Authors: Priyanka Razdan & Peter Garrett **Version:** 1.1 **Date:** 31.07.2017

Life Cycle **Assessment**

of electricity production from
an Onshore V112-3.45 MW Wind Plant

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Life Cycle Assessment of Electricity Production from an onshore V112-3.45 MW Wind Plant

July 2017

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Vestas, (2017). Life Cycle Assessment of Electricity Production from an onshore V112-3.45 MW Wind Plant – 31st July 2017, Version 1.1. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Critical review

LIFE CYCLE ASSESSMENT OF ELECTRICITY PRODUCTION FROM AN ONSHORE V112-3.45 MW WIND PLANT (MARK 3A)

***Commissioned by*:**	*Vestas Wind Systems A/S* *Randers, Denmark*
Reviewer:	*Prof. Dr. Matthias Finkbeiner* *Berlin, Germany*
Reference:	*ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework* *ISO 14044 (2006): Environmental Management - Life Cycle Assessment – Requirements and Guidelines* *ISO/TS 14071 (2014): Environmental management -Life cycle assessment - Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006*

Scope of the Critical Review

The reviewer had the task to assess whether

- the methods used to carry out the LCA are consistent with the international standards ISO 14040 and ISO 14044,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

The review was performed according to paragraph 6.2 of ISO 14044, because the study is not intended to be used for comparative assertions intended to be disclosed to the public. This review statement is only valid for this specific report in its final version 1.1 received on 31st July 2017.

The analysis and the verification of individual datasets and an assessment of the life cycle inventory (LCI) model are outside the scope of this review.

Review process

The review process was coordinated between Vestas and the reviewer. The review was performed at the end of the study. As a first step the draft final report of the study was provided to the reviewer on 05.06.2017. The reviewer provided 56 comments of general, technical and editorial nature to the commissioner by the 12.06.2017.

The feedback provided and the agreements on the treatment of the review comments were adopted in the finalisation of the study. The final version of the report was provided on 31st July 2017. All critical issues were comprehensively addressed, and basically all recommendations of the reviewer were addressed in a comprehensive and constructive manner.

The reviewer checked the implementation of the comments and agreed to the final report. The reviewer acknowledges the unrestricted access to all requested information as well as the open and constructive dialogue during the critical review process.

General evaluation

The current LCA builds upon a history of conducting LCAs of Vestas turbines since 2001. As a result, the methodology has reached a high level of maturity and the study is performed in a professional manner using state-of-the-art methods. The LCI modelling used for the study is outstanding with regard to the level of detail and the amount of primary data used. It covers around 25,000 components representing over 99.9% of the total mass of materials of the product. For the manufacturing part, the study includes information from over 100 sites. For plausible use phase scenarios, Vestas can rely on real-time performance data of over 33,200 wind turbines around the world, which covers 13% of current worldwide installed wind capacity.

As a result, the report is deemed to be representative for a V112-3.45 MW Mark 3a WIND PLANT. The defined and achieved scope for this LCA study was found to be appropriate to achieve the stated goals.

Conclusion

The study has been carried out in conformity with ISO 14040, ISO 14044 and ISO/TS 14071. The reviewer found the overall quality of the methodology and its execution to be of a high standard for the purposes of the study. The study is reported in a comprehensive manner including a transparent documentation of its scope and methodological choices.

Matthias Finkbeiner

Prof. Dr. Matthias Finkbeiner

01st August 2017

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Executive summary

The present Life cycle assessment (LCA) is the final reporting for the electricity produced from a 100MW onshore wind power plant composed of Vestas V112-3.45 MW turbines (Mark 3a). Vestas Wind Systems A/S has prepared the report and the underlying LCA model.

The study has been critically reviewed by an external expert, Prof. Dr. Matthias Finkbeiner, according to ISO TS 14071 (2014) paragraph 6.2 of ISO 14044 (2006a), as the study is not intended for comparative assertions intended to be disclosed to the public.

Context

The current LCA builds upon a history of conducting LCAs of Vestas turbines since 2001 as part of the Vestas' ongoing sustainability agenda.

This study represents an update to the environmental profile from previous studies of the same onshore turbine conducted in 2014 of the V112-3.3MW turbine (Mark 2a) by Vestas (2014b).

This LCA report presents the environmental performance of the latest V112-3.45 MW (Mark 3a) turbine that was launched for sale in 2015. The Mark 3a turbine includes further product improvements relating to optimised turbine design, improved electricity production, increase in power rating to 3.45 MW and an increase in wind class for the turbine.

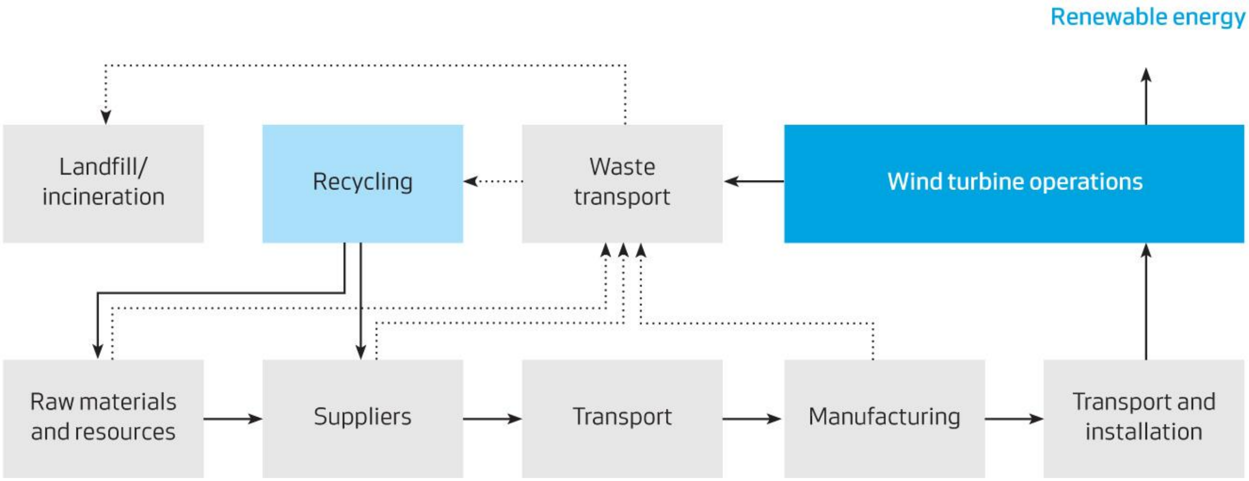
The scope of the V112 Mk3 design is to increase the turbine wind class and MW rating in order to reduce the levelised cost of energy and to increase product competiveness within the higher wind class.

This LCA of the V112-3.45 MW power plant has assessed the turbine's entire bill-of-materials accounting for around 25,000 parts that make up the turbine. The complete wind power plant is assessed up to the point of the electricity grid, including the turbine itself, foundations, site cabling that connects the turbines together and other site parts such as the transformer station.

This LCA has covered over 99.9% of the total mass of the turbine itself, and over 99.95% of the entire mass of the power plant. Missing information relates to parts where the material was not identified. Scaling of the turbine up to 100% of total mass has not been conducted.

Each part of the wind plant is assessed over the entire life cycle from cradle to grave. The potential environmental impacts are calculated for each turbine component relating to the specific material grade of the part, manufacturing processes, country of origin, part maintenance, and specific disposal and recycling steps at end-of-life. This provides a comprehensive view of the environmental performance. The figure below shows the generic turbine life cycle assessed in the LCA.

Life cycle of the wind power plant



Turbine specification

The Table below gives an overview of the baseline wind power plant assessed in this life cycle assessment.

Baseline wind plant assessed

Description	Unit	Quantity
Lifetime	years	20
Rating per turbine	MW	3.45
Generator type	-	Induction
Turbines per power plant	pieces	29
Plant size	MW	100
Hub height	m	94
Rotor diameter	m	112
Wind class	-	High (IEC1A)
Tower type	-	Steel
Foundation type		Low ground water level (LGWL)
Production @ 7.5 m/s (low wind)	MWh per year	-
Production @ 8.5 m/s (medium wind)	MWh per year	-
Production @ 10.0 m/s (high wind)	MWh per year	15725
Grid distance	km	20
Plant location	-	Europe
Vestas production location	-	Global average

Note: The above figure for electricity production includes all losses, assuming an availability of 98%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

The functional unit

The functional unit is the ‘reference unit’ used to report the environmental performance of the wind power plant, which is assessed according to the following:

The functional unit for this LCA study is defined as:

1 kWh of electricity delivered to the grid by a 100MW wind power plant.

The functional unit is based on the design lifetime of the power plant (of 20 years), along with the total electricity produced over the lifetime based on average high wind conditions.

Benchmarking performance

Vestas turbines are designed to meet different functional requirements both in terms of onshore and offshore locations, as well as the wind classes for which they are designed to operate. The wind class determines which turbine is suitable for a particular site, and effects the total electricity output of the power plant and the design of the turbine itself [1].

When benchmarking a wind turbine performance from one wind turbine to another it is important that this is made on an equivalent functional basis, and should only be compared within the same wind classes. There are three wind classes for wind turbines which are defined by an International Electrotechnical Commission standard (IEC 61400-1), corresponding to high, medium and low wind[2].

The Vestas V112-3.45 MW wind turbine has been designed to operate under high wind conditions and for this study, high wind conditions have been selected to evaluate environmental performance.

Additionally, this report presents in Annex H a proposed new benchmark in order further to improve and more transparently assess and compare the environmental performance of a wind plant for current and future turbine designs.

Environmental impacts

The Table below presents the total potential environmental impacts of a 100MW onshore wind power plant of V112-3.45 MW turbines, covering the entire power plant over the life cycle, per kWh of electricity delivered to the grid.

The results show that raw material and component production dominate the environmental impacts of the power plant, followed by end-of-life recycling credits, and other phases to a lesser extent. Of production the blades, nacelle, tower, site parts and foundations contribute most significantly to all studied environmental impact indicators (ranging from 50% to 90% across all impact categories). The next most significant components are the blades, gear & mainshaft and the hub. Vestas factories contribute between 3% and 15% across all impact categories. Transport of the turbine components

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[1] Other site parameters are also important when establishing the performance of a wind power plant, such as, wind plant size, turbine power output, distance to grid, availability, plant losses, etc.

[2] Refer to Annex E of the report further details of wind class and Vestas turbines within each classification.

contributes between around 1% and 38% across all impact categories, and 9% to the total global warming potential impacts[3].

The primary reason for changes in impacts versus the previous V112 assessment is due to improvements in annual energy production, which has typically reduced impacts per kWh by around 20-30%. However, some impacts increase per kWh (such as MAETP and TETP) which is due to changes in background datasets and data changes for the characterisation of impacts. Refer to Section 5.4 for further details.

Whole-life environmental impacts of V112-3.45 MW plant (shown in g, mg or MJ per functional unit of 1kWh)

Environmental impact categories:	Unit	Quantity per functional unit of 1 kWh
Abiotic resource depletion (ADP elements)	mg Sb-e	0.10
Abiotic resource depletion (ADP fossils)	MJ	0.06
Acidification potential (AP)	mg SO2-e	21
Eutrophication potential (EP)	mg PO4-e	2.4
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38
Global warming potential (GWP)	g CO2-e	5.3
Human toxicity potential (HTP)	mg DCB-e	1032
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	615
Photochemical oxidant creation potential (POCP)	mg Ethene	2.6
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	31

Note: impact indicators are based on CML impact assessment method Version 2016 (CML, 2016)

The Figure below also presents the environmental impacts for different components of the power plant for the production, maintenance and operation (i.e. all life cycle stages excluding end-of-life).

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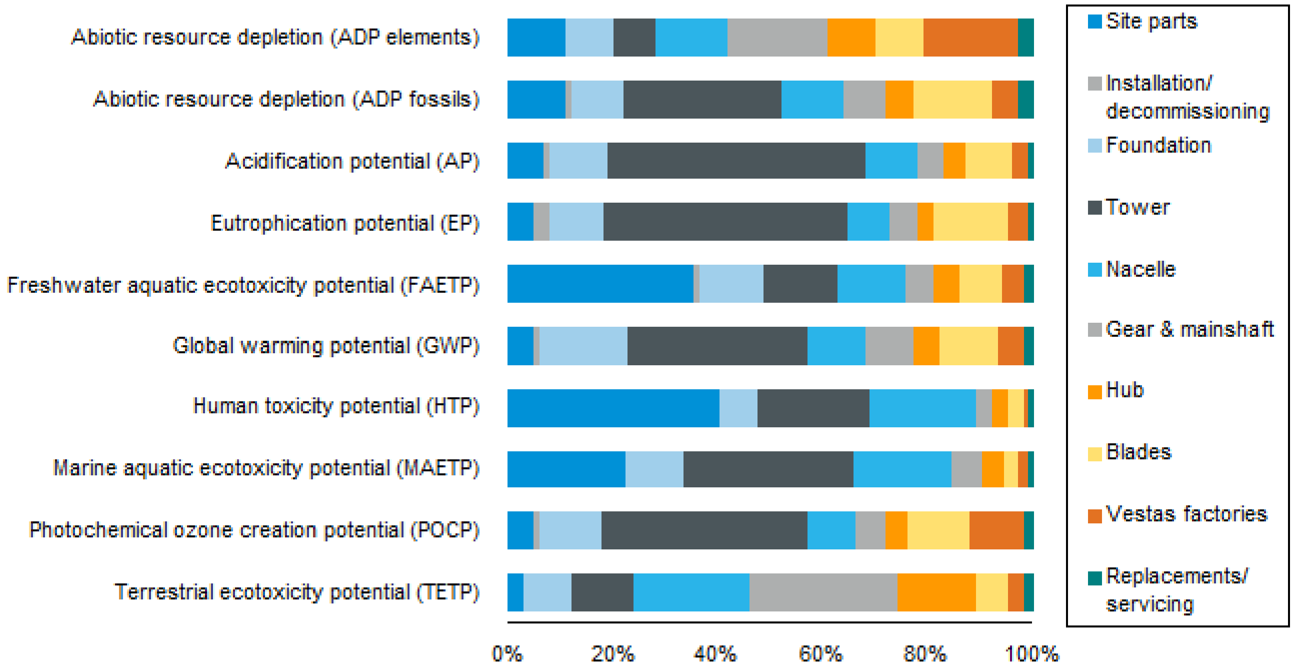
[3] *Transport refers to the aggregated impacts covering transport stages for incoming materials, supplier transport, project transport to site and end-of-life transport for all wind plant components in the life cycle. Secondary transport included in aggregated datasets is not shown separately.*

Production and use-phase environmental impacts of V112-3.45 MW



Other environmental indicators

The Table below shows the other environmental indicators assessed as part of the LCA, including return-on energy of the wind plant. Return-on energy provides an indication of the energy balance of power plant, showing the relationship between the energy requirement over the whole life cycle of the wind plant (i.e. to manufacture, operate, service and dispose) versus the electrical energy output from the wind plant. The payback period is measured in months where the energy requirement for the life cycle of the wind plant equals the energy it has produced.

The breakeven time of the V112-3.45 MW is 5.4 months for high wind conditions. This may be interpreted that over the life cycle of the V112-3.45 MW wind power plant will return 45 times (high wind) more energy back than it consumed over the plant life cycle.

Due to design optimisations which result in reduced material requirements, the turbine recyclability has been slightly decreased; driven primarily by savings of steel in the tower.

A new circularity indicator has been introduced to measure the material flows of the turbine in relation to circular economy (EMF, 2015) considering

- using feedstock from reused or recycled sources
- reusing components or recycling materials after the use of the product
- keeping products in use longer (e.g., by reuse/redistribution)
- making more intensive use of products (e.g. via service or performance models)

Given this scope, it is evident that improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. Nonetheless, a widespread use of this methodology could form part of such a systems improvement.

It should be noted that this indicator does adopt a life cycle perspective but is calculated at the product bill-of-material level. Refer to Section 5.3.6 for further description and indicator limitations.

For the V112-3.45MW turbine, this has been calculated as 0.63. This means that 63% of the turbine product is managed according to circular economy principles mentioned above while 37% of the product has linear material flows (refer to Section 5.3.6) for details.

Additionally, a new indicator is introduced called *Product waste* which supersedes the *Recyclability* indicator and represents the amount of waste generated per kWh from the turbine components (refer to Section 5.3.5 for details).

Whole-life environmental indicators of V112-3.45 MW (shown in g or MJ per functional unit of 1kWh)

Non-impact indicators:	**Unit**	**Quantity per functional unit of 1 kWh**
*Primary energy from renewable raw materials	MJ	0.01
*Primary energy from resources	MJ	0.07
Water consumption	g	46
**Return-on energy	Number of times	45
***Turbine recyclability (not life cycle based, turbine only)	% (w/w)	86%
****Product waste (not life cycle based, turbine only)	g	0.16
*****Turbine Circularity (not life cycle based, turbine only)	-	0.63

** Net calorific value*

*** Based on ‘Net energy’ calculation defined in Section 6.*

**** Rounded up or down to the nearest half percentage point.*

***** Refer to Section 5.3.5*

****** Based on circularity indicator calculation defined in section 5.3.6*

Study assumptions and limitations

In accordance with ISO standards for LCA (ISO 14040/44), the assumptions and limitations of the study have been identified and assessed throughout the study. In general, there have been few places of uncertainty, but where there has been, a conservative approach has been adopted, which would have the tendency to overestimate the potential environmental impacts. The primary parameters for the study relate to the following:

- *Power plant lifetime*: the power plant lifetime is a dominant factor when determining the impacts of the electricity production per kWh. This LCA assumes a turbine lifetime of 20 years which matches the standard design life. Nonetheless, the wind turbine industry is still young (starting for Vestas in 1979), and few turbines have ever been disposed, with some turbines reaching operational lives of 30 years and over, for other Vestas turbine models. Although variations occur, the design lifetime for this study of 20 years for a ‘typical’ plant, is considered reasonable and accurate. The sensitivity of this assumption is tested in the LCA.

- *Electricity production*: the electricity production per kWh is substantially effected by the wind plant siting and site-specific wind conditions that the turbine operates under (i.e. low, medium or high wind classes defined by the IEC). Vestas wind turbines are designed to match these different wind classes and wind speeds, so it is not always the size of the rotor or the generator rating (in MW) that determines the electricity production of the turbine; but wind class is a dominant factor. Nonetheless, electricity production is very accurately measured for Vestas turbines when the wind speed and conditions are known. The V112-3.45 MW turbine assessed in this LCA is designed for the high wind class, and has been assessed for high wind conditions, which fairly reflects a 'typical' power plant.
- *Impacts of material production and recycling*: the turbine is constructed of around 91% metal (primarily iron and steel, and to a lesser extent aluminium and copper), and it is the production-phase and end-of-life phase that dominate the studied environmental impacts. Datasets for metal production are based on established and credible industry association sources (such as those from worldsteel and the European Aluminium Association). End-of-life recycling of metals in the power plant also provides environmental credits. This LCA uses an 'avoided impacts' approach accounting also for burdens of input scrap of raw materials; methodologically speaking, this is a consistent approach to environmental crediting for recycling. Additionally, specific parts of the turbine and power plant are applied different recycling rates dependent on their ease to disassemble and recycle. Furthermore, the effect of using a 'recycled content' approach is also estimated in the LCA. Concrete is the other main mass-flow material, which uses industry-specific production datasets accounting for the concrete grade. Polymer materials also use established and credible industry datasets. The impacts of electronics production have been evaluated at an individual component level.

Vestas operates sophisticated real-time diagnostic tools and sensors which measure individual turbine performance, power output and health status (such as fatigue loading and turbine condition). These systems operate on over 33,200 wind turbines around the world, correlating to over 66.5 GW total capacity, which represents around 13 per cent of current worldwide installed wind capacity (WWEA, 2016). This provides highly detailed and valuable data for specific turbine performance and site operating conditions, which allows the above assumptions relating to the turbine to be carefully understood and reflected in the LCA.

Updates over recent LCAs

Several updates have been made in the current LCA since the previous study of the V112 turbine conducted by Vestas in 2014 (Vestas, 2014b). Most notably, there have been the following updates:

- The turbine design reflects the complete bill-of-materials for the V112-3.45 MW turbine (Mark 3a) turbine, which has improvements in turbine design and optimisation relating to:
  - nominal power rating of 3.45 MW, with an option for higher power mode of 3.6 MW;
  - increased energy production due power performance optimisation;
  - design updates giving product cost-out and reduced material requirements;
  - Vestas production data has been updated to reflect production in 2015; and
  - repairs of major components have been included for the first time where previously it was assumed that all service parts were replaced with new parts .
- Two new indicators for wind turbine *Circularity* and *Product waste* are now included.
- LCA model updates:

- CML impact method uses version 4.2 (CML, 2016);
- GaBi datasets updated to version 6.115 for secondary datasets (thinkstep, 2016); and
- Turbine annual energy production reflects IEC top-end wind speed (and not mid-point wind speed as previous LCAs).

Conclusions and recommendations

Overall, the study represents a robust and detailed reflection of the potential environmental impacts of a 100MW onshore wind power plant consisting of twenty nine V112-3.45 MW turbines. The LCA is based upon accurate product knowledge and current state-of-the-art in the field of LCA, both in the methodologies applied and datasets used to account for environmental impacts, as well as the LCA tools and software applied. The LCA could further benefit by considering the following:

- explore improvements in accounting methods for water flows; and
- explore potential use of other impact assessment methods.
- periodic and systematic updates of datasets and databases for consistent benchmarking between product generations.

Glossary

Abbreviation	Definition
3D CAD	three-dimensional computer aided design
AP	acidification potential
$ADP_{elements}$	abiotic resource depletion (elements)
ADP_{fossil}	abiotic resource depletion (fossils)
AEP	annual energy production
BOM	bill of materials
CML	Institute of environmental sciences (CML), Leiden University, The Netherlands.
CNC	computer numerical control
DCB	dichlorobenzene
DfX	DfX is a GaBi LCA software extension that allows automated import of an entire product bill of materials (consisting of thousands of parts) into the software LCA model.
DFIG	double fed induction generator
EIA	environmental impact assessment (a complimentary assessment technique to LCA)
EP	eutrophication potential
EPD	environmental product declaration
FAETP	freshwater aquatic ecotoxicity potential
GHG	greenhouse gas
GWP	global warming potential
HGWL	high ground water level (referring to water level of turbine foundations)
HTP	human toxicity potential
IEC	International electrotechnical commission
ILCD	international reference life cycle data system
ISO	International organization for standardization
ICT	information and communications technology
JRC	Joint research centre
KPI	key performance indicator
kWh	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory
LCIA	life cycle impact assessment

LGWL	low ground water level (referring to water level of turbine foundations)
MAETP	marine aquatic ecotoxicity potential
MCI	material circularity indicator
MVA	megavolt amp
MW	megawatt
MWh	megawatt hour
PCB	printed circuit board
POCP	photochemical oxidant creation potential
T-CAT	technology cost assessment tool
TETP	terrestrial ecotoxicity potential
UNEP	United nations environment programme
VOC	volatile organic compound
Wind plant	the wind power plant includes the wind turbines, foundations, site cabling (connecting the individual wind turbines to the transformer station) and site equipment (e.g. transformer station) up to the point of the existing grid.
Wind turbine	the wind turbine refers to the turbine itself and excludes the foundation and other site parts.
w/w	weight for weight

1. Introduction

The present Life cycle assessment (LCA) is the final reporting for the electricity produced from a 100MW onshore wind power plant composed of Vestas V112-3.45 MW turbines. Vestas Wind Systems A/S (hereafter called Vestas) has prepared the report and the underlying LCA model. This study conforms to the requirements of the ISO standards for LCA (ISO 14040: 2006, ISO 14044: 2006) and has undergone an external critical review according to ISO TS 14071 (2014) to assure the robustness and credibility of the results, conducted by Prof. Dr. Matthias Finkbeiner.

The 3MW turbine platform was first put into operation in 2010 as a 3.0 MW turbine (Mark 0) and is currently at the Mark 3 version, with around 4200 turbines installed worldwide, representing around 13 GW of total installed capacity. Since the initial launch of the 3MW turbine platform there have been significant improvements in design and turbine optimisation which are captured in the current assessment of the Mark 3a version.

1.1 Background

As part of the Vestas' ongoing sustainability agenda, previous LCAs have been conducted for a number of wind turbines. The current LCA builds upon a history of conducting LCAs of Vestas turbines since 2001.

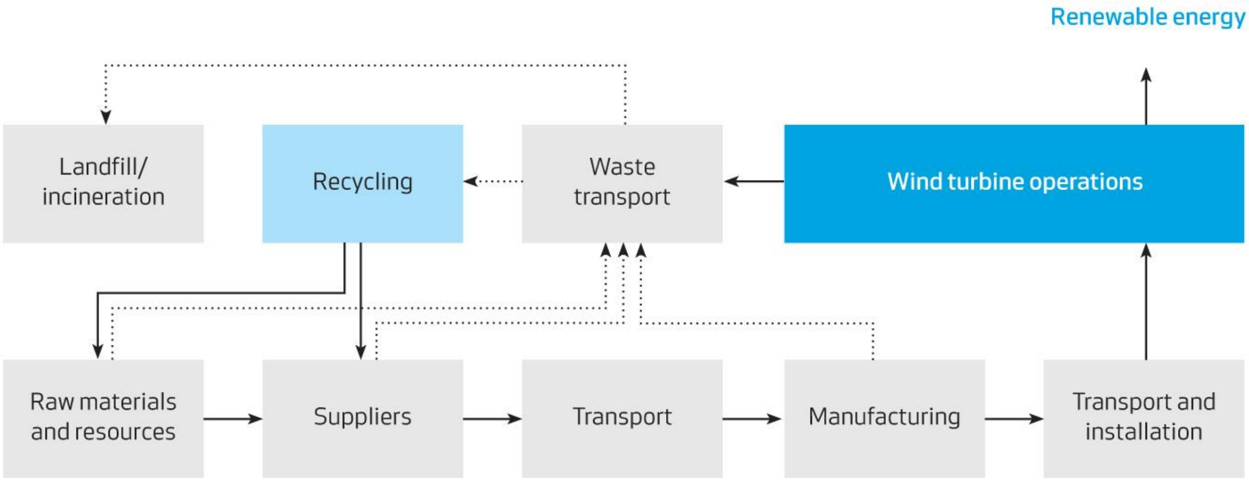
The present LCA represents an update to the previous studies (Vestas, 2014a, 2014b, 2014c, 2014d, 2015a) of the same onshore turbine. This LCA report presents the environmental performance of the latest V112-3.45 MW (Mark 3a) launched in 2015.

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 like risk assessment, environmental performance evaluation and environmental impact assessment are valuable supplementary tools in addressing other types of environmental aspects (e.g. noise and impacts on fauna). Likewise, other tools may be used to address social and economic aspects which are not included in environmental LCA.

1.2 Life cycle assessment

LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and environmental consequences of releases) throughout a product's life cycle from raw material acquisition through to 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 power plant



According to the International Organization for Standardization (ISO) 14040/44 standards, a 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 and ISO 14044, 2006).

This section introduces the goal and scope for the LCA of the onshore V112-3.45 MW turbine.

The V112-3.45 MW turbine is part of the 3MW platform of turbines which includes the V105, V112, V117, V126 and V136. These five turbines share a significant number of common components (around 90% of total weight), for example the nacelle, tower and all site parts (cabling, transformer, etc). The primary difference between the turbines relates to the total diameter of the blades (i.e. 105m, 112m, 117m, 126m or 136m total diameter) and the 'hub and nose cone' module which has some differences in construction. Additionally, the turbines operate with different tower heights depending on the market and wind conditions that they are designed to operate within. The turbines are built to meet specific wind conditions which range from low to high wind speeds (see Section 3.4.2 for further details). The size of the turbine (e.g. blade diameter and MW rating of generator) does not alone determine the total amount of electricity production from the turbine, but the siting of the turbine and the particular wind class that it is operating under (i.e. low, medium or high wind conditions) is also a dominant factor.

