Final Report

Life Cycle Assessment Of Electricity Production from a Vestas V112 Turbine Wind Plant

Title of the Study: **Life Cycle Assessment of Electricity Production from a V112 Turbine Wind Plant**

Client: **Vestas Wind Systems A/S**

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CRITICAL REVIEW STATEMENT

Review Summary of the Study

“Life Cycle Assessment of Electricity Production from a V112 Turbine Wind Park” by PE North West Europe ApS

Commissioned by: Vestas Wind Systems A/S

Date: January 31, 2011

Scope of the Review

Independently of PE NWE and Vestas, the review assessed whether

- the method used to carry out the LCA is consistent with the current best practices of LCA and is scientifically acceptable,
- the data used are appropriate relative to the goal of the study,
- the interpretation of results reflects the goal of the study and the limitations identified in the study, and
- the study report is transparent and consistent.

The analysis of product and process technologies and individual datasets (e.g., input data, emission factors), as well as the verification of the employed LCA model were outside the scope of this review.

General evaluation

The defined scope of the LCA study was found to be appropriate to achieve the stated goal. Data quality was found to be adequate and the use of data justifiable. Various assumptions were noted, and all were found to be defensible. Sensitivity analyses were conducted on some critical data and methodological choices. The study was reported in a consistent and transparent manner.

The reviewer acknowledges unrestricted access to all requested information, as well as the open and constructive dialogue during the review process.

Conclusion

The study has been carried out in compliance with the currently best LCA practices and in accordance with the ISO 14044 standard. The review found the overall quality of the methodology, data, and the execution of the study appropriate for the goal of the study.

Arpad Horvath, Ph.D.

Berkeley, California

List of Contents

List of Figures

List of Tables

Nomenclature

Abbreviation	**Explanation**
AP	Acidification Potential
$ADP_{elements}$	Abiotic Resource Depletion (ADP elements)
ADP_{fossil}	Abiotic Resource Depletion (ADP fossils)
BOM	Bill Of Materials
CNC	Computer Numerical Control
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FAETP	Freshwater Aquatic Ecotoxicity Potential
GWP	Global Warming Potential
HTP	Human Toxicity Potential
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MAETP	Marine Aquatic Ecotoxicity Potential
MVA	Mega Volt Ampere
PEX	Polyethylene, Cross-linked
POCP	Photochemical Ozone Creation Potential
ODP	Ozone Depletion Potential
TDS	Technical Data Sheet
TETP	Terrestrial Ecotoxicity Potential
TPS	Technical Product Specification

Executive Summary

Goal

The goal of this study was to evaluate the potential environmental impacts associated with production of electricity from a 100 MW onshore wind plant comprised of thirty-three V112 3.0 MW wind turbines from a life cycle perspective. The LCA study and this report have been prepared by PE International on behalf of Vestas Wind Systems A/S. Vestas has carried out several previous LCA studies on their wind turbines but this current study marks a step-change in detail and complexity – modelling products down to the level of individual components. It is intended that the models developed for this study will be used to create a definitive framework for future LCA studies.

Functional Unit

The Vestas V112 3.0 MW wind turbine has been designed to operate under low to medium wind conditions (IEC II and III) and for this study, medium wind conditions have been selected as the baseline scenario, as Vestas predicts medium wind sites to be the main world market.

The functional unit for this LCA study is defined as:

1 kWh of electricity delivered to the grid by a wind power plant operating under medium wind conditions (IEC II).

Results

Overall, the results show that for every impact category assessed the largest impacts are associated with the raw material production and manufacturing phase of the life cycle. In most cases these are much greater than those occurring elsewhere in the life cycle of the wind plant.

Within the manufacturing stage, the production of the tower itself typically accounts for the largest impacts; this reflects the large quantity of steel required to produce this part of the wind turbine. The production of the gear and mainshaft and the nacelle also results in significant impacts. Manufacture of the blades for the turbine also has quite significant impacts, while production of other parts of the wind turbine is generally less important in comparison.

End of life processes are also significant for many impact categories and normally credit the product system – showing the benefits of the high overall recycling rate achieved for wind plant infrastructure.

Wind plant construction and site operations generally do not make a significant contribution to the overall life cycle impacts of the wind plant.

Transport of wind plant components to site make a very insignificant contribution to the overall life cycle impacts of the wind plant

The top level results of the assessment are given in the table below.

Top level results for the life cycle impact assessment

Impact Category	Unit	Impact/kWh of electricity
Abiotic resource depletion (ADP elements)	mg Sb eq.	0.45
Abiotic resource depletion (ADP fossils)	MJ	0.08
Acidification potential (AP)	mg SO_2 eq.	28
Eutrophication potential (EP)	mg PO_4^- eq.	2.7
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB eq	33.5
Global warming potential (GWP)	g CO_2 eq.	7
Human toxicity potential (HTP)	mg DCB eq.	833
Marine aquatic ecotoxicity potential (MAETP)	g DCB eq.	2546
Photochemical ozone creation potential (POCP)	mg C_2H_4 eq.	6.3
Primary energy (renewable) (net calorific value)	MJ	0.03
Primary energy (non-renewable) (net calorific value)	MJ	0.09
Terrestrial ecotoxicity potential (TETP)	mg DCB-Equiv	29
USEtox2008 ecotoxicity	PAF cm3.day	16
Waste to landfill	g	4.9
Water consumption	g	27.7
Recyclability (average over components of V112 wind turbine), %		80.9

Sensitivity analyses

The sensitivity analyses show that assumptions on the lifetime of the wind plant can have a large influence on the results. Increasing the lifetime from 20 to 24 years, results in a 27% drop in all environmental impact categories. This does not account for any increased maintenance that may be required, but a second sensitivity analysis shows that the results are not particularly sensitive to this issue.

The recycling methodology used also plays an important role in the results. Recycling rates for wind turbines are quite high and, as noted above, in the baseline scenario (where credits are given for recycling) the end of life has a significant contribution to the total results. If no benefit is given for recycling, the end of life stage will have a much smaller contribution and overall impacts will increase substantially as the production impacts are no longer offset by recycling credits.

Scenario analyses

Wind conditions for the wind plant determine how much energy is generated over its lifetime. If the wind plant operates in low wind conditions (IEC III) then the impacts per kWh electricity produced increases by 23% compared to medium wind conditions (IEC II). This finding emphasises the importance of location in wind plant planning to maximise the efficiency of electricity generation. The findings also reinforce the fact that any comparison between wind power plants should only be made within a specific wind class.

Another location-dependent issue is the level of the water table, which determines the size of the foundations required to support the wind turbines. Regions with a high water table require more robust foundations. However, with the exception of waste to landfill, the results are not sensitive to this difference. Likewise, the transport distance of the components from the factory to the wind plant site is shown to have very little impact on the overall results.

The location of the wind plant with respect to the local grid infrastructure plays a more important role as it affects distribution losses and adds additional requirement for cabling. Doubling the distance to the grid from 50 km to 100 km typically increases impacts per kWh by 3-5%.

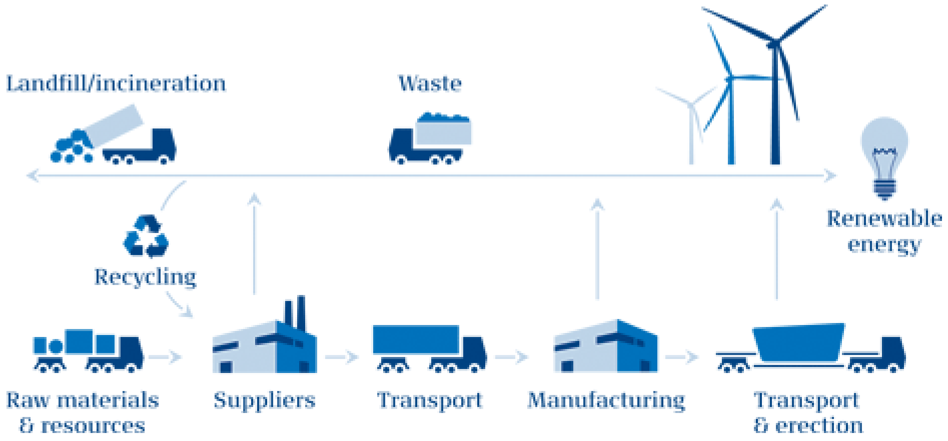
1 Introduction

Public awareness of, and concern for, the effects of climate change and other environmental impacts has dramatically increased in recent years.

As a leading international provider of wind energy technology, Vestas Wind Systems is well-placed to contribute towards the global drive to mitigate the effects of climate change and environmental impacts associated with the use of fossil fuels. As part of their own internal sustainability agenda, Vestas has previously conducted a number of life cycle assessment (LCA) studies of their wind turbines. Seeking to build on the experience gained from these studies and further develop their internal capacity on sustainability issues, Vestas has contracted PE to carry out a LCA of a 100 MW wind plant composed of the new Vestas 3.0 MW V112 wind turbines.

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) as shown in Figure 1.

Figure 1: Life cycle of a wind turbine



Although LCA often is a comprehensive exercise – as is also the case for the present LCA – in general it cannot stand alone in the assessment of technologies. Other environmental management techniques including 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 that are not included in environmental LCA.

According to the International Organization for Standardization (ISO) 14040/44 standards, an LCA study consists of four phases: (1) goal and scope (framework and objective of the study); (2) life cycle inventory (input/output analysis of mass and energy flows from operations along the product's value chain); (3) life cycle impact assessment (evaluation of environmental relevance, e.g. global warming potential); and (4) interpretation (e.g. optimisation potential) (ISO 14040: 2006, ISO 14044: 2006).

The goal and scope stage outlines the rationale of the study, the anticipated use of the results of the study, the boundary conditions, the data requirements and the assumptions made to analyse the product system under consideration, and other similar technical specifications for the study. The goal of the study is to answer the specific questions that have been raised by the target audience and the stakeholders involved, while considering potential uses of the study's results. The scope of the study defines the system's boundary in terms of technological, geographical, and temporal coverage of the study, attributes of the product system, and the level of detail and the complexity addressed by the study.

The life cycle inventory (LCI) stage qualitatively and quantitatively analyses the materials and energy used (inputs) as well as the products and by-products generated and the environmental releases in terms of non-retained emissions to specified environmental compartments and the wastes to be treated (outputs) for the product system being studied. The LCI data can be used on its own to: understand total emissions, wastes and resource-use associated with the material or the product being studied; improve production or product performance; or be further analysed and interpreted to provide insights into the potential environmental impacts from the system (life cycle impact assessment and interpretation, LCIA).

Vestas has previously carried out a life cycle assessment of another 3.0 MW wind turbine, the Vestas V90 model. However, the V90 turbine is designed to operate on sites with high wind conditions; whereas the V112 turbine is designed to operate on sites with medium and low wind conditions (Vestas estimates that 75% of the world's wind resources are at medium and low wind sites). Thus, the V112 turbine should not be benchmarked against the V90 turbine on a high wind site, but rather a turbine in a similar wind class. The classification for wind is specified by the DS/EN 61400-1:2005 for wind turbines, which specifies low, medium and high wind class designations (refer to Supplement E for more details on wind classes).

With PE's support, Vestas intends to use this current study as the baseline for future LCA studies as well as for defining key performance indicators (KPIs) for the measurement and monitoring of wind turbine performance from a life cycle perspective and to enable and help integrate the environmental dimension in product design, target setting and decision making.

This report describes the outcomes of the V112 LCA study including a description of the goal and scope, data, assumptions, methodologies, results and interpretation.

This study complies with the requirements of the ISO standards for LCA [ISO 14040: 2006, ISO 14044: 2006] and has undergone an external peer review to assure the robustness and credibility of the results.

2 Goal of the Study

The goal of this study is to evaluate the potential environmental impacts associated with production of electricity from a 100 MW onshore wind plant comprised of thirty-three V112 3.0 MW wind turbines from a life cycle perspective. This includes the production of raw materials, fabrication of the wind turbine and site parts (e.g. transformers, grid connections etc.), use phase replacements, servicing and losses (e.g. transformer losses etc.), end of life treatment and transport. An additional goal of the study is to improve on the past LCA models that Vestas has used and create a definitive framework for future LCA studies. The study does not make any comparative assessments with other wind turbines or electricity generation methods.

The impacts are to be evaluated using a set of KPIs that were developed during the course of this study that include the range of commonly applied conventional impact categories (e.g. GWP, AP, EP etc.) as well as other indicators such as recyclability, water consumption and total waste to landfill. These are listed in section 3.8 and further explained in Supplement A.

The wind plant size, power output and other site parameters (e.g. distance to grid etc.) are chosen to represent an average onshore wind plant consisting of V112 turbines. A new approach for the calculation of use phase power output of the turbine (using wind classes as described in Supplement E) is used in this study and together, they allow for a more robust benchmarking of turbine parks composed of different turbine models in future assessments. When comparisons are made between turbines, these should only be compared within specific wind classes for which the turbine is designed.

The results of the study will be used by Vestas to:

- inform senior management involved in decision making processes
- identify optimisation and improvement areas for technology and product development within Vestas
- to support environmental reporting at a product-level
- to develop a framework for product LCAs at Vestas to integrate environmental considerations in product design, target setting and decision making
- develop marketing materials to communicate environmental the environmental performance of their products to their customers and other stakeholders

Hence the main audience for the study results will be:

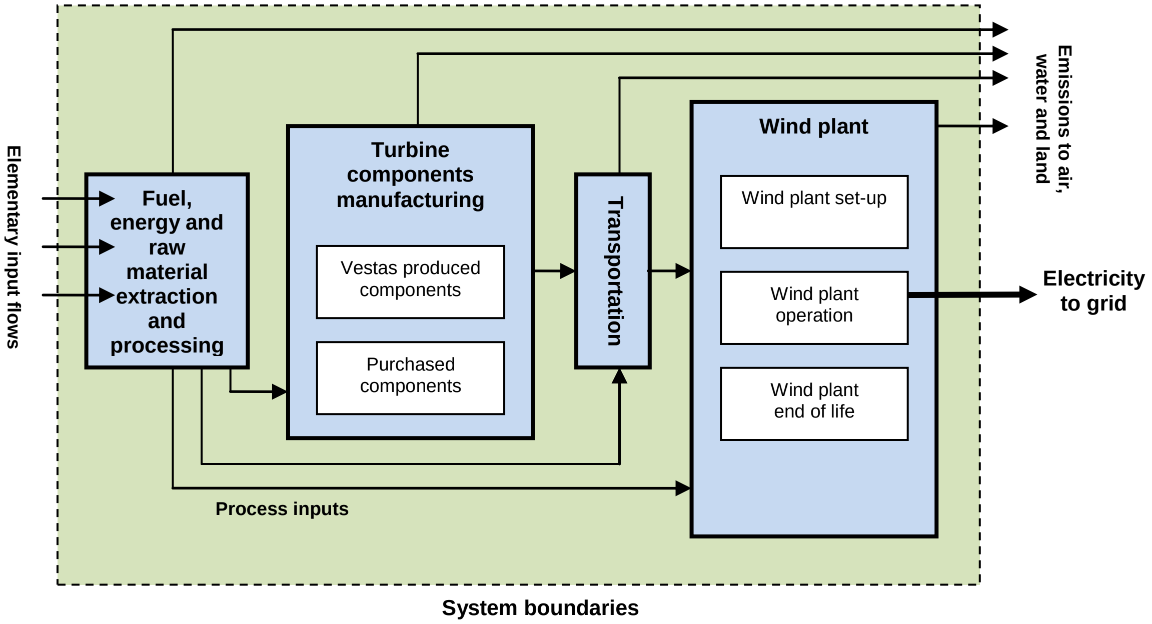
- internal Vestas Wind Systems A/S
- customers of Vestas
- investors of Vestas Wind Systems A/S
- other stakeholders and members of the general public with interests in renewable energy from wind and its associated potential environmental impacts

3 Scope of the study

This study is a cradle-to-grave LCA, assessing the potential environmental impacts associated with electricity generated from a 100 MW onshore wind plant comprising of thirty-three Vestas V112 3.0 MW wind turbines over its full life cycle.

This includes extraction of raw materials from the environment, manufacturing processes of components, production of the assembled wind turbines, logistics, use through to the point at which the product is disposed of and returned to the environment at end of life (or is reused or recycled). Production and maintenance of infrastructure and capital goods have been excluded from the scope of this study unless specifically noted.

Figure 2: Scope of V112 100 MW wind plant LCA



The following processes have been considered:

- Production of all parts of the wind plant (a description of main components can be found in Supplement B). This includes parts that are manufactured by Vestas' factories as well as supplier fabricated parts. Most of the information on parts and components (materials, weights, manufacturing operations, scrap rates) was obtained from bills of materials, design drawings and supplier data, covering 99% of the turbine weight. The remaining 1% of components not accounted for are assumed to have the average composition of the rest of the turbine.
- Manufacturing processes at Vestas' sites, which include not only the factories, but also other Vestas activities (e.g. sales, servicing etc.)
- Transportation of turbine components to wind plant site
- Site servicing and operations (including transport)
- Replacement parts (due to wear and tear of moving parts within the lifetime of a wind turbine)

- Use phase power production including wind turbine availability (the capability of the turbine to operate when wind is blowing), wake losses (arising from the decreased wind power generation capacity of wind a certain distance downwind of a turbine in its wake) and transmission losses.
- End of life treatment of turbines

3.1 Functional Unit

It is important to be able to compare the potential environmental impacts associated with electricity from a wind plant using specific turbines with other forms of electricity generation. However with wind power, the wind conditions on site are additional considerations that contribute significantly to the power generation.

The Vestas V112 3.0 MW wind turbine has been designed to operate under low to medium wind conditions (IEC II and III) and for this study, medium wind conditions have been selected as the baseline scenario, as Vestas predicts medium wind sites to be the main world market. The effects of low wind conditions are addressed in the scenario analysis in section 7 of this report.

The functional unit for this LCA study is defined as:

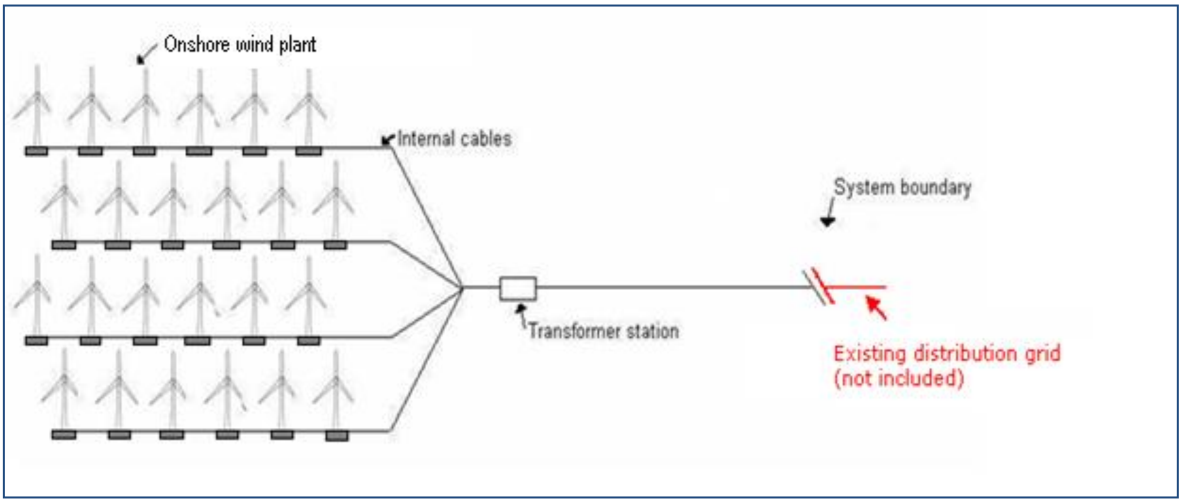
1 kWh of electricity delivered to the grid by a wind turbine plant operating under medium wind conditions (IEC II).

3.2 System Description

The wind plant itself accounts for the wind turbines, cabling and transformer station as shown in Figure 3 along with associated site amenities.

The boundaries of the wind plant are taken to be the point at which the power is delivered to the existing distribution grid.

Figure 3: Scope of the use phase



3.2.1 Life cycle stages

The entire life cycle of a wind plant can be broken down into individual life cycle stages. Figure 4 below shows the life cycle stages of a wind plant used for this study.

