarations of wind power from Vestas-based wind power plants.

It is noticed that the study applies a conservative approach where necessary, i.e. that the choices made do not favour the wind power. An obvious example of this is the arbitrary choice of the location of the wind mill park, the assumption being that this is at a continent where Vestas has no production facilities and extensive transportation of raw materials and components therefore is included. Another example is recycling of metals, where it has been conservatively assumed that there is loss of 10% in the recycling process from dismantling to production of secondary metals. One exception from the conservative approach is recycling of plastics from cables, where it is assumed that the plastic is either recovered as secondary plastic or incinerated with energy recovery. This assumption may be valid in special cases today – and perhaps more so in the future – but it should be acknowledged that plastic recycling in general is not a common process.

The study uses system expansion instead of allocation where possible and relevant, e.g. when dealing with recycling of metal and plastic components of the wind turbine. Allocation is used when scaling site-specific production to the actual component level, e.g. when addressing nacelle production, where the annual environmental impacts on a production site has been distributed on single nacelles according to their weight.

One serious omission is that transportation of raw materials to the production facilities of Vestas and its sub-suppliers has not been included. It is demonstrated in the sensitivity analysis that GWP may increase by about 4% if the transportation is included, and it is therefore strongly recommended that future calculations should also include this aspect in order to further enhance the credibility of the study and to ensure that the goal that the report should allow for a preparation of an environmental product declaration is fulfilled

The functional unit, one kWh produced at a wind power plant, is a natural choice, allowing both an EPD to be developed and documented and comparison with other power production technologies.

Data base and data quality

The calculations are performed in GaBi4, a well-reputed PC calculation tool. The basic data base used is the EDIP database, addressing a number of conventional industrial processes. The EDIP database has been complemented with more recent data for some of the main materials used in the wind turbine, and there is little doubt that this has increased the data quality. As mentioned previously, the documentation of how the new data were integrated in the existing database is relatively poor, but spot-checks of the final PC-model has not revealed any obvious errors. It is, however, suggested that Vestas in future LCA-work continues the dialogue with data suppliers like IISI and ICA in order to ensure that the most appropriate datasets have been used.

Special emphasis has been given to establishing full inventories with respect to consumption of energy and materials at the individual production sites. Detailed environmental statements from Vestas’ own production facilities and from the suppliers have been used in almost all cases. The level of detail could be significantly higher, e.g. by including more information regarding the production of electronic components, but it must be acknowledged that a consistent approach to this is very demanding in terms of resources and will most probably only result in small changes in the overall impacts.

The data quality analysis is relatively poor, with only few details about the basic data sources. It is, however, evident throughout the study and its choice of data sources that the aim has been to use best possible data – and this aim has been fulfilled. It is suggested that future developments and refinements of the LCA-model developed by Vestas should be accompanied by a corresponding documentation. This would also make the report more transparent, which is a general requirement in the ISO 14044 standard.

Inventory analysis

The most important exchanges are reported in edited tables, however, with full inventory tables being provided in annexes. The study thus fulfils the basic requirements with respect to reporting of inventory results. It is suggested to refine the tables by dividing the inventory results up in different headings, e.g. energy, metal and mineral resources.

Impact assessment

The methodology used for the impact assessment is the Danish EDIP-method, which is internationally recognised as being scientifically valid. In comparison with many other impact assessment methods, the EDIP method includes a normalisation step, in which the basic impact assessment results are related to the annual contribution caused by an “average” citizen.

This approach allows a distinction between important and “not-so-important” impacts in the overall picture. This possibility has, however, not been used in the current study, and for the international target group the basic results in terms of e.g. GWP in CO_2-equivalents is probably the most usable.

Interpretation

The interpretation section presents a commendable wide range of issues being handled by sensitivity analysis. In this way, the most important of the assumptions made in the basic scenario are tested with respect to how other – and perhaps equally well-founded – solutions influences on the overall results.

Some issues in the sensitivity analysis are more or less trivial, e.g. that an extension of the life time of the wind mill park from 20 to 30 years decreases the impacts per produced kWh with about 35%. Other issues, e.g. examination of the difference between current and future decommissioning of the wind mills provides a very good insight into the improvement potential related primarily to recycling of different materials and components. This knowledge is judged to be useful in discussions with current customers as well as product developers on how the best solution can be obtained in a cost-effective way.

Many of the elements examined in the sensitivity analysis induce relatively small changes in the results, the order of magnitude being a few percent. As such, they are described by Vestas as being “without significance” or of “almost no importance”. It is suggested to use a more elaborate wording, e.g. that “the sensitivity analysis of xx shows that a different choice of system boundaries does not change the environmental profile of electricity produced in wind mill parks significantly”. One exception from this is the already mentioned missing transportation of raw materials, underestimating as an example GWP with 4%. This finding should be taken very seriously as it may compromise the possibility of using the LCA as background documentation in relation to Environmental Product Declarations.

Conclusions

There are no formal requirements to the Conclusions section, but Vestas could consider using the section (or the Summary at the beginning of the report) as a vehicle for providing the large amount of information derived in the study in a condensed way.

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