The LCA model, which is developed in the GaBi 7 DfX software (Thinkstep, 2016), has been created for the complete '3MW platform' which includes many turbine options and design variants which can be 'selected' to make-up any particular turbine configuration and wind plant setup.

The LCA reflects the complete bill-of-materials for the V112-3.45 MW turbine (Mark 3a) and the main improvements in turbine design relate to increase in energy production due to increase in wind IEC class versus Mark 2, as well as nominal generator rating increasing from 3.3 MW to 3.45 MW. Refer Section 1.2.4 for further details.

1.2.1 Goal and scope phase

In general terms, the goal and scope phase outlines the: rationale for the study; the anticipated use of the results of the study; the boundary conditions; the data requirements and assumptions made to analyse the product system under consideration; and any other similar technical specifications.

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; attributes of the product system; and the level of detail and complexity addressed by the study.

1.2.2 Life cycle inventory (LCI) and life cycle impact assessment (LCIA) phases

The life cycle inventory (LCI) phase qualitatively and quantitatively analyses the following for the product system being studied:

- the materials and energy used (inputs);
- 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).

The LCI data can be used to: understand total emissions, wastes and resource-use associated with the material or the product being studied; improve production or product performance; and be further analysed and interpreted to provide insights into the potential environmental impacts from the product system being studied (i.e. life cycle impact assessment (LCIA) and interpretation).

1.2.3 Benchmarking wind turbine performance

Vestas turbines are designed to meet different functional requirements both in terms of onshore and offshore locations, as well as the wind classes for which they are designed to operate within. The wind class determines which turbine is suitable for a particular site, and effects the power output of the turbine. Other site parameters are also important when establishing the performance of a wind power plant, such as, wind plant size, turbine power output, distance to grid, availability and electrical losses, amongst others.

The calculation of use-phase power output of the turbine is based on defined wind classes in this study which allows for a more robust benchmarking of wind power plants.

There are three wind classes for wind turbines which are defined by an International Electrotechnical Commission standard (IEC 61400-1), corresponding to high, medium and low wind. Each wind class is primarily defined by the average annual wind speed (measured at turbine hub height), along with turbulence intensity and extreme winds (occurring over 50 years).

When benchmarking a wind turbine performance from one wind turbine to another it is important that this is made on an equivalent functional basis, and should only be compared within the same wind classes for the wind turbine (Garrett, 2012). Annex E provides further details of the wind classes and shows which Vestas turbines operate in different wind classes.

The current LCA (as with previous Vestas LCAs) has been performed in a way that makes it possible to compare the impacts of electricity produced from a wind power plant with electricity produced from power plants based on different technologies.

1.2.4 Improvements over recent LCAs

Several improvements were made in the LCA of the V112 turbine in 2015 compared to the assessment of the V112 Mark 2 turbine in 2014 (Vestas, 2014b), which are also included in this assessment and summarised again below. Several further improvements are also made for this 2015 study, as outlined.

Data improvements:

- *GaBi 2016 databases* (including a software upgrade to GaBi 7) are included as updates in the current LCAs. Additionally, CML has been updated to version 4.6, January 2016. Overall, these updates cause relatively small increases or decreases overall in the inventory and impact assessment results.
- *Vestas production*: updates have been made to include Vestas production for year 2015 which represents production for the entire year.
    - Data for consumables at Vestas production units is no longer gathered from 2014 (this from previous studies of the 3MW platform represents a minor amount (e.g. < 4% GWP of Vestas production) when compared data for energy use, raw materials, wastes, water and emissions as a whole.
- *V112 turbine bill-of-materials*: the study assesses the latest turbine design for Mark 3a turbine which includes all components within the turbine (i.e. almost 50,000 lines in the product-tree for the complete platform) and the associated improvements and changes in product design, for the latest turbine (Mark 3a), including for example, increased energy production due to power performance optimisation at nominal power and design updates giving product cost-out and reduced material requirements. Refer to Section 7 for further details of these changes.
- *Repairs and replacements*: lifetime repairs of main components like gearbox and generator have been included in this study, where a component is repaired or refurbished for a second use[4]. Previous LCA studies only included lifetime replacement of parts which assumed all components were replaced with new parts and there was no repair of components.
- *Electronics mapping*: the electronics have been mapped at an individual component-level in this study rather than at a generic total mass level, as with previous assessments. Vestas designs its own controllers and holds details of nearly all components used in the turbine, representing for this LCA around 9,500 lines in the product-tree for one turbine. All these components are mapped in the current assessment.

Turbine operation improvements:

- *Annual Energy Production*: as proposed in previous LCAs of V112-3.3 MW turbine (Vestas, 2015a) and 2MW Platform (Vestas, 2015b,c) there have been some updates to turbine configuration and annual energy production to better reflect Vestas' commercial offering and the functional design of the wind turbine. These are fully detailed in Annex H. As such, in previous LCAs annual energy production was measured at mid-point of the wind class. In the current LCA the top-end wind speed of the wind class is used which reflect the IEC standards and functional design of the turbine. This has the effect to increase energy production.
- *Availability*: the availability of the wind turbine has improved from 3% to 2% which has the effect to increase energy production. Availability represents the energy production losses when the turbine is not running (e.g. due to maintenance operations).

Method updates:

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[4] The improvement to include repaired/refurbished parts reduces impacts by around 10%-70% across all impact categories versus assumption of 100% replacement.

- *Water flows*: updates made in 2013 and since to GaBi datasets account for water flows differently from the previous GaBi databases published in 2006. Whereby water inputs and outputs are aggregated, as well as inclusion of some nomenclature changes. This has had the effect to dramatically increase water consumption per kWh generated by the wind plant. In the current LCAs, adjustments have been made to remove both lake water and river water from the 'non-impact' indicator for water-use (refer to Section 5.3), as well as being removed from the complete power plant inventory, shown in Annex G. These adjustments aim to give consistency with previous LCAs using the 2006 GaBi databases, which reflect similar results as previous LCA studies.

Indicator improvements:

- *Product waste*: a new performance indicator is included in the report to indicate the amount of materials that are not recyclable (or reusable) at turbine end-of-life. The indicator is quantified as grams of (non- recyclable) material per kWh. It relates to the turbine-only. Part of the reason for its introduction is to avoid the conflict that *Recyclability* indicator has with other impacts measured per kWh (for example grams CO_2-e per kWh). For example, when optimising turbine design then material weight is removed from components; however, if, for example, steel is saved from the tower then all potential impacts per kWh improve, whilst recyclability is made worse. The *Product waste* indicator essentially measures the non-recyclable material and avoids this conflict. Additionally, when used for product improvement it encourages both more efficient utilisation of materials per kWh, as well as selection of more recyclable materials. It should be noted that this indicator does adopt a life cycle perspective but is calculated at the product bill-of-material level.
- *Circularity indicator:* a new indicator is included to estimate the circularity or the restorative nature of the product flows. This indicator relates to the turbine-only and has a value from 0-1; where 1 means a product is fully circular and 0 means a product is entirely linear. This indicator is based on the Ellen MacArthur Foundation method (EMF, 2015) in the context of a circular economy. It is used for the first time in a LCA by Vestas with the aim to understand how to measure product-level circular material flows considering::

    - using feedstock from reused or recycled sources
    - reusing components or recycling materials after the use of the product
    - keeping products in use longer (e.g., by reuse/redistribution)
    - making more intensive use of products (e.g. via service or performance models)

    Given this scope, it is evident that improving the MCI of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. Nonetheless, a widespread use of this methodology could form part of such a systems improvement.

    It should be noted that this indicator does adopt a life cycle perspective but is calculated at the product bill-of-material level. Refer to Section 5.3.6 for further description and indicator limitations.

2. Goal of the study

The goal of this study is to evaluate the potential environmental impacts associated with production of electricity from a 100MW onshore wind plant comprised of twenty nine V112-3.45 MW wind turbines from a life cycle perspective. A 100MW plant represents a typical plant size for these turbines. This assessment includes the production of raw materials, fabrication and assembly of the wind turbine by Vestas and its suppliers, site parts (e.g. transformers, grid connections, cabling, etc.), use-phase replacements, repairs, servicing and losses (e.g. transformer losses, etc.), end-of-life treatment and transport. The study assesses a 'typical' plant layout and does not make any comparative assessments with other wind turbines or electricity generation methods. As a consequence, the results of the study are not intended to be used in comparative assertions intended to be disclosed to the public.

Nonetheless, since the initial launch of the V112 turbine there have been improvements in design and turbine optimisation which are reflected in the current assessment, which primarily relate to increased power rating from 3.3 MW to 3.45 MW resulting in higher electricity generation, increase in wind class, design updates giving product cost-out and reduced material requirements and increase in wind class for the turbine. Additionally, the turbine has an option to operate in 3.6 MW power mode (which is analysed in Section 7 for sensitivity analysis).

The environmental impacts evaluated in this study include a range of commonly applied LCA impact categories, such as global warming potential and abiotic resource depletion, as well as other, non-impact indicators, such as recyclability and water-use. These are listed in Section 3.8 and further explained in Annex A.

The wind plant size, power output and other site parameters (e.g. distance to grid, etc.) are chosen to represent a 'typical' onshore wind plant consisting of V112-3.45 MW turbines. As mentioned in Section 1.2.3, the calculation of use-phase power output of the turbine is based on wind classes, which allows for a more robust benchmarking of wind power plants.

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: and
- 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:

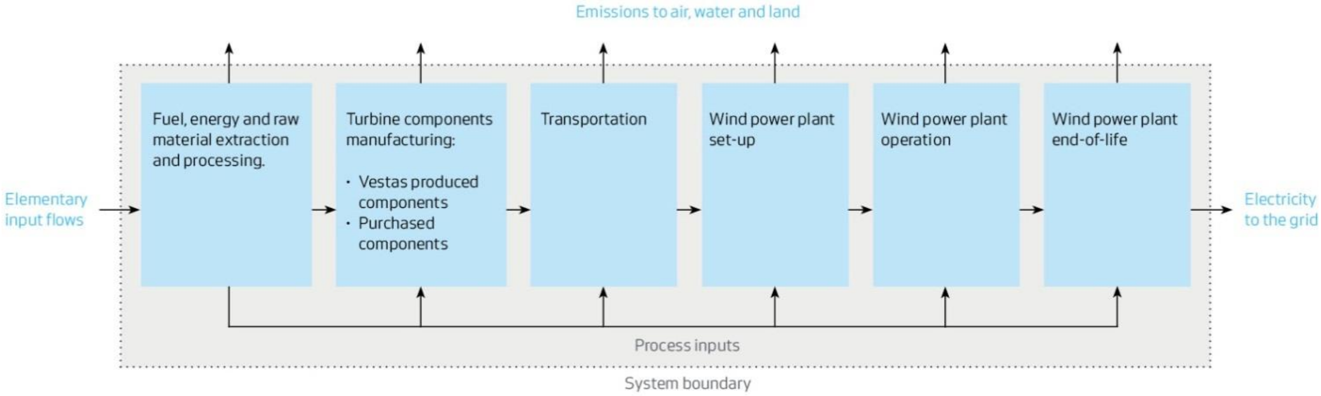
- customers of Vestas;
- internal Vestas Wind Systems A/S;
- investors of Vestas Wind Systems A/S; and
- other stakeholders and members of the general public with interests in renewable energy from wind and its associated potential environmental impacts.

3. Scope of the study

This study is a cradle-to-grave LCA, assessing the potential environmental impacts associated with electricity generated from a 100MW onshore wind power plant comprising of Vestas V112-3.45 MW wind turbines over the full life cycle.

This includes extraction of raw materials from the environment through to manufacturing of components, production of the assembled wind turbines, logistics, power plant maintenance, and end-of-life management to the point at which the power plant is disposed and returned to the environment (or is reused or recycled). Production and maintenance of capital goods (i.e. used for manufacture of turbine components) have been excluded from the scope of this study, unless specifically noted. However, power plant infrastructure itself is included in the study, i.e. those parts relating to cabling, roads, etc. needed to construct a complete wind power plant. Figure 2 shows the system boundary for the for the wind power plant system.

Figure 2: Scope of LCA for a 100MW onshore wind power plant of V112-3.45 MW turbines



The following processes have been considered:

- **Production of all parts of the wind plant:** (a description of main components can be found in Annex 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 over 99.9% of the turbine mass.
- **Manufacturing processes at Vestas' sites:** which includes both the Vestas global production factories (i.e. for casting, machining, tower production, generator production, nacelle assembly and blades production), as well as other Vestas activities (e.g. sales, servicing, etc.)
- **Transport:** of turbine components to wind plant site and other stages of the life cycle including, incoming raw materials to production and transport from the power plant site to end-of-life disposal;
- **Installation and erection:** of the turbines at the wind power plant site, including usage of cranes, onsite vehicles, diggers and generators;
- **Site servicing and operations (including transport):** serviced parts, such as oil and filters, and replaced components (due to wear and tear of moving parts within the lifetime of a wind turbine) are included;

- **Use-phase electricity 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; and
- **End-of-life treatment:** of the entire power plant including decommissioning activities.

3.1 Functional unit

The function of the wind power plant is the production of electricity including its delivery to the electricity grid.

It is important to consider the wind conditions onsite when assessing the potential environmental impacts from a wind plant. The Vestas V112-3.45 MW wind turbine has been designed to operate under high wind conditions and for this study, high wind conditions (IEC 1A) have been selected as the baseline scenario.

Refer to Section 3.4.2 for further details of turbine electricity generation.

The functional unit for this LCA study is defined as:

1 kWh of electricity delivered to the grid by a 100MW wind power plant.

The total electricity production of the 100MW wind power plant is 9121 GWh over a 20 year plant lifetime which results in a reference flow of 1.09642E-10

The functional unit and reference flow have been derived on the design lifetime of the power plant (of 20 years), along with the total energy produced over the lifetime based on electricity production in high wind conditions. Refer to Section 3.4.2 and Annex E for further details.

It is also worth noting that the functional unit could have been derived on the ‘total electricity production’ basis (i.e. total electricity over the lifetime of the plant), but it has been chosen to define the functional unit in this study on a ‘unit of electricity delivery’ basis (i.e. per one kWh).

Please also note that the functional unit is for electricity delivered to the electricity grid, as with other Vestas LCAs, and not delivered to the consumer. If this study should be used for comparison with electricity delivered to the consumer, then grid distribution losses should be considered.

3.2 System description

The wind power plant itself includes the wind turbines, foundations, cabling (connecting the individual wind turbines to the transformer station) and the transformer station, up to the point of existing grid as shown in Figure 3.

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

Figure 3: Scope of the power plant components

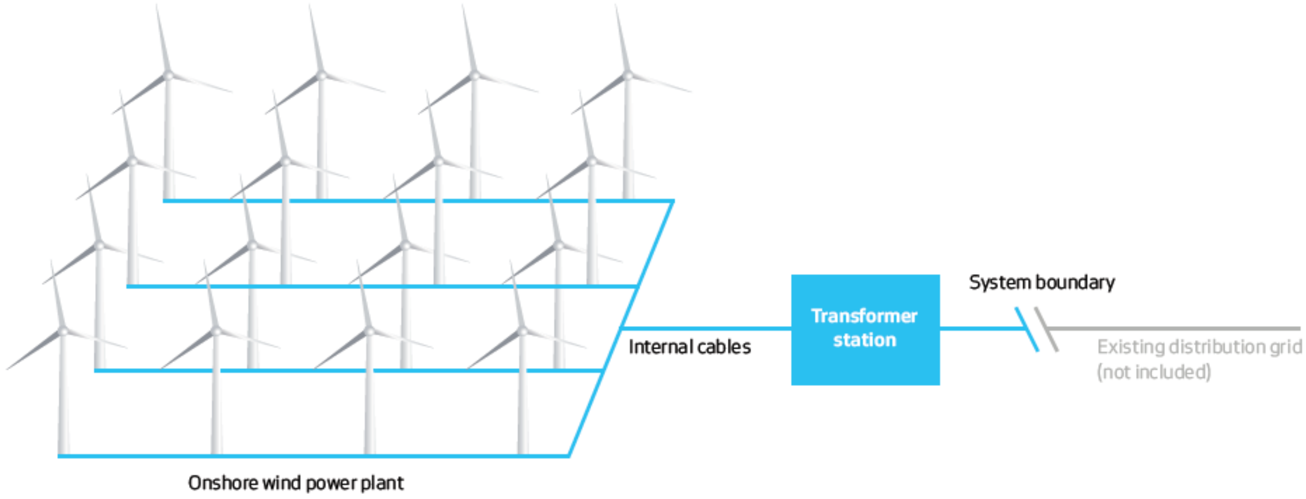


Table 1 gives an overview of the baseline wind power plant assessed in this life cycle assessment, which is further described in detail throughout Section 3.

Table 1: Baseline wind plant assessed

Description	Unit	Quantity
Lifetime	years	20
Rating per turbine	MW	3.45
Generator type	-	Induction
Turbines per power plant	pieces	29
Plant size	MW	100
Hub height	metres	94
Rotor diameter	metres	112
Wind class	-	High (IEC1A)*
Tower type	-	Steel
Foundation type		Low ground water level (LGWL)
Production @ 7.5 m/s (low wind)	MWh per turbine per year	-
Production @ 8.5 m/s (medium wind)	MWh per turbine per year	-
Production @ 10.0 m/s (high wind)	MWh per turbine per year	15725
Grid distance	km	20
Plant location	-	Europe
Vestas production location	-	Global average

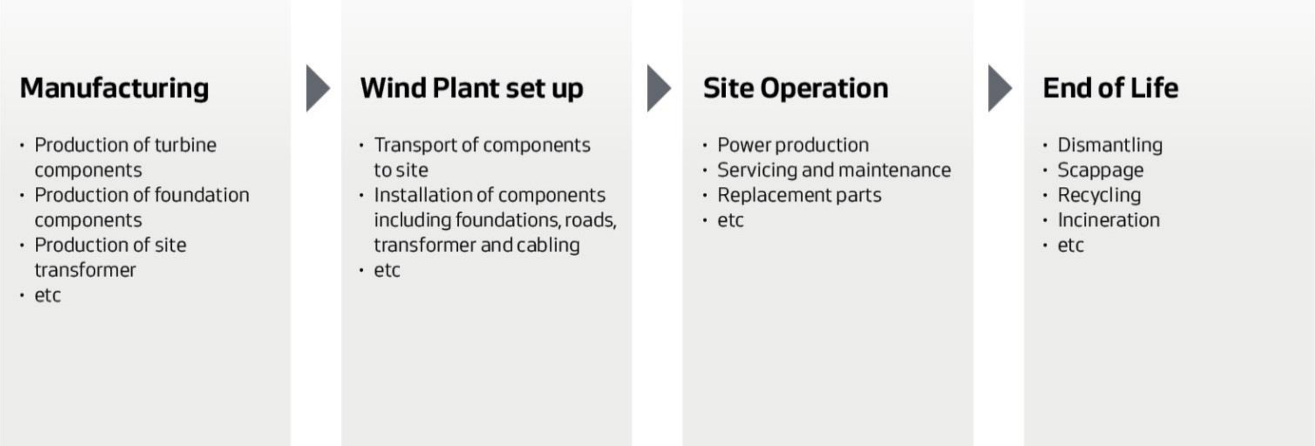
Note: The above figure for electricity production includes all losses, assuming and availability of 98%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

**The scope of the V112 Mk3 design is to increase the turbine wind class and MW rating in order to reduce the levelised cost of energy and to increase product competiveness within the higher wind class.*

3.2.1 Life cycle stages

The entire life cycle of a wind plant can be separated into individual life cycle stages, as shown in Figure 4 used for this study.

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



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 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 and installation and erection of the wind power plant. Construction work on site, such as the provision of roads, working areas and turning areas, also falls 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 included in the scope of the study.

This study provides an update over previous LCAs for the power plant layout (i.e. of cable lengths and specification of the high voltage cables used for inter-connecting the turbines in the wind plant).

Transport to site for installation of the wind power plant includes transport by truck and by sea vessel. Vestas has established global production facilities that operate within their global region to service that particular region. As such, transport reflects a reasonable description of the current supply chain. The current LCA uses truck and sea vessel fuel consumption (and vehicle utilisation) with specific data for the transport of the various turbine components (such as, tower sections, blades and the nacelle).

As part of the sensitivity (see section 7.2.4) analysis, a best-case and worst-case approach has been assumed.

3.2.1.3 Site -operation

The site-operation phase deals with the general running of the wind turbine plant as it generates electricity. Activities here include change of oil and filters, and renovation/replacement of worn parts (e.g. the gearbox) over the life time of the wind plant. The transport associated with operation and maintenance, to and from the turbines, is included in this phase and has been updated to reflect typical vehicles and servicing.

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). It has been assumed in this LCA that any land use change (e.g. resulting in the removal of vegetation for set-up of the plant) is restored to original site conditions. This reflects a common condition for site permits. The end-of-life treatment of materials is also considered in this phase. Waste management options include: recycling; incineration with energy recovery; component reuse; and deposition to landfill. The LCA model for disposal of the turbine accounts for specific recycling rates of different components, depending on their material purity and ease of disassembly, based upon industry data. Section 3.4.4 provides further details of end-of-life treatment and section 7.2.8 presents a sensitivity analysis on this issue.

3.2.2 Technology coverage

This study assesses the production of the Vestas V112-3.45 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 2015 which was chosen as it is the most representative and the most recent year for annual throughput of turbines. The time period for service/maintenance represents the typical 20 year design life. The V112-3.45 MW (Mark 3a) turbine represents the most recent model of turbine. For turbine production at Vestas facilities a global production for the calendar year of 2015 is selected for this LCA study as it is deemed the most complete and representative of the supply chain. Refer to Section 1.2.4.

3.2.4 Geographical coverage

For the purpose of this study a typical “virtual” wind plant site has been assessed. The aim is to give an overall picture of wind power production rather than to assess any particular location. The actual electricity output is based on wind classes (described in Annex E). Nonetheless, specific sensitivity analyses have been conducted to assess the importance on the overall impacts for both:

- transport distances to the site; and
- distance to the grid for delivered electricity.

The geographical coverage of the “virtual” wind plant ~~primarily~~ relates to a European scenario, for example, relating to the following:

- the production of metals (iron, steel, copper and aluminium) uses European average datasets (such as those from worldsteel), of which the wind turbine is constituted around 89% metals by weight;
- other material production datasets are European-focused, such as those used for polymer and composite production (e.g. Plastics Europe), as well as concrete; and
- end-of-life recycling also uses European datasets (such as those from worldsteel) for crediting.

For Vestas operations, the following is assumed:

- Vestas manufacturing of the turbine represents the weighted average of all Vestas global production facilities in 2015;
- turbine transport represents Vestas global footprint for transport – which is based on Vestas' approach to "be in the region for the region", offering a regional supply chain.

The above European data covers the majority of flows with environmental significance. Datasets selected are considered the most comprehensive and representative of the supply chain and dataset selection take a conservative approach to estimate impacts. This is further discussed in Annex D.

3.2.5 Data collection / completeness

Previous LCAs of Vestas turbines show that the most significant environmental impacts will typically arise during manufacturing of the turbines and final disposal of the turbines. Conversely, the operation of the turbine does not directly contribute in a significant way to overall environmental impacts, except that electricity production and turbine lifetime are significant factors when assessing the impacts per kWh of electricity produced (PE, 2011 and Vestas, 2006, 2011a, 2011b, 2011c, 2013a, 2013b, 2014a, 2014b, 2014c, 2014d, 2015a). Therefore, data collection has focused on procuring as precise data as possible for the production and disposal stages of the life cycle. Additionally, other areas have been updated for this LCA relate to the wind plant layout, the composition of electronics and controls used in the turbine, and the recycling efficiencies at end-of-life.

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 item lists, via technical drawings, from the 3D CAD system used for component design, and from supplier declarations in the form of technical specification documents.

Instances where primary data have been used in this study include:

- 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, such as, the gearbox and transformer, etc. (directly from suppliers);
- transport of Vestas components to erection site (fuel and vehicle utilisation data from suppliers);
- utilities and materials consumption for wind plant site preparation, operation and maintenance;

- electricity production of the wind plant based on measured data for turbine performance and using the Vestas software that forecasts power output; and
- electrical losses in the entire power plant (for transformers, site cables and turbine electricity consumption, etc) from Vestas; and
- recycling rates of specific components used in the turbine.

Where primary data have not been readily available from Vestas or component 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 include:

- country-specific electricity grid mix information;
- production of primary materials (e.g. steel, iron, aluminium, fibre glass, plastic granulates);
- transport processes for raw material inputs;
- material 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 and stamping); and
- end-of-life processes, for example, the landfill, incineration and recycling of steel.

Most secondary datasets are supplied by Thinkstep (2016) and also include secondary sources from industry association, such as:

- worldsteel;
- Eurofer;
- European aluminium association; and
- Plastics Europe.

Details of data source and discussion of data quality is shown in Annex D.

3.3 Cut-off criteria

The following cut-off criteria were used to ensure that all relevant potential environmental impacts were appropriately represented:

- **Mass** – if a flow is less than 1% of the mass at a product-level, then it may be excluded, provided its environmental relevance is not of concern.
- **Energy** – if a flow is less than 1% of the energy at a product-level, then it may be excluded, provided its environmental relevance is not a concern.
- **Environmental relevance** – if a flow meets the above criteria for exclusion, but is considered to potentially have a significant environmental impact, it has been 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, at a product-level.

Over 99.9% of the total mass of materials in the V112-3.45 MW turbine (i.e. covering all parts of the turbine-only, excluding foundation, site cables and site parts) has been accounted for, covering around 25,000 components that make-up the entire turbine. Scaling of the turbine up to 100% of total mass has not been conducted. Additionally, all site parts, foundations and cables are also included in their entirety for the complete wind power plant. As such, the LCA includes all materials and all components of environmental significance, with around 99.95% of the entire power plant accounted for by mass. The cut-off-criteria applied in the secondary data is addressed in the respective documentation (Thinkstep, 2016).

3.4 Assumptions

This section outlines the primary assumptions used in the LCA which affect the environmental performance of the wind power plant.

3.4.1 Lifetime of turbine and site parts

The lifetime of the wind plant is assumed to be 20 years. This corresponds to the design lifetime of the V112-3.45 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) the actual lifetime 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. Additionally, other site components such as the site cabling and foundations may have a significantly longer useful lifetime (around 50 years). The effects of varying the lifetime of a wind plant on potential environmental impacts are discussed in Section 7.

3.4.2 Electricity production

A typical site for a V112-3.45 MW turbine with a high wind of 10 m/s with a 94m hub height is assessed for the LCA, which represents, for example, a realistic site placement in Europe. Table 1 shows the electricity production from the power plant.

Based on typical high wind speed curves, the electricity production from a 100MW onshore wind power plant of V112-3.45 MW turbines is 9121 GWh over 20 years (equivalent to 15725 MWh per turbine per year).

All electrical losses are included up to the grid, including within the turbine, transformer station and site cables. These are estimated to be 2.5% based on Vestas plant layout for medium voltage (MV) of 36kV cables connecting between the turbines and a 20km distance to grid with a voltage of 110kV. The wake losses (which result from turbine losses downstream of each other) are also included within the above electricity production figures which represent an average 6% loss for this turbine and power plant size. Turbine availability losses are also included which represent the time the turbine is not operating (e.g. due to site maintenance), which represents 2.0% total loss. Previous LCAs assumed average availability loss of 3.0%, but this has significantly improved due to improved reliability.

Table 2 shows the electricity production, as delivered to the grid, for the V112 turbines.

Table 2: Electricity production

Turbine	Wind class	Wind speed ms^{-1}	Location	Grid distance km	Per turbine per year (AEP) MWh	Per 100MW plant per 20 years GWh
V112-3.45 MW (Mk3)	High	10	Onshore	20	15725	9121

Source: Vestas internal data for the electricity production of the wind turbine. This is based upon actual turbine test data for a typical power production curve and using analysis software (based on T-CAT) of the specific turbine performance. The annual energy production is reported in increments of 0.25 ms^{-1} within the different wind classes and total electricity production is determined over the range of 0 ms^{-1} to 25 ms^{-1} of the entire power curve for the specific turbine. Note: The above figure for electricity production includes all losses, assuming and availability of 98%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

3.4.3 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 primary material; however, for iron, steel, aluminium and copper, the secondary (or scrap metal) inputs to primary production have been adjusted to assign a burden to all secondary metal inputs (using primary production or worldsteel 'scrap value' for these burdens). This provides a fair and representative approach to assess the impacts of metal production and recycling. See Section 3.4.4 for further details of recycling approaches adopted in the LCA.