Figure 4: Life cycle stages of a typical onshore wind plant including typical activities in each stage

The life cycle of the wind plant has been modelled using a modular approach corresponding to the life cycle stages shown in Figure 4. This allows the various life cycle stages of the wind plant to be analysed individually.

An overview of the modelling approach of each of the life cycle stages is presented in section 3.7

3.2.1.1 Manufacturing

This phase includes production of raw materials and the manufacturing of wind plant components such as the foundations, towers, nacelles, blades, cables and transformer station. Transport of raw materials, e.g. steel, copper, epoxy etc. to the specific production sites is not included within the scope of this study.

3.2.1.2 Wind plant set up

This phase includes transport of wind plant components to site. Construction work on site such as the provision of roads, working areas and turning areas also fall under this phase. Processes associated with laying the foundations, erecting the turbines, laying internal cables, installing/erecting the transformer station and connecting to the existing grid are additional activities that make up this phase but that have not been included in the scope of this study.

3.2.1.3 Site operations

The site operations phase deals with the general running of the wind turbine plant as it generates electric power. Activities here include change of oil, lubrication and renovation/replacement of worn parts (e.g. the gearbox) over the life time of the wind plant. Transport to and from the turbines for operation and maintenance purposes is included in this phase.

3.2.1.4 End of Life

At the end of its useful life the wind plant components are dismantled and the site is remediated to the agreed state (which is usually specified as a condition of obtaining planning permission and may vary from site to site). Final waste management of materials is also considered in this phase. Waste management options include recycling, incineration with energy recovery or by deposition in landfill sites.

3.2.2 Technology coverage

This study assesses the production of the Vestas V112 3.0 MW wind turbine, transportation of components to site, erection of wind turbines/wind plant set up, site operations/maintenance as well as dismantling and scrapping of the wind plant components at end of life. These processes have been modelled based on state-of-the-art technologies used by Vestas.

3.2.3 Temporal coverage

The reference year for this study is 2009. Although the V112 did not go into full scale production in 2009, this was chosen as it was the most representative year for annual throughput of turbines.

3.2.4 Geographical coverage

For the purpose of this study an average “virtual” wind plant site was chosen. The aim is to give an overall picture of wind power production rather than model any particular location. The actual power output is based on wind classes (described in Supplement E) while scenario analyses have been carried out to assess the importance of transport distances to the site and to the grid on the overall impacts. Production of the V112 turbine represents the weighted average of all Vestas production facilities globally.

3.2.5 Data collection / completeness

Primary data have been collected from Vestas and from their suppliers. These primary data have been sourced through close co-operation with relevant functions at Vestas within their production processes, taken from items lists, via technical drawings and from supplier declarations in the form of TPS/TDS documents. Instances where primary data have been used in this study are:

- Materials composition of Vestas produced wind plant components
- Manufacturing process for Vestas produced wind plant components e.g. casting and machining
- Utilities and materials consumption for Vestas production sites
- Materials composition of larger purchased components of the wind plant e.g. the generator, transformer, etc. (directly from suppliers)
- Utilities and materials consumption for wind plant site preparation, operation and maintenance

Where primary data have not been readily available from Vestas or their suppliers, secondary data have been used to fill these gaps. Secondary data have also been used to account for background processes that are upstream in the supply chain. Instances where secondary data have been used in this study are:

- Power grid mix information
- Production of primary materials e.g. steel, aluminium, fibre glass, plastic granulates
- Transport processes
- Materials composition of smaller standard purchased items e.g. seals, washers, hex-nuts, screws and bolts
- Manufacturing processes for smaller standard purchased items e.g. plastics injection moulding, thread turning, stamping
- End of life processes such as landfill, incineration and recycling of steel

Most secondary datasets are supplied by PE and are available on a commercial basis [PE INTERNATIONAL 2006]. Other sources of secondary datasets include industry associations such as the World Steel Association, Plastics Europe, Eurofer and the European Aluminium Association. Details of data sources and a discussion on data quality can be found in Supplement D.

3.3 Cut-off criteria

The following cut-off criteria were used to ensure that all relevant environmental impacts were represented in the study:

- **Mass** – if a flow is less than 1% of the cumulative mass of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Energy** – if a flow is less than 1% of the cumulative energy of all the inputs and outputs (depending on the type of flow) of the LCI model, it may be excluded, provided its environmental relevance is not a concern.
- **Environmental relevance** – if a flow meets the above criteria for exclusion, yet is thought to potentially have a significant environmental impact, it will be included. All material flows which leave the system (emissions) and whose environmental impact is higher than 1% of the whole impact of an impact category that has been considered in the assessment, shall be included.
- The **sum** of the neglected material flows shall not exceed 5% of total mass, energy or environmental relevance.

In actuality, approximately 99% of the total mass of materials in the V112 3.0 MW turbine has been accounted for. These results have been scaled up 100% of the full mass of the turbine (i.e. the 1% of components not accounted for are assumed to have the average composition of the rest of the turbine).

3.4 Assumptions

3.4.1 Lifetime of Turbine

The life time of the wind plant is assumed to be 20 years. This corresponds to the design life time of the V112 3.0 MW turbine and applies to all components of the wind plant, except for certain replacement parts. However, as the wind turbine industry is still relatively young (starting up in 1979, 32 years ago) the actual life time of a particular wind plant is uncertain and some variance around this assumed 20 year figure is expected. For instance, Vestas has direct knowledge of a number of its turbines exceeding the design life time of 20 years. The effects of varying the life time of a wind plant on potential environmental impacts are discussed in Section 6.

3.4.2 Materials Input

At the time that this study was carried out, it was not possible to obtain reliable data on the degree of recycled content of materials used in the product system. As such, it has been assumed that all materials entering the production system are sourced from virgin material. This is a very conservative assumption as it is certain that, for example, a substantial proportion of metal components will actually be derived from secondary sources.

3.4.3 End of Life treatment

End of life treatment of the turbine is extensive and detailed. It is assumed that the entire turbine is “collected” at the end of life. However, the entire turbine is not recycled homogeneously; this is further explained below.

All large metal components that are primarily mono-material (e.g. gears, transformers, tower sections, etc.) are assumed to be 98% recycled. Cables are 95% recycled and other parts of the turbine are treated as shown in Table 1.

Table 1: End of life treatment of turbine components not already mentioned in the text

Material	Treatment
Aluminium	90% recycled + 10% landfilled
Copper	90% recycled + 10% landfilled
Steel	90% recycled + 10% landfilled
Polymers	50% incinerated + 50% landfilled
Lubricants	100% incinerated
Other waste (including concrete)	100% landfilled

This information comes from expert judgement and from data obtained from previous LCA studies performed by Vestas. Material losses from the recycling process itself are calculated on top of these recycling rates. Full credits are given for the material recovered. This approach is consistent with ISO 14044 and for purposes of environmental modelling, decision-making, and policy discussions involving recycling of metals. The metals industry strongly supports the closed-loop approach compared to the recycled-content approach

[ATHERTON, 2007]. For a more detailed description and the implications of these two approaches, please refer to the Life Cycle Assessment of Aluminum Beverage Cans for the Aluminum Association Inc., Washington DC [PE AMERICA, 2010].

Vestas has calculated the average recyclability across the components of a V112 wind turbine to be approximately 81%. Details of recyclability can be found in section 5.2.16

3.4.4 Sulphur hexafluoride (SF_6)

The production of sulphur hexafluoride gas in the switchgear of the turbine has not been accounted for in the study. This is justified based on expert judgement and past experience with the production of similar gases that indicates that the potential environmental impacts associated with their production are negligible in the context of this study.

Nonetheless, sulphur hexafluoride is a very potent greenhouse gas. For the switchgear application this usually only becomes an issue when the gas is released into the environment during a blow-out. Occurrences of blowouts are extremely rare and have not been modelled in this study. The treatment of the gas at recycling stations is not known and therefore it is assumed that all of the sulphur hexafluoride gas in the switchgear is released to the environment at the end of life as a worst case scenario.

3.4.5 Onboard turbine cabling

At the time of data collection for this study, it was not possible to ascertain the material composition for all the on-board cabling within the wind turbine system. However, detailed materials information on the high voltage cable connecting the turbine generator to the turbine transformer was available from suppliers. These data were used as proxy data for all the onboard cable and wiring in the wind turbine system. As a significant proportion of the onboard cabling and wiring is expected to consist of simpler wire forms (e.g. single plastic sheath and copper), the use of the more complicated materials composition of the high voltage cable as a proxy is considered a worst case scenario.

3.4.6 Foundations

There are two basic kinds of foundations for onshore wind turbine towers depending on the ground water level, as follows:

- High groundwater level - indicates a (maximum) groundwater level equal to the level of the terrain (requires more concrete and steel)
- Low groundwater level – low ground water scenario

The low groundwater level case has been chosen as the base case as it is representative of the majority of wind park sites.

3.4.7 Electrical/electronic components in turbine

Due to the complexities of the electrical/electronics sub-systems in the wind turbine system it was not possible to obtain specific data on these components within the data collection period. PE datasets for generic signal and signal & power electronic systems were used here as a proxy, which estimates a worst-case scenario. The use of these datasets is extremely conservative and is most likely “over counting” potential impacts but this approach is aligned with taking a conservative approach throughout study where assumptions may be required.

3.4.8 Transport

As mentioned in earlier sections of this report, transport of raw materials to production sites have been excluded from this study. Transport steps that have been included in this study are discussed below:

- Transport associated with moving wind plant components to the site are given in Table 2.

Table 2: Transport of wind plant components to the site

Component	Transport
Nacelle	1000 km by truck
Hub	1000 km by truck
Blades	1000 km by truck
Tower	700 km by truck
Foundation	200 km by truck

- Transportation of maintenance crew to and from the site during site operations is assumed to be 900 km per turbine per year.

A scenario analysis on the transport of components to the wind plant has been carried out to determine the significance of these activities in the context of the full life cycle.

3.5 Allocation

Wind turbines have electricity as the single appreciable output. However, since Vestas produces several models of turbines and production data were collected at a factory level, allocation was required to assign the correct production burdens (from the different manufacturing locations) to the V112 turbine. This is discussed in detail in Supplement C.

3.6 Inventory analysis

This LCA study follows an attributional approach. The life cycle inventories generated for each product are compiled from the inputs and outputs of the component processes. All environmentally relevant flows of energy and materials crossing the system boundaries have been accounted for (e.g. energy, material resources, wastes and emissions). These flows are recorded for each unit process and summarised across the entire wind plant system.

GaBi 4 Professional LCA software and databases together with GaBi DfX have been used to model the scenarios and generate the life cycle inventories and impact assessments on which the study conclusions are based. This software is a state-of-the-art tool for carrying out LCAs [GaBi 2010].

3.7 Modelling the life cycle phases

Modelling of the lifecycle begins with a bill of materials (BOM) detailing a “part tree” of the entire turbine. Each part is associated with a material, manufacturing process and country of origin. This can be extremely extensive – the BOM for the V112 turbine accounts for over 50,000 parts. Modelling this many components “conventionally” in GaBi is not practicable. However using GaBi DfX allows this BOM to be automatically imported into the tool where materials and manufacturing processes are mapped to life cycle inventories provided by GaBi 4.

Vestas’ manufacturing process models are created with energy and consumables linked to life cycle inventories (as turbine parts are already included in the BOM). Site operations are modelled similarly.

The LCA software generates a “product model” that includes all the material and energy resources involved in the production of the turbine (including material losses from the production processes and possible internal recycling loops).

GaBi DfX provides the opportunity to automatically disassemble the entire turbine (or parts of it) into its source components. This allows for an extremely detailed end of life model that can be part-specific. This feature is used for the end of life treatment of the turbine where certain parts that can be easily dismantled are recycled with higher efficiencies than the rest of the turbine.

3.8 Impact assessment categories and relevant metrics

The selection of the impact categories assessed in this study is based on priority areas as indentified in the Vestas Sustainability Strategy. The KPIs from the sustainability strategy that have been evaluated within the context of this LCA are:

- Abiotic resource depletion (ADP elements)
- Abiotic resource depletion (ADP fossils)
- Acidification potential (AP)
- Eutrophication potential (EP)
- Freshwater aquatic ecotoxicity potential (FAETP)
- Global warming potential (GWP)
- Human toxicity potential (HTP)
- Marine aquatic ecotoxicity potential (MAETP)
- Photochemical ozone creation potential (POCP)
- Primary energy from renewable raw materials (net calorific value)
- Primary energy from resources (net cal. value)
- Terrestrial ecotoxicity potential (TETP)
- USEtox2008 ecotoxicity

- Waste to landfill
- Water consumption
- Recyclability

CML (2009 update) and USETox (2008) characterisation factors have been applied in this study [GUINÈE ET AL. 2001, ROSENBAUM ET AL. 2008]. These impact indicators focus on the so-called “midpoints” of the cause-effect chain. This means that they aggregate data on emissions (the starting points in the cause-effect chain) to potential impacts in various categories (e.g. global warming, acidification, etc.), but do not go as far as to assess the endpoints, such as loss of biodiversity, damage to human health, etc. caused by these impacts. As such, the impact assessment results generated are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

These impact categories occur on different scales ranging from global (GWP), to regional (AP) and local (POCP, EP and HTP), and the relevance of the point of emission becomes more important as more local impacts are considered. For example, a kilogram of carbon dioxide emitted anywhere in Denmark will give the same contribution to global warming as a kilogram of carbon dioxide emitted anywhere else in the world, whereas for more regionally confined impact categories (such as eutrophication), only emissions that occur nearby will have a real impact. As such, results generated using these impact categories should be considered to be worst-case potential impacts rather than actual impacts on the environment. Further details on the impact indicators can be found in Supplement A.

No normalisation, grouping, ranking or weighting have been applied to the results.

3.9 Sensitivity analyses

Sensitivity analyses are conducted to better understand the effect and importance of uncertainties in the data or of applying different methodologies during the modelling. The following sensitivity analyses have been carried out in this study:

- Variation in wind plant lifetime: ± 4 years
- Variation in frequency of parts replacement
- End of life credits: to see the impact of recycling on the life cycle, a scenario will be presented without credits factored into the results.

3.10 Scenario analyses

Scenario analyses allow the practitioner to assess how the results of the LCA will vary if the model is set up in different ways e.g. representing different possible operating conditions. The following scenario analyses have been carried out in this study to assess the effects that possible changes to a wind plant system will have on its environmental performance over its life cycle:

- Operating the 100 MW wind plant under IEC III wind conditions (low wind)

- Varying the transport distances for components to wind plant and site maintenance/operations trips
- Varying the distance of the wind plant to the existing grid taking into account corresponding line losses
- Changing the type of foundation used from low ground water level type to high ground water level type.

3.11 Critical review

The outcomes of this LCA study are intended to support external communication. To assure the rigour of the study and robustness of the results, an independent critical review of the study has been conducted.

The goal and scope of the critical review is defined in accordance with ISO 14044, paragraph 6.1. Following ISO 14044, the critical review process shall ensure that (ISO, 2006b):

- the methods used to carry out the LCA are consistent with this 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
- the study report is transparent and consistent

Dr. Arpad Horvath has been selected by Vestas based on his expertise in the field of sustainability and his experience of reviewing technical LCA studies.

4 Materials Inventory of 100 MW V112 Wind Plant

The materials inventory for the entire 100 MW V112 wind plant is given in this section. Classification is based on Germany's Association of the Automotive Industry (VDA) Materials Grouping; a widely accepted and established materials classification system used across the international automotive industry. Materials for replacement parts are not included in this analysis.

Table 3: VDA material classification data for thirty-three 3.0 MW V112 wind turbines

VDA Material Classification	Amount, tonnes
Steel and iron materials	
Steel and iron materials (unspecified)	8
Unalloyed, Low alloyed	6634
Highly alloyed	1442
Cast iron	2170
Lights alloys, cast and wrought alloys	
Aluminium and aluminium alloys	113
Nonferrous heavy metals, cast and wrought alloys	
Copper	160
Copper alloys	0.3
Zinc alloys	0.01
Special metals	
Special metals	3000g
Polymer materials	
Thermoplastics	227
Thermoplastic elastomers	12
Elastomers / elastomeric compounds	42
Duromers	88
Polymeric compounds	324
Process polymers	
Lacquers	25
Adhesives, sealants	0.24

VDA Material Classification	Amount, tonnes
Other materials and material compounds	
Modified organic natural materials	5
Ceramic/ glass	792
Other materials and material compounds	100
Electronics / electrics	
Electronics	34
Electrics	29
Magnet	16
Fuels and auxiliary means	
Lubricants	42
Other fuels and auxiliary means	0.24
TOTAL	**12263**

Table 4: VDA material classification data for foundations of the 100 MW V112 wind plant

VDA Material Classification	Amount, tonnes
Steel and iron materials	
Steel and iron materials (unspecified)	1491
Polymer materials	
Thermoplastics	3
Other materials and material compounds	
Concrete and mortar	29770
TOTAL	**31264**

Table 5: VDA material classification data for internal wind plant cables of the 100 MW V112 wind plant

VDA Material Classification	Amount, tonnes
Lights alloys, cast and wrought alloys	
Aluminium and aluminium alloys	20
Nonferrous heavy metals, cast and wrought alloys	
Copper	12
Polymer materials	
Thermoplastics	18
TOTAL	**50**

Table 6: VDA material classification data for the 100 MW V112 wind plant power transmission cables (connection to grid)

VDA Material Classification	Amount, tonnes
Steel and iron materials	
Steel and iron materials (unspecified)	14
Lights alloys, cast and wrought alloys	
Aluminium and aluminium alloys	75
TOTAL	**89**

Table 7: VDA material classification data for the 100 MW V112 wind plant transformer

VDA Material Classification	Amount, tonnes
Steel and iron materials	
Steels / cast steel / sintered steel	32
Lights alloys, cast and wrought alloys	
Aluminium and aluminium alloys	0.1
Nonferrous heavy metals, cast and wrought alloys	
Copper	8
Polymer materials	
Duromers	1
Process polymers	
Lacquers	0.4
Other materials and material compounds	
Modified organic natural materials	3
Ceramic/ glass	0.5
Fuels and auxiliary means	
Lubricants	13
TOTAL	**58**

5 Impact Assessment

5.1 Top level results

Section 5.1 provides a top level view of the potential environmental impacts associated with the V112 wind plant. Section 5.2 provides a more detailed discussion of the results of this LCA showing the contribution from each life cycle stage.

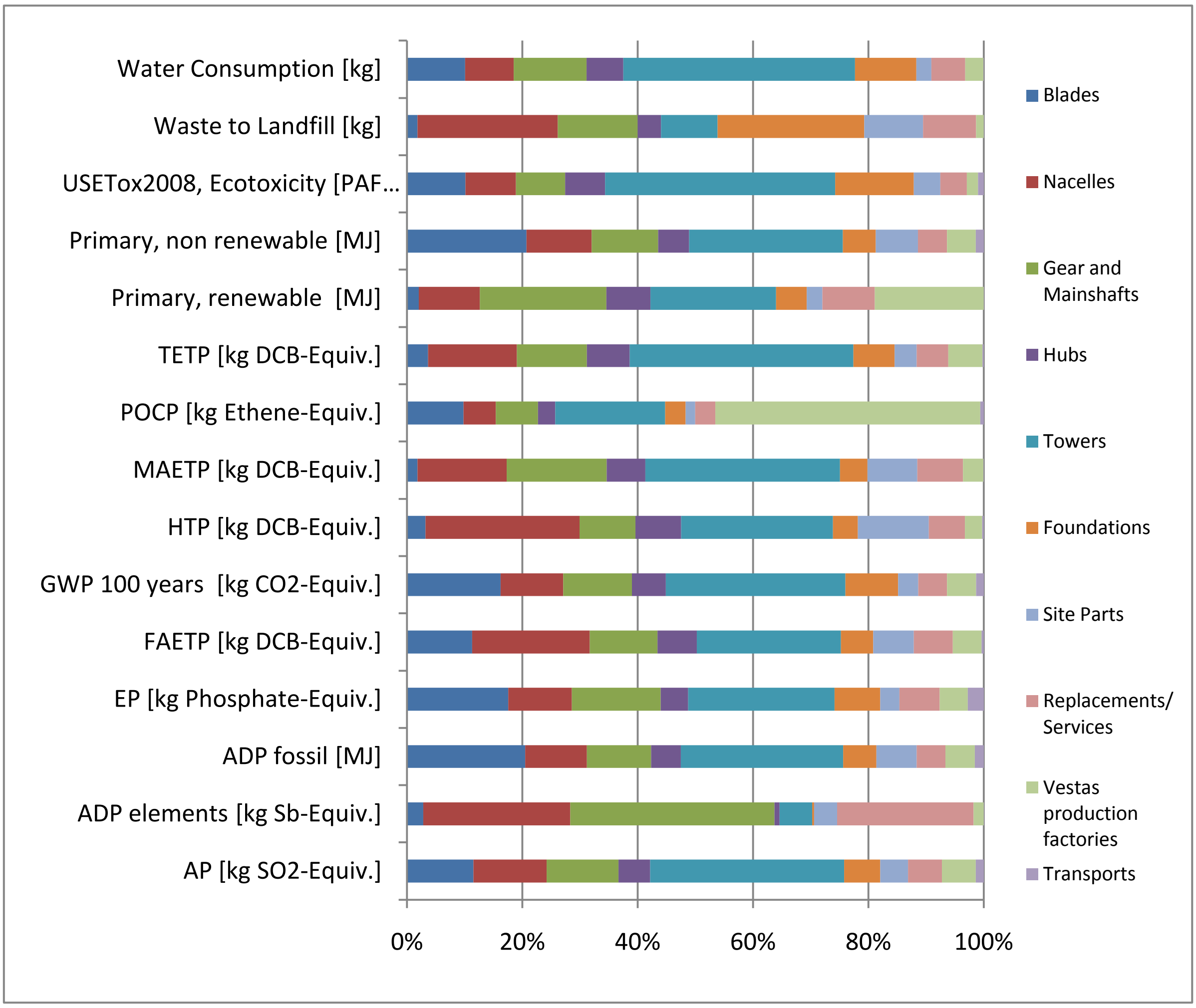
Table 8 below shows the eco-profile of the 100 MW V112 wind plant over its entire life cycle.