The V112-3.45 MW turbine does not use rare earth elements (i.e. neodymium and dysprosium) in the turbine generator, but uses a Single Fed Induction Generator (SFIG) that is primarily constructed of iron/steel and copper. There is some use of rare earth elements within the turbine tower for attaching internal fixtures. The production of these materials is based on specific production datasets for their sourcing from Europe and Asia.

3.4.4 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; as further explained below.

All large metal components that are primarily mono-material (e.g. tower sections, cast iron frame in nacelle, etc.) are assumed to be 98% recycled. Other major components, such as generator, gearbox, cables and yaw system parts are 95% recycled and all other parts of the turbine are treated as shown in Table 3.

Table 3: End-of-life treatment of turbine components not already mentioned in the text

Material	Treatment	Credited material datasets*
Steel	92% recycled + 8% landfilled	Value of scrap from worldsteel. No further distinction made between material grades.
Aluminium	92% recycled + 8% landfilled	Aluminium ingot mix (2010). No further distinction made between material grades.
Copper	92% recycled + 8% landfilled	Copper mix (global) from Thinkstep International. No further distinction made between material grades.
Polymers	50% incinerated + 50% landfilled	No credit assigned.
Lubricants	100% incinerated (no energy recovery assigned)	No credit assigned.
All other materials (including concrete)	100% landfilled	No credit assigned.

**Refers to the general datasets used for end-of-life crediting for these material groups for the entire turbine and wind plant*

The information for recycling rates of turbine components comes from the full recycling of a nacelle of a Vestas turbine (Vestas and Averhoff, 2012), along with expert judgement and data obtained from previous LCA studies performed by Vestas. This represents an update from previous LCA studies of this turbine platform. Material losses from the recycling process itself are calculated on top of these recycling rates.

At end-of-life, full credits are given for the material recovered (i.e. relating only to metal parts made of steel, iron, copper and aluminium), which is based upon an ‘avoided impacts approach’ to providing credits for recycling. This ‘avoided impacts approach’ (also called closed-loop approach) is supported by the metals industry (Atherton, 2007; PE International 2014), and is consistent with ISO 14044 and for purposes of environmental modelling, decision-making, and policy discussions involving recycling of metals.

Additionally, the use of an avoided impacts approach provides a business measure to drive-up the total recyclability of the wind turbine, which can be accurately measured using the LCA models; allowing Vestas to promote business activities in this area, for example by focusing on recycling/reuse of non-metallic parts, such as composite blade materials, controllers and polymers. Details of turbine recyclability can be found in Section 5.3.4.

However, it is also recognised that, from a scientific perspective, that a ‘recycled-content’ approach for crediting may also be applied to wind turbines (Garrett, 2012). As such, Section 7.2 presents the LCA results if a ‘recycled content’ approach for crediting were applied. This is based upon the standard industry datasets (such as worldsteel) which contain average recycled content for metal materials and therefore represent an estimate for the actual situation for a Vestas turbine, as the exact recycled content of all the turbine parts is not known.

The datasets for landfill disposal relate to the material type being disposed to sanitary landfill, for example, for generic polymers or steel and aluminium material for metals. The datasets for incineration of lubricants does not include a credit for thermal energy recovery, while incineration of plastics relates to a glass-filled nylon polymer type, also with credits for energy recovery.

3.4.5 Sulphur hexafluoride (SF_6) gas

Sulphur hexafluoride is a very potent greenhouse gas which is used in switchgears for medium- and high-voltage applications. The gas acts as an electrical insulator for the operation of the switchgear. Each turbine contains a switchgear and they are also used onsite for connecting the turbines and transformer substation.

For the switchgear application this usually only becomes an issue if the gas is released into the environment during a blow-out. Occurrences of blow-outs are extremely rare and have not been modelled in this study. During normal operation the turbine switchgear may potentially release up to 0.1% w/w of the sulphur hexafluoride per year, accounting for a potential 2% w/w total release over 20 years of operation. The potential effect of a blow-out is assessed in the sensitivity analysis, as shown in Section 7.2.7.

At end-of-life the switchgears are collected and the sulphur hexafluoride gas is reclaimed for reuse in new equipment. Vestas has established procedures and is working in partnership with customers and suppliers to assure the safe disposal of switchgears used in Vestas power plants. Based on supplier data it is estimated that a maximum of 1% w/w of the SF_6 gas may be released to atmosphere during the reclamation and recycling process at end-of-life. Vestas estimates that 95% of all switchgears will be returned for reclamation at end-of-life. The remaining 5% are assumed to have all the sulphur hexafluoride gas released to atmosphere at end-of-life.

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 (HGWL): indicates a (maximum) groundwater level equal to the level of the terrain, which requires more concrete and steel reinforcement; and
- low groundwater level (LGWL): low ground water scenario (requiring less concrete and steel reinforcement).

The low groundwater level case has been chosen as the base case as it is more representative of the majority of wind power plant sites. The size of the foundation will also vary depending on the turbine tower height and the wind class for the V112-3.45 MW turbine, which affects the mechanical loads on the foundation. These variations are also accounted for in the study.

3.4.7 Electrical/electronic components in turbine

This study provides an update over previous LCA studies, whereby all individual electronic components and printed circuit boards have been mapped much more accurately on an individual part-by-part basis. All controllers on the turbine were mapped specifically for component types, such as, resistors, capacitors, integrated circuits, etc according to component size and specification. Vestas designs the electronic controllers and components on the turbine and as such it was possible to map all component types on the turbine, covering around 9500 parts for the entire platform.

3.4.8 Transport

Transport steps that have been included in this study are described below:

- **Transport associated with incoming raw materials** to Vestas' suppliers is assumed to be 600km by truck, except for foundation concrete materials where 50km is assumed. This covers the transport from raw material manufacturers to Vestas suppliers.

- **Transport associated with incoming large components to Vestas production sites** is assumed to be 600km by truck. This accounts for 90% of turbine mass (excluding foundation) and covers the transport of the components from the supplier to Vestas' factories.

- **Transport associated with moving wind plant components** from Vestas' factories to the site are given in Table 4 below.

Table 4: Transport of wind plant components from Vestas to the wind plant site

Component	Truck (km)	Ship (km)
Nacelle	800	0
Hub	800	0
Blades	800	600
Tower	500	6200
Foundation	50	0
Other site parts	600	0

Note: transport distances assume a German plant location and the supply chain distances are based on average sales for 2015. Foundations and other site parts are estimated distances by Vestas. Refer to Section 7.2.4 for a sensitivity analysis of another transport scenario.

- **Transport associated with end-of-life recycling or disposal** assumed to be 200km to a regional recycling or disposal operator, except for foundation concrete materials where 50km is assumed.

- **Transportation of maintenance crew** to and from the site during servicing operations is updated based on servicing data and is estimated to be 2880 km per plant per year.

The current LCA also uses truck and sea vessel fuel consumption (and vehicle utilisation) with specific data for the transport of the various turbine components (such as, tower sections, blades and the nacelle). These are based on measured data and specific distances with actual wind turbine transports. 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, assuming a likely best-case and worst-case approach.

3.4.9 Vestas-owned wind plants

As part of its corporate profile and as a means of reaching both company and product specific environmental targets, Vestas in 2015 achieved the 100% WindMade (2015) accreditation. As part of reaching the 100% WindMade accreditation Vestas made significant investment in and retained credits from Vestas-owned wind plant located in Romania with the intent of balancing out non-renewable electricity consumed elsewhere in Vestas.

From a business perspective, this LCA aims to provide an important tool to both measure and incentivise the respective product-level and business-unit-level environmental targets; and to demonstrate traceability across these levels for improvements achieved.

As such, Vestas intended to show how it's ambitious corporate environmental targets (e.g. of sourcing 100% renewable electricity) extends to also impact upon its products performance, from a life cycle perspective in the current LCA study. However, according to the definitions in the ISO 14000 series (e.g. 14040 and 14067) this credit is essentially seen as an "offset" which, under 14067 standard for carbon footprinting, this is a "mechanism for compensating for all or for a part of the carbon footprint through the prevention of the release of, reduction in, or removal of an amount of greenhouse gas emissions in a process outside the boundary of the product system." The Carbon Footprint Standard ISO 14067 clearly states that these offsets cannot be calculated into the baseline result, but only reported separately.

From the perspective of ISO 14040, to which the assessment is reviewed against for ISO conformity, a similar constraint applies, requiring that "double-counting has to be avoided", which is clearly recognised by the authors as essential in conducting any assessment.

Nonetheless, Vestas intends to take a robust and transparent approach in conducting life cycle assessment and the credit for investing in Vestas-owned wind plants is not included in the baseline LCA results; however, a sensitivity analysis is presented in Section 7.2 which includes this credit.

3.5 Allocation

Wind turbines have electricity as the single appreciable product output. However, since Vestas produces several models of turbines and production data were collected at a factory level for all global production facilities, allocation was required to assign the correct production burdens (from the different manufacturing locations) to the particular wind turbine model. Similarly, allocation is used to assign the proportion of credits from Vestas-owned wind plants to the particular turbine model, based on a MJ per MJ basis. This is described in Annex C. Also refer to Annex F.3 for information on allocation procedures in the secondary datasets.

3.6 Inventory analysis

This LCA study follows an attributional, process-based approach, which focuses on quantifying the relevant environmental flows related to the wind power plant itself and describes the potential impacts of the power plant based on physical material and energy flows[5].

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

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[5] Note: in contrast, a 'consequential approach' to conducting a LCA could also be adopted; however, this approach, does not aim to describe the impacts of the actual wind power plant itself, but rather it aims to describe the 'response to decisions' that might arise from installing the wind power plant. For example, how will electricity consumers react to purchasing the quantity of available of wind energy, etc. The 'consequential approach' is not suitable for the goal of this study.

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 power plant system.

The GaBi LCA software and databases together with GaBi DfX were used to model the scenarios and to generate the life cycle inventories and impact assessments on which the study conclusions are based. The DfX software extension allows import of a complete product bill-of-materials (BOM) into a LCA model, which represents a state-of-the-art tool for carrying out LCAs (Thinkstep, 2016).

3.7 Modelling the life cycle phases

Modelling of the life cycle begins with a bill-of-materials (containing a part-tree of the entire turbine). Each part is associated with a material, manufacturing process and country of origin. This is extremely extensive, where a selected BOM (i.e. excluding all turbine options) for the V112-3.45 MW turbine accounts for around 25,000 parts. Modelling this many components “conventionally” in LCA is not practicable. However, using GaBi DfX allows this BOM to be imported into the LCA software where materials and manufacturing processes are mapped to individual components in the complete BOM.

Vestas’ manufacturing process models are created with only the energy and consumables linked to these 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.

The DfX software also provides the functionality to disassemble the entire turbine (or parts of it) into its source components. This allows for an extremely detailed end-of-life model to be created that is part-specific. This feature is used for the end-of-life treatment of the turbine where certain parts that can be more easily dismantled and recycled will receive 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 representative of those impacts that are likely to arise from a wind plant system, based on the CML (2016) baseline characterisation factors for mid-point potential impacts. For example, the selected impact categories cover those associated with metal production, fabrication and recycling (of which the turbine itself is constituted of around 89% metals), as well as other materials contained with the turbine and power plant, such as concrete, polymers and composite materials. Ozone depletion potential (ODP) has been omitted from the selected impact categories as this is not considered to be a significant issue since the introduction of the Montreal Protocol in 1987 which has drastically reduced both the consumption and emission of ozone depleting substances (UNEP, 2007). Previous LCAs (published from 2010 to 2015) used the CML 2009 version.

The following environmental impact categories and non-impact indicators are evaluated in the LCA:

Environmental impact categories (based on CML method):

- 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 oxidant creation potential (POCP)
- Terrestrial ecotoxicity potential (TETP)

Non-impact indicators (not based on CML method):

- Primary energy from renewable raw materials (net calorific value)
- Primary energy from resources (net calorific value)
- Water consumption
- Turbine recyclability (not life cycle based, turbine only)
- Product waste (not life cycle based, turbine only)
- Turbine Circularity (not life cycle based, turbine only)

The impact modelling method used is that developed and maintained by the Centre for Environmental Science, Leiden University (CML, 2016) and which is incorporated into the GaBi LCA software tool. The chosen CML-method has been used in the current and previous LCAs by Vestas to give robust results for mid-point potential impacts. It is noted that CML contributed to the more recent ReCipE impact assessment method; and it is recognised that other impact assessment methods may be beneficial as they develop or become appropriate. However, a recent harmonisation whitepaper of 16 industry associations still recommends CML as an equally proper choice, as well as ReCiPe (PE, 2014).

Annex H describes in full detail the assumptions to establish the baseline to assess wind turbine performance, including the datasets and impact methods, as well as turbine and wind plant configuration. The results presented in Annex H include the following updates:

- impact assessment using the Product Environmental Footprint (EC, 2012).

In relation to the indicator for water-use, adjustments have been made to the Thinkstep 2016 datasets in order to give a consistent approach used with previous LCAs (PE 2011, Vestas 2011a, 2011b, 2011c, 2013a, 2013b, 2014a, 2014b, 2014c, 2014d, 2015a), where in the 2006 datasets river water and lake water were treated differently.

The CML impact categories 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) and characterise their 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 end-points, the exceeding of thresholds, safety margins or risks.

These impact categories occur on different geographical scales, ranging from global impacts (such as GWP) to regional impacts (such as acidification potential) and local impacts (such as, aquatic toxicity or human toxicity potential), and the relevance of the point of emission becomes more important the more localised the impact that is being considered. For example, one kilogram of carbon dioxide emitted anywhere in Denmark will give the same contribution to global warming as one kilogram of carbon dioxide emitted anywhere else in the world; whereas for more regionally confined impact categories, only emissions that occur in that location will have a measurable 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 Annex A.

For the ‘non-impact’ indicators assessed in the LCA some additional comments should also be noted in relation to water use and water footprinting. There is a new standard to provide the framework for internationally harmonised metrics for water footprints: *ISO 14046, Water footprint – Requirements and guidelines (ISO, 2014)*. This complements existing standards for life cycle assessment (i.e. ISO 14040/44), as well as others for product carbon footprints and greenhouse gas (GHG) accounting and verification.

At present, an LCA study only accounts for freshwater consumption - meaning the net balance of water inputs and outputs of freshwater for production and disposal processes. However, for this to be treated more thoroughly further consideration should be made regarding types of water used, inclusion of local water scarcity, as well as differentiation between watercourses and quality aspects (Berger, 2010), which will aid more accurate decision making.

Also, in general, a life cycle assessment does not address some other environmental concerns, such as the potential impacts of land use, noise and local impacts on flora and fauna. In general, a LCA should not stand alone in the assessment of technologies; but other environmental management techniques, such as risk assessment and Environmental Impact Assessment (EIA), are valuable tools that address these environmental concerns. These types of assessments are normally conducted as part of the local permitting and planning process for installation of the wind power plant.

Additionally, it is noted that guidance already exists for preparing an Environmental Product Declaration (EPD) based on ISO 14025 (2006b) for electrical energy via the Product Category Rules (Envirodec, 2015) for electricity generation and distribution. In general, those rules align with the current LCA in terms of functional unit, system boundaries and general data quality requirements. Although the current LCA has not adopted the EPD approach, but is in conformity with ISO 14040/44 (2006). Some differences in approach arise where end-of-life and recycling credits are excluded from the EPD boundary (but a recycled-content approach is adopted in the EPD), as well as the reporting of results, for example, where the EPD includes reporting of potential impacts both to the point of existing grid (as this LCA does), as well as to the point of the consumer (i.e. defined by voltage delivered). Some additional indicators are also reported within the EPD, such as waste generation, noise, land-use, impacts on biodiversity, as well as environmental risk assessment, which are not included in the LCA.

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

3.9 Interpretation

The interpretation stage of the LCA has been carried out in accordance with the main steps defined in ISO (2006a) for life cycle assessment, which includes an assessment of the significant environmental flows and environmental impacts based upon the results of the life cycle inventory

(LCI) and life cycle impact assessment (LCIA). The most significant turbine components, life cycle stages and inventory flows (substance extraction and emissions to/from the environment) are identified and assessed.

An evaluation of both the completeness and consistency of datasets and assumptions has been qualitatively evaluated in the LCA. The LCI datasets have been qualitatively assessed based on the requirements shown in Table 5.

Table 5: Data quality requirements for inventory data

Parameter	Description	Requirement
Time-related coverage	Desired age of data and the minimum length of time over with data should be collected.	Data should represent the situation in 2015 and cover a period representing a complete calendar year.
Geographical coverage	Area from which data for unit processes should be collected.	Data should be representative of the Vestas global supply chain.
Technology coverage	Technology mix.	Technology (for manufacture, product usage and end-of-life management) should be representative of global supply conditions and technology.
Precision	Measure of the variability of the data values for each data category expressed.	No requirement specified.
Completeness	Assessment of whether all relevant input and output data are included for a certain data set.	Specific datasets will be compared with literature data and databases, where applicable.
Representativeness	Degree to which the data represents the identified time-related, geographical and technological scope.	The data should fulfil the defined time-related, geographical and technological scope.
Consistency	How consistent the study methodology has been applied to different components of the analysis.	The study methodology will be applied to all the components of the analysis.
Reproducibility	Assessment of the methodology and data, and whether an independent practitioner will be able to reproduce the results.	The information about the methodology and the data values should allow an independent practitioner to reproduce the results reported in the study.
Sources of the data	Assessment of data sources used.	Data will be derived from credible sources and databases.

Sensitivity analyses have also been conducted to better understand the scale and importance of uncertainties in data and of the modelling assumptions for the wind power plant system. The following sensitivity analyses have been carried out for this study:

- variation in wind power plant lifetime: ± 4 years;
- variation in frequency of parts replacement;
- operating the 100MW wind plant under 3.6 MW power mode;
- varying the transport distances for components to wind plant erection site;
- varying the distance of the wind plant to the existing grid taking into account corresponding cable losses;
- changing the type of foundation used from low ground water level type to high ground water level type;
- incidence of a potential turbine switchgear blow-out; and
- potential effects of method used for crediting recycling of metals.

Additionally, the major conclusions and recommendations for improvement have been identified (refer to Section 7). The study limitations are highlighted throughout the report, where relevant.

As part of the interpretation of the study, reference has also been made to recent LCA guidance and documents, including:

- ILCD handbook: General guide for life cycle assessment (EC, 2010); and
- UNEP Global Guidance Principles for Life Cycle Assessment Databases (UNEP, 2011).

3.10 Report type and format

This report will be made available electronically via the Vestas website.

3.11 Critical review

The outcomes of this LCA study are intended to support external communication. In order to assure the rigour of the study and robustness of the results, an independent critical review of the study according to ISO TS 14071 (2014) 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; and
- the study report is transparent and consistent.

Prof. Dr. Matthias Finkbeiner has been nominated by Vestas based on his expertise in the field of sustainability and his experience of reviewing technical LCA studies. The review is performed as a critical review by an external expert according to paragraph 6.2 of ISO 14044 (2006a), as the study is not intended for comparative assertions intended to be disclosed to the public. The review is performed at the end of the study and excluded an assessment of the life cycle inventory (LCI) model, as well as an assessment of individual data sets.

4 Material breakdown of V112-3.45 MW wind power plant

Table 6 and Table 7 present the material breakdown for the complete onshore 100MW wind power plant of V112-3.45 MW turbines. The entire power plant is included in the presented inventory, with the exception of replacement parts. Additionally, Figure 5 shows the percentage breakdown of wind turbine-only and Figure 6 shows the material breakdown for the entire wind power plant by mass.

The complete life cycle inventory results for the power plant is shown in Annex G, divided into substance flows and reported per main life cycle stage.

Figure 5: Material breakdown of V112-3.45 MW turbine-only (% mass)

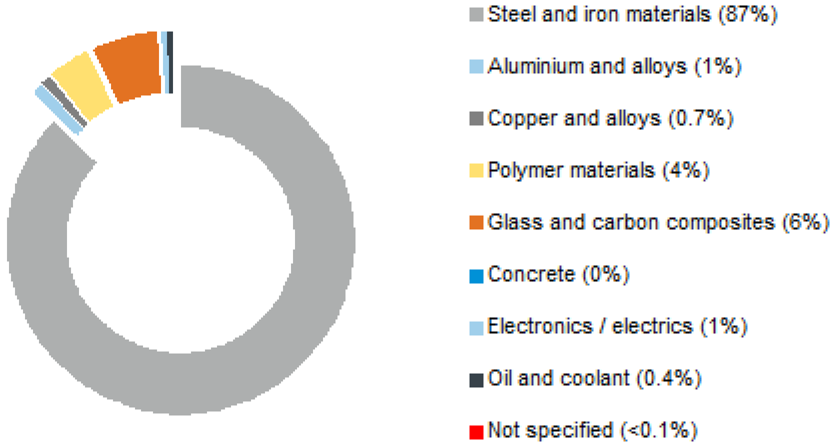


Figure 6: Material breakdown of 100MW power plant of V112-3.45 MW turbines (% mass)

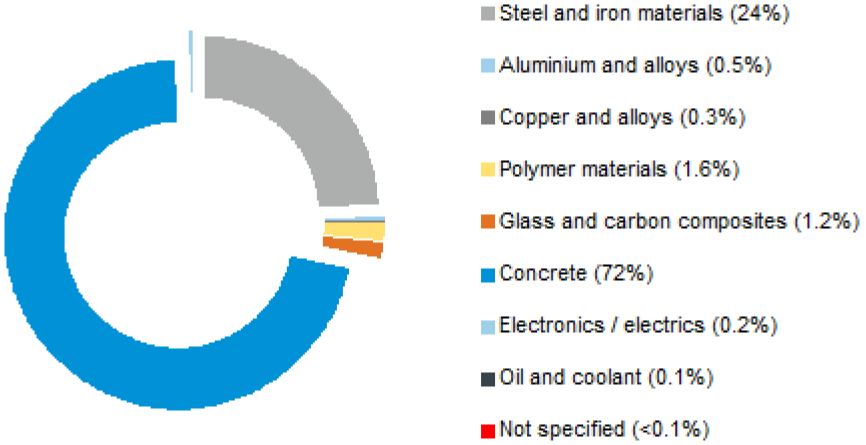


Table 6: Material breakdown of 100MW power plant of V112-3.45 MW turbines (units shown in tonne or kg per total wind plant)

Material classification	Unit	Turbines	Foundations	Site cables	Site switchgears	Site transformer
Steel and iron materials (total)	tonne	11072	2616	0	6	32
Unalloyed, low alloyed	tonne	7985	2407	0	0	0
Highly alloyed	tonne	1054	209	0	5	32
Cast iron	tonne	2033	0	0	0	0
Steel and iron materials (unspecified)	tonne	0	0	0	0	0
Lights alloys, cast and wrought alloys (total)	tonne	130	0	166	0	0
Aluminium and aluminium alloys	tonne	130	0	166	0	0
Nonferrous heavy metals, cast and wrought alloys (total)	tonne	93	2	43	2	8
Copper	tonne	91	2	43	2	8
Copper alloys	tonne	2	0	0	0	0
Polymer materials (total)	tonne	485	2	373	0	1
Process polymers (total)	tonne	21	0	0	0	0
Lacquers	tonne	21	0	0	0	0
Adhesives, sealants	tonne	0	0	0	0	0
Other materials and material compounds (total)	tonne	760	40457	1	0	4

Modified organic natural materials	tonne	3	0	0	0	3
Ceramic / glass	tonne	752	0	1	0	1
Concrete	tonne	0	40457	0	0	0
SF6 Gas	kg	234	0	0	42	0
Magnets	tonne	5	0	0	0	0
Electronics / electrics (total)	tonne	95	0	0	0	0
Electronics	tonne	25	0	0	0	0
Electrics	tonne	70	0	0	0	0
Lubricants and liquids (total)	tonne	54	0	0	0	13
Lubricants	tonne	38	0	0	0	13
Coolant / other glycols	tonne	16	0	0	0	0
Not specified	tonne	5	0	0	0	0
Total mass	tonne	12706	43078	584	8	58
Total number of pieces		29	29	1	6	1
Mass of piece	tonne	438	1485	584	1	58

Note: the material breakdown represents the ‘as-built’ mass of the power plant and excludes production wastes or parts for servicing.

Table 7: Material breakdown of 100MW power plant of V112-3.45 MW turbines (units shown in mg or µg per kWh)

Material classification	Unit	Turbines	Foundations	Site cables	Site switchgears	Site transformer
Steel and iron materials (total)	mg per kWh	1214	287	0	1	4
Unalloyed, low alloyed	mg per kWh	876	264	0	0	0
Highly alloyed	mg per kWh	116	23	0	1	4
Cast iron	mg per kWh	223	0	0	0	0
Steel and iron materials (unspecified)	mg per kWh	0	0	0	0	0
Lights alloys, cast and wrought alloys (total)	mg per kWh	14	0	18	0	0
Aluminium and aluminium alloys	mg per kWh	14	0	18	0	0
Nonferrous heavy metals, cast and wrought alloys (total)	mg per kWh	10	0	5	0	1
Copper	mg per kWh	10	0	5	0	1
Copper alloys	mg per kWh	0	0	0	0	0
Polymer materials (total)	mg per kWh	53	0	41	0	0
Process polymers (total)	mg per kWh	2	0	0	0	0
Lacquers	mg per kWh	2	0	0	0	0
Adhesives, sealants	mg per kWh	0	0	0	0	0
Other materials and material compounds (total)	mg per kWh	83	4436	0	0	0

Material classification	Unit	Turbines	Foundations	Site cables	Site switchgears	Site transformer
Modified organic natural materials	mg per kWh	0	0	0	0	0
Ceramic / glass	mg per kWh	82	0	0	0	0
Concrete	mg per kWh	0	4436	0	0	0
SF6 Gas	µg per kWh	26	0	0	5	0
Magnets	mg per kWh	1	0	0	0	0
Electronics / electrics (total)	mg per kWh	10	0	0	0	0
Electronics	mg per kWh	3	0	0	0	0
Electrics	mg per kWh	8	0	0	0	0
Lubricants and liquids (total)	mg per kWh	6	0	0	0	1
Lubricants	mg per kWh	4	0	0	0	1
Coolant / other glycols	mg per kWh	2	0	0	0	0
Not specified	mg per kWh	1	0	0	0	0
Total mass	mg per kWh	1394	4723	64	1	6

Note: the material breakdown represents the ‘as-built’ mass of the power plant and excludes production wastes or parts for servicing.

5 Impact assessment

5.1 Summary of results

Table 8 presents the total potential environmental impacts associated with an onshore 100MW wind power plant of V112-3.45 MW turbines, covering the entire power plant over the life cycle. An additional breakdown of the results is shown in Section 5.2, which provides an assessment of each impact category by life cycle stage. Annex A contains a description of the impact categories assessed in the study.