Table 8: Top level results for the life cycle impact assessment

Impact Category	Unit	Impact/kWh of electricity
Abiotic resource depletion (ADP elements)	mg Sb eq.	0.45
Abiotic resource depletion (ADP fossils)	MJ	0.08
Acidification potential (AP)	mg SO_2 eq.	28
Eutrophication potential (EP)	mg PO_4^- eq.	2.7
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB eq	33.5
Global warming potential (GWP)	g CO_2 eq.	7
Human toxicity potential (HTP)	mg DCB eq.	833
Marine aquatic ecotoxicity potential (MAETP)	g DCB eq.	2546
Photochemical ozone creation potential (POCP)	mg C_2H_4 eq.	6.3
Primary energy (renewable) (net calorific value)	MJ	0.03
Primary energy (non-renewable) (net calorific value)	MJ	0.09
Terrestrial ecotoxicity potential (TETP)	mg DCB-Equiv	29
USEtox2008 ecotoxicity	PAF cm3.day	16
Waste to landfill	g	4.9
Water consumption	g	27.7
Recyclability (average over components of V112 wind turbine), %		80.9

Figure 5 below shows the contribution to each impact category of the various components and life cycle stages of the wind plant (excluding end of life, since for most impact categories the recycling of materials offsets a proportion of the environmental impacts associated with the production of).

Figure 5: Contribution of wind plant components to impact categories



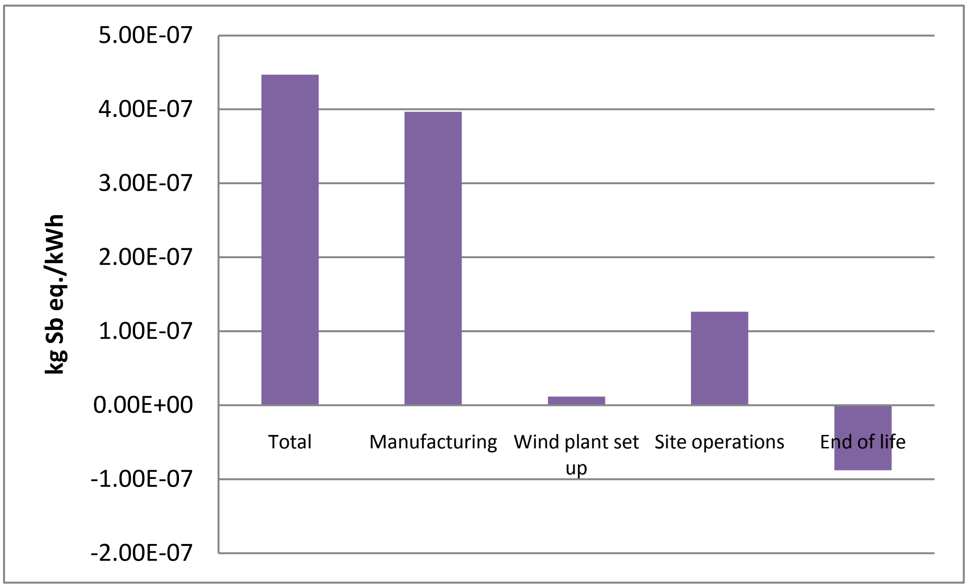
In general, the manufacture of the towers has the greatest contribution (most significant for twelve of the fifteen categories assessed). For waste to landfill, the foundations along with the production of nacelle components are responsible for the majority of impacts. Vestas production operations are the most significant contributor to photochemical ozone creation potential. In the case of abiotic depletion elements, production of gear and mainshaft components has the largest impacts. Overall, transport has no significant contribution to any of the impact categories covered by this study.

5.2 Detailed results

The results for each impact category assessed in this LCA study are described in detail in the following sections. In the accompanying charts, the total impact is shown and then the contributions from each stage in the life cycle are shown.

5.2.1 Abiotic resource depletion (ADP elements)

Figure 6: Contribution from each life cycle stage towards ADP elements



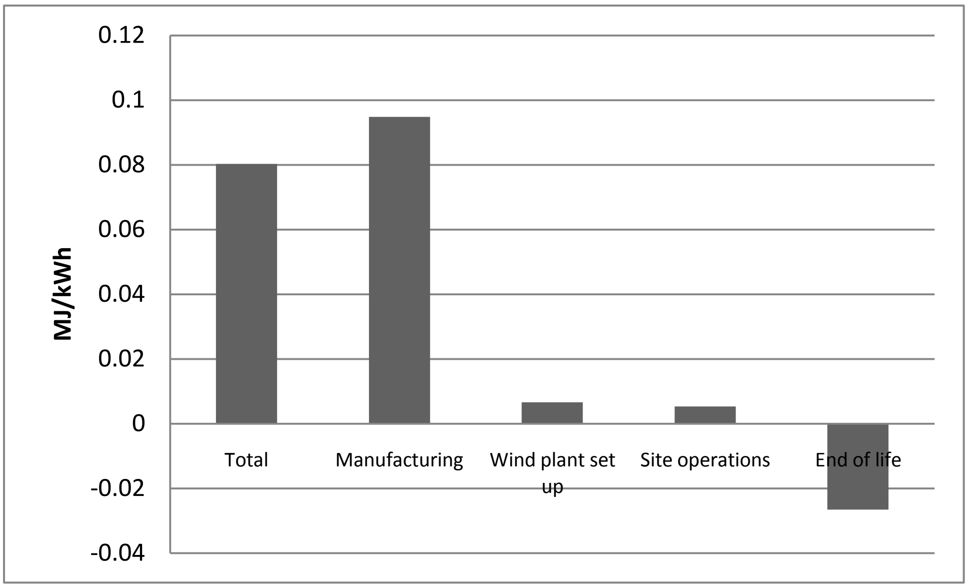
The chart above shows the abiotic resource depletion (elements) potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest contribution. Within the manufacturing phase, production of components for the gear and mainshaft modules is the largest contributor to this impact category with around a 35% share. The production of nacelle components follows with an 18% share.

The major contributing flow to this impact category is copper-molybdenum-gold-silver ore, accounting for about 75% of the total.

5.2.2 Abiotic resource depletion (ADP fossils)

Figure 7: Contribution from each life cycle stage towards ADP fossils



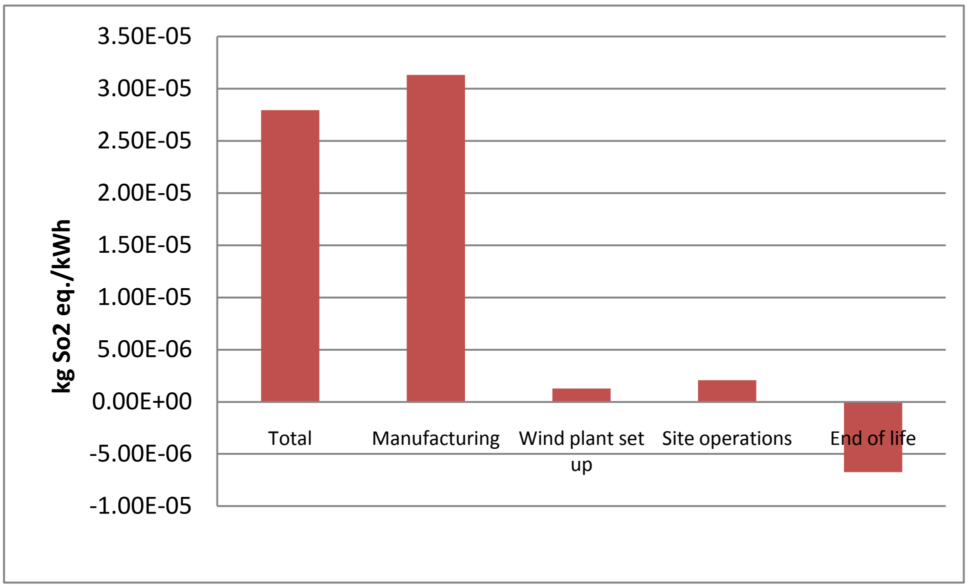
The chart above shows the abiotic resource depletion (fossils) potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest contribution. Within the manufacturing phase, production of the tower components is the largest contributor to this impact category with a 26% share. The production of blade components accounts for a 21% share of impacts in this category. This is followed by gear and mainshaft components production responsible for 11% of the overall impacts.

The major flows contributing to this impact are natural gas (40%), crude oil (34%) and hard coal (18%).

5.2.3 Acidification potential (AP)

Figure 8: Contribution from each life cycle stage towards AP



The chart above shows the acidification potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest contribution. Within the manufacturing phase, the production of tower components is the largest contributor to this impact category with around a 32% share. Other significant process steps are production of gear and mainshaft components (13%), nacelle (12%) and blade components (12%).

Sulphur dioxide is by far the largest contributing flow to acidification potential, accounting for about 71% of total impacts followed by nitrogen oxides with a further 26%.

5.2.4 Eutrophication potential (EP)

Figure 9: Contribution from each life cycle stage towards EP

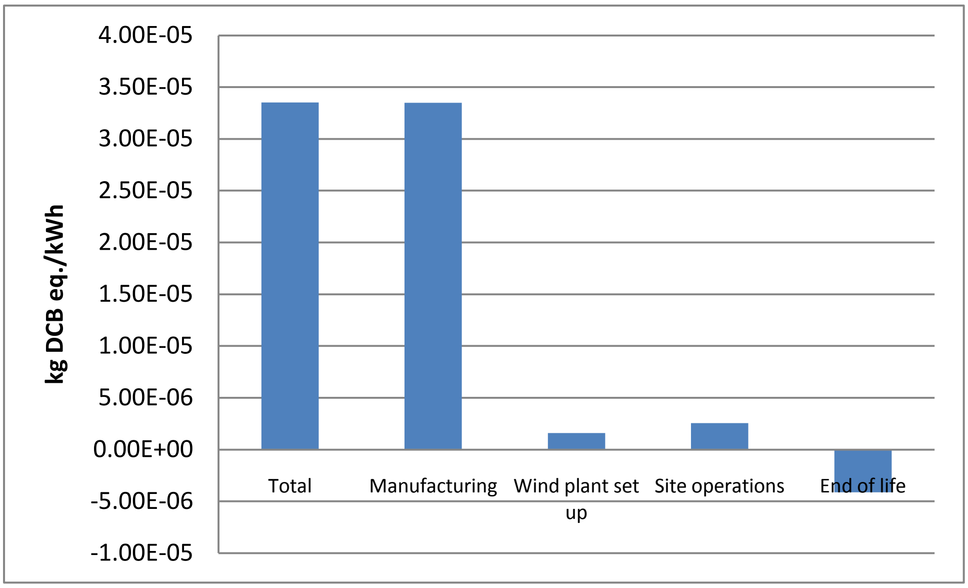
The chart above shows the eutrophication potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, tower components production is the largest contributor to this impact category with a 24% share. Production of blade components contributes about 18 % while gear and mainshaft components production contributes 16% to the total impacts. Production of nacelle components accounts for an additional 11% of impacts in this category.

Nitrogen oxides are the most significant flow contributing to the impacts of EP, accounting for about 70% of the total impacts.

5.2.5 Freshwater aquatic ecotoxicity potential (FAETP)

Figure 10: Contribution from each life cycle stage towards FAETP



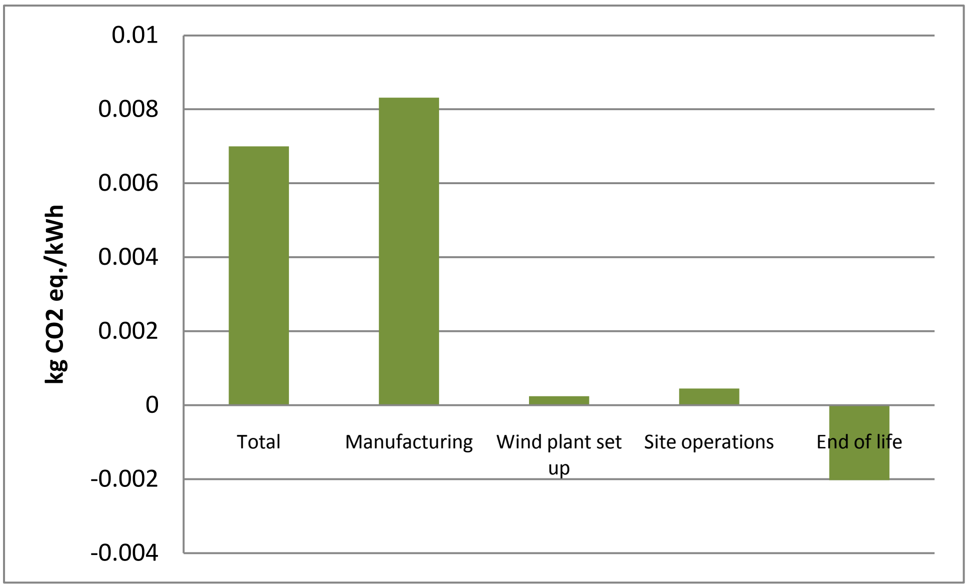
The chart above shows the freshwater aquatic ecotoxicity potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components is the largest contributor to this impact category with a 20% share closely followed by nacelle components production with 17%. Production of gear and mainshaft components contributes 12% to manufacturing impacts while blade components production accounts for a further 11%.

Emissions of heavy metals are responsible for the majority of impacts in this category accounting for about 79% of the total.

5.2.6 Global warming potential (GWP)

Figure 11: Contribution from each life cycle stage towards GWP



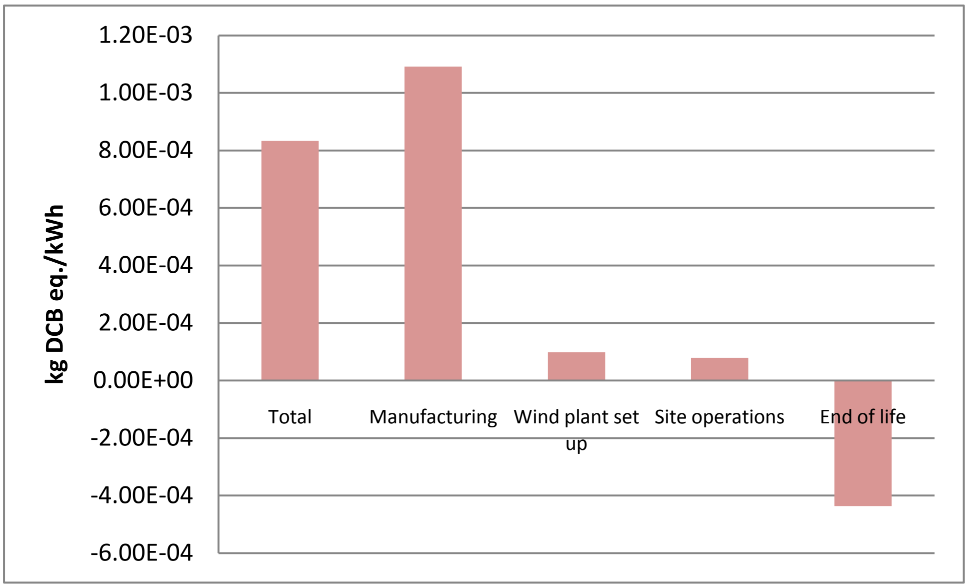
The chart above shows the global warming potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components has the largest contribution (29%), followed by blade components (16%), gear and mainshaft components (12%) and nacelle components (10%).

Carbon dioxide is the most significant emission contributing to this impact category (82%) followed by sulphur hexafluoride (10%).

5.2.7 Human toxicity potential (HTP)

Figure 12: Contribution from each life cycle stage towards HTP



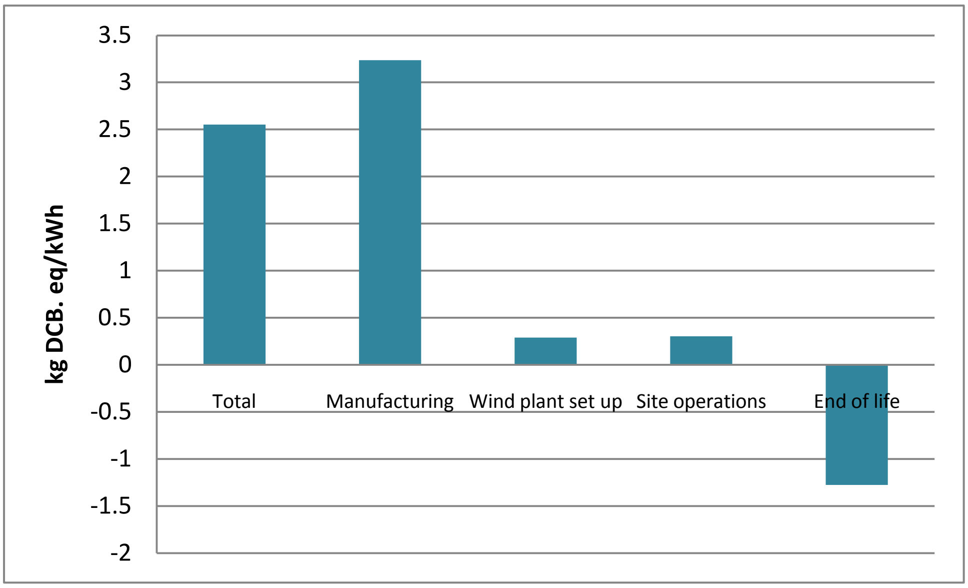
The chart above shows the human toxicity potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of nacelle components has the largest impact (24%), closely followed by tower components (23%), then gear and mainshaft components (10%).

Heavy metals to air account for about 56% of the total impacts. Hydrogen fluoride accounts for about a further 20% of impacts.