Table 8: Whole-life environmental impacts of V112-3.45 MW plant (in g, mg or MJ per kWh)

Environmental impact categories:	**Unit**	**Quantity per functional unit of 1 kWh**
Abiotic resource depletion (ADP elements)	mg Sb-e	0.10
Abiotic resource depletion (ADP fossils)	MJ	0.06
Acidification potential (AP)	mg SO_2-e	21
Eutrophication potential (EP)	mg PO_4-e	2.4
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38
Global warming potential (GWP)	g CO_2-e	5.3
Human toxicity potential (HTP)	mg DCB-e	1032
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	615
Photochemical oxidant creation potential (POCP)	mg Ethene	2.6
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	31
Non-impact indicators:		
*Primary energy from renewable raw materials	MJ	0.01
*Primary energy from resources	MJ	0.07
Water consumption	g	46
**Return-on energy	Number of times	45
***Turbine recyclability (not life cycle based, turbine only)	% (w/w)	86%
****Product waste (not life cycle based, turbine only)	g	0.16
*****Turbine Circularity (not life cycle based, turbine only)	-	0.63

** Net calorific value*

*** Based on 'Net energy' calculation defined in Section 6.*

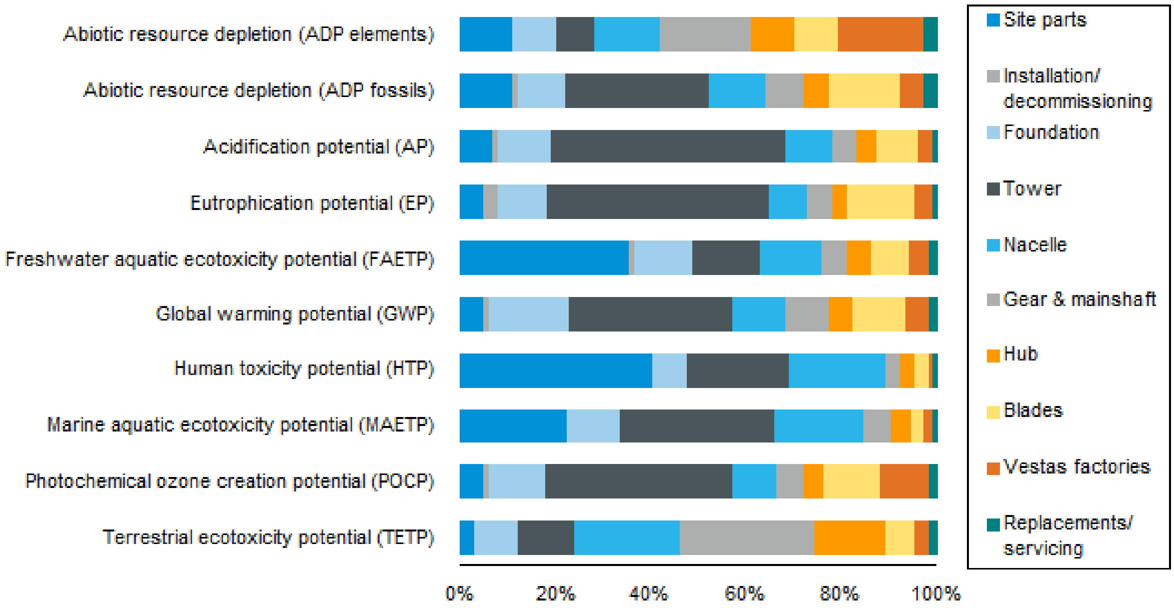
**** Rounded up or down to the nearest half percentage point.*

***** Refer to Section 5.3.5*

****** Based on circularity indicator calculation defined in section 5.3.6*

Figure 7 presents the potential environmental impacts for raw material and component production stages of the life cycle, inducing servicing, maintenance during operation (i.e. all life cycle stages excluding end-of-life). The results show that for the turbine components, the nacelle, tower, site parts and foundations contribute most significantly to all environmental impact indicators. The next most significant components are the blades, gear & mainshaft and the hub. Vestas factories contribute around 3% to15% across all impact categories. It should be noted that transport, where this occurs, is included for each part and has not been disaggregated.

Figure 7: Production and use-phase environmental impacts of V112-3.45 MW



5.2 Analysis of results: impact categories

The results for each impact category are described in further detail in the following sections, identifying the potential impacts by life cycle stage of the wind power plant, and major contributing components and substances. Table 9 shows the results for each impact category, for the following main life cycle stages:

- *manufacture*: includes raw material extraction through to factory gate and transport to site;
- *plant set-up*: includes roads and onsite installation equipment (e.g. cranes, generators, etc);
- *operation*: includes power plant maintenance, servicing and transport; and
- *end-of-life*: includes decommissioning, recycling and waste disposal.

Annex A contains a description of the impact assessment methods and impact categories evaluated in this LCA.

Table 9: Whole-life environmental impacts of V112-3.45 MW by life cycle stage (units shown in g, mg or MJ per kWh)

Impact category	Unit	Manufacture	Plant setup	Operation	End-of-life	Total
Abiotic resource depletion (ADP elements)	mg Sb-e	0.17	0.00	0.01	-0.07	0.10
Abiotic resource depletion (ADP fossils)	MJ	0.08	0.00	0.00	-0.03	0.06
Acidification potential (AP)	mg SO_2-e	28	0	0	-8	21
Eutrophication potential (EP)	mg PO_4-e	2.5	0.1	0.0	-0.2	2.4
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38	1	1	-2	38
Global warming potential (GWP)	g CO_2-e	7.5	0.1	0.1	-2.4	5.3
Human toxicity potential (HTP)	mg DCB-e	3547	6	26	-2549	1032
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	1686	4	9	-1084	615
Photochemical oxidant creation potential (POCP)	mg Ethene	3.8	0.1	0.0	-1.3	2.6
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	30	0.1	0.7	-0.1	31
Non-impact indicators:						
[*]Primary energy from renewable raw materials	MJ	0.01	0.00	0.00	0.00	0.01
[*]Primary energy from resources	MJ	0.09	0.00	0.00	-0.02	0.07
Water consumption	g	67	1	1	-23	46

[*] *Net calorific value*

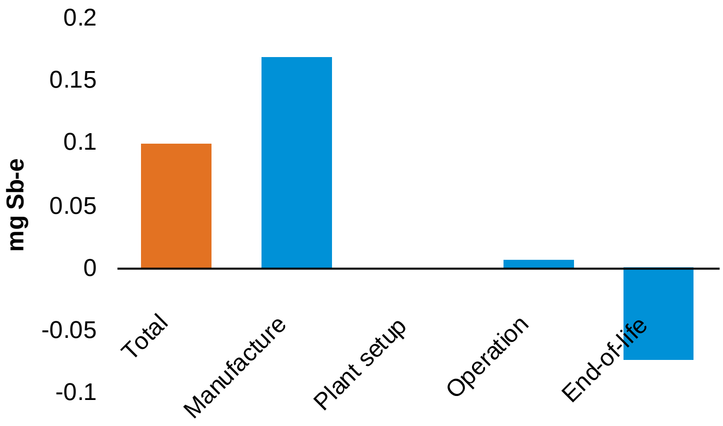
5.2.1 Abiotic resource depletion (elements)

Abiotic resource depletion (elements) provides an indication of the potential depletion (or scarcity) of non-energetic natural resources (or elements) in the earth's crust, such as iron ores, aluminium or precious metals, and it accounts for the ultimate geological reserves (not the economically feasible reserves) and the anticipated depletion rates. It is measured in mass of antimony equivalents.

Figure 8 shows the potential impacts by life cycle stage for abiotic resource depletion (elements) per kWh of electricity produced by the power plant. The manufacturing stage dominates the life cycle. This is primarily driven by use of metals, such as silver (32%), lead (29%), zinc (11%), copper (9%) and molybdenum (9%). This potential impact mainly relates to copper usage, along with use of high-alloy steels in the nacelle parts, such as generator and gearbox, etc. Silver consumption is principally driven by copper usage and to a small extent by electronics. The end-of-life phase also has a significant overall contribution, providing an environmental credit for the recycling of metals (around -43%), where production of these materials is avoided. The end-of-life stage is dominated by the recycling of copper and steel. The impact from operation relates primarily to replacement parts over the lifetime of the turbine.

The contribution of rare earth elements (such as neodymium and dysprosium) used in the magnets for tower fittings, make a negligible contribution to total resource depletion. The turbine generator does not use permanent magnets or rare earth metals.

Figure 8: Contribution by life cycle stage to Abiotic resource depletion (element) per kWh

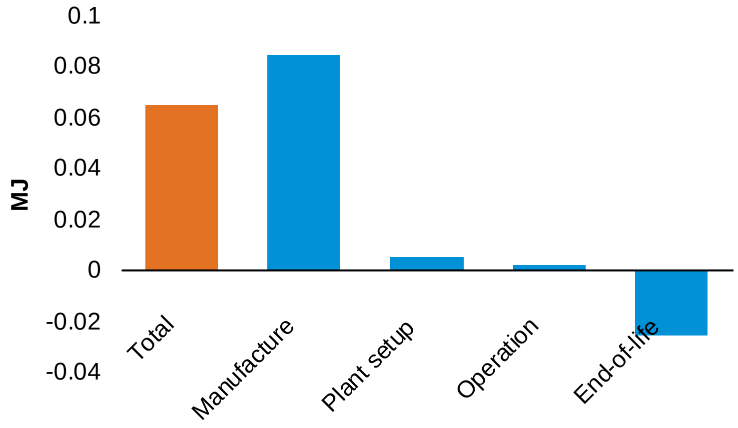


5.2.2 Abiotic resource depletion (fossil)

Abiotic resource depletion (fossil) provides an indication of the potential depletion (or scarcity) of non-renewable resources (except for nuclear power resources) that are non-living, measured in terms of energetic value (as MJ.

Figure 9 shows the potential impacts by life cycle stage for abiotic resource depletion (fossil) per kWh of electricity produced by the power plant. The manufacturing stage dominates the potential impacts for the abiotic resource depletion (fossil), which is primarily driven by production of the turbine (74%), followed by the foundations (11%) and site cables (6%). Within production, the tower, nacelle and blades contribute most significantly to this impact category. Overall, the impacts relate to the consumption of oil (37%), natural gas (32%) and coal (23%) for the production of metals and polymers. End-of-life also provides significant environmental credits relating to avoided resource depletion associated with recycling of metals (of around -30%).

Figure 9: Contribution by life cycle stage to Abiotic resource depletion (fossil) per kWh



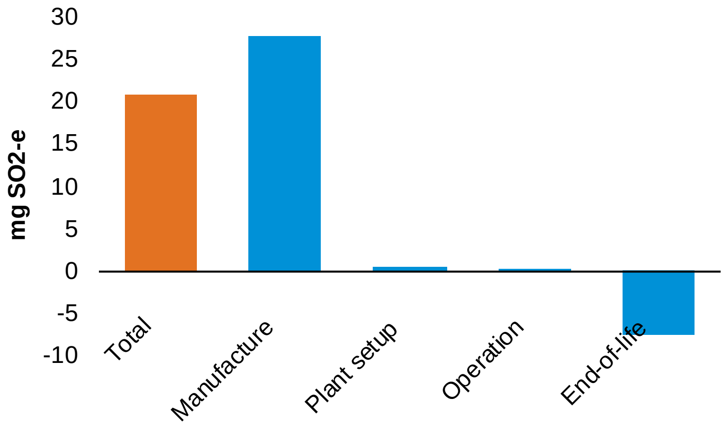
5.2.3 Acidification potential

Acidification potential provides a measure of the decrease in the pH-value of rainwater and fog, which has the effect of ecosystem damage due to, for example, nutrients being washed out of soils and increased solubility of metals into soils. Acidification potential is generally a regional impact and is measured in mass of sulphur dioxide equivalents.

Figure 10 shows the potential impacts of acidification per kWh of electricity produced by the power plant. The manufacturing stage of the power plant dominates this impact category, which primarily relates to production of the tower (48%), nacelle (10%), foundations (11%) blades (9%) and site cables (5%). The emissions to air of sulphur dioxide (62%) and nitrogen oxides (35%) associated with the production of iron and steel are the primary contributing substances.

The end-of-life phase also has a significant overall contribution, providing an environmental credit (of around -28%) for the recycling of metals, which avoids production of these materials. Similarly, the substances driving the environmental credit for end-of-life relate to the avoidance of sulphur-dioxide and nitrogen-oxide emissions to air.

Figure 10: Contribution by life cycle stage to Acidification potential per kWh

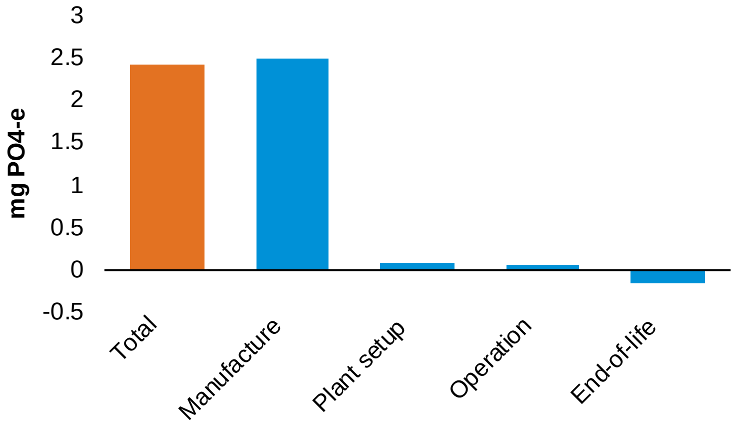


5.2.4 Eutrophication potential

In general terms, eutrophication potential provides a measure of nutrient enrichment in aquatic or terrestrial environments, which leads to ecosystem damage to those locations from over-enrichment, and is measured in mass of phosphate equivalents.

Figure 11 shows the potential impacts of eutrophication per kWh of electricity produced by the power plant. As with other impact categories, it is the manufacturing stage of the power plant that dominates the overall life cycle. The environmental credits associated with end-of-life are relatively small for this category. The principal turbine components contributing to eutrophication potential are the tower (44%), nacelle (8%), blades (14%), foundation (10%) and gear and mainshaft (5%). Additionally, installation and decommissioning processes contribute around 3%, as well as shipping transport of the towers (28%). Over the complete life cycle, the primary substances contributing to eutrophication are the emissions to air of nitrogen oxides (79%), nitrous oxide (3%) and inorganic emissions to fresh water (10%). The relatively low credit at end-of-life for this impact category (in comparison to other impact indicators) relates to the relatively lower contribution of steel production to this impact category which corresponds to lower credits for steel recycling.

Figure 11: Contribution by life cycle stage to Eutrophication potential per kWh

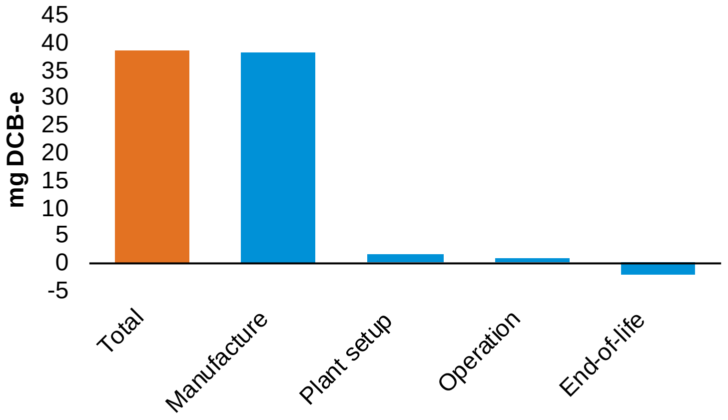


5.2.5 Freshwater aquatic ecotoxicity potential

Freshwater aquatic ecotoxicity potential, in general terms, refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents.

Figure 12 shows the potential impacts of freshwater aquatic ecotoxicity per kWh of electricity produced by the power plant. The manufacturing stage dominates the life cycle impacts, with the production of site parts (mainly cables) (30%), nacelle (13%), gear and mainshaft (5%), hub (5%), blades (8%), foundation (13%) and tower (13%). For the cables, it is the production of polymer materials (polyvinylchloride and polyethylene), which results in the emission of polychlorinated dibenzo-p-dioxins to fresh water, that contributes around 30% of total life cycle impacts. While other contributing substances relate to the release of heavy metals (45%) to water and to air, such as molybdenum, nickel, vanadium and copper. These heavy metal releases result from the production processes for metals used in the turbine and anchor cage of the foundation. The environmental credit for end-of-life is also associated with the avoidance of heavy metal release to air and water (around -3%) from recycling.

Figure 12: Contribution by life cycle stage to Freshwater aquatic ecotoxicity potential per kWh

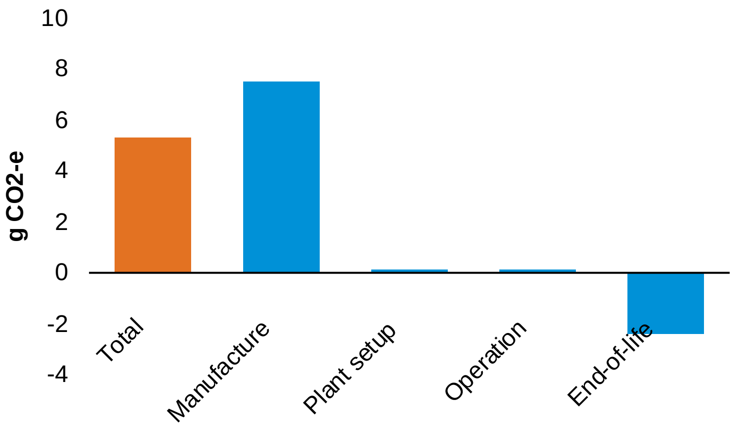


5.2.6 Global warming potential

Global warming potential impacts result in a warming effect of the earth's surface due to the release of greenhouse gases into the atmosphere and is measured in mass of carbon dioxide equivalents.

Figure 13 shows the potential impacts of global warming per kWh of electricity produced by the power plant. As with other impact categories, it is the manufacturing stage that dominates the life cycle, with the production of the tower (33%), nacelle (11%), gear and mainshaft (9%), foundations (17%), blades (12%) and cables (4%), being the primary components contributing to this impact category. Vestas production and operations contribute around 5% of the global warming impacts. The end-of-life phase also has a significant contribution (-32%), providing environmental credits associated with avoided metal production of iron, steel, copper and aluminium. The emission to air of carbon dioxide (92%) is the primary contributing substance, which results from the combustion of fuels in production of the turbine raw materials, as well as methane (6%) resulting from steel production. Other lesser contributing substances to global warming potential include the release of sulphur hexafluoride gas to air (1%) from improperly disposed switchgears, and nitrous oxide (1%) from various production processes, including glass fibre production used in the blades.

Figure 13: Contribution by life cycle stage to Global warming potential per kWh

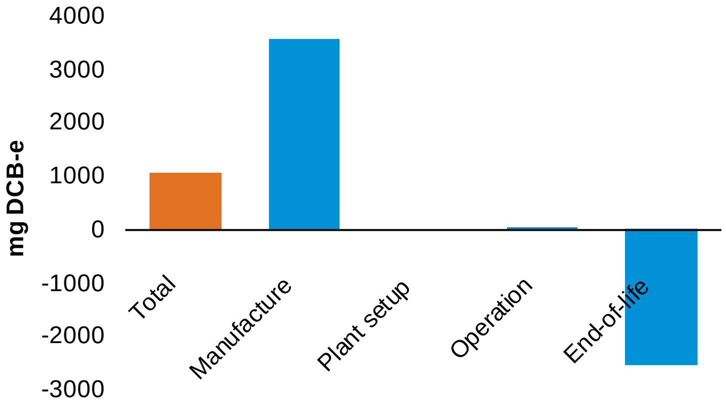


5.2.7 Human toxicity potential

Human toxicity potential, in general terms, refers to the impact on humans, as a result of emissions of toxic substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents.

Figure 14 shows the potential impacts of human toxicity per kWh of electricity produced by the power plant. The manufacturing stage dominates the life cycle impacts, with the production of site parts (40%), nacelle (20%), gear and mainshaft (3%), hub (3%) and towers (21%) being the principal contributing components. The end-of-life phase also provides a large environmental credit (around -71%) from the recycling of metals. The main contributing substances to human toxicity are the release to air of heavy metals (38%), such as arsenic and nickel, which result, for example, from the production of stainless steel materials. The emissions of non-methane volatile organic compounds to air contribute around 41%, while the emission to fresh water of molybdenum (2%) and polychlorinated dibenzo-p-dioxins (5%) also contribute to this impact category.

Figure 14: Contribution by life cycle stage to Human toxicity potential per kWh

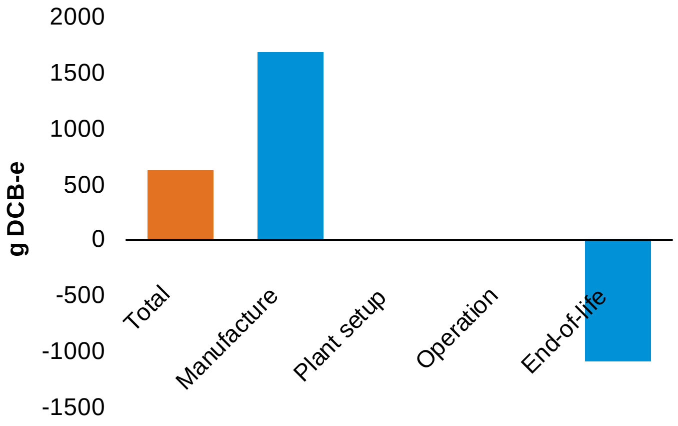


5.2.8 Marine aquatic ecotoxicity potential

Marine aquatic ecotoxicity potential, in general terms, refers to the impact on marine water ecosystems, as a result of emissions of toxic substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents.

Figure 15 shows the potential impacts of marine aquatic ecotoxicity per kWh of electricity produced by the power plant. As with the other toxicity impacts presented the LCA, it is the manufacturing stage dominates the life cycle impacts. The potential impacts for marine aquatic ecotoxicity are primarily due to emissions of hydrogen fluoride to air (83%) from both aluminium and steel production processes, where the aluminium is used in the site cables, and steel throughout many parts of the turbine. The remaining impacts primarily result from emissions of heavy metals to air (9%), fresh water (3%) and sea water (2%), which result, for example, from the production of stainless steel materials. The end-of-life stage also offers substantial environmental credits (around -64%), which is mainly associated with the avoided emissions of hydrogen fluoride to air from aluminium and steel production.

Figure 15: Contribution by life cycle stage to Marine aquatic ecotoxicity potential per kWh

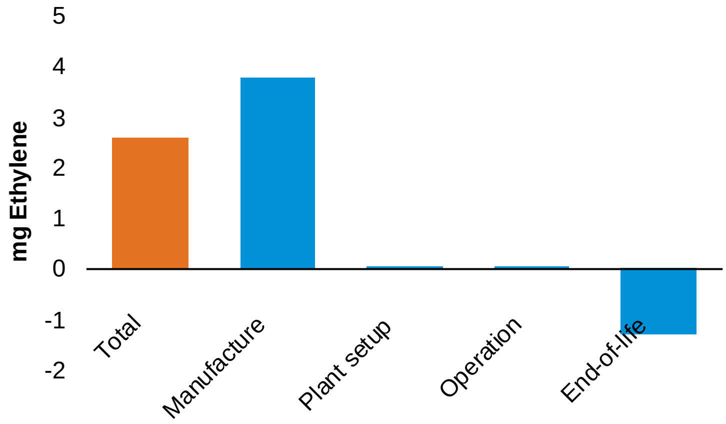


5.2.9 Photochemical oxidant creation potential

Photochemical oxidant creation provides a potential indication of low level oxidant formation, also known as summer smog, which damages vegetation and in high concentrations is toxic to humans.

Figure 16 shows the potential photochemical oxidant creation per kWh of electricity produced by the power plant. The results show that manufacturing stage dominates the life cycle, which is primarily related to the tower (38%), nacelle (8%), gear and mainshaft (6%), foundation (12%), blades (12%) and hub (4%). The main contributing substances are carbon monoxide (18%), nitrogen oxides (16%), sulphur dioxide (20%) and VOCs (47%) from steel and aluminium production processes. End-of-life recycling provides a credit of around -34% of potential impacts. Vestas production and operations contribute about 10% overall to this impact category.

Figure 16: Contribution by life cycle stage to Photochemical oxidant creation potential per kWh

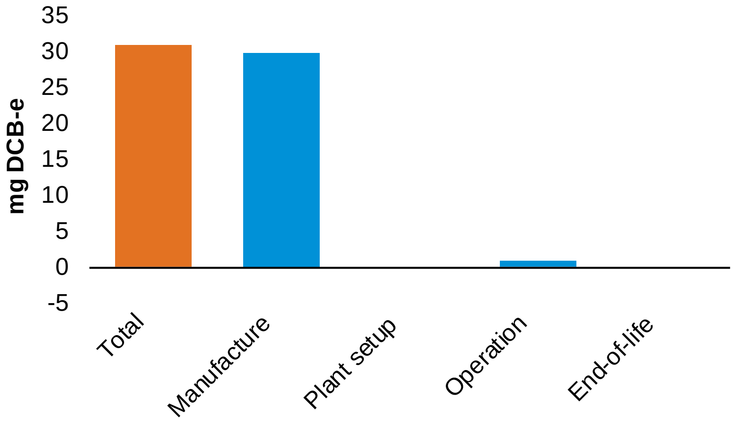


5.2.10 Terrestrial ecotoxicity potential

Terrestrial ecotoxicity potential, in general terms, refers to the impact on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil, and is measured in mass of dichlorobenzene equivalents.

Figure 17 shows the potential impacts of terrestrial ecotoxicity per kWh of electricity produced by the power plant. As with other impact categories in the LCA, the results show that the manufacturing stage dominates the life cycle which is primarily driven by the release of heavy metals to air (93%) which relates mainly to chromium, mercury, vanadium and arsenic, as well as heavy metal emissions to soil (4%), . These emissions result from the production of metals used in the turbine, particularly production of steel and stainless steels in the nacelle (21%), gear and mainshaft (28%), hub (15%), foundations (9%) and tower (11%). End-of-life recycling provides an overall impact (of around 0.4%) due to the steel recycling scrap value causes an overall detrimental impact. Vestas production and operations contribute around 3% in total to this impact category.

Figure 17: Contribution by life cycle stage to Terrestrial ecotoxicity potential per kWh



5.3 Analysis of results: non-impact indicators

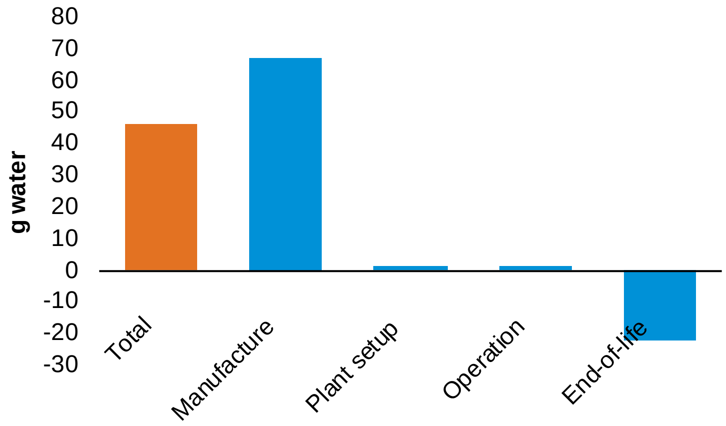
This section provides an analysis of the non-impact related indicators for the life cycle assessment.

5.3.1 Water consumption

Water consumption provides an indication of the net balance of water inputs and outputs of freshwater throughout the life cycle of the power plant, presented in grams per kWh. This does not correspond to a water footprint, but represents the net balance of water inputs and outputs of freshwater for production and disposal processes from the LCI datasets used in the study. It is recognised, however, for ‘water’ to be treated more thoroughly further consideration should be made regarding types of water used, inclusion of local water scarcity, as well as differentiation between watercourses and quality aspects (Berger, 2010), in order to aid more accurate decision making. Refer to Section 3.8 for some further discussion on water footprint metrics and the ISO standards.

Figure 18 shows the water consumption per kWh of electricity produced by the power plant, which is primarily related to the manufacturing phase of the life cycle. Within manufacturing, the production of the tower (25%), foundation (16%), nacelle (11%), gear and mainshaft (10%), blades (14%) and site cables (4%) are the most significant contributors. The end-of-life stage provides a credit of around -34%. Water consumption is primarily driven by the production of iron and steel used in the wind power plant.

Figure 18: Contribution by life cycle stage to Water consumption per kWh

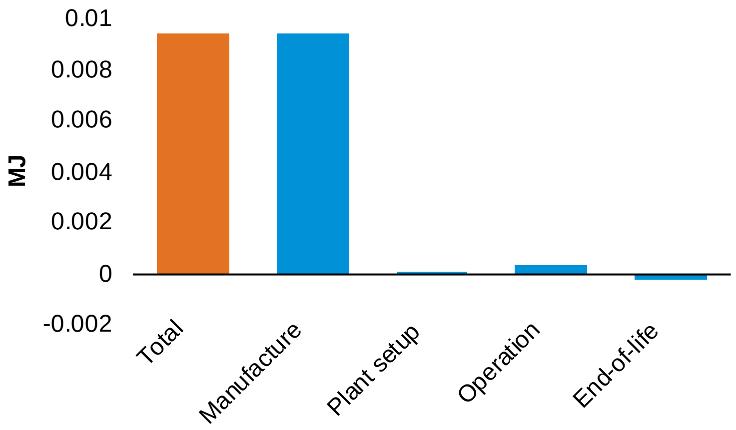


5.3.2 Primary energy from renewable raw materials (net calorific value)

Primary energy from renewable raw materials gives a measure of the quantity of renewable energy consumed from hydropower, wind power, solar energy and biomass, measured in MJ.

Figure 19 shows the consumption of primary energy from renewable raw materials per kWh of electricity produced by the power plant. As with other results in the LCA, the manufacturing stage dominates the life cycle, with end-of-life also providing a significant credit for this indicator. Within the manufacturing stage, the most significant components are the site cables (10%), nacelle (14%), gear and mainshaft (19%), foundation (9%), blades (9%) and Vestas production (around 18%), while end-of-life also provides around -5% credit. The contributions to this indicator mainly arise from wind energy, hydropower and solar energy.

Figure 19: Contribution by life cycle stage to Primary energy from renewable raw materials (net calorific value) per kWh



5.3.3 Primary energy from resources (net calorific value)

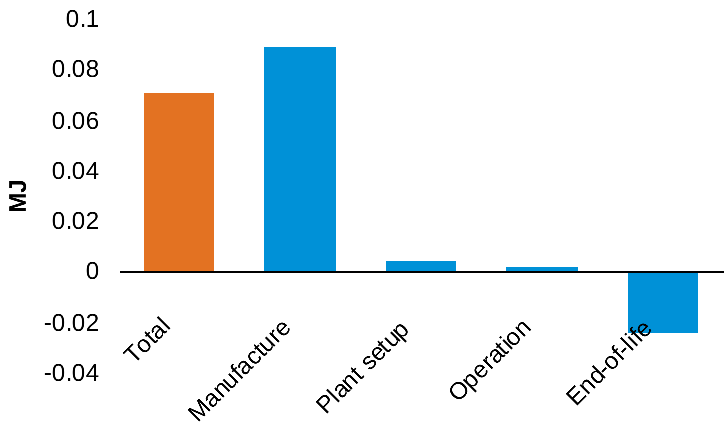
Primary energy from resources provides a measure of the consumption of non-renewable energy over the life cycle, for example, from coal, oil, gas and nuclear energy, measured in MJ.

Figure 20 shows the consumption of primary energy from resources per kWh of electricity produced by the power plant. As with other results in the LCA, the manufacturing stage dominates the life cycle, with end-of-life also providing a significant credit for this indicator.

Within the manufacturing stage, the most significant components are the tower (27%), nacelle (16%), gear and mainshaft (5%), foundation (8%), blades (16%) and site cables (6%), while end-of-life provides a -26% credit.

Vestas production contributes around 5% to the total life cycle. The contributions to this indicator mainly arise from oil (34%), natural gas (30%), coal (21%) and uranium (9%).

Figure 20: Contribution by life cycle stage to Primary energy from resources (net calorific value) per kWh



5.3.4 Recyclability (not life cycle based, turbine only)

Recyclability provides a measure of the proportion of the turbine that can be usefully recycled at end-of-life. It accounts for specific recycling rates of various components within the turbine (refer to Section 3.4.4) and is measured as a percentage of total turbine mass. The measure only relates to the turbine itself and excludes the foundations, site parts and other components of the wind plant. The following equation is used to calculate this indicator:

$$\text{Turbine recyclability (\%)} = \text{[sum for all turbine parts]}\ \frac{\text{metal recycling rate (\%)[6]} \times \text{metal part mass (kg)}}{\text{total part mass (kg)}}$$

The overall recyclability of the V112-3.45 MW turbine is 86.0%[7]. The components contributing to recyclability relate to metal parts manufactured from iron, steel, aluminium and copper. Overall, the V112-3.45 MW turbine is constructed from around 89% metals.

Other components within the entire wind power plant (i.e. the non-turbine parts, such as foundations, site cables, transformer station) are not included in the above indicator. From a LCA modelling perspective these parts are recycled at varying rates, such as the site cables receive a 95% recycling rate (as described in Section 3.4.4); however, these non-turbine components are not included in the 'recyclability' indicator.

The use of a 'recyclability' indicator (i.e. using an avoided impacts approach to crediting) provides a very 'usable' business measure to drive up the total recyclability of the wind turbine, which is accurately measured using the LCA models. This in turn drives business activities, for example by focusing on recycling/reuse of non-metallic parts, such as composite blade materials, controllers and polymers.

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[6] Refer to Section 3.4.4 for the recycling rates for the different metal parts of the turbine.

[7] Note: recyclability is rounded up or down to the nearest half percentage point

5.3.5 Product waste (not life cycle based, turbine only)

Product waste is a new indicator included in this LCA report which provides a measure of the amount of non-recycled material contained in the turbine at the end-of-life. It accounts for the wind-turbine bill-of-materials only and is measured as grams of (non-recycled or non-reusable) material per kWh. The following equation is used to calculate this indicator:

$$\textit{Product waste (g/kWh)} = \frac{\textit{non-recycled material mass (kg)}}{\textit{lifetime energy production of the turbine (MWh)}}$$

The overall recyclability of the V112-3.45 MW turbine is 0.16g per kWh. The components contributing to *Product waste* relate to all non-metal parts contained in the wind turbine. Overall, the V112-3.45 MW turbine is constructed from around 11% non-metal components.

This indicator has been introduced to supersede the *Recyclability* indicator. *Recyclability* on its own provides a good measure of the recycled content of the turbine; however, it also presents a conflict with other impact indicators that are measured per kWh. For example, when optimising turbine design then it is usually beneficial to reduce quantity of materials needed for a component design; however, a reduction in the metallic content of the turbine reduces *Recyclability* but improves other impacts per kWh. As such, the *Product waste* indicator avoids this conflict and at the same time increases focus on strategies to reduce material waste and select more recyclable materials.

5.3.6 Circularity indicator (not life cycle based, turbine only)

This section presents a new indicator to measure the Circularity of the present Mk3 turbine which is Vestas' first attempt to measure this new indicator. A Circularity indicator aims to measure the restorative nature of the material flows of a product in the context of a Circular Economy, giving an indication of the circular flow of material resources.

The method applied follows the approach published by the Ellen Mc Arthur Foundation (EMF, 2015) with Granta Design and co-funded by LIFE, European Union's financial instrument.

This method aims to indicate the potential utilisation of materials relating to material flows into the product (i.e. virgin/recycled/reused content), the product lifetime and, lastly, the utilisation of materials at disposal (i.e. unrecovered/recycled/reused outputs). The indicator contains several aspects and is built on the following principles:

- using feedstock from reused or recycled sources
- reusing components or recycling materials after the use of the product
- keeping products in use longer (e.g., by reuse/redistribution)
- making more intensive use of products (e.g. via service or performance models)

Indicators covering these drivers aspects are aggregated into a single score, which is not straightforward to interpret. Given this scope, it is evident that improving the Circularity Indicator of a product or a company will not necessarily translate as an improvement of the circularity of the whole system. It should be also noted, that the indicator is not covering the full life cycle of a product and a product with a better circularity score might be worse in terms of environmental impact.

Specifically, the indicator is developed from the following four main flows:

1. Material input: aim is to maximise input of recycled and reused material content in the product bill-of-materials
2. Product lifetime: aim is to maximise lifetime measured against industry average
3. Material output: aim is to maximise recycling and reuse of material at disposal stage
4. Disposal efficiency: aim is to minimise disposal of materials directly to landfill or energy recovery and minimise leakage of materials from recycling or reuse processes that go to landfill (i.e. to minimise unrecovered materials)

A formulae has been developed (EMF, 2015) which provides a score ranging from 0 to 1, where 1 indicates a maximum circularity (refer to Section 7.1). For this wind turbine, the indicator has been calculated for the turbine-only and excludes site parts, such as the foundations, site cables, site switchgears and the balance of plant as well as the other upstream and downstream elements of the product system according to LCA. This limited scope is consistent with turbine *Recyclability* and turbine *Product waste* indicators (shown in Sections 5.3.4 and 5.3.5).

5.3.6.1 Circularity formula

The Material Circularity Indicator (MCI) is calculated using the following formula as described below and in Figure21.

Figure 21: Diagrammatic view of the Material Circularity Indicator based on Ellen Mc Arthur Foundation (2015)

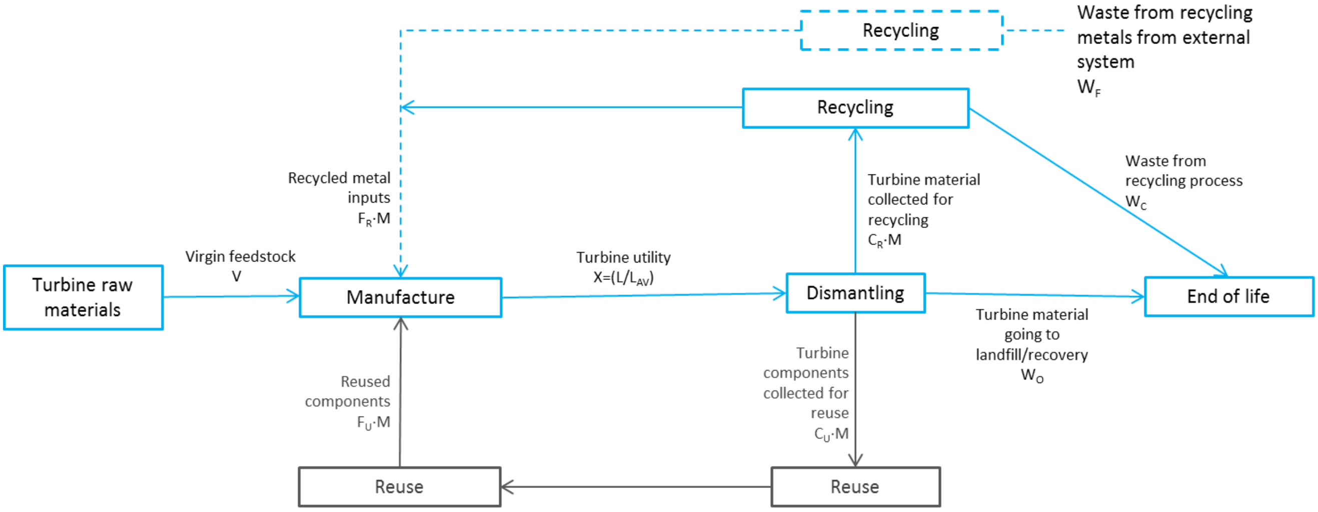


Figure 21 identifies the basic product flows which are:

- Amounts of virgin (V), reused (FuM) or recycled (FrM) feedstock on the input side
- Amounts of reusable (CuM), recyclable (CrM) and waste fractions (W) on the output side
- Utility of the product (X)

The Circularity indicator is calculated through the following steps:

- The linear flow index measures the proportion of material flowing in a linear fashion. These materials are sourced from virgin materials and finish as unrecoverable waste.

  Linear flow index, LFI = $\frac{Amount\ of\ material\ flowing\ in\ a\ linear\ fashion}{Total\ mass\ flow}$

- Utility measures the duration and the intensely of the product use.

  Utility, X = $\frac{Lifetime}{Industry\ average\ lifetime} * \frac{Functional\ units\ achieved\ during\ the\ life\ of\ product}{UavIndustry\ average\ functional\ units\ during\ the\ life\ of\ product}$

- Material circularity indicator, MCI = 1 – LFI * F (X)

  This indicator holds a value from 0 to 1 where 1 means a product is fully circular.

Calculation of circularity index of the V112 turbine has been carried out as shown in Table 10.

Table 10: Circularity index of the V112 turbine

		Unit	Formula	Values
Turbine weight	M	tonne		438
Virgin feedstock	V	tonne	$(M - \mathrm{FR.M} - \mathrm{FU.M})$	297
Recycled feedstock	F_R.M	tonne	*Scrap content of metal proportion of the turbine*	142
Components reused	F_U.M	tonne	*Not included*	0
Components collected for reuse	C_U.M	tonne	*Not included*	0
Material collected for recycling	C_R.M	tonne	*100% of the turbine is collected for recycling*	438
Material going to landfill/energy recovery	W_O	tonne	$M - metal\ content\ of\ the\ turbine$	49
Waste from recycling process	W_F	tonne	$M * \frac{(1-EF)FR}{EF}$ *Fraction of feedstock from recycled sources, FR:0.32* *Efficiency of recycling process used to produce recycled feedstock for a product, EF:0.97*	4
Utility	X		$\frac{lifetime\ (20\ years)}{industry\ average\ lifetime\ (20\ years)}$	1
Unrecoverable waste from recycling	W_C	tonne	$(1 - FR) * metal\ content\ of\ the\ turbine$	12
Total waste	W	tonne	$W_O + W_F + W_C$	65
Linear flow index	LFI		$\frac{(V+W)}{2.M + \frac{WF - WC}{2}}$	0.41
Material circularity index	MCI		$\left(1 - LFI * \left[\frac{0.9}{X}\right]\right)$	0.63

5.3.6.2 Discussion and analysis

The data used to calculate recycled material inputs to the wind turbine are based on recycled content of metals-only in the turbine using global average datasets from GaBi databases (2016). This gives a recycled input of about 32% of total turbine weight. Reused or repaired components are not currently included in the measure. The amount of recycled material after turbine-use relates to recycling of metals-only based on the same assumptions as the *Recyclability* indicator (see Section 5.3.4 and 3.4.4) which estimates recycling efficiency and losses by major turbine component. This indicates that 89% of the turbine total weight is usefully recycled at end-of-life. The wind turbine lifetime is evaluated to be the same as the industry average of 20 years design lifetime.

Based on the method outlined in Section 5.3.6, the Circularity score for the V112-3.45 MW turbine is 0.63. As such, this estimates that 63% of the product's materials are managed in a restorative or circular nature, while the remaining 37% of materials act in a linear manner.

Overall, the Circularity indicator calculates a theoretical estimate of circular flows of materials within the turbine product system.

Turbine components having a high metal content like towers and bearings are also high in circularity score because they have a high recyclability at end-of-life, as well as a recycled-content in the input raw material. However, components heavy with polymers, glass fibres, etc. like blades are generally low in circularity as they are often made of virgin materials and do not always have viable recycling processes at end-of-life.

In order to improve Circularity performance the following options may be applied:

- increase the recycled-content of metals within the turbine;
- increase recycled-content of other materials in the turbine and select higher recyclable materials;
- increase the repairability or reuse of service components;
- extend or optimise turbine lifetime; and
- improve efficiency of recycling processes.

As an example, if it were possible to 100% recycle a wind turbine blade then the Circularity indicator for the V112-3.45 MW turbine would improve from 0.63 to 0.66; or for example, increasing the recycled-content of steel to 60% (from 37% baseline) would also improve the Circularity score quite significantly from 0.63 to 0.72.

When considering the boundary of the Circularity indicator it is the same as the non-impact indicators for *Recyclability* and *Product waste* and accounts for the turbine-only. Nonetheless, important material flows also exist for replaced and repaired components during turbine operation which would also be relevant to capture in a circularity indicator. Additionally, there are many resource flows in other parts of the supply-chain, for example up-stream activities for production, where this also may be potentially relevant.

Data availability would also need to be improved if improvements are to be measured, for example, if recycled content of metal components is increased then Vestas would need its suppliers to report specific data, rather than using industry average datasets as currently. Additionally, if (recycled) material quality were to be measured then this may increase difficulty in data availability.

Although not explored in this LCA, a potential application to wind could be to adopt a circulatory measure that indicates amount of ‘circular material’ per kWh (or ‘non-circular material’ per kWh). This would then align the indicator with other environmental impacts per kWh, as well as aligning with reducing levelised cost-of-energy.

Adopting a circular approach involves taking a systems viewpoint to resource flows rather than only at a product-level; thus requiring new ways of thinking and wider collaboration to achieve such goals.

Overall, the Circularity of the turbine should be assessed in conjunction with other potential environmental impacts, such as global warming potential, resource depletion, toxicity impacts, as well as indicators for return-on energy or water-use, and should not be evaluated in isolation.

5.4 Analysis of changes compared to previous studies

Section 5.4 presents a general description of the drivers affecting change in environmental performance of the V112 Mk3 turbine compared to the previous V112 Mk2 model.

Overall, the Mk3 turbine has been designed for a higher wind class (from medium wind to high wind) which increases plant-level annual energy production by around 23% for the life cycle assessment (Vestas, 2014b). This has the effect to similarly reduce impacts per kWh. Nonetheless, increasing wind class also increases wind loading on the turbine requiring a new design and higher material requirements to accommodate these higher loads. For example, the turbine mass and foundation mass increase by around 38% at plant-level, which will increase overall impacts per kWh. The balance-of-plant equipment, installation and decommissioning remain unchanged, with the only exception that 29 turbines rather 30 turbines are needed for the 100MW reference plant size. Additionally, there have been data updates to the background datasets (from GaBi 2014 to GaBi 2016 databases), as well as updating the CML impact method (from CML version 3.6 2009 to CML version 4.2 2016). These data changes have the effect to leave overall results relatively unchanged, with the exception of several toxicity-related impact categories which increase due to specific background database updates (e.g. there is an increase in MAETP due to the increase in the emission of hydrogen fluoride from aluminium manufacture and TETP is increased due to the increased emission of chromium from cast iron production).

When evaluating the drivers for changes to global warming potential the following overall summary may be made:

- increased AEP leads to a 23% reduction in GWP while increase in turbine mass causes around a 17% increase in GWP. Updates in Vestas production leads to around 1.3% increase in GWP.
- the main inventory datasets were checked for changes over the previous LCA model on a per kg basis e.g. GWP for concrete reduces by 0.1%, GWP for steel plate increases by 0.7%, GWP for the changed aluminium dataset in plant cables decreases by around 11% and GWP for cast iron increases about 15%. This has the effect to increase GWP at plant level by around 2%.
- the characterisation factors for CML 4.2 (2016) were compared with the previous LCA that used CML 3.6 (2009). For GWP, there is a 12% increase in the characterisation factor for methane, 11% decrease in the characterisation factor of nitrous oxide and 3% increase in the characterisation factor of sulphur hexafluoride. This has the effect to reduce GWP less than 0.6%.

Overall, the primary driver for change in results versus the previous LCA is the increase in AEP due to increasing turbine wind class and increased generator rating, as well as changes to turbine material requirements.

A similar trend to GWP is apparent for all other impact categories with exception of TETP and MAETP, which increase due to data changes resulting in increased emissions of chromium (for cast iron production) and increased emissions hydrogen fluoride (for aluminium production), respectively. The HTP impacts change due to change of aluminium dataset versus previous LCA, which now has higher PAH emissions. Also, some impacts reduce more significantly, for example, for ADP elements the copper production datasets are changed resulting in reduced impact.

In summary, the above changes indicate a general overall improvement in turbine design for most impact categories, with the exception of TETP and MAETP (which increase due to data changes).

However, it should be noted that turbine performance should only be compared within the same wind class and not from a product-to-same-product perspective (as presented above), because the turbine is functionally designed for the specific wind class (see Section 1.2.3). Nonetheless, the description above is provided to give the reader greater transparency of the changes in results compared to previous life cycle assessments.

Annex J provides an update to Vestas corporate product improvement targets of the Mk3 turbine which compares different turbines within the same wind class.

6 Return-on-energy from V112-3.45 MW wind power plant

Section 6 presents the environmental performance of the wind power plant in terms of return-on-energy over the life cycle of the plant. This provides an indication of the energy balance of power plant, showing the relationship between the energy requirement over the whole life cycle of the wind plant (i.e. to manufacture, operate, service and dispose) versus the electrical energy output from the wind plant. The payback period is measured in months where the energy requirement for the life cycle of the wind plant equals the energy it has produced.

There are two approaches that have been taken to measure this indicator:

1. *Net energy*: the energy requirement for the whole life cycle of the wind plant is divided by the electrical energy output from the wind plant and then multiplied by the power plant lifetime in months. This is an absolute indicator, as follows:

   $$\text{Net energy payback (months)} = \frac{\text{life cycle energy requirement of the wind plant (MJ)}}{\text{electrical energy output from the wind (MJ)}} \times 240$$

2. *Primary energy*: the second approach, is to conduct the same equation but to convert the electrical output from wind into the equivalent primary energy requirement from an example electricity grid (for example European average grid). This is a relative indicator, as follows:

   $$\text{Primary energy payback (months)} = \frac{\text{life cycle energy requirement of the wind plant (MJ)}}{\text{primary energy input of EU average grid (MJ)}} \times 240$$

Following the net-energy approach, as defined above, the breakeven time of the onshore V112-3.45 MW is 5.4 months for high wind. This may be interpreted that over the life cycle of the V112-3.45 MW wind power plant, the plant will return 45 times (high wind) more energy back than it consumed over the plant life cycle.

The results of the second approach estimates a theoretical return on primary energy, based on typical electrical grid mix for different world regions. The approach accounts for the efficiency of the electricity power stations when determining the primary energy. There is no distinction made here as to whether base-load energy mix or marginal-load energy mix should be assessed. Nonetheless, the results show an estimated breakeven point for the V112-3.45 MW wind plant of 2 months for high wind conditions, for this indicator when assessing example electricity mixes for Europe, Australia and the United States. The results differ slightly for each region which is a reflection of the primary fuels used for the particular electricity grid mix, as well as the electricity generation efficiencies of the power plants in those regions.

Overall, it may be concluded that the ‘net return-on energy approach’ does not include any relative conversions, which are required for the primary energy approach (as defined above), and therefore the ‘net return-on energy’ provides an absolute indication of performance (Garrett, 2012) and would be seen as the preferred indicator of energy-investment indicator.

7 Interpretation

7.1 Results and significant issues

The results described in this report show the environmental profile for the production of electricity from a wind power plant comprising of twenty nine V112-3.45 MW wind turbines. This LCA is a comprehensive and detailed study covering over 99.9% of the total mass of the turbine itself, and over 99.95% of the entire mass of the power plant. The missing mass relates to components in the power plant where the material was not identified.

Both the life cycle inventory data (presented in Annex G) and the life cycle impact assessment (shown in Section 5) clearly show that the production phase of the life cycle dominates all potential environmental impacts and inventory flows for the V112-3.45 MW power plant. Additionally, the avoided potential impacts associated with end-of-life recycling also provide substantial environmental credits, which represents the second most important phase in the power plant life cycle. Operation, maintenance, installation and servicing are much less significant stages in the life cycle.

The impacts of transport of the turbine from Vestas production locations to the wind plant erection site are also reasonably significant (between 1% and 38% depending per impact category). Transport includes specific fuel use (and vehicle utilisation) data for the transport of specific turbine components (for towers, nacelles and blades). These are based on measured data and specific distances with actual wind turbine transports. These specific datasets result in higher fuel consumption compared to default containerised-transport models used in previous LCAs of Vestas turbines (PE 2011 and Vestas 2006, 2006a). Additionally, a sensitivity assessment shows that the transport of the wind turbine components from their Vestas production locations to a wind plant erection site, where Vestas does not have regional production facilities, results in reasonably significant life cycle impacts.

In general, the parts of the turbine that contribute most significantly to the LCI and LCIA results are the largest metal parts within the power plant (both for the manufacturing and end-of-life phases). In particular, this relates to the turbine tower, nacelle, blades, site cabling and foundations. Previous LCA studies of Vestas turbines (PE, 2011, Vestas 2011a,b,c, Vestas 2013a,b, Vestas 2014a,b,c,d, Vestas, 2015a,b,c) have shown similar results.

When considering Vestas production facilities, the results show that the impacts of fuels, electricity and consumables contribute around 3% to 15% of all potential environmental impacts. This is similar in scale to previous LCA studies of Vestas turbines. The LCA is temporally representative of 2015.

In 2015 Vestas achieved the 100% WindMade (2015) accreditation, whereby Vestas invested and purchased credits in Vestas-owned wind plants located in Romania. However, this electricity consumption has not been included in this life cycle assessment as it conflicts with the ISO standards for LCA (ISO 14040/44, 2006) and carbon footprint printing (ISO14067, 2013). Refer to Section 3.4.9 for further discussion of this assumption. Nonetheless, the inclusion of this renewable electricity benefit has been evaluated in a sensitivity analysis.

The contribution of specific substance releases and extractions to/from the environment are not listed specifically here (refer to Section 5.2); however, the consumption of iron, steel, aluminium and concrete (in the turbines, site cabling and foundations) are the primary contributors to almost all elemental flows to and from the environment, and the resulting potential impacts. The careful LCA modelling of these materials, both in terms of datasets used for production and recycling, as well as accurately reflecting the grades of the material used (for example with high alloy steels), is essential for producing a reliable and accurate study. These assumptions have been accurately reflected in this life cycle assessment.

The results of the life cycle assessment also indicate the importance of wind plant siting and wind conditions that the turbines operates under (i.e. medium or high wind classes) which has a considerable effect on the overall impacts of the power plant, when referenced to the functional unit of 1 kWh of delivered electricity to the grid. The wind turbine is functionally designed to match the different wind classes and wind speeds, so it is not always the size of the rotor or the generator rating (in MW) that determines the electricity production of the turbine; but wind class is a dominant factor. These effects have been assessed in the sensitivity analysis. For this LCA, the IEC top wind speed has been chosen for the wind-classes (i.e. high wind speed), which represents a typical 'virtual' power plant and is a reasonable assumption. This is a change from previous LCAs which used a mid-point average wind speed per wind class. Nonetheless, higher or lower wind speeds will affect the LCA results for a specific plant location operating under different conditions.

The power plant lifetime is also a dominant factor when determining the impacts of the electricity production per kWh from the wind plant. The LCA assumes a lifetime of 20 years which matches the standard design life; however, the wind turbine industry is still young (starting for Vestas in 1979), and few turbines have ever been disposed, reaching operational lives of 30 years and over, for other Vestas turbine models. It is often wear or fatigue of the load-bearing components of the turbine (such as tower fatigue) which limit the overall turbine lifetime. Many components can be routinely replaced as part of maintenance, except for the fixed parts (such as the tower, foundation and cables, etc) which are generally not replaced and may limit the physical lifetime of the plant. Vestas operates sophisticated real-time diagnostic tools and sensors which measure individual turbine performance and fatigue and it is possible to predict lifetime of specific components for specific site conditions. These systems operate on over 33,200 wind turbines around the world, equivalent to around 66.5GW of global installed capacity, providing Vestas with detailed information. These assessments are also conducted in the permit and planning phase of a new power plant, which are used accurately to predict component lifetime for specific site conditions. The plant lifetime, based on these assessments, informs the business case and contractual arrangements for the development of a new wind plant. For example, the LCA of the Roaring 40s wind power plant of V90-3.0 MW turbines in Australia (PE, 2011a) calculated lifetime of the turbine to be 24 years, based on such assessments. Although these variations occur, the design lifetime for this study of 20 years for a typical 'virtual' plant is considered to be a reasonable and accurate estimate.

The current assessment does not consider the potential impacts of land use change, for example, of the clearance of vegetation when erecting the turbines or laying cables to connect the wind plant to the electricity grid. In a site specific study of the Musselroe wind plant in Australia consisting of V90-3.0 MW turbines (PE, 2013a) the removal of vegetation for overhead lines was included in the assessment, which indicated a potential maximum worse-case scenario, that contributed around 14% to the total global warming impacts for that particular wind plant.

Overall, when comparing the scale of environmental impacts, per 1 kWh for the V112-3.45 MW wind plant, the results are very similar to that of previous LCAs of Vestas turbines. The study, in general, is considered to be in alignment with LCAs of other Vestas turbines; and it also includes some additional updates which improve the robustness and accuracy of the overall assessment.