5.2.8 Marine aquatic ecotoxicity potential (MAETP)

Figure 13: Contribution from each life cycle stage towards MAETP



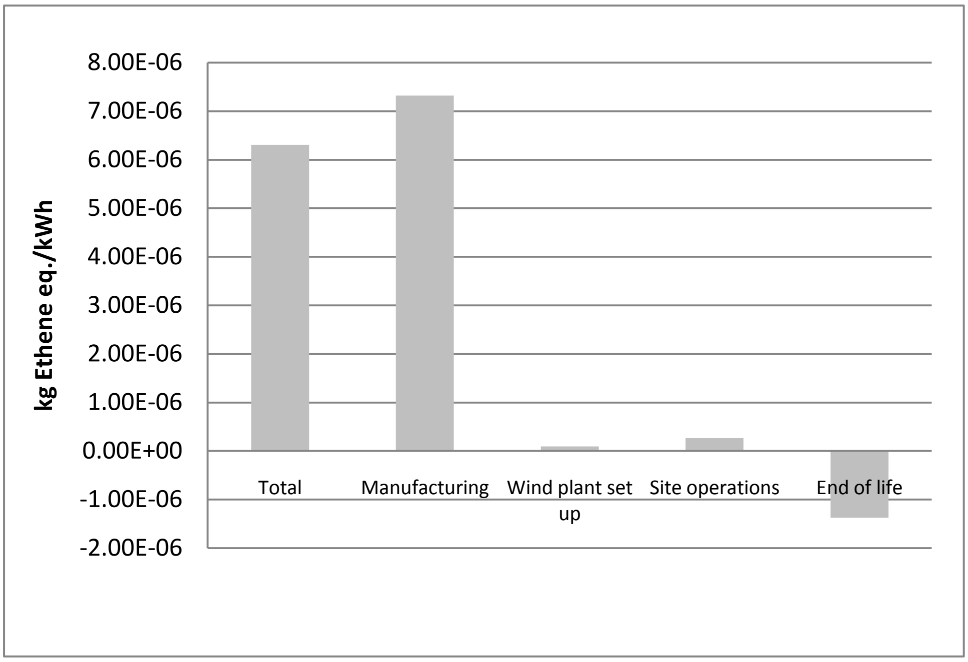
The chart above shows the marine aquatic ecotoxicity impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components has the largest contribution (31%), followed by gear and mainshaft (17%) and nacelles components (15%).

Hydrogen fluoride accounts for about 94% of impacts in this category.

5.2.9 Photochemical ozone creation potential (POCP)

Figure 14: Contribution from each life cycle stage towards POCP



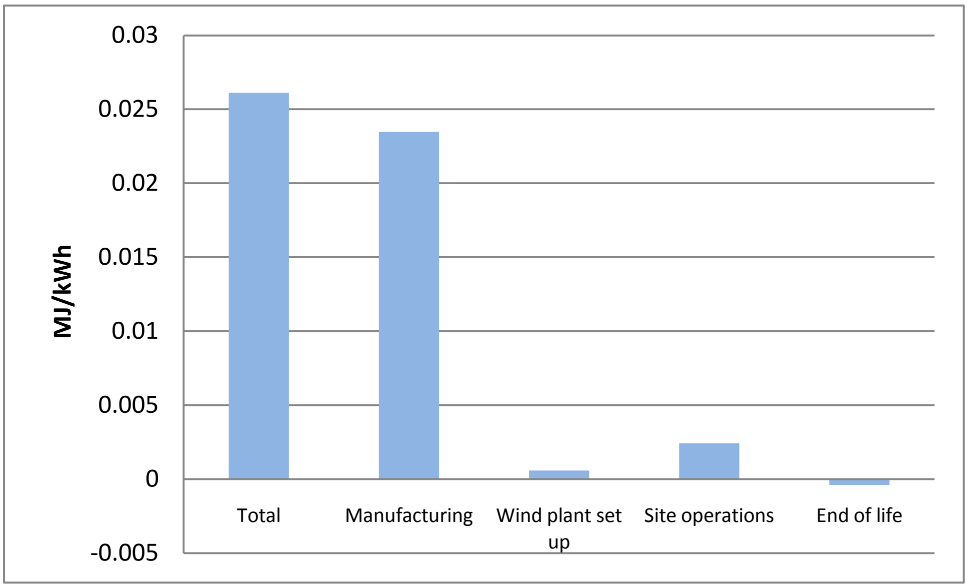
The chart above shows the photochemical ozone creation potential impacts per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, Vestas factory operations are is the biggest contributor to this impact category with the generator factory accounting for a 37% share of the impacts. Tower components production contributes about 18% to manufacturing impacts while blades components production accounts for 10% of impacts with gear and mainshaft components production accounting for about 7% of the impacts in this category.

Volatile organic compounds (VOCs) are responsible for the majority of impacts (79%) followed by sulphur dioxide (13%) and nitrogen oxides (6%).

5.2.10 Primary energy from renewable raw materials (net calorific value)

Figure 15: Contribution from each life cycle stage towards primary energy (renewables)



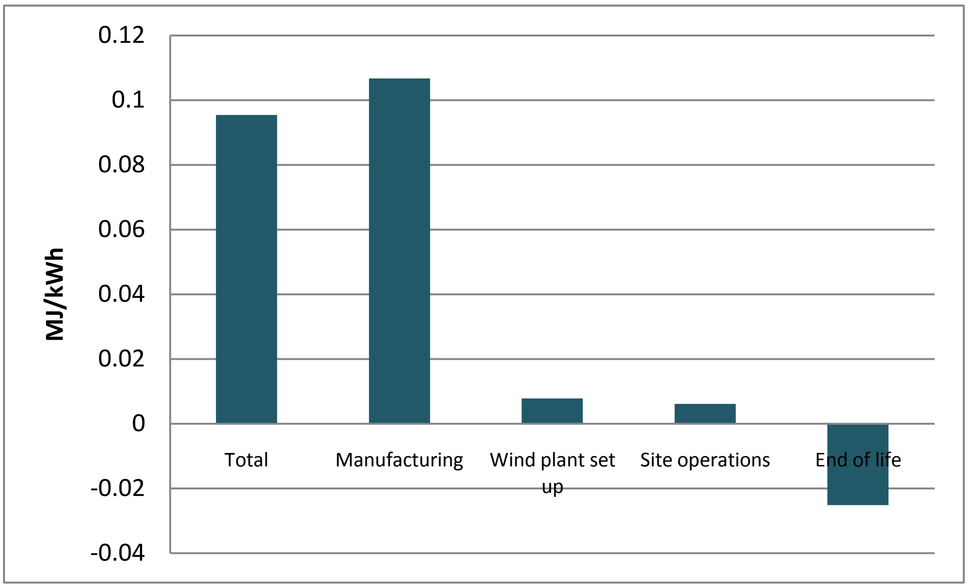
The chart above shows the primary energy from renewable raw materials consumed per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of gear and mainshaft components accounts for the largest impacts with a 22% share. Production of tower components and Vestas factory operations are the next largest contributors to this impact category, each with a 19% share.

Wind power accounts for about 75% of the total contribution to this impact category (this does not account for wind power generated during the use phase).

5.2.11 Primary energy from resources (net cal. value)

Figure 16: Contribution from each life cycle stage towards primary energy (non renewable)



The chart above shows the primary energy from resources consumed per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components is the largest contributor to this impact category (26%) followed by blade components (18%) and then nacelle components (11%).

The main contributing flows are natural gas (34%), crude oil (29%), uranium (16%) and hard coal (15%).

5.2.12 Terrestrial ecotoxicity potential (TETP)

Figure 17: Contribution from each life cycle stage towards TETP

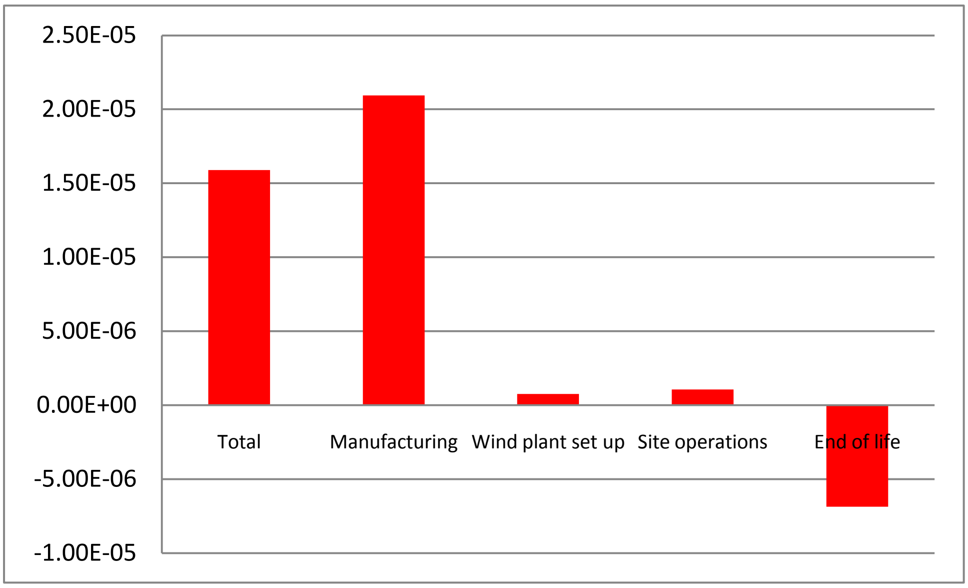
The chart above shows the abiotic resource depletion (elements) per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components is the largest contributor to this impact category (37%) followed by nacelle components (15%) and gear and mainshaft components (12%).

Emissions of heavy metals account for 99% of impacts in this category.

5.2.13 USEtox2008 ecotoxicity

Figure 18: Contribution from each life cycle stage towards USEtox



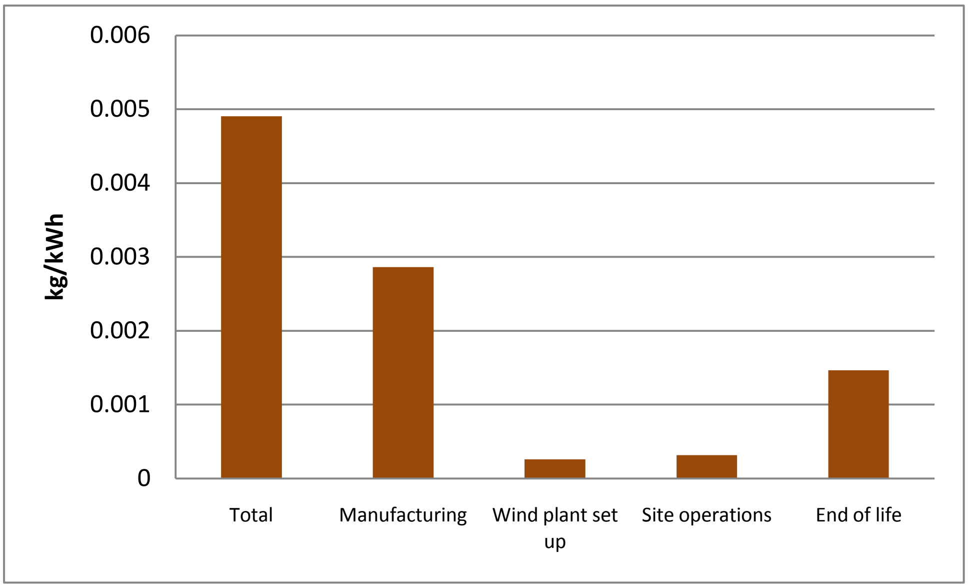
The chart above shows the USETox ecotoxicity potential per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, production of tower components is the major contributor to this impact category (46%) followed by blade components (12%), gear and mainshaft component production (11%), nacelle components (10%) and hub module components production (9%).

Sulphuric acid to fresh water accounts for about 63% of USETox impacts with hydrocarbons to sea water accounting for a further 15%.

5.2.14 Waste to landfill

Figure 19: Contribution from each life cycle stage towards waste to landfill

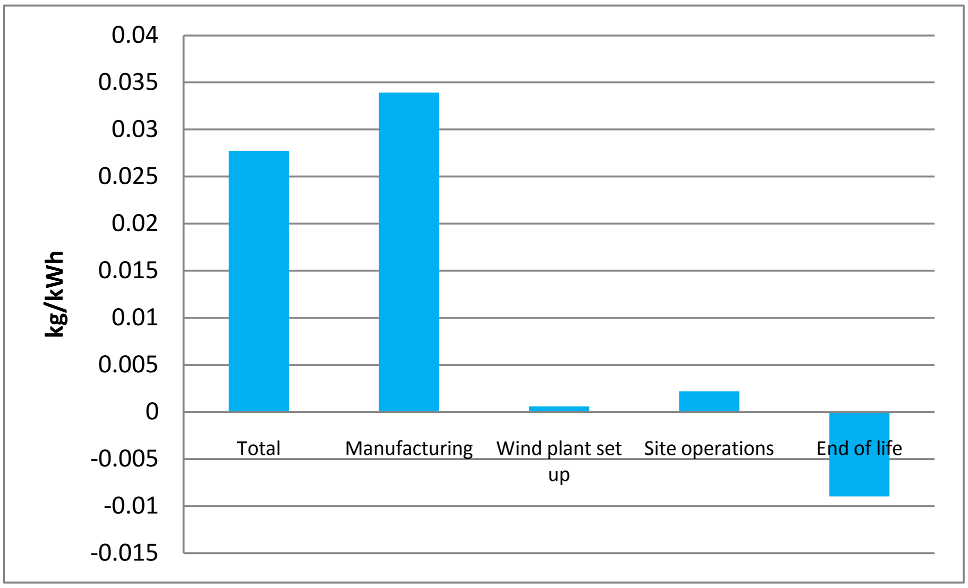


The chart above shows the waste to land fill per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, the production of nacelle components is the major contributor to this impact category (28%), closely followed by gear and mainshaft components (25%).

5.2.15 Water consumption

Figure 20: Contribution from each life cycle stage towards water consumption



The chart above shows the water consumption per kWh of electric power generated by the V112 wind plant over its life cycle.

Manufacturing accounts for the largest impacts. Within the manufacturing phase, the production of tower components is the largest contributor to this impact category with a 37% share. Gear and mainshaft component production is another significant contributor to the manufacturing phase impacts with 13% of the burdens. The production of nacelles components accounts for 8% of total water consumption.

5.2.16 Recyclability

The average recyclability for the Vestas V112 3.0MW wind turbine has been calculated as 81%. This figure is specific to the turbine itself and excludes the foundations, the site parts and other components of the wind plant.

The table below shows recyclability according to the each major assembly of the V112 turbine; namely the nacelle, the rotor and the tower. The “remainder assembly” includes all other turbine components that do not fall within the three main assemblies.

Table 9: Recyclability of the major assemblies of the V112 wind turbine

Nacelle (% of wind turbine by weight)	**32%**
% recyclability of Nacelle:	87%
Gearbox (% of Nacelle)	44%
Steel and iron	99%
Non-ferrous metals	<1%
Polymers	<1%
Electronics	<1%
Other materials	1%
Transformer (% of Nacelle)	8%
Steel and iron	82%
Non-ferrous metals	10%
Polymers	8%
Other materials	<1%
Generator (% of Nacelle)	7%
Steel and iron	85%
Non-ferrous metals	9%
Polymers	<1%
Electronics	3%
Other materials	3%
Remainder (% of Nacelle)	41%
Steel and iron	80%
Non-ferrous metals	10%
Polymers	1%
Electronics	3%
Other materials	6%
Recyclability: metals >90%	

Rotor (% of wind turbine by weight)	**20%**
% recyclability of Rotor:	38%
Blades (% of rotor)	11%
Polymers and laquers	40%
Ceramic / glass	52%
Other materials	8%
Hub (% of rotor)	9%
Steel and iron	95%
Non-ferrous metals	<1%
Polymers	2%
Other materials	3%
Recyclability: metals >90%	
Tower (% of wind turbine by weight)	**46%**
% recyclability of Tower:	97%
Steel and iron	99%
Non-ferrous metals	<1%
Other materials	<1%
Recyclability: metals 98%	
Remainder (% of wind turbine by weight)	**2%**
% recyclability of Remainder:	47%
Steel and iron	28%
Non-ferrous metals	23%
Polymers	28%
Electronics	5%
Other materials	16%
Recyclability: metals >90%	

It can be seen that the high recycling rates of metals in the various components of the V112 wind turbine contribute the largest share towards the overall recyclability of the turbine.

6 Sensitivity Analyses

This section details the sensitivity assessments that have been carried out in this study to better understand the effect and importance of uncertainties in the data or of applying different methodologies during the modelling.

6.1 Wind plant life time

The life time of the wind plant in the baseline scenario is assumed to be 20 years. Vestas has indicated based on professional experience that this figure might vary up to even 30 years. The analysis in this section has been carried out to account for this uncertainty in the duration of the life time of the wind plant**.** A variance of ±4 years has been chosen for this analysis.

Assuming all other variables remain fixed it is obvious that increasing the life time of the wind plant will lead to lower emissions per kWh as the impacts associated with manufacturing the wind turbines are amortised over a longer period of time.

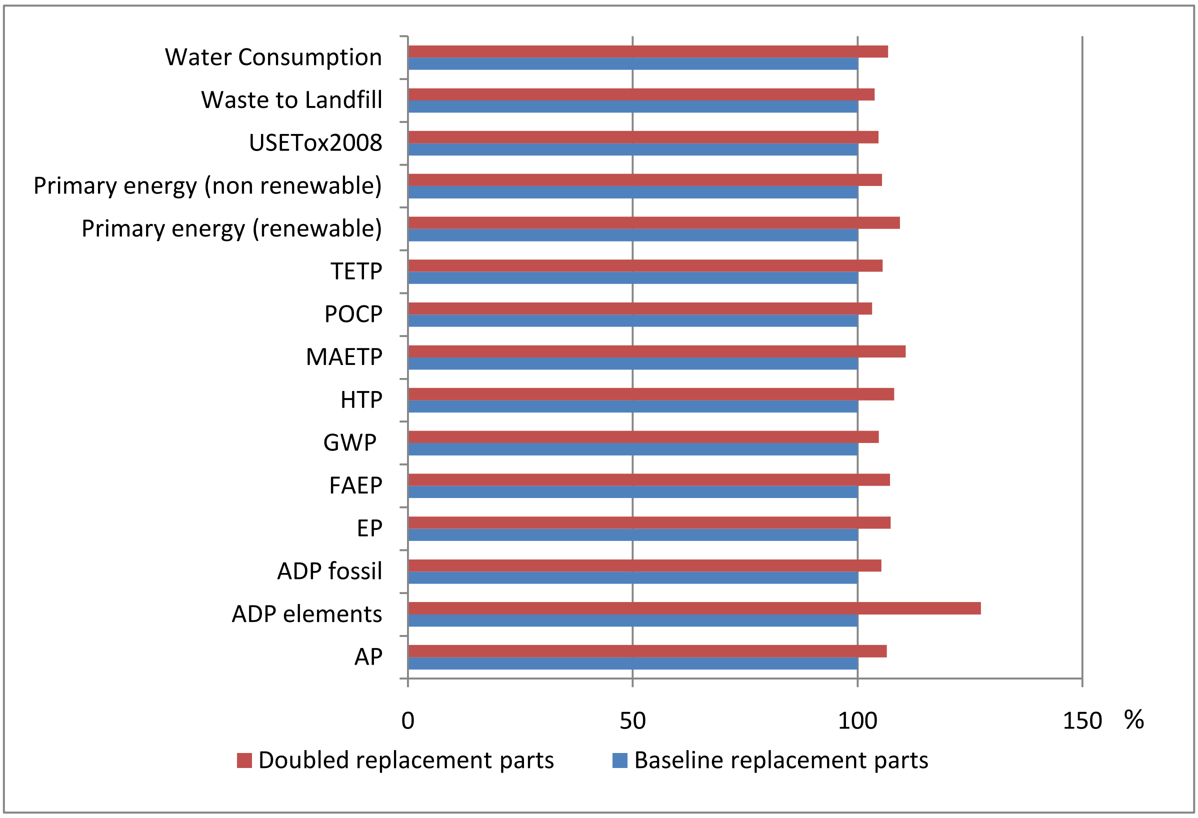
This assessment shows that all impact categories show a 25% increase in potential environmental impacts when the life time of the wind plant is reduced by 4 years, and a 27% reduction when the lifetime is increased by 4 years.

It may be expected that the requirement for maintenance and replacement parts will correlate with the life time of the wind plant (i.e. longer life time implies increased maintenance). However there is considerable uncertainty and variation in the frequency and requirement of maintenance and replacement parts and so this issue is considered in a separate sensitivity analysis.

6.2 Replacement parts

As noted in section 6.1, there is significant variation in the degree of maintenance and the need for replacement parts for a given wind turbine park. Based on Vestas' experience, "typical" figures for replacement parts have been built into the LCA model of the V112 wind plant for a baseline scenario. The analysis carried out in this section explores the impacts of doubling the frequency of the need for replacement parts (a very conservative estimate).

Figure 21: A comparison of the effects of doubling replacement parts used over the life of the wind plant



For most impact categories, doubling the frequency of the need for replacement parts increases impacts by 5-10%. This indicates that the frequency with which parts have to be replaced has a moderately significant effect on the environmental performance the wind plant.

The exception to this rule is Abiotic Resource Depletion (elements), which shows a much greater than average sensitivity to this issue.