7.2 Sensitivity analyses

Sensitivity analysis provides a purposeful evaluation of the underlying assumptions, parameters and methodological choices of the LCA, which aims to provide an understanding of the importance and scale of the choices made in the LCA. Section 7.2 shows the results of the sensitivity analyses, which assess the following eleven scenarios:

1. variation in wind power plant lifetime: ± 4 years;
2. variation in frequency of parts replacement;
3. operating the 100MW wind plant under 3.6 MW power mode;
4. varying the transport distances for components to wind plant erection site;
5. varying the distance of the wind plant connection to the existing grid;
6. changing the type of foundation used to high ground water level type;
7. potential incidence of turbine switchgear blow-out;
8. potential effects of method used for recycling; and
9. potential effects of Vestas renewable electricity consumption.

These scenarios represent the most significant assumptions made in the LCA study. One new sensitivity analysis is added to assess the 3.6 MW power mode.

7.2.1 Wind plant lifetime

The lifetime of a wind power plant is designed for 20 years; however, this may vary depending on the specific conditions of operation, and could be up to 30 years lifetime or over, when considering performance of other Vestas turbines. Power plant lifetime is an important assumption in the LCA because environmental impacts are amortised over the lifetime of the turbine per kWh of electricity generated. As such, changes in lifetime have a substantial overall effect on impacts per kWh produced by the power plant.

This sensitivity analysis presents the results for a variance of ±4 years in lifetime of the power plant. No account is made for changes to replacement parts and servicing for this variation in plant lifetime, but this is shown as a separate sensitivity analysis in Section 8.2.2 to indicate the significance of that assumption.

Table 11 shows that all potential environmental impacts either increase by around 25%, for reduced lifetime of 4 years, or decrease by around 17%, for an increased lifetime of 4 years. As the results indicate, the impacts per kWh directly correspond to the power plant lifetime.

Table 11: Whole-life environmental impacts of varying power plant lifetime (units shown in g, mg or MJ per kWh)

Environmental impact categories:	Unit	Reduced lifetime (16 years)	Baseline (20 years)	Increased lifetime (24 years)
Abiotic resource depletion (ADP elements)	mg Sb-e	0.12	0.10	0.08
Abiotic resource depletion (ADP fossils)	MJ	0.08	0.06	0.05
Acidification potential (AP)	mg SO_2-e	26	21	17
Eutrophication potential (EP)	mg PO_4-e	3.0	2.4	2.0
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	48	38	32
Global warming potential (GWP)	g CO_2-e	6.6	5.3	4.4
Human toxicity potential (HTP)	mg DCB-e	1290	1032	860
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	769	615	513
Photochemical oxidant creation potential (POCP)	mg Ethene	3.2	2.6	2.2
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	38	31	26
Non-impact indicators:				
*Primary energy from renewable raw materials	MJ	0.01	0.01	0.01
*Primary energy from resources	MJ	0.09	0.07	0.06
Water consumption	g	57	46	38

* *Net calorific value*

7.2.2 Replacement parts

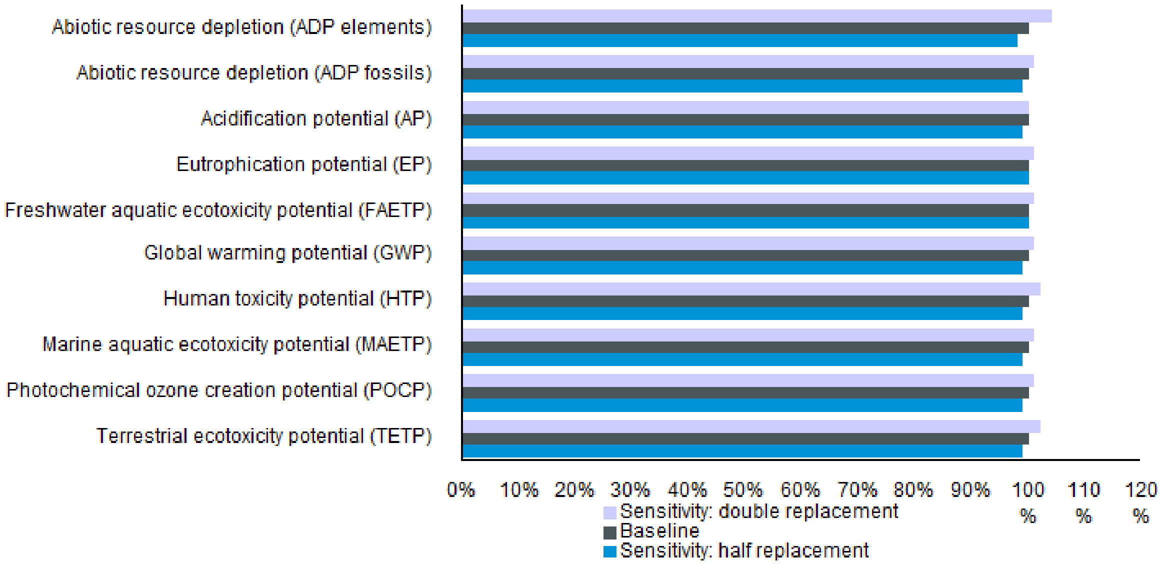
There may be variation in the level of maintenance and the need for replacement parts for any particular wind turbine power plant. Based on both monitored and calculated data, a typical rate for the replacement of parts is included in the LCA for the V112-3.45 MW turbine.

This sensitivity analysis evaluates the effects of doubling the frequency of replacement parts, which represents an extremely conservative estimate, as well as halving replacement parts.

Figure 22 shows the results of the sensitivity analysis which shows that doubling of replacement parts has the effect of increasing all impact categories in the range of 1% to 4%. The impact category effected most significantly is abiotic resource depletion elements (+4%), while most other impacts increase by around 1% to 2%. For abiotic resource depletion elements the increase generally relates to increased use of high alloy steels, relating to the alloying elements in the steel, such as molybdenum and chromium.

Halving the replacement parts has the effect of reducing all impacts between -1% to -2%.

Figure 22: Whole-life sensitivity assessment of doubling or halving replacement parts



7.2.3 3.6 MW power mode

The nominal power rating of the V112 turbine generator is 3.45 MW. However, the V112 Mark 3a turbine has a new power mode to operate at 3.6 MW for some operating conditions, which may be restricted, for example, by wind speed, ambient temperature or reactive power. The V112-3.6 MW turbine operates at the same maximum wind speed of 10m/s as the nominal power mode.

This sensitivity analysis evaluates the effects of the increased power rating at high wind. There are no major changes made to the turbine as the 3.6 MW power mode is primarily implemented through software updates. The primary changes are that the annual energy production increases by around 3% due to higher power mode. The results are presented in Table 12 below. Also as a consequence of increase to 3.6 MW power mode, only 28 turbines are needed to make a 100 MW power plant size.

Table 12 presents the results of the assessment which indicate an increase of around 2% to 3% for all impact indicators per kWh of electricity produced which is a direct result of increased annual energy production in the 3.6 MW power mode.

Table 12: Whole-life environmental impacts of 3.6 MW power mode (units shown in g, mg or MJ per kWh)

Environmental impact categories:	Unit	Baseline: High wind 3.45 MW @ 10m/s	Sensitivity: High wind 3.6 MW at 10 m/s**
Abiotic resource depletion (ADP elements)	mg Sb-e	0.12	0.11
Abiotic resource depletion (ADP fossils)	MJ	0.08	0.07
Acidification potential (AP)	mg SO_2-e	27	25
Eutrophication potential (EP)	mg PO_4-e	3.0	2.8
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	44	42
Global warming potential (GWP)	g CO_2-e	6.4	6.0
Human toxicity potential (HTP)	mg DCB-e	1191	1124
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	765	720
Photochemical oxidant creation potential (POCP)	mg Ethene	3	2.9
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	37	34
Non-impact indicators:			
*Primary energy from renewable raw materials	MJ	0.01	0.01
*Primary energy from resources	MJ	0.09	0.08
Water consumption	g	54	51

* *Net calorific value*

7.2.4 Transport distance from production to wind plant site

The baseline case for transport represents Vestas' global production facilities that operate within their global region to service that particular region, reflecting the supply chain in 2015 for a European wind power plant site location, such as Germany or the UK.

This sensitivity analysis evaluates the significance of the transport of the wind turbine components from their production locations to the wind plant erection site. A *Long distance* scenario is assumed where the wind power plant is erected in a continent where Vestas does not have full production facilities, such as Australia, as well as a *Regional supply* scenario with all production facilities in the same region, such as manufacture and supply in the North American market which assumes baseline transport without shipping of towers. Table 13 shows the transport distances and modes. It should also be noted that the current LCA uses truck and sea vessel fuel consumption (and vehicle utilisation) with specific vehicle data for transport of the tower sections, blades and nacelles, which results in significantly higher fuel consumption per tkm for the transport of turbine parts compared to the GaBi default containerised transport datasets.

Table 13: Transport distances for sensitivity analysis of wind plant components

Component	Baseline		Long distance		Regional supply	
	Truck (km)	Ship(km)	Truck (km)	Ship (km)	Truck (km)	Ship (km)
Nacelle	800	0	300	11700	1200	0
Hub	800	0	300	11700	1200	0
Blades	700	110	300	10410	1200	0
Tower	500	5787	1070	0	1200	0
Foundation	50	50	50	0	50	0
Other site parts	600	600	600	0	600	0

Figure 23 shows the results of the scenario analysis which indicates that for the *Long distance* scenario most impact category results increase by around 6% or less compared to the baseline, with the exception of potential impacts for acidification, eutrophication and photochemical ozone creation, which increase in range of 11% to 12%[8]. For the *Regional supply* scenario most impact category results reduce by around 3%, with the exception of potential impacts for acidification, eutrophication and photochemical ozone creation, which reduce in range of -25% to -30%. These larger changes are primarily driven the by the impacts from shipping operations which substantially increases emissions of sulphur dioxides and nitrogen oxides to air, from the combustion of fuel.

When evaluating global warming potential only, the baseline transport scenario (covering all transport stages within the LCA model) contributes around 9% to the life cycle impacts for this category, while in this sensitivity analysis the *Long distance* scenario contributes around 10% and the *Regional supply* scenario around 7% to total global warming impacts.

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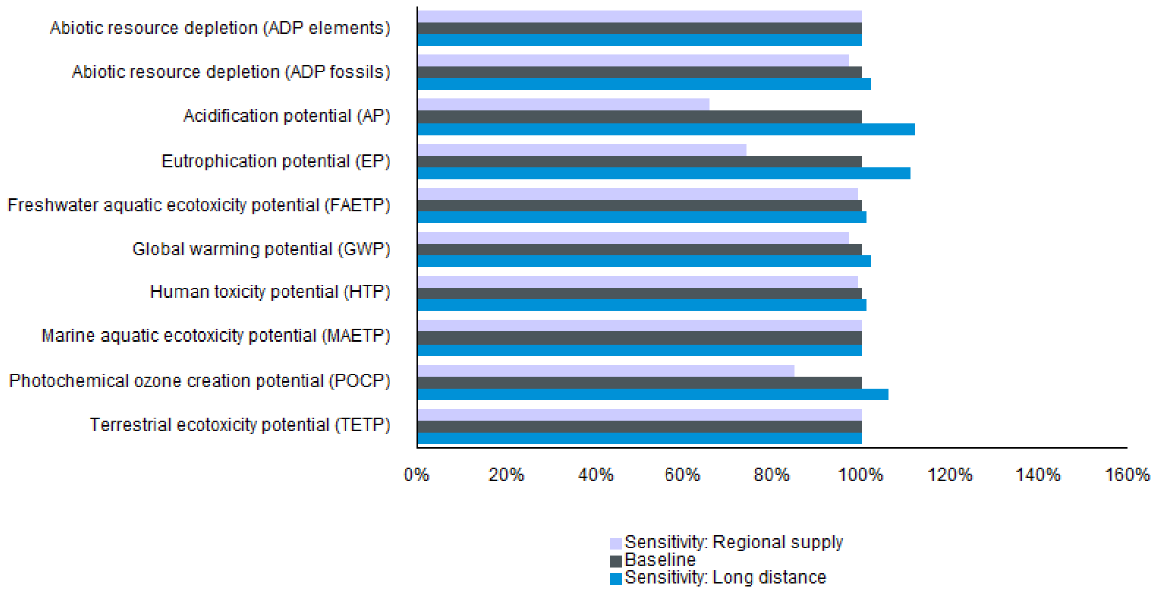
[8] Towers were supplied locally within Australia in 2015 thus the transport of towers via shipping in the long distance scenario is actually only a short distance.

Figure 23: Whole-life sensitivity analysis of increased transport



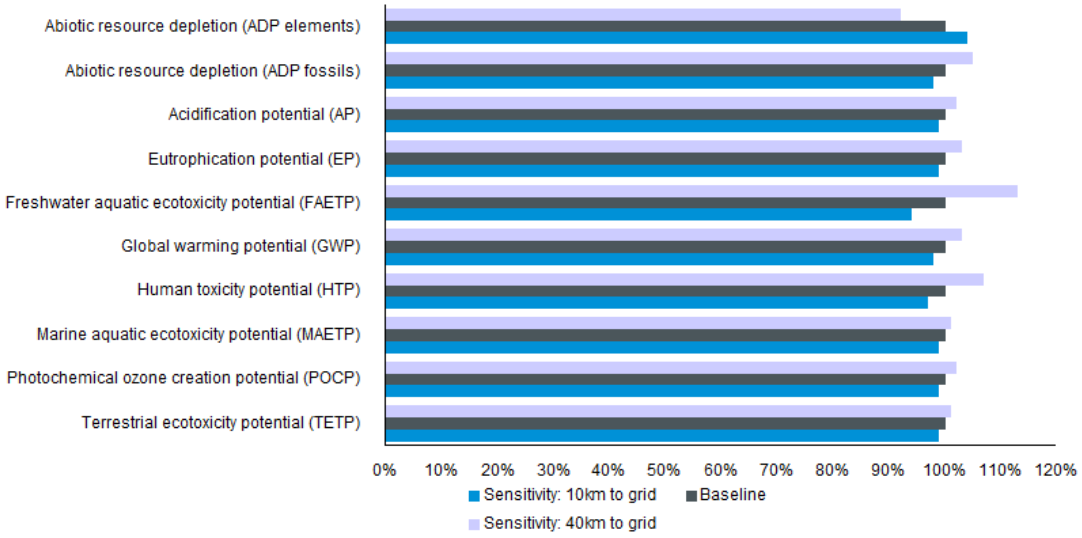
7.2.5 Distance of wind plant to electricity grid

The distance of the wind plant from the existing grid is another variable that will change depending on the site location. The baseline scenario for this study assumes that the wind plant is located 20km from the existing grid and includes electrical loss of 2.5% for the entire power plant.

This sensitivity analysis evaluates two alternative scenarios of the power plant being located either 10km or 40km from the existing grid, which results in an estimated electrical loss of 2.0% and 3.5%, respectively. The analysis also accounts for the differences in amounts of 110kV high voltage electrical cable that connects the power plant to the grid.

Figure 24 shows the results of the analysis which indicates that the impacts do not change significantly with changing grid distance. A doubling of the distance to grid, from 20km to 40km, increases all environmental impact indicators from 1% to 13%, with freshwater aquatic ecotoxicity most notably affected, which primarily results from greater use of copper and polymers in the high-voltage cable. While halving the grid distance, from 20km to 10km, reduces all potential impact indicators in the range of -1% to -6%. An exception is observed with the ADP elements category which shows an 8% decrease when cable length is doubled and a similar increase when cable length is halved. This is due to inconsistency between the scrap burden and end-of-life datasets.

Figure 24: Whole-life impacts for doubling and halving distance to grid to 40km

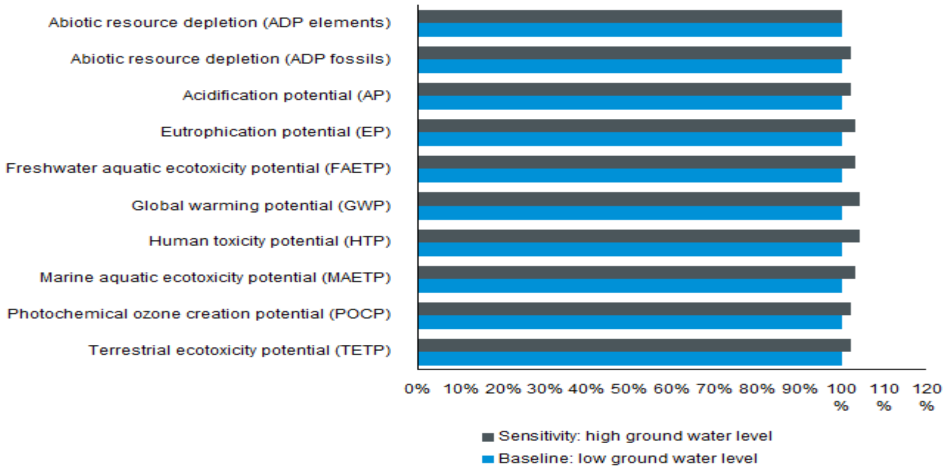


7.2.6 High ground water level type foundations

The baseline assessment assumes a low ground water level (LGWL) foundation for the turbine which has been chosen as the base case as it is more representative of the majority of wind power plant sites. This sensitivity evaluates the use of a high groundwater level (HGWL) foundation which indicates a (maximum) groundwater level equal to the level of the terrain, which requires increased quantities of concrete and steel reinforcement.

Figure 25 shows the results of the analysis for the use of the high groundwater level foundation which indicates that this does not significantly change the environmental impacts, increasing the potential impacts between 2% to 5% across all indicators. The increase in potential impacts directly correlates to the increased use of steel and concrete for this foundation type.

Figure 25: Whole-life impacts for changing from LGWL to a HGWL foundation



7.2.7 Potential incidence of turbine switchgear blow-out

The baseline assessment does not include potential switchgear blow-outs as part of the overall analysis of the wind plant, as these occurrences are rare. If a blow-out does occur then sulphur hexafluoride gas (SF_6) is released to atmosphere, which is a highly potent greenhouse gas. This sensitivity estimates the contribution of blow-out to the potential global warming impacts.

Based on estimates made by Vestas, it has been assumed for this sensitivity estimation that 1 in 2000 switchgears may have an incidence of a blow-out over a 20 year operating period. For a power plant containing twenty nine V112-3.45 MW turbines, this would result in a release of approximately 100 grams of SF_6 over the lifetime, which equates to below 0.01% of the total global warming potential impacts.

7.2.8 Potential effects of recycling method

The baseline assessment uses an *avoided-impacts approach* to credit the recycling of metals at end-of-life, as described in Section 3.4.4.

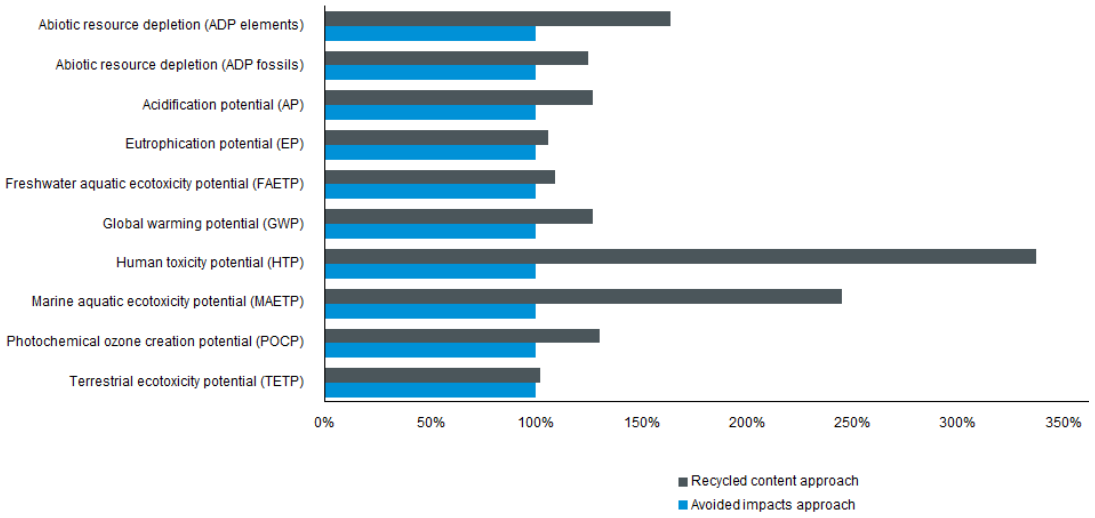
An alternative approach is to use a *recycled-content approach*, whereby environmental credits are received for the incoming raw-materials used to manufacture the wind-plant based upon the actual recycled material content of the wind turbine. For this approach no credit is given at end-of-life, but received by the incoming raw materials only.

Around 89% of the wind-turbine itself is constructed from metal components (primarily iron and steel, as well as copper and aluminium). However, the exact recycled content of all the turbine components is not known. As such, an estimate is made based upon the standard industry datasets (such as worldsteel) which contain average global recycled content for iron and steel materials. Therefore, this sensitivity provides an estimate for using the *recycled-content approach* for environmental crediting.

In LCA modelling terms for this sensitivity analysis, the end-of-life credits are removed from the LCA models, as well as removing the burdens associated with input scrap (for iron, steel, copper and aluminium), which were added to the LCI datasets for the *avoided-impact approach* (see Section 3.4.3).

Figure 26 shows the results of the assessment which indicate that across all impact categories these increase between 2% and 60% compared to the baseline, with the exception of the potential toxicity indicators for marine aquatic ecotoxicity (+145%) and human toxicity (+240%). For the marine aquatic ecotoxicity potential, this primarily increases due to the reduced end-of-life recycling credit associated with both aluminium and steel production which is driven by hydrogen fluoride emissions to air. The increase to human toxicity potential mainly relates to reduced credits for stainless steel recycling which is driven by heavy metal emissions (to air and water). The global warming potential increases by 27%.

Figure 26: Whole-life impacts using a recycled-content approach for metal recycling credits

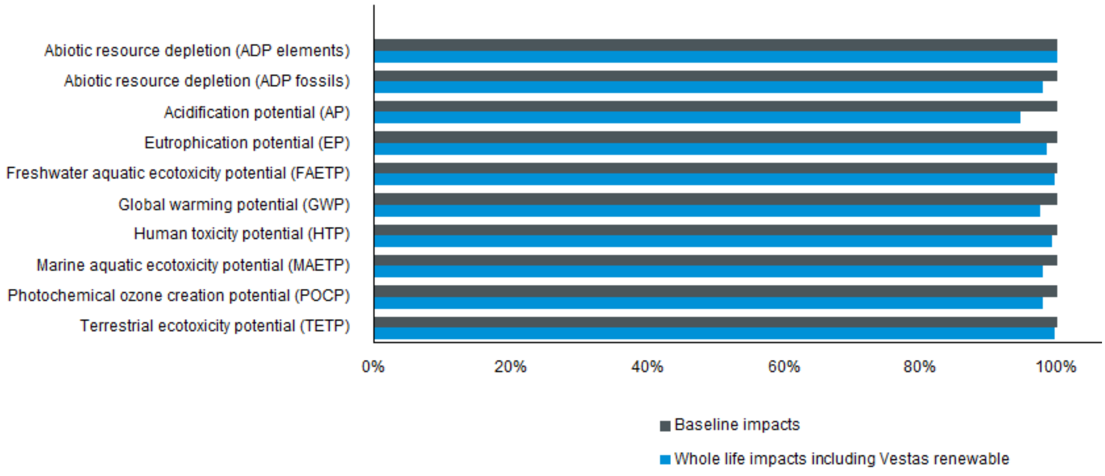


7.2.9 Potential effects of Vestas renewable electricity consumption

The baseline assessment excludes the 100% WindMade (2015) accreditation, whereby Vestas invested and purchased credits in Vestas-owned wind plants located in Romania in 2015. In this sensitivity analysis, this electricity consumption has been included by giving a credit for the average grid mix per MWh for the specific country and energy generated of wind plant location. This sensitivity estimates the additional contribution if this credit were included in the baseline LCA results.

Figure 27 shows the results of the analysis which indicates that this has a relatively small to moderate effect on the environmental impacts, reducing the potential impacts generally in the range between -0.05% to -6% across all indicators. For global warming potential, this credit has the total effect to provide around -0.1 grams CO_2-e per kWh, equivalent to around 2% of total potential global warming impacts.

Figure 27: Whole-life impacts of including Vestas renewable electricity consumption



7.3 Data quality checks

As indicated previously, there are certain stages of the life cycle where study assumptions and inventory datasets that will dominate the environmental impacts of the wind plant. It is these important areas that have been focused upon when conducting checks for data completeness, consistency and representativeness. The following important areas are identified for this LCA:

- production LCI datasets for iron, steel, aluminium, concrete, copper, composites and polymers;
- end-of-life crediting method and LCI datasets used for crediting;
- power plant lifetime;
- power plant electricity production;
- transport datasets; and
- coverage of LCIA characterisation factors.

Refer to Annex D for a summary of results for each of the above areas in relation to the original requirements set in the goal and scope. The following text provides an overall summary.

In general, all foreground data supplied by Vestas is representative of 2015, which includes the data for all Vestas' global production units and all other business functions (such as sales), consisting of over 100 sites. This accounts for material, energy and fuel inputs, as well as product outputs, wastes and recycled materials (refer to Section 1.2.4 for further details).

Other foreground data from Vestas relates to the material breakdown of the turbine which has accounted for the entire bill-of-materials for the specific turbine model, which consists of around 25,000 components. Each component is assessed in terms of specific material grade (such as stainless steel grades), production processes and country of production. Country of production is used to define country-specific electricity production mix for materials and processing, where relevant. Where components in the turbine are not designed or manufactured by Vestas (such as the site transformer or turbine gearbox), then the manufacturer of these items has provided a specific material composition of these items, or the data has been collected from published EPDs.

For background datasets for material production, these have been obtained from various established and credible published sources, such as, worldsteel, Eurofer, Plastics Europe, as well as Thinkstep (2016) generated datasets. These are, in general, considered to be of good or high quality. The updated Thinkstep datasets seem generally to be in alignment also with previous datasets from 2014. Checks have not been conducted for the entire wind power plant; although, some spot checks have been made relating to the environmentally significant datasets, such as metals and concrete. Overall, these are in alignment with previous datasets since 2006 from an environmental impacts perspective for the complete power plant, with an estimated difference of below 5%, across all impact categories with exception of ecotoxity impacts which are about 15%.

The accounting of ‘water flows’ has changed, both in terms of method and some nomenclature changes in the latest GaBi databses (PE, 2015). The primary change is in relation to accounting method of flows, whereby input- and output-water flows for a process (e.g. hydro power or metal production) appear to be aggregated rather than subtracted to obtain water-consumption. Vestas has made adjustments to the water flows (refer to Section 1.2.4) in order to maintain reasonable consistency with the previous accounting method. Nonetheless, it may be stated that in general, the LCI accounting for water-flows is still in relatively early level of maturity in terms of LCA data availability, as well as methods at an international level (such as, recently published *ISO 14046, Water footprint – Requirements and guidelines*), as such, the ‘water-use indicator’ will be subject to improvements with recognised best-practice.

In relation to the recycling methodology used, this LCA uses an ‘avoided impacts approach’ for the crediting, accounting also for burdens of input scrap from primary production of metals; methodologically speaking, this is a consistent approach to crediting and is a fair representation. Additionally, specific parts of the turbine and power plant are applied different recycling rates dependent on their ease to disassemble and recycle. A sensitivity analysis was also conducted for a recycled-content approach from crediting.

As discussed previously in Section 7.1, two important assumptions in the LCA relate to power plant lifetime and electricity production. These have, potentially, a very significant effect on the overall results and environmental performance of the turbine (relative to 1 kWh of production). The assumptions made for both these parameters are considered representative and robust.

Transport includes specific fuel use (and vehicle utilisation) data for the transport of specific turbine components (for towers, nacelles and blades). These are based on measured data and specific distances with actual wind turbine transports. These specific datasets result in higher fuel consumption compared to default containerised-transport models used in previous LCAs of Vestas turbines and considered representative data.