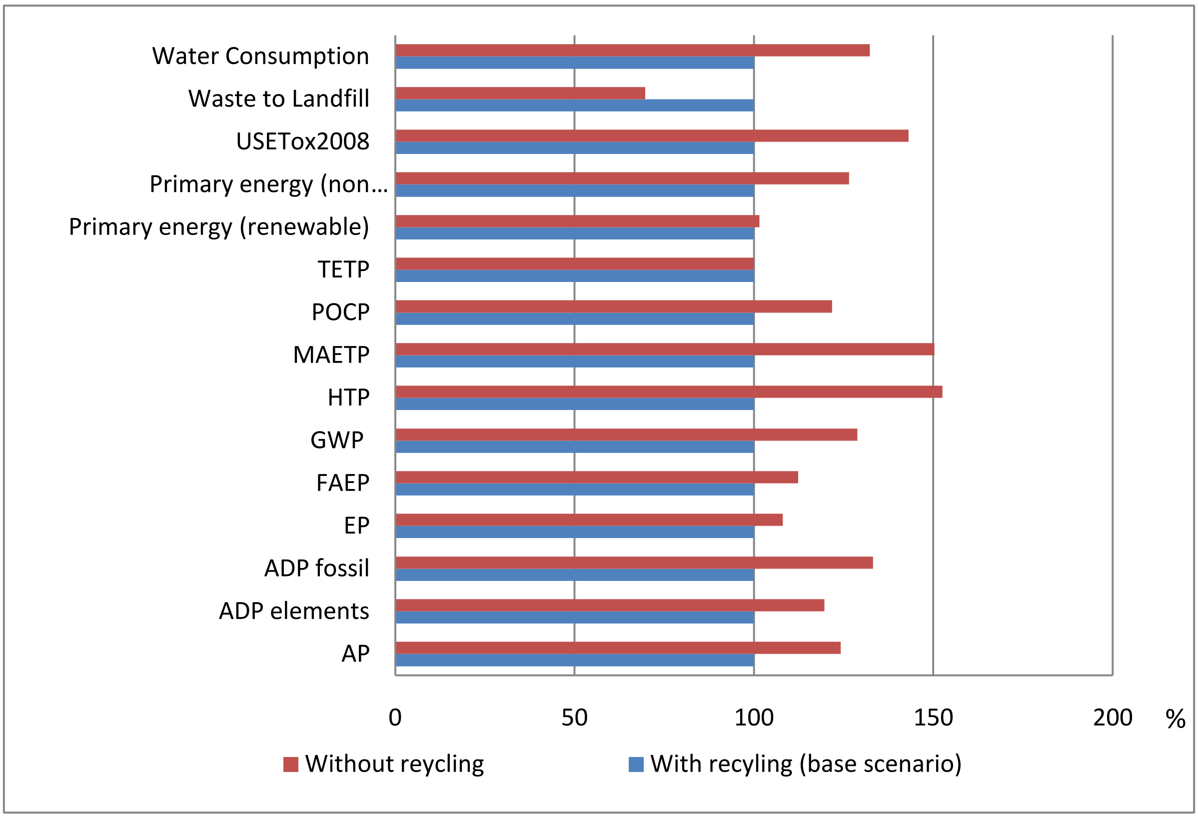
Production of gear and mainshaft components accounts for about 36% of the impacts in the ADP (elements) category across the full life cycle. Of this, the contribution from the high alloyed steels used in the gear box accounts for the overwhelming majority of impacts (>94%), and is due to consumption of alloying elements. It follows that doubling the frequency of replacements parts has a particularly marked impact in this category.

6.3 Environmental profile with and without end of life credits

The results given in Section 5 above clearly show that recycling has a net positive effect on the potential environmental impacts of the V112 wind plant over its life cycle for most impact categories. The figures for recycling used in the LCA modelling in this study are primarily sourced from data provided by Vestas research and estimates based on Vestas expert judgment.

This sensitivity analysis examines the effects on the results of modelling the product system with no credits given for recycling at end of life.

Figure 22: A comparison of the effects of discounting the effects of recycling wind plant components at end of life



The chart clearly shows, as expected, that when credits are not given for end of life recycling there is generally an increase in environmental impact. However, the range of this increase varies from very small (such as for terrestrial ecotoxicity and renewable primary energy), through to very large (such as for water consumption, USEtox, marine aquatic ecotoxicity, human toxicity) with other impact categories also showing significant increases.

When recycling is not modelled, the amount of waste sent to landfill is seen to reduce. This is because the recycling process has some wastes associated with it. If recycling is not modelled then this waste is not included in the results.

7 Scenario Analyses

The following scenario analyses have been carried out in this study to assess the effects that possible changes to a wind plant system will have on its environmental performance over its life cycle

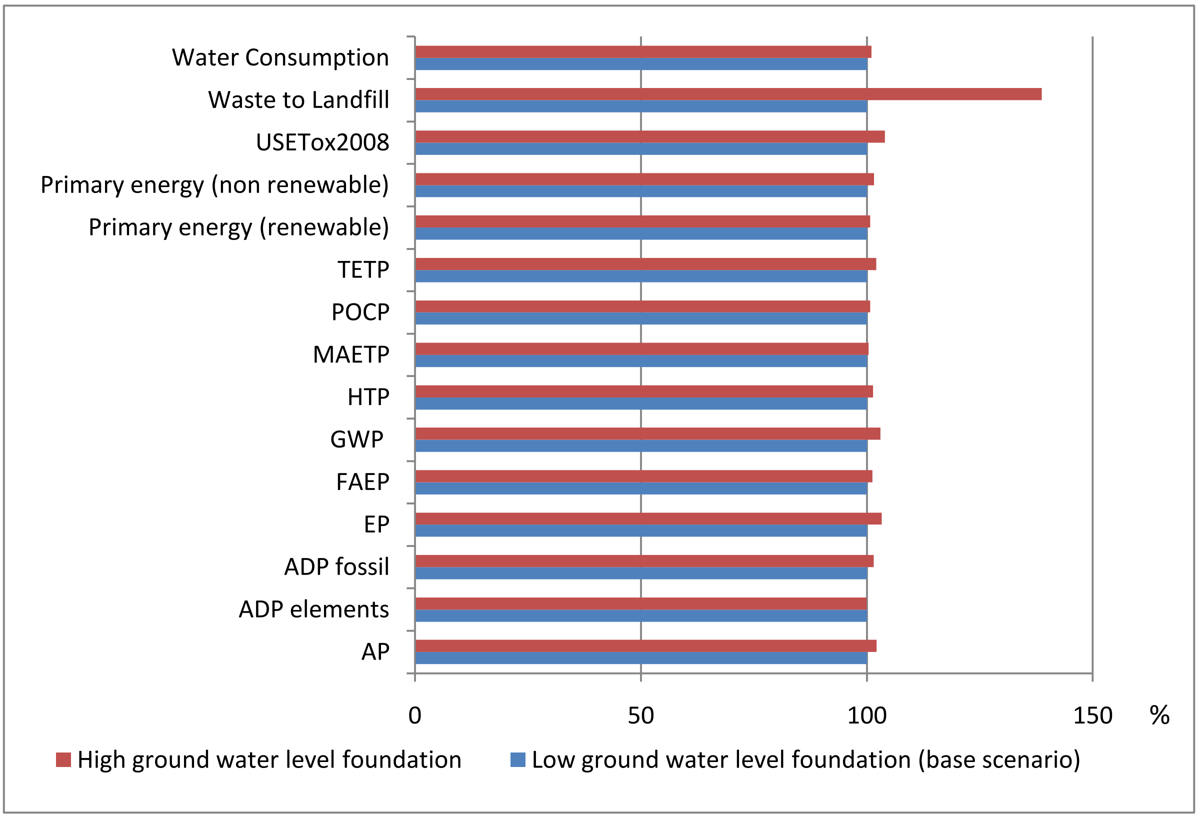
7.1 100 MW wind plant operating under low wind (IEC III) vs. medium wind (IEC II) conditions

For the baseline case in this study it was assumed that the wind plant is located on a site with medium wind conditions (IEC II). This is based on Vestas' experience of the industry as well as their expert judgement in the field. However, the Vestas V112 3.0 MW wind turbine is designed to operate under low (IEC III) to medium (IEC II) wind conditions.

The only major difference between the two scenarios is that low wind conditions result in a lower overall power output. Hence this analysis is similar to that in section 6.1 comparing wind plant life time. It is found that low wind conditions results in a 23% increase in potential environmental impacts across all categories compared to medium wind conditions. Recyclability, however, remains unchanged.

7.2 Low ground water level type foundation vs. high ground water level type foundations

Figure 23: A comparison of the effects of using low ground water level type foundations of high ground water level type foundations



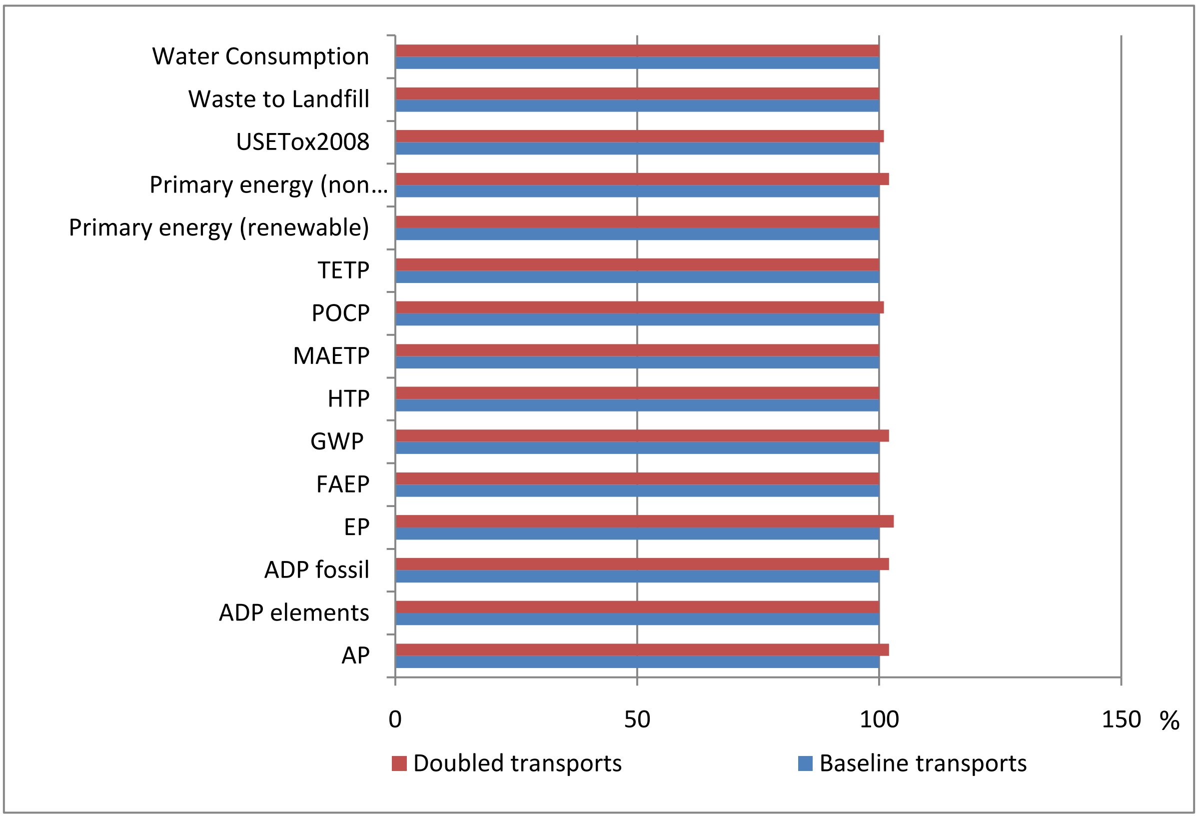
The baseline scenario for this LCA study assumes that the wind plant site is located on an area with a low ground water level. This assessment considers the impact on the results of building the wind plant in a location with a high ground water level – requiring more robust foundations (increased quantities of concrete and steel). Other factors in the model are unchanged.

Figure 23 shows that the choice of foundation has only minor effects on the environmental performance of the wind plant. A majority of the impact categories show a slight increase with the use of the high ground water level type foundations. This increase ranges from 0.3 to 3% across all impact categories apart from waste to landfill category.

A significant amount of the materials in the wind plant are recycled at end of life. The concrete in the foundations, however, is assumed to go directly to landfill and is responsible for the majority of this landfilled waste. The large increase in the proportion of waste to landfill in the chart above directly corresponds to the increase in the amount of concrete used in the high ground water level foundation as compared to the low ground water level foundations.

7.3 Transport distance to wind plant

Figure 24: A comparison of the effects of doubling all transport distances considered in the scope of the LCA study



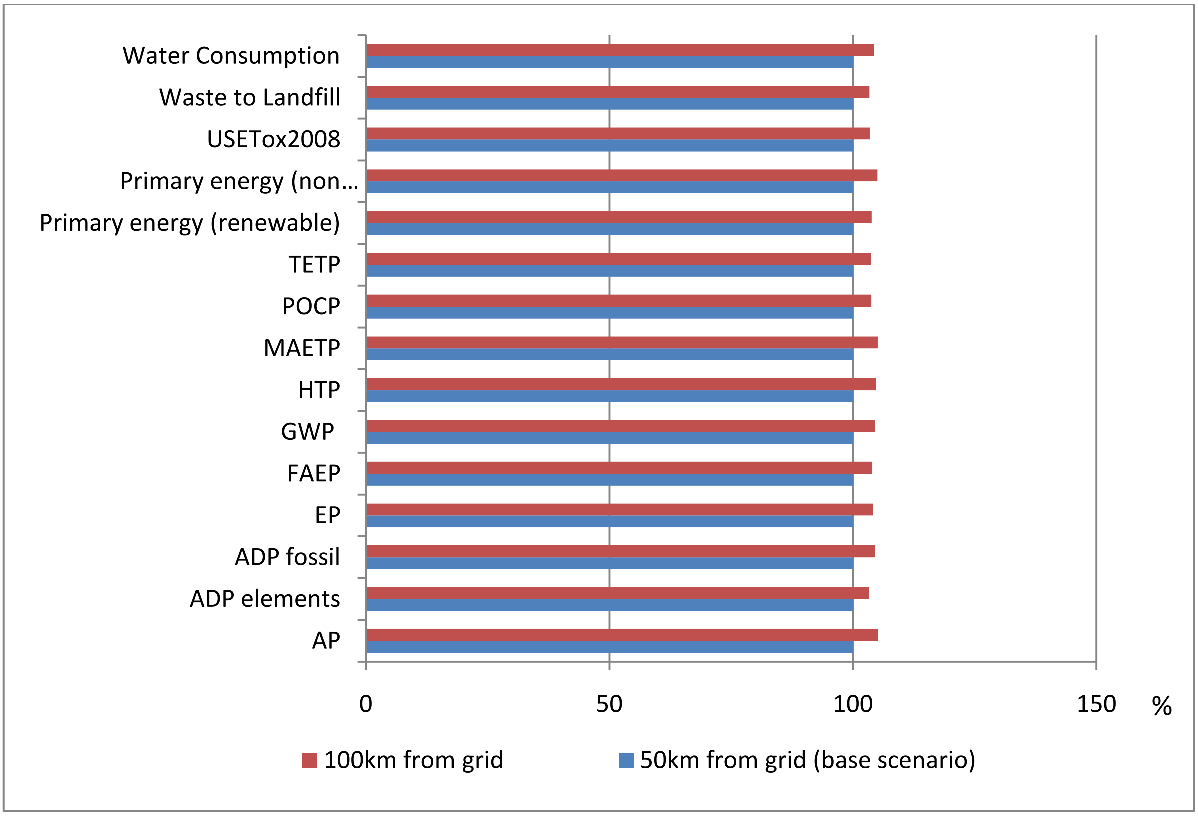
The transport distance for moving components from the Vestas production site to the wind plant obviously depends on the location of the wind plant. This scenario analysis explores the importance of transport impacts on the overall environmental performance of the wind plant by comparing the transport distances in the baseline scenario to a situation where all transport distances are doubled.

Figure 5, in section 5 shows that impacts from transport have only a minor contribution to the overall life cycle impacts of a wind plant. As a result, and as shown in the chart above, doubling the transport does not have a noticeable impact on the results – with an increase in the range of 1-3% across all categories.

7.4 Distance of wind plant from grid

The distance of the wind plant from the existing grid is another variable that will change from site to site. The baseline scenario for this study assumes that the wind plant is located 50 km away from the grid and includes an assumed 3% distribution total loss. This analysis considers the situation where the wind plant is located 100 km and from the existing grid away and accounts for the increased quantity of transmission cabling required and assumed that distribution losses are doubled to 6%.

Figure 25: A comparison of the effects of doubling the distance of the wind plant to an existing power grid



The chart above shows that increasing the distances of the wind plant from the grid, factoring in more materials used for transmission cables and corresponding losses does not have such a significant effect on the environmental performance of a wind plant. There is a general increase of 3-5% in the impacts across each category when the distance from the wind plant to the existing grid is doubled.

8 Wind power compared to conventional grid electricity

An interesting aspect to consider when assessing the environmental performance of wind plants is the point in time after which the environmental burdens of producing the wind plant are outweighed by the environmental benefits of the renewable energy that is generated.

In Vestas' previous LCA studies an energy balance was calculated showing the relationship between the energy requirement for the whole life cycle of the wind plant and the power output from the wind plant. Following this approach, the breakeven time after which the power production outweighs the power required over the lifetime of the V112 wind plant is:

$$\frac{253{,}695 \text{ MWh/wind plant}}{376{,}061 \text{ MWh/wind plant.year}} = 0.67 \text{ years} \approx 8.0 \text{ months}$$

An alternative way of assessing this balance is to compare against the impacts from the local grid mix in the region where the wind plant is located.

The following approach has been taken to calculate this breakeven point for primary energy and global warming potential:

- The power output of the wind plant over one year is compared against impacts produced by an equivalent amount of power from the grid in three regions – Australia, Europe (EU) and the USA.
- The impacts of the total wind plant life cycle are assessed and scaled against each grid mix to determine how much grid power this equates to.
- The time required to offset this amount of grid power is then calculated and reported in months.

Table 10: Breakeven point for primary energy and GWP assessed against grid production in different regions (wind plant operating in medium wind conditions)

Category	Recycling scenario	Breakeven point, months		
		Australia	Europe	USA
Primary energy	With recycling	2.2	2.4	2.4
	Without recycling	2.7	3.0	2.9
Global warming potential	With recycling	1.4	2.9	2.1
	Without recycling	1.8	3.7	2.8

Table 11: Breakeven point for primary energy and GWP assessed against grid production in different regions (wind plant operating in low wind conditions)

Category	Recycling scenario	Breakeven point, months		
		Australia	Europe	USA
Primary energy	With recycling	2.7	3.0	2.9
	Without recycling	3.3	3.5	3.5
Global warming potential	With recycling	1.7	3.6	2.6
	Without recycling	2.2	4.6	3.4

The different values for each region are a reflection of the differing grid mixes in each region. For example the breakeven point for global warming potential in Europe is longer than that for Australia because European grid power production is less carbon intensive. The results show a breakeven point of less than 3 months for the V112 wind plant at medium wind conditions in all cases and under 5 months for low wind conditions.

These results also show that the breakeven point is shorter when modelling the system with credits for recycling at end of life (as this approach reduces the overall impact of the wind plant life cycle).

9 Interpretation

9.1 General

The results described in this report show the environmental profile of the production of electricity from a wind plant comprising thirty-three V112 3.0 MW wind turbines. This LCA is the most comprehensive and detailed ever undertaken by Vestas and will provide the benchmark for future studies by the company.

Overall, the results show that for every impact category assessed the largest impacts are associated with the raw material production and manufacturing phase of the life cycle. In most cases these are much greater than those occurring elsewhere in the supply chain for the complete wind park.

Within the manufacturing stage the production of the tower itself typically accounts for the largest impacts; this reflects the large quantity of steel required to produce this part of the wind turbine. The production of the nacelle and of the gear and mainshaft also result in significant impacts. Manufacture of the blades for the turbine also has quite significant impacts, while production of other parts of the wind turbine is generally less important in comparison.

End of life processes are also significant for many impact categories and normally credit the product system – showing the benefits of the high recycling rate achieved for wind turbine infrastructure.

Wind plant construction and site operations generally do not make a significant contribution to the overall life cycle impacts of the wind plant.

Transport of wind plant components to site make a very insignificant contribution to the overall life cycle impacts of the wind plant.

9.2 Sensitivity analyses

The sensitivity analyses show that assumptions on the lifetime of the wind plant can have a large influence on the results. Increasing the lifetime from 20 to 24 years, results in a 27% drop in all environmental impacts. This does not account for any increased maintenance that may be required, but a second sensitivity analysis shows that most impact categories are not particularly sensitive to this issue.

The recycling methodology used also plays an important role in the results. Recycling rates for wind turbines are quite high and, as noted above, in the baseline scenario (where credits are given for recycling) the end of life has a significant contribution to the total results. If no benefit is given for recycling, the end of life stage will have a much small contribution and overall impacts in most categories will increase substantially as the production impacts are no longer offset by recycling credits.

9.3 Scenario analyses

Wind conditions for the wind plant determine how much energy is generated over its lifetime. If the wind plant operates in low wind conditions (IEC III) then the impacts per kWh electricity produced increases by 23% compared to medium wind conditions (IEC II). This finding emphasises the importance of location in wind plant planning to maximise the efficiency of electricity generation. The findings also reinforce the fact that any comparison between wind power plants should only be made within a specific wind class.

Another location-dependent issue is the level of the water table, which determines the size of the foundations required to support the wind turbines. Regions with a high water table require more robust foundations. However, with the exception of waste to landfill, the results are not sensitive to this difference. Likewise, the transport distance of the components from the factory to the wind plant site is shown to have very little impact on the overall results

The location of the wind plant with respect to the local grid infrastructure plays a more important role as it affects distribution losses and adds additional requirement for cabling. Doubling the distance to the grid from 50 km to 100 km typically increases impacts per kWh by 3-5%.

9.4 Robustness of results

9.4.1 Data completeness

A wind plant comprising thirty-three V112 3.0 MW wind turbines has been assessed and data have been collected and modelled according to the cut-off criteria defined in the Goal & Scope Definition Document developed at the start of the study and summarised in Section 3.3. Based on these criteria all relevant inputs of fuels and power and of raw materials have been measured and included in the assessment.

9.4.2 Data consistency

All foreground data have been provided by Vestas for the same period of operation. Background data have been obtained from various reputable sources (e.g. ELCD, trade association and PE datasets) and are considered to be of high quality.

9.4.3 Data representativeness

The representativeness of the data used in the model is summarised in Table 14 in Appendix B and is considered to be good.

9.4.4 Reproducibility

The product system being modelled is very complex and requires specialist LCA software (GaBi DfX) to generate results. Some of the datasets used are also specialised and are derived from PE’s extensive experience of LCA modelling in a wide range of industry sectors.

However, it is our expectation that an independent practitioner following the same standards and using LCA tools with the same functionality and with appropriate support from Vestas would be able to closely reproduce the results of this study.

9.4.5 Opportunities for improvement

Future LCA studies carried out by Vestas could be further improved by considering the following activities:

- Obtain more disaggregated information on Vestas' manufacturing operations (currently data are only available at factory level)
- Improve reporting of manufacturing data to more comprehensively account for mass flow inputs and outputs
- Develop a better understanding of applicable recycling technologies and the recyclability of different components to enable more precise modelling of the end of life process stage
- Improve understanding of the fate of sulphur hexafluoride in the switch gear
- Gather additional information on electrical/electronics components so these can be modelled in greater detail
- Collect information on inbound transport of purchased components so these processes steps can be included in future assessments

10 Literature

ABB 2005	ABB - Environmental Product Declaration, Power transformer TrafoStar 500MVA
ATHERTON, J. 2007	Atherton, J. - Declaration by the metals industry on recycling principles, International Journal of LCA, vol. 12 (1), Pg 59-60
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NKT CABLES 2005	NKT Cables - Green account from NKT Cables, Asnaes, 2005
PE AMERICA 2010	PE America - Life Cycle Assessment of Aluminum Beverage Cans for the Aluminum Association Inc., Washington DC, 2010
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Supplement A Description of result parameters

Supplement A 1 Primary energy consumption

Primary energy demand is often difficult to determine due to the various types of energy source. Primary energy demand is the quantity of energy directly withdrawn from the hydrosphere, atmosphere or geosphere or energy source without any anthropogenic change. For fossil fuels and uranium, this would be the amount of resource withdrawn expressed in its energy equivalent (i.e. the energy content of the raw material). For renewable resources, the energy-characterised amount of biomass consumed would be described. For hydropower, it would be based on the amount of energy that is gained from the change in the potential energy of the water (i.e. from the height difference). As aggregated values, the following primary energies are designated:

The total **“Primary energy consumption non renewable”**, given in MJ, essentially characterises the gain from the energy sources natural gas, crude oil, lignite, coal and uranium. Natural gas and crude oil will be used both for energy production and as material constituents e.g. in plastics. Coal will primarily be used for energy production. Uranium will only be used for electricity production in nuclear power stations.

The total **“Primary energy consumption renewable”**, given in MJ, is generally accounted separately and comprises hydropower, wind power, solar energy and biomass.

It is important that the end energy (e.g. 1 kWh of electricity) and the primary energy used are not miscalculated with each other; otherwise the efficiency for production or supply of the end energy will not be accounted for.

The energy content of the manufactured products will be considered as feedstock energy content. It will be characterised by the net calorific value of the product. It represents the still usable energy content.

Supplement A 2 Waste categories

There are various different qualities of waste. Waste is categorised according to e.g. German and European waste directives.

From the balancing point of view, it makes sense to divide waste into three categories. The categories overburden/tailings, industrial waste for municipal disposal and hazardous waste will be used.

Overburden / tailings in kg: This category is made up of the layer which has to be removed in order to get access to raw material extraction, ash and other raw material extraction conditional materials for disposal. Also included in this category are tailings such as inert rock, slag, red mud etc.

Industrial waste for municipal disposal in kg: This term contains the aggregated values of industrial waste for municipal disposal.

Hazardous waste in kg: In this category, materials that will be treated in a hazardous waste incinerator or hazardous waste landfill, such as painting sludges, galvanic sludges, filter dusts or other solid or liquid hazardous waste and radioactive waste from the operation of nuclear power plants and fuel rod production.

Supplement A 3 Global Warming Potential (GWP)

The mechanism of the greenhouse effect can be observed on a small scale, as the name suggests, in a greenhouse. These effects are also occurring on a global scale. The occurring short-wave radiation from the sun comes into contact with the earth's surface and is partly absorbed (leading to direct warming) and partly reflected as infrared radiation. The reflected part is absorbed by so-called greenhouse gases in the troposphere and is re-radiated in all directions, including back to earth. This results in a warming effect at the earth's surface.

In addition to the natural mechanism, the greenhouse effect is enhanced by human activities. Greenhouse gases that are considered to be caused, or increased, anthropogenically are, for example, carbon dioxide, methane and CFCs. The figure shows the main processes of the anthropogenic greenhouse effect. An analysis of the greenhouse effect should consider the possible long term global effects.

The global warming potential is calculated in carbon dioxide equivalents (CO_2-Eq.). This means that the greenhouse potential of an emission is given in relation to CO_2 Since the residence time of the gases in the atmosphere is incorporated into the calculation, a time range for the assessment must also be specified. A period of 100 years is customary.

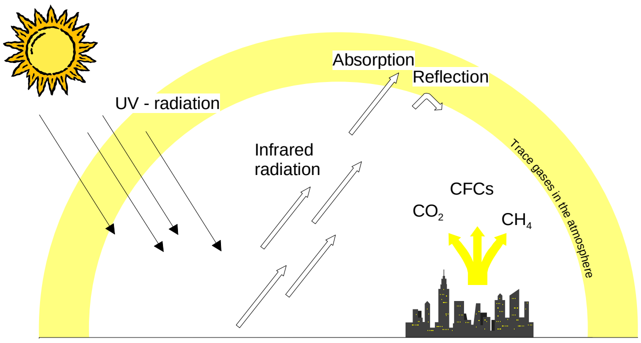


Figure 26: Greenhouse effect (KREISSIG & KÜMMEL 1999)

Supplement A 4 Acidification Potential (AP)

The acidification of soils and waters occurs predominantly through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater and fog from 5.6 to 4 and below. Sulphur dioxide and nitrogen oxide and their respective acids (H_2SO_4 und HNO_3) produce relevant contributions. This damages ecosystems, whereby forest dieback is the most well-known impact.

Acidification has direct and indirect damaging effects (such as nutrients being washed out of soils or an increased solubility of metals into soils). But even buildings and building materials can be damaged. Examples include metals and natural stones which are corroded or disintegrated at an increased rate.

When analysing acidification, it should be considered that although it is a global problem, the regional effects of acidification can vary. The figure displays the primary impact pathways of acidification.

The acidification potential is given in sulphur dioxide equivalents (SO_2-Eq.). The acidification potential is described as the ability of certain substances to build and release H^+ -ions. Certain emissions can also be considered to have an acidification potential, if the given S-, N- and halogen atoms are set in proportion to the molecular mass of the emission. The reference substance is sulphur dioxide.

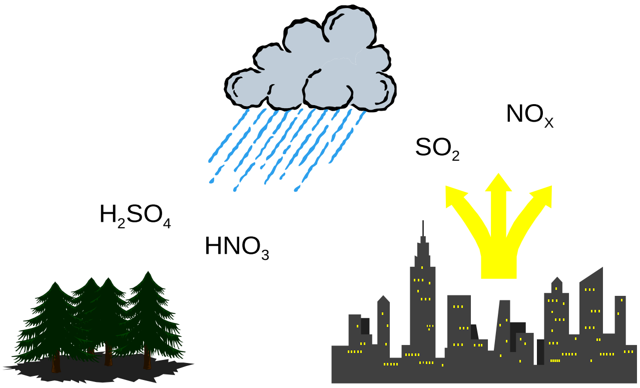


Figure 27: Acidification Potential (KREISSIG & KÜMMEL 1999)

Supplement A 5 Eutrophication Potential (EP)

Eutrophication is the enrichment of nutrients in a certain place. Eutrophication can be aquatic or terrestrial. Air pollutants, waste water and fertilization in agriculture all contribute to eutrophication.

The result in water is an accelerated algae growth, which in turn, prevents sunlight from reaching the lower depths. This leads to a decrease in photosynthesis and less oxygen production. In addition, oxygen is needed for the decomposition of dead algae. Both effects cause a decreased oxygen concentration in the water, which can eventually lead to fish dying and to anaerobic decomposition (decomposition without the presence of oxygen). Hydrogen sulphide and methane are thereby produced. This can lead, among others, to the destruction of the eco-system.

On eutrophicated soils, an increased susceptibility of plants to diseases and pests is often observed, as is a degradation of plant stability. If the nutrification level exceeds the amounts of nitrogen necessary for a maximum harvest, it can lead to an enrichment of nitrate. This can cause, by means of leaching, increased nitrate content in groundwater. Nitrate also ends up in drinking water.

Nitrate at low levels is harmless from a toxicological point of view. However, nitrite, a reaction product of nitrate, is toxic to humans. The causes of eutrophication are displayed in the figure. The eutrophication potential is calculated in phosphate equivalents (PO_4-Eq). As with acidification potential, it’s important to remember that the effects of eutrophication potential differ regionally.

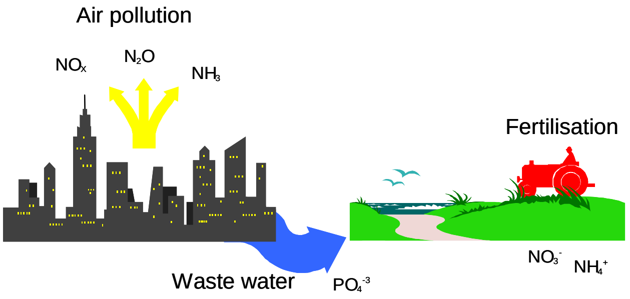


Figure 28: Eutrophication Potential (KREISSIG & KÜMMEL 1999)

Supplement A 6 Photochemical Ozone Creation Potential (POCP)

Despite playing a protective role in the stratosphere, at ground-level ozone is classified as a damaging trace gas. Photochemical ozone production in the troposphere, also known as summer smog, is suspected to damage vegetation and material. High concentrations of ozone are toxic to humans.

Radiation from the sun and the presence of nitrogen oxides and hydrocarbons incur complex chemical reactions, producing aggressive reaction products, one of which is ozone. Nitrogen oxides alone do not cause high ozone concentration levels.

Hydrocarbon emissions occur from incomplete combustion, in conjunction with petrol (storage, turnover, refuelling etc.) or from solvents. High concentrations of ozone arise when the temperature is high, humidity is low, when air is relatively static and when there are high concentrations of hydrocarbons. Today it is assumed that the existence of NO and CO reduces the accumulated ozone to NO_2, CO_2 and O_2. This means, that high concentrations of ozone do not often occur near hydrocarbon emission sources. Higher ozone concentrations more commonly arise in areas of clean air, such as forests, where there is less NO and CO.

In Life Cycle Assessments, photochemical ozone creation potential (POCP) is referred to in ethylene-equivalents (C_2H_4-Äq.). When analysing, it's important to remember that the actual ozone concentration is strongly influenced by the weather and by the characteristics of the local conditions.

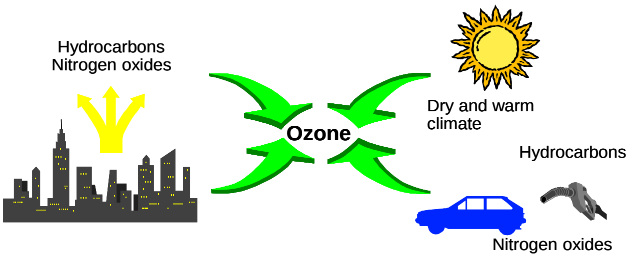


Figure 29: Photochemical Ozone Creation Potential (Kreissig & Kümmel 1999)

Supplement A 7 Ozone Depletion Potential (ODP)

Ozone is created in the stratosphere by the disassociation of oxygen atoms that are exposed to short-wave UV-light. This leads to the formation of the so-called ozone layer in the stratosphere (15 - 50 km high). About 10 % of this ozone reaches the troposphere through mixing processes. In spite of its minimal concentration, the ozone layer is essential for life on earth. Ozone absorbs the short-wave UV-radiation and releases it in longer wavelengths. As a result, only a small part of the UV-radiation reaches the earth.

Anthropogenic emissions deplete ozone. This is well-known from reports on the hole in the ozone layer. The hole is currently confined to the region above Antarctica; however another ozone depleted region can be identified, albeit not to the same extent, over the mid-latitudes (e.g. Europe). The substances which have a depleting effect on the ozone can essentially be divided into two groups; the fluorine-chlorine-hydrocarbons (CFCs) and the nitrogen oxides (NOX). The figure depicts the procedure of ozone depletion.

One effect of ozone depletion is the warming of the earth's surface. The sensitivity of humans, animals and plants to UV-B and UV-A radiation is of particular importance. Possible effects are changes in growth or a decrease in harvest crops (disruption of photosynthesis), indications of tumours (skin cancer and eye diseases) and decrease of sea plankton, which would strongly affect the food chain. In calculating the ozone depletion potential, the anthropogenically released halogenated hydrocarbons, which can destroy many ozone molecules, are recorded first. The so-called Ozone Depletion Potential (ODP) results from the calculation of the potential of different ozone relevant substances.

This is done by calculating, first of all, a scenario for a fixed quantity of emissions of a CFC reference (CFC 11). This results in an equilibrium state of total ozone reduction. The same scenario is considered for each substance under study whereby CFC 11 is replaced by the quantity of the substance. This leads to the ozone depletion potential for each respective substance, which is given in CFC 11 equivalents. An evaluation of the ozone depletion potential should take into consideration the long term, global and partly irreversible effects.

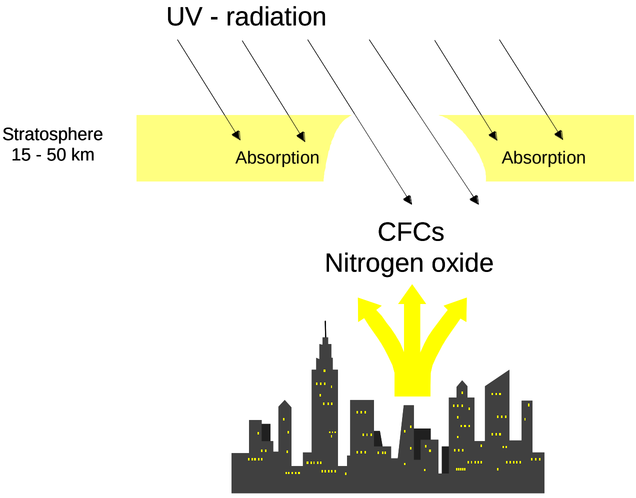


Figure 30: Ozone Depletion Potential (KREISSIG & KÜMMEL 1999)

Supplement A 8 Human Toxicity Potential and Terrestrial, Freshwater & Marine Aquatic Eco-toxicity Potentials

The method for the impact assessment of toxicity potential is still, in part, in the development stage. The Human Toxicity Potential (HTP) assessment aims to estimate the negative impact of, for example, a process on humans. The Eco-Toxicity potential aims to outline the damaging effects on an ecosystem. This is differentiated into Terrestrial Eco-Toxicity Potential (TETP), Fresh water Aquatic Ecotoxicity Potential (FAETP) and Marine Aquatic Eco-Toxicity Potential (MAETP).

In general, one distinguishes acute, sub-acute/sub-chronic and chronic toxicity, defined by the duration and frequency of the impact. The toxicity of a substance is based on several parameters. Within the scope of life cycle analysis, these effects will not be mapped out to such a detailed level. Therefore, the potential toxicity of a substance based on its chemical composition, physical properties, point source of emission and its behaviour and whereabouts, is characterised according to its release to the environment. Harmful substances can spread to the atmosphere, into water bodies or into the soil. Therefore, potential contributors to important toxic loads are ascertained.

Characterisation factors are calculated through the “Centre of Environmental Science (CML), Leiden University”, and the “National Institute of Public Health and Environmental Protection (RIVM), Bilthoven“, based on the software USES 1.0 [GUINÉE ET AL. 1996]. The model, LCA-World, which underlies the calculation, is based on the assumptions of a slight exchange of rainwater and air (western Europe), long residence times of substances, moderate wind and slight transposition over the system boundaries.

The surface of the model is divided into 3% surface water, 60% natural soil, 27% agricultural soil and 10% industrial soil. 25% of the rainwater is infiltrated into the soil.

The potential toxicities (human, aquatic and terrestrial ecosystems) are generated from a proportion based on the reference substance 1,4-Dichlorbenzol ($C_6H_4Cl_2$) in the air reference section. The unit is kg 1,4-Dichlorbenzol-Equiv. (kg DCB-Äq.) per kg emission [GUINÉE ET AL. 2002].

The identification of the toxicity potential is afflicted with uncertainties because the impacts of the individual substances are extremely dependent on exposure times and various potential effects are aggregated. The model is therefore based on a comparison of effect and exposure assessment. It calculates the concentration in the environment via the amount of emission, a distribution model and the risk characterisation via an input sensitive module. Degradation and transport in other environmental compartments are not represented.

Toxicity potential can be calculated with toxicological threshold values, based on a continuous exposure to the substance. This leads to a division of the toxicity into the groups mentioned above (HTP, MAETP, TETP) for which, based on the location of the emission source (air, water, soil), three values are calculated. Consequently, there is a matrix for toxic substances with rows of the various toxicities that have impacts on both humans and aquatic and terrestrial ecosystems, and columns of the extent of the toxic potential, considering the different emission locations.