Based on a check of the completeness of the characterisation factors used in the CML method (for the impact categories assessed in this LCA), it is considered that all relevant substances have been characterised that are of relevance to the turbine life cycle. There are also no unusual or special elements or substances that have been identified in the data collection stage which require special account.

The general conclusion is that the robustness of the important data is considered, overall, to be complete, consistent and representative of the system being assessed.

7.4 Conclusions and recommendations

Overall, the study represents a robust and detailed reflection of the potential environmental impacts of the 100MW wind power plant consisting of V112-3.45 MW turbines. The LCA is based upon accurate product knowledge and current best-practice in the field of life cycle assessment, both in the methodologies applied and datasets used to account for environmental impacts, as well as the LCA tools and software applied.

The study has been critically reviewed by an external expert, Prof. Dr. Matthias Finkbeiner, according to paragraph 6.2 of ISO 14044 (2006a), as the study is not intended for comparative assertions intended to be disclosed to the public.

The life cycle assessment could further benefit from considering the following:

- explore improvements in accounting methods for water flows; and
- explore potential use of other impact assessment methods.
- periodic and systematic updates of datasets and databases for consistent benchmarking between product generations.

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Annex A Impact category descriptions

A.1 Impact category descriptions

The following impact categories, as used by CML 4.6 (2016) method, are described below (Goedkoop, 2008):

Environmental impact categories:

- 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 oxidant creation potential (POCP)
- Terrestric ecotoxicity potential (TETP)

Non-impact indicators:

- Primary energy from renewable raw materials (net calorific value)
- Primary energy from resources (net calorific value)
- Water consumption
- Turbine recyclability (not life cycle based, turbine only)
- Product waste (not life cycle based, turbine only)
- Turbine circularity (not life cycle based, turbine only)

A.2 Impact categories

- *Abiotic resource depletion (elements)*. This impact category is concerned with protection of human welfare, human health and ecosystem health. This impact category indictor is related to extraction of minerals and fossil fuels due to inputs into the system. The abiotic depletion factor (ADF) is determined for each extraction of minerals and fossil fuels (kg antimony equivalents/kg extraction) based on ultimate geological reserves (not the economically feasible reserves) and rate of de-accumulation. The geographic scope of this indicator is at a global scale.

- *Abiotic resource depletion (fossil)* 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 MJ.

- *Acidification*. Acidifying substances cause a wide range of impacts on soil, groundwater, surface water, organisms, ecosystems and materials (buildings). Acidification Potentials (AP) for emissions to air are calculated with the adapted RAINS 10 model, describing the fate and deposition of acidifying substances. AP is expressed as kg SO_2 equivalents per kg emission. The time span is eternity and the geographical scale varies between local scale and continental scale.

- *Eutrophication* (also known as nutrification) includes all impacts due to excessive levels of macro-nutrients in the environment caused by emissions of nutrients to air, water and soil. Nutrification potential (NP) is based on the stoichiometric procedure of Heijungs (1992), and expressed as kg PO4 equivalents/ kg emission. Fate and exposure is not included, time span is eternity, and the geographical scale varies between local and continental scale.

- *Fresh-water aquatic eco-toxicity*. This category indicator refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. Eco-toxicity Potential (FAETP) is calculated with USES-LCA, describing fate, exposure and effects of toxic substances. The time horizon is infinite. Characterisation factors are expressed as 1,4-dichlorobenzene equivalents/kg emission. The indicator applies at global/continental/ regional and local scale.

- *Global warming* can result in adverse effects upon ecosystem health, human health and material welfare. Climate change is related to emissions of greenhouse gases to air. The characterisation model as developed by the Intergovernmental Panel on Climate Change (IPCC, 2007) is selected for development of characterisation factors. Factors are expressed as Global Warming Potential for time horizon 100 years (GWP100), in kg carbon dioxide/kg emission. The geographic scope of this indicator is at a global scale.

- *Human toxicity*. This category concerns effects of toxic substances on the human environment. Health risks of exposure in the working environment are not included. Characterisation factors, Human Toxicity Potentials (HTP), are calculated with USES-LCA, describing fate, exposure and effects of toxic substances for an infinite time horizon. For each toxic substance HTP's are expressed as 1.4-dichlorobenzene equivalents/ kg emission. The geographic scope of this indicator determines on the fate of a substance and can vary between local and global scale.

- *Marine aquatic ecotoxicity* refers to impacts of toxic substances on marine ecosystems (see description fresh-water toxicity).

- *Terrestrial ecotoxicity*. This category refers to impacts of toxic substances on terrestrial ecosystems (see description fresh-water toxicity).

- *Photo-oxidant formation* is the formation of reactive substances which are injurious to human health and ecosystems and which also may damage crops. This problem is also indicated with "summer smog". Winter smog is outside the scope of this category. Photochemical Oxidant Creation Potential (POCP) for emission of substances to air is calculated with the UNECE Trajectory model (including fate), and expressed in kg ethylene equivalents/kg emission. The time span is 5 days and the geographical scale varies between local and continental scale.

A.3 Non-impact indicators

- *Primary energy demand* is often difficult to determine due to the existence multiple energy sources when modelling a system. 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 is the quantity of resources withdrawn, and is expressed in its energy equivalent (i.e. the energy content of the raw material). For renewable resources, the primary energy is characterised by the energetic quantity of biomass consumed. For hydropower, the primary energy is characterised on the quantity of potential energy gained by the water. As aggregated values, the following indicators for primary energy are expressed:
    - *Primary energy consumption (non-renewable)* essentially characterises the gain from the energy sources of natural gas, crude oil, lignite, coal and uranium. Natural gas and crude oil are 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. Primary energy consumption (non-renewable) is measured in MJ.
    - *Primary energy consumption (renewable)* comprises hydropower, wind power, solar energy and biomass. It is important that the primary energy consumed (e.g. for the production of 1 kWh of electricity) is calculated to reflect the efficiency for production or supply of the energy system being characterised. The energy content of the manufactured products is considered as feedstock energy content. It is characterised by the net calorific value of the product and represents the usable energy content. Primary energy consumption (renewable) is measured in MJ.
- In this assessment *water consumption* is calculated very simply as the quantity of liquid water taken from the environment minus the liquid water returned to the environment, as freshwater. Water in the form of vapour or steam emitted to atmosphere, or water incorporated into the finished product is considered to be lost and not directly available for reuse. The data for this assessment have been obtained from primary sources and data for raw material production, transport and other background data are sourced from Thinkstep (2016) datasets. There is no consideration made regarding the types of water used, inclusion of local water scarcity, as well as differentiation between watercourses and quality aspects (Berger, 2010), which would provide a more valid and accurate assessment.
- Turbine recyclability (not life cycle based, turbine only) – refer section 5.3.4 for detail on turbine recyclability
- Product waste (not life cycle based, turbine only) – refer section 5.3.5 for detail on product waste
- Turbine circularity (not life cycle based, turbine only) - refer section 5.3.6 for detail on turbine circularity

Annex B General description of wind plant components

A wind turbine is constructed of around 25,000 components which are grouped into several main systems, such as, the tower, nacelle, hub and blades. Within the nacelle, many of the electrical and mechanical components are contained, such as the gearbox, main shaft, generator and control systems. For this LCA, detailed part information on the turbine components has been taken from the bill-of-materials and engineering drawings, which provide specific data for material type and grade, as well as component mass.

Other components that form the main part of an onshore wind plant are the turbine foundations, the plant transformer, switchgears and site cabling (i.e. connecting between turbines, transformer and to the grid), as well as access roads. Data describing these components for the LCA was sourced from EPDs, directly from the manufacturers and design drawings.

B.1 Nacelle module

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

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:

B1.1 Gearbox

Data for the V112-3.45 MW gearbox is based on supplier statement of the material composition by specific grade of iron and steel, as well as expert judgement.

B1.2 Generator

The generator is manufactured by Vestas and mainly consists of steel, cast iron and copper. The complete bill-of-materials was used to model the generator. No permanent magnets are used in the generator.

B1.3 Nacelle foundation

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

B.1.4 Nacelle cover

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

B1.5 Other parts in the nacelle

In addition to the above-mentioned components, the nacelle also consists of a range of other components, including:

- yaw system;
- coupling;
- cooler top;
- cables; and
- controls.

All parts within the turbine have been assessed in the LCA based on the part mass and material composition from the bill-of-materials for the turbine.

B.2 Blades

The turbine blades are mainly produced at Vestas' blades factories. Each blade is55 metres long and comprises a main spar which is glued between two blade shell sections. The main materials used in the blades are carbon fibre and woven glass fibres infused with epoxy resin. Polyurethane (PUR) glue is the primary material used to assemble blade shells and web. After the gluing process, the blades are ground and polished to ensure the correct finish.

There are also auxiliary materials, such as vacuum fleece and various plastic films, which are used in the production of the blades production steps. These materials are also included in this LCA as part of the bill-of-materials for the wind turbine.

B.3 Hub

The hub and spinner are parts of the rotor system. The finished spinner is 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. Specific data for material type, grade and mass has been used in the LCA.

B.4 Tower

The tower accounts for a significant proportion of the entire wind turbine, both in size and mass.

The baseline tower is 94 m high and is built for IEC 1A (high) wind conditions. Other tower heights are available for other wind conditions for the turbine. Towers are designed for different heights to suit different wind speeds and local site conditions and physical loading.

Towers for Vestas' turbines are to a minor extent manufactured at Vestas' own factories, but the majority are purchased from sub-suppliers. In this LCA, data from towers manufactured by Vestas has been used.

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. The steel plates are then rolled and welded into tower sections. Subsequent surface treatment (i.e. sandblasting) and painting of towers is performed by either Vestas or at sub-suppliers.

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.

B.5 Turbine transformer

Data for the V112-3.45 MW turbine transformer is based on supplier data, which shows that the transformer mainly consists of steel, copper, aluminium and resin.

B.6 Cables

Data for the cables in the tower is based on supplier statement. According to the supplier, the cables mainly consist of aluminium, copper, steel and polymers.

B.7 Controller units and other electronics

The controller units mainly consist of signal and power electronics, which have been mapped on component-specific basis covering the complete bill-of-materials for the turbine of around 9500 electronic items. Material and mass details for the switchgears used for the power plant originate from information from the sub-suppliers and experts at Vestas.

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 wind turbine.

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, as described below. There are two general kinds of foundations depending on the water level, as follows:

- high groundwater level - indicates a (maximum) groundwater level equal to the level of the terrain, which requires more concrete and steel reinforcement; and
- 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 plant sites. The foundation size also varies depending on the wind speed and loading, which has been accounted for in the LCA. The data for material composition is from Vestas design specifications.

B.10 Site cables

29 km of 33 kV PEX cables with aluminium conductor is used for internal cables in the wind power plant i.e. for connecting between the turbines and between the turbine plant and the 100 MVA transformer. This cable length consists of various cables with differing aluminium conductor area of 95mm^2 (16km), 240mm^2 (4.5km) and 400mm^2 (9km), which represent a layout for this size of plant. According to the supplier, the cables mainly consist of aluminium, copper and polymer materials. The manufacturer has provided data for the materials used.

20km of high voltage 110kV PEX cables with aluminium conductor (630mm^2) is used to connect the wind plant to the grid. These are mainly composed of aluminium, copper and polymer materials.

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 250 MVA and scaled down to 100 MVA (based on MVA rating).

B.12 Access roads

Generally a combination of tarred roads and dirt roads need to be built to provide access to the power plant turbines, which are often located in remote locations. It has been estimated that 10 km of tarred road is needed per power plant.

Annex C Manufacturing processes

Vestas' resource consumption and emissions for manufacturing of turbines is reported on a quarterly basis from each of the more than 100 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 C1. 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, which have been allocated on a MJ per MJ basis for the purchased credits of Vestas-owned wind plant located in Romania.

Table C1: Vestas manufacturing locations and other sites

Factory Class	Description	Allocation Rule
Assembly	Factories where the nacelle and all other turbine parts are put together.	Number of turbines produced
Tower	Tower shells are fabricated and assembled into sections.	kg of tower produced
Blades	Manufacturing of blades. See Annex B.2 for more details.	kg of blades produced
Generator	Production of the generator.	MW of power shipped
Controls	Fabrication of controller equipment (electronics).	Number of turbines produced
Sales	Includes sales, servicing and installation.	Number of turbines produced
Overheads	General offices and research and development.	Number of turbines produced
Casting	Cast houses and foundries.	kg of metal cast
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. An assumption for the transport of raw materials is included in the model, and a sensitivity analysis for transport is included in the LCA.

In 2012, Vestas casted 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 but are not treated.

Annex D Data quality evaluation

Annex D provides a summary of the checks made in the LCA for data completeness, consistency and representativeness. The following important areas are identified for this LCA:

- production LCI datasets for iron, steel, aluminium, concrete, copper, composites, polymers and electronics;
- end-of-life crediting method and LCI datasets used for crediting;
- power plant lifetime;
- power plant electricity production;
- transport datasets; and
- coverage of LCIA characterisation factors.

Table D1 provides further details of the results of the evaluation which indicates where there have been deviations and also gives an overall brief summary of consistency.

Table D1: Data quality evaluation (part 1)

Parameter	Requirement	Production LCI datasets for iron	Production LCI datasets for steel	Production LCI datasets for aluminium	Production LCI datasets for concrete
General description	-	Iron is primarily used as structural components in the nacelle and hub, as well as the generator housing; comprising of about 16% mass of the turbine itself. Different cast grades are used, such as EN GJS 400 18 LT, EN GJS 350 22 LT and EN GJS 250.	Steel is primarily used in the tower, nacelle, hub & nose cone (comprising about 71% of the turbine mass), as well as the turbine foundations. Different steel grades are used, including plate steel (tower), structural steel and stainless steels (used for example in the gearbox and fixing bolts).	Aluminium is mainly used in the site cables (around 56%) and the turbine nacelle and tower (around 44%) for the wind power plant, along with other components in the turbine.The Aluminium grades vary according to the application in the wind plant. But generally the aluminium ingot dataset is used.	Concrete is used in the turbine foundation and three different grades are used (C12, C30 and C45), which are represented in the LCA datasets.
LCI dataset used (where applicable)	-	Datasets include: DE: Cast iron component	Datasets include: RER: Steel plate worldsteel RER: Steel hot dip galvanized worldsteel Fixing material screws stainless steel Steel billet (42Cr4)	Datasets include: Aluminium ingot mix Aluminium ingot for extrusion Aluminium cast parts	Datasets include: Concrete C12/15 Concrete C30/37 (also used for C45 concrete)
Time-related coverage	Data should represent the situation in 2015 and cover a period representing a complete calendar year.	ThinkStep datasets published in 2016 have been used and are considered representative.	ThinkStep datasets published in 2016 have been used and are considered representative.	ThinkStep datasets published in 2016 have been used and are considered representative.	ThinkStep datasets published in 2016 have been used and are considered representative.
Geographical coverage	Data should be representative of the Vestas global supply chain.	The data set does not necessarily fit for any possible specific supply situation, but is representative for a common supply chain situation. The dataset represents a production mix at producer for German	Primarily worldsteel, Eurofer and ThinkStep datasets have been used in the LCA. Datasets generally based on a weighted average site-specific data (gate-to-gate) of European steel producers. This is considered representative of	The dataset does not necessarily fit for any possible specific supply situation, but is representative for a common supply chain situation. The dataset represents a production mix at producer for German	The dataset does not necessarily fit for any possible specific supply situation, but is representative for a common supply chain situation. The dataset represents a production mix at producer for

		infrastructure.	the supply chain.	infrastructure.	German infrastructure.
Technology coverage	Technology (for manufacture, product usage and end-of-life management) should be representative of global supply conditions and technology.	The dataset represents a technology mix for manufacture in a cupola furnace and sand casting. The technology is considered representative.	Primarily worldsteel, Eurofer and ThinkStep datasets have been used in the LCA which represent European averages. This is considered representative of the supply chain.	The dataset represents a technology mix for primary production. The technology is considered representative.	The dataset represents provision of a standard technical product and is considered representative.
Precision	No requirement specified.	No comments.	No comments.	No comments.	No comments.
Completeness	Specific datasets will be compared with literature data and databases, where applicable.	A comparison has not been made with other datasets, as these were not readily available in GaBi 7.	Comparison has been made with global worldsteel sources of data, which show similar overall potential impacts. For example, on per kg basis of plate steel basis (used in tower) reveals for the global dataset that ecotox impacts are slightly higher (around +10%), GWP lower (-4%), ADP and TETP higher (around +30%). These datasets used are considered the most comprehensive and representative available.	In general, comparisons have not been made with other sources of data. Datasets available relate only to European average and Germany. The datasets used are considered the most comprehensive and representative available.	Comparisons have not been made with other sources of data, as only datasets for Europe were available.
Representativeness	The data should fulfil the defined time-related, geographical and technological scope.	Dataset considered representative for time-related, geographical and technological scope.	Dataset considered representative for time-related, geographical and technological scope.	Dataset in general considered representative for time-related, geographical and technological scope.	Dataset in general considered representative for time-related, geographical and technological scope.
Consistency	The study methodology will be applied to all the components of the	Dataset is considered internally consistent across the thinkstep (2016) database of inventories which are generally applied	Dataset is considered internally consistent across the thinkstep (2016) database of inventories which are generally applied	Dataset is considered internally consistent across the thinkstep (2016) database of inventories which are generally applied	Dataset is considered internally consistent across the thinkstep (2016) database of inventories which are generally applied

	analysis.	throughout the LCA.	throughout the LCA.	throughout the LCA.	throughout the LCA.
Reproducibility	The information about the methodology and the data values should allow an independent practitioner to reproduce the results reported in the study.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.
Sources of the data	Data will be derived from credible sources and databases.	Dataset is published by ThinkStep (2016) and considered credible source.	Dataset is published by ThinkStep (2016) and considered credible source. Original data sources include: worldsteel Life Cycle Inventory Study for Steel Industry Products, 2011 and Eurofer publications.	Dataset is published by ThinkStep (2016) and considered credible source. Original data sources include: European Aluminium Association, Environmental Profile Report for the European Aluminium Industry, 2008 and Gesamtverband der Aluminiumindustrie e.V.	Dataset is published by Thinkstep (2016) and considered credible source. Based on following reference: Eyerer, P.; Reinhardt, H.-W.: Ökologische Bilanzierung von Baustoffen und Gebäuden, Birkhäuser, Zürich / Switzerland, 2000

Table D1: Data quality evaluation (part 2)

Parameter	Production LCI datasets for copper	Production LCI datasets for polymers	Production LCI datasets for composites	Power plant lifetime
General description	Copper is mainly used in the turbine (around 60%) and the site cables (around 40% plant mass) for the wind power plant, along with other plant components. The copper grade may vary according to the application in the wind plant. But generally a copper ingot dataset is used.	Polymers are mainly used in the turbine (20%), excluding blades, along with the site cables for the plant (80%). The polymer type varies according to the application in the wind plant. But generally a representative dataset from PlasticsEurope or ThinkStep database has been used.	Composite materials of epoxy resin combined with either glass fibres or carbon fibres are primarily used in construction of the blades, and also the nacelle and hub covers. The percentage of polymer to fibre depends on the location in the blade. Generally a representative dataset from PlasticsEurope is used or ThinkStep database has been used.	The power plant lifetime represents the design life of the power plant. The LCA assumes a lifetime of 20 years which matches the standard design life; however, the wind turbine industry is still young (starting for Vestas in 1979), and few turbines have ever been disposed, reaching operational lives of 30 years and over, for other Vestas turbine models.
LCI dataset used (where applicable)	Datasets include: DE: Copper ingot mix	Datasets include: RER: Polyethylene high density granulate ELCD/PlasticsEurope RER: Polyvinylchloride injection moulding part (PVC) PlasticsEurope Ethylene Propylene Diene Elastomer	Datasets include: Epoxy resin ts Glass fibres ts	Not relevant.
Time-related coverage	Thinkstep datasets published in 2016 and are considered representative.	Thinkstep datasets published in 2016 and are considered representative.	Thinkstep datasets published in 2016 and are considered representative.	Representative of specific turbine being assessed in reference time period.
Geographical coverage	The dataset represents consumption mix at consumer. The dataset represents a production mix at producer for German infrastructure.	Generally the dataset represents an average production mix for European infrastructure.	Generally the dataset represents an average production mix for European infrastructure.	Representative of specific turbine being assessed for geographical coverage.
Technology coverage	The dataset represents a technology mix for primary production. The technology is considered representative.	The datasets represents a European technology mix that is considered representative.	The datasets represents a European technology mix that is considered representative.	Representative of specific turbine being assessed for technology coverage.
Precision	No comments.	No comments.	No comments.	No comments.

Completeness	A comparison has been made with global Thinkstep dataset for copper ingot. On a per kg basis this shows, generally higher overall potential impacts for the global dataset. For example, on per kg basis the global copper dataset has about 17% higher GWP impacts. The datasets used are considered representative.	In general, comparisons have not been made with other sources of data. Datasets available relate only to European average and Germany. The datasets used are considered the most comprehensive and representative available.	In general, comparisons have not been made with other sources of data. Datasets available relate only to European average and Germany. The datasets used are considered the most comprehensive and representative available.	The design life is a standard 20 years across all Vestas turbines (except V164 offshore platform which is 25 years).
Representativeness	Dataset in general considered representative for time-related, geographical and technological scope.	Dataset in general considered representative for time-related, geographical and technological scope.	Dataset in general considered representative for time-related, geographical and technological scope.	The lifetime is considered representative.
Consistency	Dataset is considered internally consistent across the ThinkStep (2016) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the ThinkStep (2016) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the ThinkStep (2016) database of inventories which are generally applied throughout the LCA.	Not relevant.
Reproducibility	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Not relevant.
Sources of the data	Dataset is published by ThinkStep (2016) and considered credible source.	Dataset is published by ThinkStep (2016) and considered credible source. Original data sources include: PlasticsEurope, Association of Plastics Manufacturers, Brussels, and Boustead LCI database: Boustead model, Horsham, UK 2005.	Dataset is published by ThinkStep (2016) and considered credible source.	Vestas wind turbine specifications.

Table D1: Data quality evaluation (part 3)

Parameter	Power plant electricity production	Transport datasets	End-of-life crediting method and LCI datasets used for crediting	Coverage of LCIA characterisation factors.
General description	Electricity production is substantially effected by the wind plant siting and site-specific wind conditions that the turbine operates under (i.e. low, medium or high wind classes defined by the IEC). Electricity production is very accurately measured for Vestas turbines. The turbine assessed in this LCA has been assessed for average high wind conditions, which fairly reflects a 'typical' power plant.	In general, incoming raw materials and components are transported via 'default' transport modes, while the transport of turbine components (e.g. blades, nacelle and tower) use vehicles with specific transport gear to move those components to power plant site and at end-of-life.	At end-of-life the wind plant components are dismantled and waste management options include: recycling; incineration with energy recovery; component reuse; and deposition to landfill. The LCA accounts for specific recycling rates of different turbine components, depending on their material purity and ease of disassembly, based upon industry data. System expansion is used to account for recycling credits for metals. In general, datasets for input materials are the same as those used for recycling credits. All input scrap metal has been applied with primary or scrap burdens.	The selection of the impact categories assessed in this study is representative of those impacts that are likely to arise from a wind plant system, based on the CML (2016) baseline characterisation factors for mid-point potential impacts. Ozone depletion potential (ODP) has been omitted from the selected impact categories as this is not considered to be significant.
LCI dataset used (where applicable)	Not relevant.	Datasets include: GLO: Container ship ELCD GLO: Rail transport cargo GLO: Truck Plus modified datasets of the above.	Datasets include: RER: Value of scrap worldsteel RER: Aluminium ingot mix (2010) EAA GLO: Copper mix ts	Not relevant.
Time-related coverage	Representative of specific turbine being assessed in reference time period.	ThinkStep datasets published in 2016 and are considered representative.	ThinkStep datasets published in 2016 and are considered representative.	The CML (2016) baseline characterisation factors are considered representative for 2015.
Geographical coverage	Representative of specific turbine being assessed for geographical coverage.	The datasets represent a global mix, while modified datasets are based on specific transport fuel-use data from European and Asian suppliers (for blades, nacelle and tower).	Generally the datasets used for crediting represent an average production mix for European infrastructure.	The impact categories occur on different geographical scales, ranging from global impacts (such as global warming potential) to regional impacts (such as acidification potential) and local impacts (such as aquatic toxicity or human toxicity

				potential). The LCA does not account for specific local or regional conditions for these emissions.
Technology coverage	Representative of specific turbine being assessed for technology coverage.	The datasets represents a European and Asian technology mix that is considered representative.	The datasets represents average European or global technology mix that is considered representative.	The selected impact categories cover those associated with the wind power plant, such as for metal production, fabrication and recycling, as well as other materials contained within the turbine and power plant, such a concrete, polymers and composite materials.
Precision	No comments.	No comments.	No comments.	No comments.
Completeness	The electricity production is representative of the actual turbine and conditions being assessed.	Comparisons have not been made with other sources of data.	Comparisons have not been made with other sources of data.	A general check was made for metal, polymer and concrete production LCIs that important substance flows were covered in the CML characterisation factors. These are considered complete. Also, the following impact categories were assessed using IMPACT 2002+ and considered reasonably similar for this study compared to CML. Similar components dominate the life cycle impacts, although often different substances are the main contributors to the impacts. • Aquatic acidification - Midpoint • Aquatic ecotoxicity - Midpoint • Aquatic eutrophication - Midpoint • Photochemical oxidation - Midpoint • Terrestrial acidification/nutrification • Terrestrial ecotoxicity - Midpoint
Representativeness	The electricity production is considered representative and has been assessed for high wind	Dataset in general considered representative for time-related, geographical and technological	The datasets in general considered representative for time-related, geographical and technological	The datasets in general considered representative for time-related, geographical and technological

	conditions.	scope.	scope.	scope.
Consistency	Not relevant.	Dataset is considered internally consistent across the ThinkStep (2016) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the ThinkStep (2016) database of inventories which are generally applied throughout the LCA.	The impact assessment method is applied consistently throughout the LCA.
Reproducibility	Not relevant.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by ThinkStep (2016) and considered accessible to reproduce.	Dataset is published by CML (2016) and considered accessible to reproduce.
Sources of the data	Vestas internal data for the electricity production of the wind turbine. This is based upon actual turbine test data for a typical power production curve and using analysis software (based on T-CAT) of the specific turbine performance data.	Dataset is published by ThinkStep (2016) and considered credible source. Modified datasets for turbine component transport are specific data from Vestas suppliers.	Dataset is published by ThinkStep (2016) and considered credible source. Includes on following reference: European Aluminium Association, worldsteel and Thinkstep database (2016).	Dataset is published by CML (2016) the Centre for Environmental Science, Leiden University.

Annex E Turbine wind class

Turbine wind class is one of the factors which needs to be considered during the complex process of planning a wind power plant. The wind class determine which turbine is suitable for the 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 Table E1. 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.

For the LCA, electricity generation from the turbine is assessed at the following wind speed for each wind class:

- high wind speed is assumed to be 10.0 m/s;
- medium wind speed is assumed to be 8.5 m/s; and
- low wind speed is assumed to be 7.5 m/s.

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 E1: 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	6.0 to 7.5 m/s
Extreme 50-year gust	70 m/s	59.5 m/s	52.5 m/s
Turbulence classes	A 18%	A 18%	A 18%
	B 16%	B 16%	B 16%

International Electrotechnical Commission standard (IEC)

Vestas has an extensive portfolio of onshore turbines which are each suited to specific conditions and requirements, Table E2 shows the various wind turbines and their wind classes.