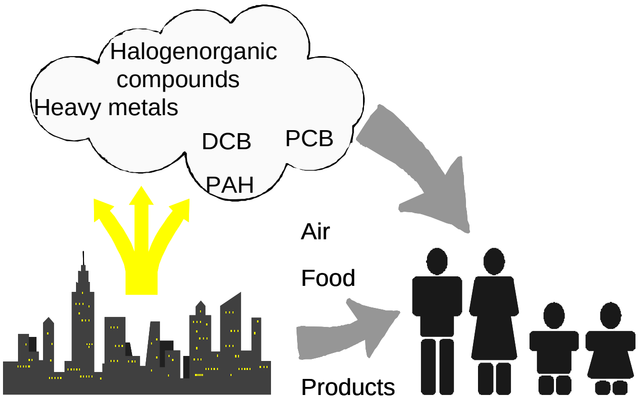


Figure 31: Human Toxicity Potential (IKP 2003)

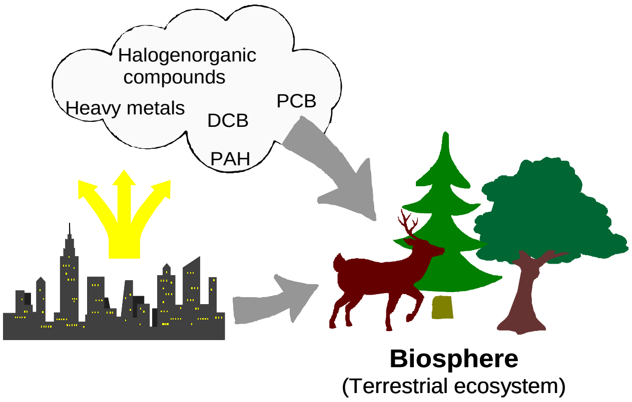


Figure 32: Terrestrial Eco-Toxicity Potential (IKP 2003)

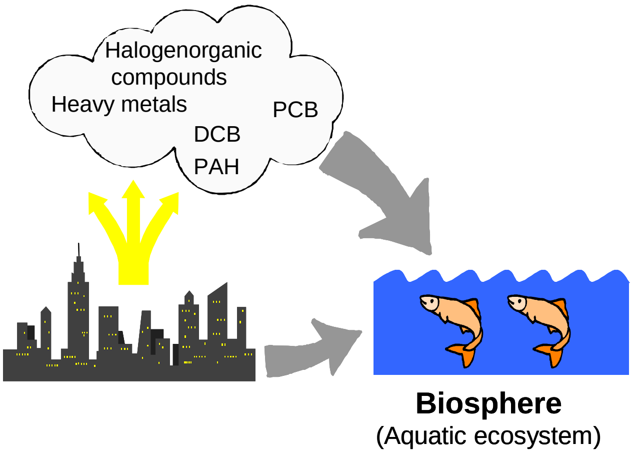


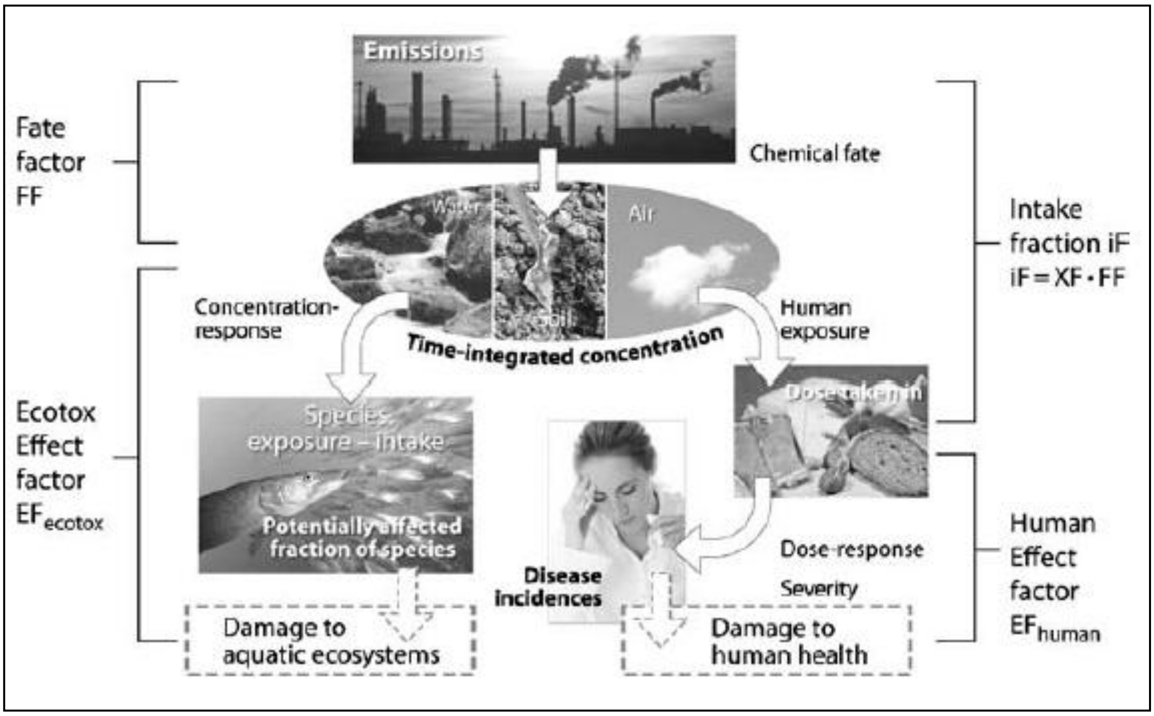
Figure 33: Marine Aquatic Eco-Toxicity Potential (IKP 2003)

Supplement A 9 USEtox 2008 Ecotoxicity

USEtox calculates characterisation factors for human toxicity and freshwater ecotoxicity. As demonstrated in Fig. A9, assessing the toxicological effects of a chemical emitted into the environment implies a cause–effect chain that links emissions to impacts through three steps: environmental fate, exposure and effects. Linking these, a systematic framework for toxic impacts modelling based on matrix algebra was developed within the OMNIITOX project (Rosenbaum et al. 2007) and peer reviewed in a UNEP–SETAC workshop by an independent expert panel, who recommended the framework for further developments within the Life Cycle Initiative, where it was then adopted for USEtox (Jolliet et al. 2006). The links of the cause–effect chain are modelled using matrices populated with the corresponding factors for the successive steps of fate (FF) in day, exposure (XF) in day−1 (only human toxicity) and effects (EF) in $\text{cases/kg}_{\text{intake}}$ for human toxicity or PAF m3/kg for ecotoxicity. This results in a set of scale-specific characterisation factors (CF) in $\text{cases/kg}_{\text{emitted}}$, as shown in the equation below.

$$(CF) = (EF) \text{ x } (XF) \text{ x } (FF) = (EF) \text{ x } (iF)$$

Figure 34: USEtox framework for comparative ecotoxicity assessment [UNEP-SETAC 2008]



USEtox provides a parsimonious and transparent tool for human health and ecosystem CF estimates. It has been carefully constructed as well as evaluated via comparison with other models and falls within the range of their results whilst being less complex. It may thus serve as an interface between the more sophisticated state-of-the-art expert models (such as those compared in this study and which frequently change due to latest scientific developments being included) and the need of practitioners for transparency, broad stakeholder acceptance and stability of factors and methods applied in LCA. Based on a referenced database, USEtox has been used to calculate CFs for several thousand substances and forms the basis of the recommendations from UNEP–SETAC's Life Cycle Initiative regarding characterisation of toxic impacts in life cycle assessment. USEtox therefore provides the largest substance coverage presently available in term of numbers of chemicals covered. Furthermore, model uncertainty has partly been quantified. USEtox thus represents a significantly improved basis for a wider application of human health and ecotoxicity characterisation factors in LCA [UNEP-SETAC 2008].

Supplement A 10 Abiotic Depletion Potential (fossil)

The abiotic depletion potential covers all natural resources (incl. fossil energy carriers) as metal containing ores, crude oil and mineral raw materials. Abiotic resources include all raw materials from non-living resources that are non-renewable. This impact category describes the reduction of the global amount of non-renewable raw materials. Non-renewable means a time frame of at least 500 years. This impact category covers an evaluation of the availability of natural elements in general, as well as the availability of fossil energy carriers. The reference substance for the characterisation factors is antimony.

Supplement A 11 Abiotic Depletion Potential (Elements)

APD describes the quantity of non energetic resources directly withdrawn from the geosphere. It reflects the scarcity of the materials in the geosphere and is expressed in Antimony equivalents. The characterization factors are published by the CML, Oers 2010.

Supplement A 12 Water use

Water is a renewable resource and in general (barring chemical reactions) it is neither created nor destroyed. However it may change from one form to another (liquid water, vapour/steam or ice) or change quality (i.e. become polluted).

In this assessment net water use is calculated very simply as the liquid water taken from the environment minus the liquid water returned to the environment. Water in the form of vapour or steam emitted to atmosphere, or water incorporated into the finished product is considered to be lost as it is no longer directly available for reuse.

The data for this assessment have been obtained from primary sources at production sites. Data on raw materials production, transport and other background data have been sourced from PE datasets.

Water quality has not been assessed but to some extent this is covered by other impact categories such as eutrophication potential.

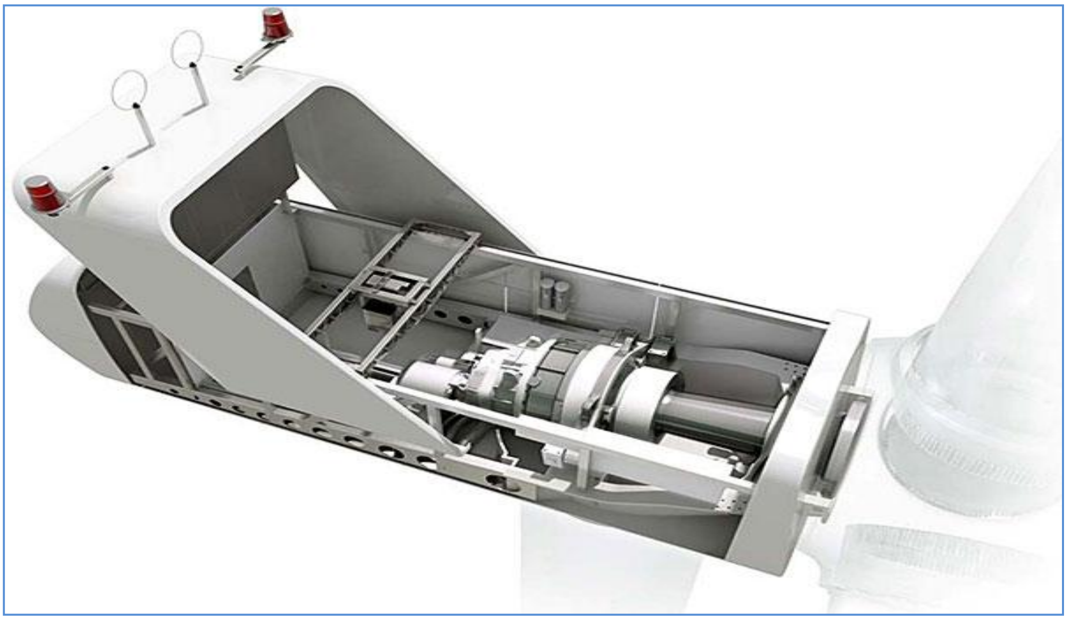
Supplement B General description of wind plant components

The key component of the typical wind plant is the wind turbine. The wind turbine is broken down mainly into the nacelle, the gear & mainshaft, the cooler top, the hub, the blades, the tower, the switch gear and the anchor. Detailed part information on the turbine components has been taken from the bill of materials and engineering drawings. These provide exact material and weight information down to the nuts and bolts that make up the turbine. Other components of an onshore wind plant are the tower foundations, internal cabling (on-site between turbines and the transformer), access roads, the wind plant transformer and cabling from transformer to the grid. Information for these parts was mostly taken from existing EPDs, design drawings as well as expert judgements.

Supplement B 1 Nacelle Module

The nacelle module is the most complicated component system of a wind turbine. The figure below shows the individual components of the nacelle module.

Figure 35: V112 3.0 MW 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. A description of the most significant individual components of the nacelle module is listed below:

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.

Main bearing

Data for the V112 3.0 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 V112 3.0 MW gearbox is based on supplier statement as well as expert judgement. According to the supplier, the gearbox mainly consists of steel and cast iron. The manufacturer has provided data for materials and energy consumption used during the manufacturing process, as well as waste generated.

Generator

According to the supplier, the generator mainly consists of steel, cast iron and copper. The manufacturer has provided data for materials and energy consumption used during the manufacturing process, as well as waste generated.

Machine foundation

The machine foundation is made from cast iron and produced at Vestas' casting facilities.

Nacelle cover

The nacelle cover is made from fibreglass, which consists of woven glass fibres, polyethylene (PET) and styrene.

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 top
- Cables

All parts mentioned above are also represented in this LCA with data about individual part's weight and materials composition listed out in the Bill of Materials

Supplement B 2 Blades

The turbine blades are a key component of the rotor system of a wind turbine. The blades are mainly produced at Vestas' blades factories.

Each blade is 55 meters long and comprises a web, which is glued between two blade shell sections. The main components of the blades are 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 36: V112 wind turbine blade

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

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 also included in this LCA as part of the Bill of Materials for the V112 3.0 MW wind turbine.

Supplement B 3 Hub

The hub and spinner are also parts of the rotor system. 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. All parts mentioned above are also represented in this LCA with data about individual part weight and material composition listed in the Bill of Materials

Supplement B 4 Tower

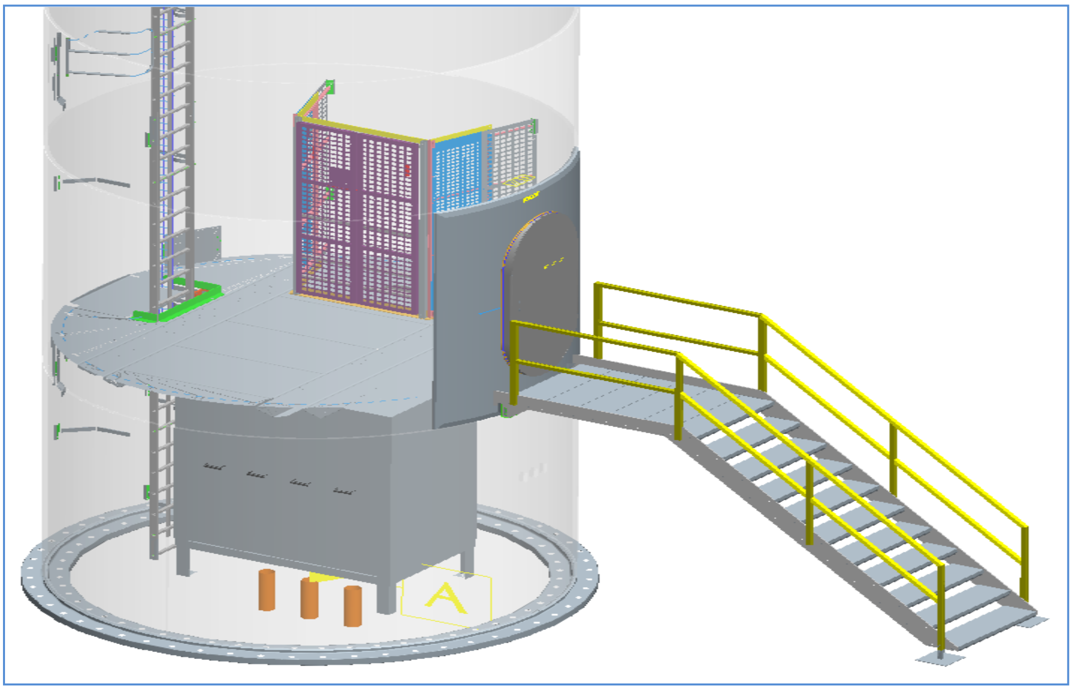
The tower accounts for a significant proportion of the entire wind turbine, both by size and mass. The figure below shows the structure of the bottom section a typical wind turbine tower and is followed by a description of the labelled parts.

The tower is 84 m high and is built for IEC IIA wind conditions. Other tower heights are available for other wind conditions for the V112 3.0 MW turbine.

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 primarily of structural 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.

Figure 37: Bottom section of tower for V112 3.0 MW Turbine



In this LCA study, 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.

Supplement B 5 Turbine Transformer

Data for the V112 3.0 MW turbine transformer is based on supplier data. According to the supplier, the transformer mainly consists of steel, copper, aluminium and resin. The manufacturer has provided data for the materials used, energy consumption used during the manufacturing process as well as waste generated.

Supplement B 6 Cables

Data for the cables in the tower is based on supplier statement. According to the supplier, the cables mainly consist of copper and plastics (Primarily EVA and EPDM). The manufacturer has provided data for the materials used, energy consumption used during the manufacturing process as well as waste generated.

Supplement B 7 Controller units and other electronics

The controller units mainly consist of signal and power electronics, which were approximated using customized GaBi datasets. Resource consumptions and emissions regarding welding wire, welding powder, paint, metalizing agent, grit for shot blasting and switchgear originates from information from the sub-suppliers and experts at Vestas.

Supplement B 8 Anchor

The anchor component is mainly composed of steel (cage), PVC and copper (for earthing). These materials are included in this LCA as part of the Bill of Materials for the V112 3.0 MW wind turbine.

Supplement B 9 Foundation

The turbines are erected on foundations. Each turbine foundation is linked to an access road and working/turning area. The construction of access roads is included in this LCA and described in more detail in a section below. There are two kinds of foundations for the 94m tower depending on the water level.

- High groundwater level - indicates a (maximum) ground water level equal to the level of the terrain; requires more concrete
- Low groundwater level – low ground water scenario

The low groundwater level case has been chosen as the base case as it represents the majority of wind park sites. Information on the material composition of the foundations was taken from design specifications. Construction of the foundation was not included in the model.

Supplement B 10 Internal and External Cables

32.54 km of 32 kV PEX cables with aluminium conductor is used as internal cables for the wind power plant, i.e. between the turbines and between the turbine plant and the 100MVA transformer. According to the supplier, the cables mainly consist of aluminium, copper and plastic. The manufacturer has provided data for the materials used, energy consumption used during the manufacturing process as well as waste generated.

50km of overhead cables are used to connect the park to the grid. These are mainly composed of aluminium and steel. Supporting structures are not included in this study.

Supplement B 11 Wind Plant Transformer

A 100 MVA transformer has been included in the wind plant. The transformer is modelled from an EPD from ABB on a Power transformer TrafoStar 500 MV and scaled down to 100 MVA.

Supplement B 12 Access roads

Generally a combination of tarred roads and dirt roads need to be built to provide access to the turbines, usually located in remote optimal wind areas. Expert judgement into the amount of road building required for the turbine park was used. This was estimated to be about 10 km of roads for the park.

Supplement C Manufacturing Processes

Vestas' resource consumption and emissions for manufacturing of turbines is reported on a monthly basis from each of the more than 90 sites which include all operations from cast houses and foundries to sales offices. All of these have been included in the LCA and grouped according to the kind of operation being carried out at the sites as shown in Table 12. Country-specific energy mixes and auxiliary material datasets have been used for each of the sites wherever possible. This also includes sustainable energy shares reported by Vestas sites.

Table 12: Vestas manufacturing location and other sites

Factory Class	Description	Allocation Rule
Nacelle Assembly	Factories where the nacelle is put together	kg of nacelle produced
Tower	Tower shells are fabricated and assembled into sections	kg of tower produced
Blades	Manufacturing of blades. See Supplement B 2 for more details.	kg of blades produced
Generator	Assembly of the generator	MW of power shipped
Assembly	Assembly of various parts of the turbine	# turbines produced
Control Assembly	Assembly of controller equipment	# turbines produced
Control Manufacturing	Fabrication of controller equipment (electronics)	# turbines produced
Sales / Services / Insulation	-	# turbines produced
Overheads	-	# turbines produced
Casting	Cast houses and foundries	kg of metal casted
Machining	Factories for machining and finishing casted products	kg of metal machined

Since all materials that form part of the turbine are included in the bill of materials, only auxiliaries (i.e. materials that are consumed in the process of fabrication) are included in these manufacturing processes. Transport of raw materials is not included in the model but a sensitivity analysis for transport has been carried out to ensure the robustness of this assumption.

Vestas casts approximately 30% of all cast parts used in the turbine. Due to lack of supplier data, the casting and machining processes from Vestas were used to proxy the casting and machining of larger parts of the turbine that are purchased. Metal waste from casting and machining is re-melted and used again in the fabrication process.

Other wastes are also included in the model (i.e. reported in the waste to landfill indicator) but are not treated.

Supplement D Data quality evaluation

Data quality was evaluated using the Weidema methodology as described in the International Journal of LCA 3 (5) page 259-265; 1998, Weidema et al.; LCA data quality. The following tables show the evaluation matrix and the evaluation.

Table 13: Data quality evaluation matrix

Score:	1	2	3	4	5
Reliability	Verified data based on measurements	Verified data partly based on assumptions OR non-verified data based on measurements	Non-verified data partly based on assumptions	Qualified estimate (e.g. by industrial expert);	Non-qualified estimate
Representativeness/ Completeness	Representative data from all sites relevant for the market considered over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data from from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/ or from shorter periods
Temporal correlation	Less than 3 years of difference to reference year	Less than 6 years of difference to reference year	Less than 10 years of difference to reference year	Less than 15 years of difference to reference year	Age of data unknown or more than 15 years of difference to reference year
Geographical correlation	Data from area under study	Average data from larger area in which the area under study is included	Data from area with similar production conditions	Data from area with slightly similar production conditions	Data from unknown area (with very different production conditions
Further technological correlation	Data from enterprises, processes and materials under study	Data from processes and materials under study but from different enterprises	Data from processes and materials under study but from different technology	Data on related processes or materials but similar technology.	Data on related processes or materials but different technology.

Table 14: Data quality evaluation results

Type of data	Reliability of Source	Representativeness / Completeness	Temporal correlation	Geographical correlation	Further technological correlation
Manufactured components	2	1	1	2	1
Manufacturing processes	1	1	1	1	1
Large purchased components	2	1	2	3	1
Small purchased components	2	1	2	3	2
Site preparation	2	1	1	3	2
End of life	3	1	2	3	1

Supplement E Wind Turbine Classes and Wind Conditions

Turbine wind class is one of the factors which need to be considered during the complex process of planning a wind power plant. Wind classes determine which turbine is suitable for the normal wind conditions of a particular site.

The DS/ EN 61400 standard specifies the essential design requirements to ensure the engineering integrity of wind turbines, including the wind turbine class. Its purpose is to provide an appropriate level of protection against damage from all hazards during the planned lifetime.

This standard is concerned with all subsystems of wind turbines, but in relation to wind, the standard specifies wind turbines for low, medium and high class designations with reference wind speed and turbulence intensity, as defined in the Table below. The wind turbine class is defined by the average annual wind speed (measured at the turbine's hub height), the speed of extreme gusts that could occur over 50 years, and how much turbulence there is at the wind site. The wind turbine class for annual average medium wind speed is assumed to be 8.0 m/s for this LCA, and 7 m/s is used for low wind turbine class when determining wind energy generation. This represents the mid-point of each wind class.

The wind turbine is functionally designed for specific wind classifications and when comparisons are made between turbines, these should only be compared within a specific wind class for which the turbine is designed.

Table 15: Wind turbine classes

Turbine Class	*IEC I High Wind*	*IEC II Medium Wind*	*IEC III Low Wind*
Annual average wind speed	8.5 to 10 m/s	7.5 to 8.5 m/s	6.5 to 7.5 m/s
Extreme 50-year gust	70 m/s	59.5 m/s	52.5 m/s
Turbulence classes	A 18% B 16%	A 18% B 16%	A 18% B 16%

International Electrotechnical Commission standard (IEC)

Supplement F Uncertainties in Life Cycle Assessments

The main assumptions made in the study and their likely effect on uncertainty in the results are described below

Foreground (primary) data

The primary data collected from the Vestas are considered to be of high quality and the modelling has been carried out to an extremely high level of detail. GaBi DfX was used to assess the wind turbine production down to the level of individual components. The BOM used contained over 50,000 lines of data and was extremely comprehensive. In some cases it was not possible to map every item to an existing dataset and 1.1% (w/w) of materials were unknown. These materials were assigned the average impacts of the rest of the wind turbine.

Manufacturing data were based on average production in Vestas global production facilities as described in supplement C and are also considered to be of high quality.

Background (secondary) data

A major source of uncertainty in any LCA study is the use of background (secondary) data rather than primary data specific to the system being studied. This study is a model of a theoretical wind plant so it is not possible to specify how accurate and representative the background data are, as this would be dependent upon the location of an actual wind plant. However, for issues relating to wind power technology it is reasonable to assume that the same production processes will be applied regardless of location so it is not expected that this will lead to major inaccuracies in the results.

Allocation

Allocation was applied to the production data as described in supplement C. Different allocation rules would generate different results but the ones selected are based on physical properties of the system and are the preferred approach specified in the ISO standards for LCA. Allocation may also be applied in some of the background datasets used in the model. These assumptions are described in the dataset documentation [PE INTERNATIONAL 2006]. These datasets have been used as received and the allocation procedures have not been modified.

Impact assessment

Uncertainty is also introduced in the impact assessment phase of the study—and this will vary according the impact categories considered. The main issues are completeness (does the impact assessment methodology consider all potential contributing emissions?) and characterization (has the degree of impact caused by each species been characterised properly?). Some impact categories, such as global warming, are considered relatively robust in both of these aspects, others, such as human toxicity and eco-toxicity, are much less well developed and consequently less robust.

Supplement G Life cycle inventory

Life cycle inventory results presented in the table below account for significant flows for 1 kWh of electricity supplied to the grid.

Table 16: LCI data for 1 kWh of wind power production (including recycling credit)

Energy resources, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Non renewable energy resources							
Crude oil	6.40E-04	4.83E-04	3.86E-05	3.50E-06	1.14E-04	2.67E-05	-2.54E-05
Hard coal	5.22E-04	1.42E-03	1.16E-04	5.77E-06	2.38E-05	9.49E-05	-1.14E-03
Lignite	6.91E-04	4.96E-04	5.99E-05	4.02E-06	2.77E-05	3.53E-05	6.79E-05
Natural gas	7.25E-04	5.58E-04	3.37E-05	3.09E-06	2.11E-05	3.07E-05	7.79E-05
Renewable energy resources							
Renewable fuels	1.27E-06	1.17E-06	5.58E-10	2.18E-11	9.13E-13	1.14E-07	-1.60E-08
Wood	4.53E-06	4.32E-06	1.37E-07	1.89E-10	1.32E-09	3.58E-08	3.60E-08

Material resources, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Non renewable elements							
Chromium	1.92E-06	1.74E-06	2.13E-12	2.99E-21	2.49E-18	1.79E-07	-1.26E-17
Copper	4.60E-06	4.60E-06	4.26E-11	4.33E-20	7.81E-15	6.08E-13	-2.97E-16
Nickel	1.42E-06	1.30E-06	1.86E-14	4.44E-12	7.05E-16	1.21E-07	-1.15E-16
Non renewable resources							
Basalt	7.12E-06	7.01E-06	1.40E-06	8.76E-08	2.72E-07	1.55E-06	-3.21E-06
Bauxite	1.60E-04	1.95E-04	1.68E-05	3.68E-07	4.76E-05	3.14E-05	-1.31E-04
Bentonite	3.34E-06	1.58E-06	1.04E-06	1.09E-08	1.44E-07	8.48E-08	4.78E-07

Material resources, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Cables 34	4.88E-05	4.88E-05	0.00E+00	0.00E+00	0.00E+00	9.77E-14	0.00E+00
Chromium ore (39%)	1.08E-04	8.90E-05	5.84E-08	6.83E-11	7.99E-10	1.85E-05	1.33E-08
Clay	1.83E-04	-1.76E-06	2.65E-05	-1.18E-09	5.02E-08	2.69E-07	1.57E-04
Colemanite ore	2.02E-05	2.02E-05	3.34E-09	9.70E-12	7.53E-11	6.94E-08	5.08E-10
Copper - Gold - Ore (1,07% Cu; 0,54 g/t Au)	-9.53E-06	5.45E-07	1.11E-09	8.42E-12	0.00E+00	1.12E-09	-1.01E-05
Copper - Gold - Silver - ore (0,51% Cu; 0,6 g/t Au; 1,5 g/t Ag)	-2.74E-05	1.57E-06	3.21E-09	2.43E-11	0.00E+00	3.24E-09	-2.90E-05
Copper - Gold - Silver - ore (1,0% Cu; 0,4 g/t Au; 66 g/t Ag)	6.17E-04	4.65E-04	1.36E-08	4.04E-05	6.01E-05	5.09E-05	-9.84E-09
Copper - Gold - Silver - ore (1,1% Cu; 0,01 g/t Au; 2,86 g/t Ag)	-1.18E-03	2.87E-04	1.81E-07	2.46E-05	3.66E-05	3.12E-05	-1.56E-03
Copper - Gold - Silver - ore (1,13% Cu; 1,05 g/t Au; 3,72 g/t Ag)	-2.92E-04	2.12E-05	3.46E-08	2.62E-10	0.00E+00	3.49E-08	-3.13E-04
Copper - Gold - Silver - ore (1,16% Cu; 0,002 g/t Au; 1,06 g/t Ag)	-6.67E-04	1.62E-04	1.02E-07	1.39E-05	2.07E-05	1.76E-05	-8.82E-04
Copper - Gold - Silver - ore (1,7% Cu; 0,7 g/t Au; 3,5 g/t Ag)	-2.32E-05	3.42E-07	2.61E-09	1.97E-11	0.00E+00	2.63E-09	-2.36E-05
Copper - Molybdenum - Gold - Silver - ore (1,13% Cu; 0,02% Mo; 0,01 g/t Au; 2,86 g/t Ag)	6.43E-05	4.31E-05	4.28E-09	2.11E-10	4.67E-09	2.12E-05	-3.69E-09
Copper - Silver - ore (3,3% Cu; 5,5 g/t Ag)	-1.54E-05	8.81E-07	1.80E-09	1.36E-11	0.00E+00	1.82E-09	-1.63E-05
Copper ore (0.14%)	7.60E-06	7.98E-06	4.08E-07	2.75E-09	1.07E-08	8.67E-07	-1.67E-06
Copper ore (1.2%)	6.40E-05	4.83E-05	1.41E-09	4.19E-06	6.24E-06	5.28E-06	-1.02E-09
Copper ore (sulphidic, 1.1%)	2.31E-05	2.31E-05	-8.64E-15	-1.87E-17	6.85E-14	3.21E-09	1.09E-13
Dolomite	3.10E-05	4.00E-05	1.44E-05	1.63E-08	1.01E-07	2.19E-06	-2.58E-05
Fluorspar (calcium fluoride; fluorite)	1.71E-06	1.92E-06	1.07E-07	6.44E-10	3.45E-07	2.66E-07	-9.20E-07
Gypsum (natural gypsum)	2.75E-05	-3.11E-06	2.18E-05	-2.20E-09	1.71E-08	-2.06E-07	9.01E-06
Heavy spar (BaSO4)	5.30E-06	4.19E-06	3.10E-07	2.67E-08	3.46E-07	2.31E-07	1.94E-07
Inert rock	8.14E-03	1.59E-02	1.32E-03	1.66E-04	5.74E-04	1.32E-03	-1.11E-02
Iron ore (56,86%)	-2.68E-04	1.65E-03	1.53E-04	8.06E-06	3.54E-06	1.25E-04	-2.21E-03
Iron ore (65%)	7.32E-06	-9.39E-07	5.73E-06	-8.97E-10	1.10E-09	-6.28E-08	2.59E-06

Material resources, kg	TOTAL	Wind turbine	Foundations	Transformer	Wind plant set up	Site operations	End of life
Kaolin ore	4.20E-05	4.05E-05	5.38E-07	3.18E-09	9.53E-11	1.44E-06	-4.38E-07
Lead - Zinc - Silver - ore (5,49% Pb; 12,15% Zn; 57,4 gpt Ag)	-1.80E-05	-5.01E-06	9.71E-08	3.55E-09	4.30E-10	-3.19E-07	-1.27E-05
Lead - zinc ore (4.6%-0.6%)	9.12E-05	9.35E-05	2.06E-06	5.21E-09	3.34E-07	4.49E-06	-9.20E-06
Limestone (calcium carbonate)	1.27E-03	3.82E-04	8.46E-04	2.11E-06	4.68E-06	3.33E-05	-7.65E-07
Magnesium chloride leach (40%)	9.38E-06	7.81E-06	2.73E-07	1.99E-08	8.41E-08	4.58E-07	7.30E-07
Manganese ore (R.O.M.)	1.31E-05	2.51E-05	3.03E-06	8.56E-08	7.11E-08	3.44E-06	-1.87E-05
Molybdenite (Mo 0,24%)	3.92E-05	2.63E-05	2.63E-09	1.29E-10	2.85E-09	1.29E-05	-2.27E-09
Natural Aggregate	5.78E-03	5.27E-04	3.30E-03	1.27E-07	1.54E-03	1.90E-04	2.23E-04
Nickel ore (1,5%)	2.36E-05	2.53E-05	1.08E-07	1.11E-09	2.10E-13	1.12E-07	-1.84E-06
Nickel ore (1.6%)	5.03E-05	4.40E-05	6.95E-08	2.76E-07	1.30E-07	6.60E-06	-8.06E-07
Perlite (Rhyolithe)	3.18E-05	2.25E-05	2.86E-06	0.00E+00	0.00E+00	6.46E-06	0.00E+00
Phosphorus ore (29% P2O5)	1.32E-06	1.04E-06	1.23E-07	1.74E-10	2.31E-16	2.88E-07	-1.31E-07
Precious metal ore (R.O.M)	1.09E-06	1.11E-06	1.82E-09	2.00E-11	1.40E-10	2.58E-09	-1.98E-08
Quartz sand (silica sand; silicon dioxide)	2.40E-04	1.67E-04	2.33E-06	9.35E-07	1.94E-06	4.69E-06	6.28E-05
Rare-earth ore	1.04E-04	7.64E-05	0.00E+00	0.00E+00	0.00E+00	2.72E-05	0.00E+00
Raw pumice	2.19E-06	7.70E-09	2.18E-06	1.61E-12	8.91E-12	8.43E-10	8.81E-11
Sodium chloride (rock salt)	1.39E-04	1.36E-04	2.44E-06	3.13E-07	1.40E-06	4.93E-06	-5.82E-06
Soil	1.31E-03	2.25E-04	6.69E-04	3.22E-07	3.10E-04	4.16E-05	6.65E-05
Talc	1.24E-06	1.23E-06	1.78E-10	2.79E-13	1.63E-11	4.25E-09	3.84E-11
Titanium ore	4.06E-06	5.18E-06	1.04E-07	7.39E-10	2.06E-09	7.54E-08	-1.30E-06
Vanadium ore (ROM)	-1.01E-05	1.11E-06	2.43E-06	1.29E-08	0.00E+00	1.66E-06	-1.53E-05
Zinc - copper ore (4.07%-2.59%)	1.28E-04	1.03E-04	1.01E-07	9.17E-06	1.37E-05	1.14E-05	-9.28E-06
Zinc - lead - copper ore (12%-3%-2%)	1.00E-04	7.86E-05	4.67E-08	6.90E-06	1.03E-05	8.64E-06	-3.99E-06
Zinc - Lead - Silver - Ore (7,5% Zn; 4,0% Pb; 40,8 g/t Ag)	-5.47E-05	-1.53E-05	2.95E-07	1.08E-08	0.00E+00	-9.71E-07	-3.87E-05
Zinc - Lead - Silver - ore (8,54% Zn; 5,48% Pb; 94 g/t Ag)	-8.37E-06	4.79E-07	9.79E-10	7.40E-12	0.00E+00	9.87E-10	-8.85E-06

Material resources, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Renewable resources							
Water	2.70E-02	2.96E-02	3.88E-03	5.79E-05	5.93E-04	2.13E-03	-9.18E-03
Air	3.69E-02	3.08E-02	1.30E-03	1.37E-04	8.19E-04	1.92E-03	1.99E-03
Carbon dioxide	1.47E-04	1.41E-04	7.23E-06	1.97E-06	3.14E-06	1.15E-05	-1.78E-05
Nitrogen	2.37E-06	1.94E-06	2.69E-08	-2.46E-10	4.13E-07	-9.97E-09	-2.96E-10
Oxygen	-5.64E-05	-5.93E-05	-3.95E-06	-1.47E-06	-2.17E-06	-6.12E-06	1.66E-05

Emissions to air, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Inorganic emissions to air							
Carbon dioxide	5.78E-03	6.88E-03	8.14E-04	3.28E-05	2.22E-04	4.31E-04	-2.60E-03
Carbon dioxide (biotic)	2.65E-05	8.34E-06	1.47E-05	2.02E-08	9.38E-07	1.06E-06	1.50E-06
Carbon monoxide	4.72E-06	3.46E-05	3.89E-06	1.02E-07	2.26E-07	2.45E-06	-3.66E-05
Nitrogen (atmospheric nitrogen)	1.46E-04	1.46E-04	8.76E-08	8.99E-08	5.40E-08	6.03E-07	-3.19E-07
Nitrogen oxides	1.44E-05	1.31E-05	1.77E-06	5.73E-08	4.96E-07	8.53E-07	-1.87E-06
Oxygen	5.30E-05	4.63E-05	1.14E-06	1.30E-08	1.43E-07	2.42E-06	2.98E-06
Steam	1.08E-02	7.61E-03	4.43E-04	5.14E-05	1.19E-03	5.66E-04	9.23E-04
Sulphur dioxide	1.64E-05	1.79E-05	9.94E-07	9.79E-08	9.07E-07	1.32E-06	-4.82E-06
Organic emissions to air (group VOC)							
Non-methane VOC (unspecified)	2.13E-06	2.14E-06	9.17E-08	4.35E-09	3.55E-08	6.91E-08	-2.10E-07
Methane	1.38E-05	1.63E-05	1.25E-06	6.03E-08	6.50E-07	7.91E-07	-5.23E-06
VOC (unspecified)	1.43E-05	1.40E-05	8.71E-08	1.48E-10	3.64E-10	2.08E-07	3.06E-09
Other emissions to air							
Exhaust	2.36E-02	1.86E-02	8.80E-04	1.06E-04	6.73E-04	1.12E-03	2.26E-03
Used air	1.55E-03	1.48E-03	2.43E-05	4.75E-06	4.32E-06	7.20E-05	-2.93E-05
Particles to air							

Emissions to air, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Dust (PM2.5)	1.18E-06	1.13E-06	6.79E-08	2.37E-09	2.12E-08	7.87E-08	-1.21E-07
Dust (unspecified)	4.80E-06	4.83E-06	3.26E-07	1.46E-08	9.45E-08	3.43E-07	-8.15E-07

Emissions to fresh water, kg	TOTAL	Wind turbine	Founda-tions	Trans-former	Wind plant set up	Site operations	End of life
Analytical measures to fresh water							
Chemical oxygen demand (COD)	1.87E-05	1.53E-05	2.31E-07	1.21E-08	4.40E-08	3.23E-06	-9.09E-08
Heavy metals to fresh water							
Iron	1.27E-06	8.87E-07	1.28E-07	6.82E-09	4.77E-08	6.89E-08	1.34E-07
Inorganic emissions to fresh water							
Calcium (+II)	4.48E-06	4.30E-06	1.42E-07	1.20E-08	5.88E-08	2.09E-07	-2.43E-07
Chloride	2.96E-05	3.22E-05	1.87E-06	1.53E-07	1.12E-06	1.86E-06	-7.59E-06
Fluoride	1.88E-06	1.53E-06	1.06E-07	8.78E-09	7.11E-08	1.07E-07	5.74E-08
Sodium (+I)	7.98E-06	7.71E-06	2.41E-07	3.84E-08	1.15E-07	4.54E-07	-5.75E-07
Sodium chloride (rock salt)	3.47E-05	3.35E-05	3.02E-07	6.38E-08	1.12E-13	8.26E-07	-8.84E-14
Sulphate	5.93E-06	5.22E-06	4.01E-07	8.60E-08	3.21E-07	3.67E-07	-4.59E-07
Other emissions to fresh water							
Waste water	5.30E-03	1.03E-02	1.79E-03	2.43E-06	0.00E+00	3.54E-04	-7.13E-03
Particles to fresh water							
Solids (suspended)	9.24E-06	7.49E-06	4.23E-07	3.12E-08	3.30E-07	2.90E-07	6.75E-07

Emissions to sea water	TOTAL	Wind turbine	Foundations	Transformer	Wind plant set up	Site operations	End of life
Inorganic emissions to sea water							
Chloride	2.38E-05	1.72E-05	1.46E-06	1.38E-07	5.15E-06	1.00E-06	-1.22E-06
Other emissions to sea water							
Waste water	8.11E-05	7.27E-05	0.00E+00	0.00E+00	0.00E+00	8.33E-06	0.00E+00

Emissions to industrial soil, kg	TOTAL	Wind turbine	Foundations	Transformer	Wind plant set up	Site operations	End of life
Inorganic emissions to industrial soil							
Calcium (+II)	9.83E-06	1.69E-09	2.75E-10	1.18E-11	2.48E-10	2.00E-10	9.83E-06