Table E2: Vestas onshore wind turbines

Turbine Class	IEC I High Wind	IEC II Medium Wind	IEC III Low Wind	Published LCA of turbine completed (year)
Onshore				
V52-850 kW	X	X		No
V60-850 kW		X	X	No
V82- 1.65 MW		X	X	Yes (2006)
V80-2.0 MW	X			Yes (2004)
V80-2.0 MW GridStreamer™	X			Yes (2011)
V90-1.8 MW		X		No
V90-1.8 MW GridStreamer™		X		No
V90-2.0 MW		X	X	No
V90-2.0 MW GridStreamer™			X	Yes (2011)
V90-2.0 MW GridStreamer™(IEC IA)	X	X	X	No
V100-1.8 MW			X	No
V100-1.8 MW GridStreamer™			X	Yes (2011)
V100-2.0 MW GridStreamer™(IEC IIA)		X	X	No
V100 – 2.0 MW		X		Yes (2015)
V100-2.6 MW		X	X	Yes (2012)
V90-3.0 MW	X	X		Yes (2012)
V110-2.0 MW			X	Yes (2015)
V112-3.0 MW		X	X	Yes (2011)
V105-3.3 MW	X			Yes (2014)
V112-3.3 MW	X	X		Yes (2015)
V117-3.3 MW		X	X	Yes (2014)
V126-3.3 MW			X	Yes (2014)
V105-3.45 MW	X			Yes (2017)
V112-3.45 MW	X			Yes (2017)
V117-3.45 MW	X	X		Yes (2017)
V126-3.45 MW		X		Yes (2017)
V136-3.45 MW		X	X	Yes (2017)

Annex F General uncertainties in life cycle assessment

The main methodological assumptions and uncertainties made in the LCA are described below.

F.1 Foreground (primary) data

The primary data collected by Vestas are considered to be of high quality and the modelling has been carried out to an extremely high level of detail. The GaBi DfX software was used to assess the wind turbine production down to the level of individual components. The BOM used contained around 25,000 items. This LCA has covered 99.9% of the total mass of the turbine itself, and about 99.95% of the entire mass of the power plant. Missing information relates to parts where the material was not identified. Manufacturing data were based on average production in Vestas global production facilities as described in Annex C and are also considered to be of high quality.

F.2 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 typical ‘virtual’ wind plant so it is not possible to entirely specify how (un)representative the background data may be, 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.

F.3 Allocation

Allocation was applied to the production data as described in Annex C. Different allocation rules would generate different results but the ones selected are based on physical properties of the system in alignment with the ISO standards for LCA. Allocation may also be applied in some of the background datasets for the production of materials, fuels and energy. These assumptions are described in the dataset documentation from Thinkstep (2016). The datasets have not been adjusted for any allocation procedures made. Lastly, allocation is also applied to the site transformer, based on MVA rating, which has been scaled down from 250MVA to 100MVA to represent the requirements of the 100MW wind plant, where material and production data were taken from the manufacturers EPD.

F.4 Recycling approach

In relation to the recycling methodology used, this LCA uses an ‘avoided impacts’ approach for the crediting, accounting also for burdens of input scrap from primary production of metals; methodologically speaking, this is a consistent approach to crediting. Additionally, specific parts of the turbine and power plant are applied different recycling rates dependent on their ease to disassemble and recycle. Also the LCA presents the results if a ‘recycled content approach’ is used for crediting the metal at end-of-life; based upon the standard industry datasets for average international recycling rates.

F.5 Impact assessment

Uncertainty is also introduced in the impact assessment phase of the LCA, which will vary according the impact categories assessed. The main issues are:

- completeness: does the impact assessment methodology consider all potential contributing substances/emissions; and
- characterisation: has the degree of impact caused by each substance species been characterised appropriately.

Certain impact categories, such as global warming potential, are considered scientifically robust in both of these aspects; however, toxicity impacts, such as human toxicity and eco-toxicity, are less well developed and consequently less reliance should be placed on these categories.

Based on a check of the completeness of the characterisation factors used in the CML method (for the impact categories assessed in this LCA), it is considered that all relevant substances have been characterised that are of relevance to the turbine life cycle. There are also no unusual or special elements or substances that have been identified in the data collection stage which require special account.

Annex G Life cycle inventory

Table G1 shows the life cycle inventory results for 1 kWh of electricity supplied to the grid for the V112-3.45 MW turbine. A mass cut-off has been applied to Table G1 in order to limit the number of flows presented to a reasonable number.

Table G1: Life cycle inventory of 100MW power plant of V112-3.45 MW turbines (units shown in mg per kWh)

Flow	Unit	Turbine	Foundations	Site parts	Plant setup	Operation	End-of-life	Total
Energy resources	mg per kWh	2.32E+03	3.67E+02	1.71E+02	1.06E+02	7.36E+01	-1.01E+03	2.02E+03
Non-renewable energy resources	mg per kWh	2.32E+03	3.67E+02	1.71E+02	1.06E+02	7.36E+01	-1.01E+03	2.02E+03
Crude oil (resource)	mg per kWh	3.45E+02	2.93E+01	5.44E+01	9.79E+01	2.87E+01	-1.27E+00	5.54E+02
Hard coal (resource)	mg per kWh	1.34E+03	2.76E+02	4.29E+01	4.86E-01	2.49E+01	-1.12E+03	5.61E+02
Lignite (resource)	mg per kWh	2.91E+02	3.73E+01	2.48E+01	5.80E-01	9.69E+00	6.11E+01	4.25E+02
Natural gas (resource)	mg per kWh	3.38E+02	2.51E+01	4.83E+01	7.04E+00	1.03E+01	5.08E+01	4.80E+02
Material resources	mg per kWh	4.05E+06	2.91E+05	2.14E+06	1.44E+04	1.20E+05	-3.61E+06	3.01E+06
Non-renewable elements	mg per kWh	7.17E+01	2.93E+01	4.95E+00	9.10E-02	2.72E+00	-2.33E+01	8.55E+01
Chromium	mg per kWh	1.29E-01	6.26E+00	3.58E-02	2.59E-05	-3.92E-01	-6.01E-02	5.98E+00
Copper	mg per kWh	1.86E+01	7.86E+00	1.14E+00	2.48E-04	1.18E+00	-2.19E+01	6.88E+00
Iron	mg per kWh	2.13E+01	8.17E+00	1.97E+00	8.00E-02	3.28E-01	-2.75E-01	3.16E+01
Lead	mg per kWh	4.25E+00	6.23E-02	2.96E-01	1.02E-03	1.70E-01	-3.39E-01	4.44E+00
Magnesium	mg per kWh	2.51E+00	2.48E+00	1.95E-05	7.20E-06	2.17E-01	8.66E-05	5.21E+00
Silicon	mg per kWh	2.78E+00	3.45E+00	2.17E-05	7.95E-06	2.39E-01	7.01E-06	6.46E+00
Zinc	mg per kWh	1.83E+01	3.00E-01	1.49E+00	7.10E-04	7.63E-01	-5.26E-01	2.03E+01

Non-renewable resources	mg per kWh	1.74E+04	8.97E+03	1.00E+03	7.54E+02	4.94E+02	-1.39E+04	1.47E+04
Bauxite	mg per kWh	1.05E+02	7.19E+00	1.07E+02	9.85E-04	1.28E+00	-1.96E+02	2.41E+01
Clay	mg per kWh	-5.02E+00	3.23E+01	1.58E+00	1.05E+00	-3.76E-02	2.07E+01	5.06E+01
Colemanite ore	mg per kWh	1.25E+01	1.05E-02	2.78E-04	9.21E-06	1.20E-01	-1.53E-06	1.26E+01
Copper - Gold - Silver - ore (1,0% Cu; 0,4 g/t Au; 66 g/t Ag)	mg per kWh	1.58E+01	3.02E-03	1.38E-04	0.00E+00	2.30E+00	5.89E-03	1.81E+01
Copper - Gold - Silver - ore (1,1% Cu; 0,01 g/t Au; 2,86 g/t Ag)	mg per kWh	1.19E+01	7.99E-01	1.10E-03	0.00E+00	1.47E+00	-4.19E+00	1.00E+01
Copper - Gold - Silver - ore (1,16% Cu; 0,002 g/t Au; 1,06 g/t Ag)	mg per kWh	6.74E+00	4.51E-01	6.19E-04	0.00E+00	8.27E-01	-2.37E+00	5.65E+00
Copper ore (sulphidic, 1.1%)	mg per kWh	6.52E+00	1.21E-01	1.48E+01	0.00E+00	1.30E-03	1.28E-07	2.14E+01
Copper ore (2.23%)	mg per kWh	3.88E+01	0.00E+00	0.00E+00	0.00E+00	8.52E-02	0.00E+00	3.89E+01
Dolomite	mg per kWh	4.91E+01	2.74E+01	1.97E-02	1.27E-02	8.90E-01	-5.25E+01	2.48E+01
Gypsum (natural gypsum)	mg per kWh	-7.10E+00	2.00E+01	7.48E-03	3.80E-03	-1.68E-01	1.06E+01	2.33E+01
Inert rock	mg per kWh	1.46E+04	3.13E+03	8.41E+02	1.13E+01	4.34E+02	-1.16E+04	7.44E+03
Iron ore (56,86%)	mg per kWh	2.03E+03	4.68E+02	4.30E+00	0.00E+00	3.28E+01	-2.06E+03	4.73E+02
Limestone (calcium carbonate)	mg per kWh	1.66E+02	9.03E+02	6.71E+00	3.59E-01	1.88E+00	7.10E+01	1.15E+03
Potashsalt, crude (hard salt, 10% K2O)	mg per kWh	8.82E+00	2.62E+00	1.39E-01	5.20E-01	3.15E-01	-6.96E+00	5.45E+00

Natural Aggregate	mg per kWh	-9.63E+01	3.60E+03	7.28E+00	6.27E+02	5.21E+00	5.84E+01	4.21E+03
Quartz sand (silica sand; silicon dioxide)	mg per kWh	1.68E+02	1.23E+01	2.11E+00	7.32E-01	4.80E+00	-2.53E+01	1.63E+02
Rare-earth ore	mg per kWh	1.16E+01	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.16E+01
Sodium chloride (rock salt)	mg per kWh	9.73E+01	1.71E+00	6.44E+00	1.46E-02	1.51E+00	-1.10E+01	9.60E+01
Soil	mg per kWh	9.28E+01	7.31E+02	9.82E+00	1.13E+02	3.31E+00	-4.17E+00	9.46E+02
Shale	mg per kWh	6.67E-03	5.07E+00	1.92E-04	6.20E-06	2.80E-04	-1.69E-04	5.08E+00
Renewable resources	mg per kWh	6.93E+04	1.21E+04	3.84E+03	9.16E+02	1.78E+03	-2.16E+04	6.63E+04
Water	mg per kWh	5.26E+04	1.11E+04	2.72E+03	8.82E+02	1.27E+03	-2.33E+04	4.53E+04
Air	mg per kWh	1.66E+04	9.13E+02	1.10E+03	3.22E+01	4.98E+02	1.64E+03	2.08E+04
Carbon dioxide	mg per kWh	1.84E+02	2.74E+01	4.49E+00	2.66E+00	7.10E+00	-1.70E+01	2.09E+02
Nitrogen	mg per kWh	4.79E+00	4.25E-02	6.74E+00	5.94E-11	5.51E-02	-6.55E-04	1.16E+01
Deposited goods	mg per kWh	1.46E+04	3.59E+03	9.45E+02	1.50E+02	4.03E+02	-1.15E+04	8.18E+03
Stockpile goods	mg per kWh	1.46E+04	3.59E+03	9.44E+02	1.50E+02	4.03E+02	-1.15E+04	8.18E+03
Overburden (deposited)	mg per kWh	1.36E+04	2.66E+03	7.95E+02	1.18E+01	3.60E+02	-9.70E+03	7.68E+03
Slag (deposited)	mg per kWh	4.66E-01	5.67E-03	1.13E+00	4.21E-11	1.20E-03	7.94E+00	9.54E+00
Spoil (deposited)	mg per kWh	3.68E+01	6.54E+02	9.14E+00	1.13E+02	1.84E+00	-1.26E+01	8.02E+02

Waste (deposited)	mg per kWh	9.36E+01	1.68E+02	4.61E+01	2.51E+01	3.40E+00	1.16E+02	4.53E+02
Emissions to air	mg per kWh	3.90E+04	4.77E+03	4.25E+03	9.59E+02	1.18E+03	-4.68E+03	4.55E+04
Inorganic emissions to air	mg per kWh	2.73E+04	3.95E+03	3.36E+03	9.35E+02	8.59E+02	-6.31E+03	3.00E+04
Carbon dioxide	mg per kWh	5.38E+03	1.21E+03	3.11E+02	6.54E+01	1.19E+02	-2.29E+03	4.79E+03
Carbon dioxide (biotic)	mg per kWh	1.53E+02	5.12E+01	3.76E+00	1.19E+00	6.25E+00	-2.97E+00	2.13E+02
Carbon dioxide (land use change)	mg per kWh	3.02E+00	6.55E-01	5.90E-02	2.65E-01	1.07E-01	-1.25E-01	3.98E+00
Carbon monoxide	mg per kWh	3.86E+01	9.53E+00	6.81E-01	2.62E-01	6.15E-01	-3.31E+01	1.67E+01
Nitrogen (atmospheric nitrogen)	mg per kWh	8.25E+01	1.18E-01	2.47E-01	4.39E-03	8.70E-01	-3.13E-01	8.34E+01
Nitrogen oxides	mg per kWh	1.36E+01	1.88E+00	5.85E-01	4.72E-01	2.05E-01	-2.45E+00	1.42E+01
Oxygen	mg per kWh	1.55E+01	1.96E+00	2.47E-01	5.81E-02	6.20E-01	2.99E-01	1.86E+01
Sulphur dioxide	mg per kWh	1.22E+01	1.62E+00	1.03E+00	1.48E-01	1.97E-01	-4.58E+00	1.06E+01
Water (evapotranspiration)	mg per kWh	1.19E+04	2.05E+03	2.36E+02	8.41E+02	4.35E+02	-5.10E+02	1.49E+04
Water vapour	mg per kWh	9.69E+03	6.17E+02	2.81E+03	2.65E+01	2.96E+02	-3.46E+03	9.98E+03
Organic emissions to air (group VOC)	mg per kWh	1.74E+01	2.27E+00	1.37E+00	5.43E-01	4.63E-01	-7.19E+00	1.48E+01
Methane	mg per kWh	1.38E+01	2.06E+00	1.13E+00	3.59E-01	3.48E-01	-6.96E+00	1.07E+01
Other emissions to air	mg per kWh	1.17E+04	8.21E+02	8.84E+02	2.29E+01	3.26E+02	1.64E+03	1.54E+04

Clean gas	mg per kWh	1.18E+01	7.95E-01	4.33E-01	1.04E-01	2.10E-01	8.74E-02	1.34E+01
Exhaust	mg per kWh	9.89E+03	6.22E+02	8.57E+02	2.01E+01	2.45E+02	1.65E+03	1.33E+04
Unused primary energy from solar energy	mg per kWh	1.05E+03	1.23E+02	1.40E+01	2.42E+00	4.36E+01	-1.91E+00	1.23E+03
Used air	mg per kWh	7.71E+02	7.54E+01	1.33E+01	2.41E-01	3.68E+01	-1.74E+01	8.80E+02
Particles to air	mg per kWh	4.81E+00	7.46E-01	1.89E-01	4.53E-02	1.19E-01	-2.21E+00	3.70E+00
Emissions to fresh water	mg per kWh	4.09E+06	2.74E+05	2.15E+06	1.32E+04	1.20E+05	-3.52E+06	3.12E+06
Analytical measures to fresh water	mg per kWh	5.07E+00	2.59E-01	1.80E-01	1.73E-02	9.67E-02	-3.08E-01	5.31E+00
Chemical oxygen demand	mg per kWh	3.64E+00	2.07E-01	1.06E-01	1.58E-02	7.97E-02	-1.21E-01	3.93E+00
Inorganic emissions to fresh water	mg per kWh	1.18E+02	6.77E+00	2.50E+00	9.45E+00	4.18E+00	-1.25E+01	1.28E+02
Chloride	mg per kWh	5.01E+01	5.64E+00	1.65E+00	9.23E+00	3.44E+00	-1.07E+01	5.94E+01
Sodium (+I)	mg per kWh	7.33E+00	3.08E-01	3.09E-01	7.59E-03	1.69E-01	-1.09E+00	7.03E+00
Sodium chloride (rock salt)	mg per kWh	2.35E+01	3.07E-05	5.26E-02	5.33E-07	2.83E-01	-2.21E-07	2.38E+01
Sodium sulphate	mg per kWh	2.54E+01	2.05E-03	2.60E-04	5.13E-05	2.64E-03	-9.55E-05	2.54E+01
Sulphate	mg per kWh	3.28E+00	1.63E-01	2.67E-01	6.08E-02	1.21E-01	-5.37E-01	3.35E+00
Other emissions to fresh water	mg per kWh	3.98E+06	2.74E+05	2.13E+06	1.27E+04	1.18E+05	-3.58E+06	2.94E+06
Waste water	mg per kWh	1.09E+04	3.20E+03	2.14E+00	1.40E-12	1.22E+02	-7.23E+03	6.97E+03

Water (river water from technosphere, rain water)	mg per kWh	3.89E+01	1.24E+02	1.64E+00	1.86E+01	2.10E+00	1.82E+02	3.67E+02
Particles to fresh water	mg per kWh	1.07E+01	1.64E+00	3.40E-01	6.72E-01	3.47E-01	4.40E-01	1.41E+01
Soil loss by erosion into water	mg per kWh	6.43E+00	1.31E+00	1.22E-01	4.46E-01	2.37E-01	-1.33E-01	8.41E+00
Solids (suspended)	mg per kWh	4.23E+00	3.29E-01	2.17E-01	2.26E-01	1.09E-01	5.74E-01	5.69E+00
Radioactive emissions to fresh water	mg per kWh	1.07E+05	-3.37E+02	1.63E+04	4.51E+02	2.37E+03	6.09E+04	1.87E+05
Radium (Ra226)	mg per kWh	1.07E+05	-3.37E+02	1.63E+04	4.51E+02	2.37E+03	6.09E+04	1.87E+05
Emissions to sea water	mg per kWh	4.76E+03	2.74E+02	4.51E+02	4.31E+01	1.12E+02	-1.01E+02	5.54E+03
Inorganic emissions to sea water	mg per kWh	1.01E+01	7.55E-01	5.67E-01	2.71E+00	8.22E-01	4.99E-01	1.55E+01
Chloride	mg per kWh	9.91E+00	7.38E-01	5.51E-01	2.65E+00	8.05E-01	4.96E-01	1.51E+01
Other emissions to sea water	mg per kWh	4.75E+03	2.73E+02	4.50E+02	4.03E+01	1.11E+02	-1.01E+02	5.52E+03
Waste water	mg per kWh	3.03E+01	2.16E-02	0.00E+00	0.00E+00	1.91E-02	0.00E+00	3.03E+01
Water (sea water from technosphere, cooling water)	mg per kWh	4.66E+03	2.73E+02	4.06E+02	3.95E+01	1.10E+02	-2.88E+01	5.46E+03
Water (sea water from technosphere, waste water)	mg per kWh	6.07E+01	6.87E-01	4.45E+01	8.06E-01	1.13E+00	-7.24E+01	3.53E+01

Annex H Description of new LCA baseline

Annex H presents the new benchmark for evaluating the environmental performance of the wind power plant, which aims both to reflect more accurately and transparently the wind plant performance, for current and future designs, and to align more consistently the wind turbine configuration and product offering from a commercial and market perspective, with the following overall updates and changes:

- results determined per IEC wind class according to the IEC definitions;
- changes to the turbine configuration (e.g. tip height restriction and tower height) to align more closely with market requirements;
- results based on latest datasets and environmental impact methods; and
- consistent application of LCA assumptions (e.g. system boundary, etc).

By developing a new baseline for evaluating environmental results it is intended that current and future product designs may be assessed in a more consistent, reliable and transparent manner, that sets the benchmark for the environmental evaluation of wind power from a life cycle assessment perspective.

The environmental results presented in the main body of this report follow the approach described in Annex H, which is described in order to give better understanding and details for the reader.

H.1 Performance according to IEC standards per wind class

As previously mentioned in the main body of the report (Section 1.2.3), a wind turbine is designed to meet different functional requirements for both onshore and offshore environments, as well as the wind class for which they are designed to operate within. Any comparisons in performance should only be made within the same wind class.

H.1.1 Benchmark wind class

Overall, the wind class (i.e. high wind, medium wind and low wind) determines which turbine is suitable for a particular site, and also influences the total electricity output of the wind power plant as well as turbine design.

Nonetheless, the wind class according to the IEC standards is divided into further categories and relates to the following parameters (according to the IEC 61400-1):

- annual average wind speed (i.e. high, medium and low wind);
- turbulence class (e.g. denoted by letter A, B or C); and
- extreme 50-year gusts and extreme 1-year gusts.

The *annual average wind speed* directly influences turbine loading and the total power production.

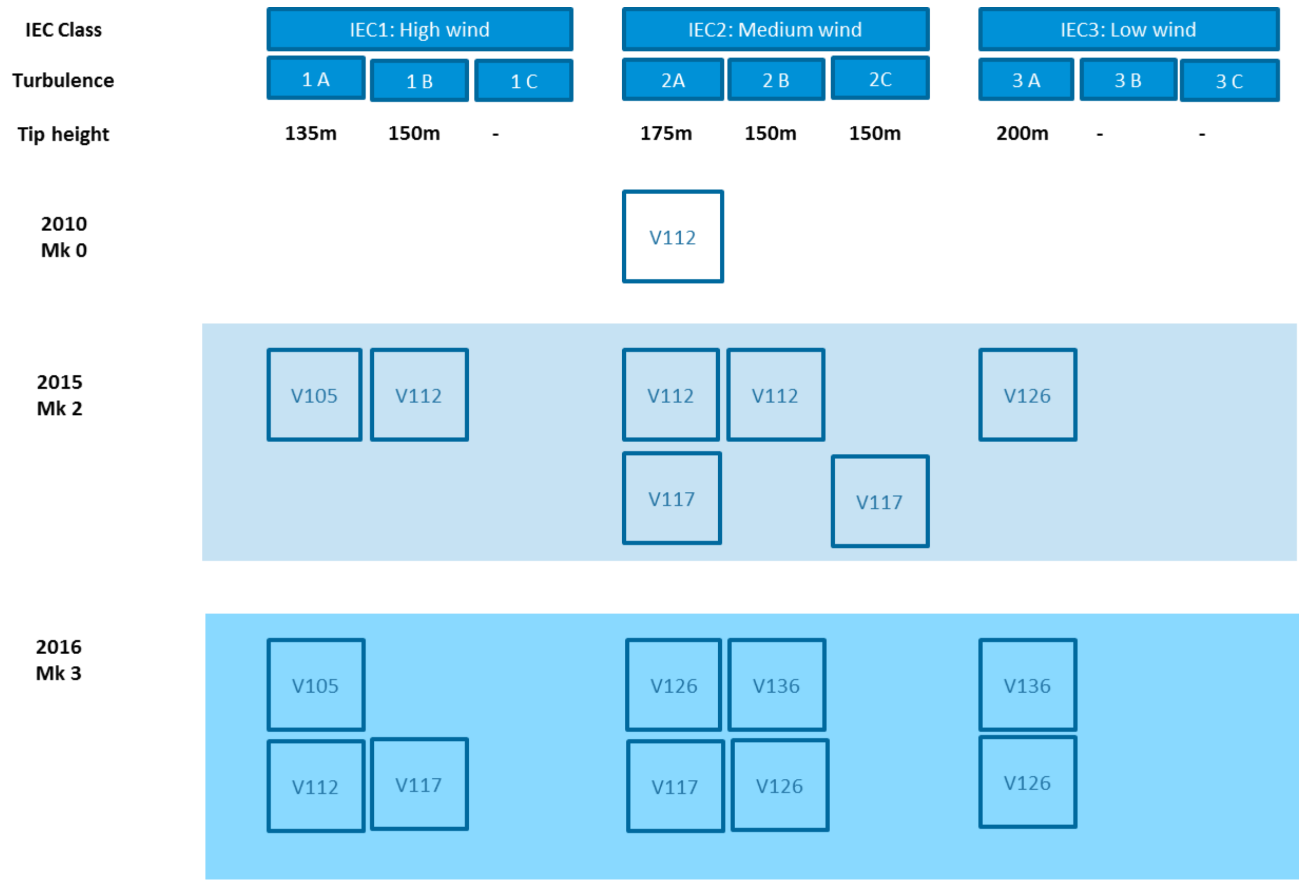
Secondly, the *turbulence class* defines the standard deviation of the wind speed, where class A represents the highest wind turbulence. The turbine is designed to correspond with the defined turbulence intensity. From a product design perspective, all the components within turbine are designed to operate in the defined class (e.g. IEC1A, 2A and 3A). The design wind class drives the design of the turbine, which will therefore vary across wind classes (e.g. turbines designed for high wind classes often has shorter blades and towers and turbines in low wind classes to provide the best fit to the wind conditions). Specific designs for lower turbulence classes for both the towers and foundations are often introduced to ensure savings in terms of material weight due to lower tower and foundation loads. For instance, a tower designed to meet IEC2B versus IEC2A may save over 15% in weight of structural steel of the tower and deliver similar benefits for the foundation.

Thirdly, the IEC standard also defines the *extreme wind speed* which is used to define the extreme loads a turbine may experience under these conditions. According to the IEC standards, the extreme wind speeds are defined with the wind conditions corresponding to a 50 year recurrence. The extreme loading will affect design of certain components (e.g. tower design).

Functionally the turbine is designed and selected to meet the defined wind class, which therefore governs the basis to compare performance on an equal basis.

From a product design perspective, the turbine is developed to adapt to changing market needs and to improve their competitiveness. This is illustrated in Figure H1, for example, where the Mark 0 V112-3.0 MW turbine was originally designed for medium wind conditions in turbulence class A (IEC2A), but has since developed to the Mark 2 variant of the V112 turbine which is designed to operate in IEC1B and IEC2B, while the V112 also operates in medium wind class as an IEC2A product. Therefore, performance comparisons should not be made on a product by product basis, but be made at the same *average wind speed* and *turbulence class* for a fair comparison.

Figure H1: Benchmark by wind class and turbulence (using example configurations)



H.1.2 Annual energy production

When considering annual energy production, then the *annual average wind speed* directly influences the total power production of the turbine. The average wind speed is determined by the wind speed distribution, defined as a Weibull distribution with a scale and shape factor. The wind shape factor is a measure of the wind speed distribution and is defined as 2.0 in the IEC standards, but may normally range from around 2.0 to 2.5 for a typical site; although in extreme cases could be higher or lower. A higher shape factor will tend to increase energy production at the same wind speed (at higher wind speeds) and therefore needs to be defined consistently when determining and comparing turbine annual energy production. The turbulence class and extreme loads do not affect annual energy production. Another important parameter to be considered is the *air density*.

The air density will also influence the annual energy production, where a lower air density will lead to a lower energy production. Air density may vary dependent on site location, mainly related to wind plant altitude or average climatic temperatures. A typical air density is assumed as 1.225 kg/m^3 (IEC recommended value), as in the current LCAs.

The performance of a Vestas turbine, when commercially offered for sale, is normally specified at standard operating conditions according to the IEC standard definitions. In previous LCA studies the LCA assumptions did not always fully align with the IEC standard for determining annual energy production. Therefore the new benchmark for the present and future LCAs will align with the IEC standards, as shown in Table H1.

Table H1: Annual energy production

Parameter	**Previous baseline**	**New baseline**	**Effect on turbine design and annual energy production**
Annual average wind speed	Assumed as mid-point of wind class: High: 9.25 m/s Medium: 8.0 m/s Low: 7.0 m/s	Defined by IEC: High: 10.0 m/s Medium: 8.5 m/s Low: 7.5 m/s	Increases AEP. No change to turbine design.
Extreme 50-year gust	As defined by IEC: High: 70 m/s Medium: 59.5 m/s Low: 52.5 m/s	No change.	No change.
Turbulence class	Only turbulence class A assessed.	Defined by IEC: Turbulence class A, B, C included where applicable.	Reduced material requirements with reduced turbulence class.
Shape factor	Assumed to be 2.3	Defined by IEC as 2.0.	Reduces AEP.
Air density	Assumed to be 1.225 kg/m^3.	No change.	No change. No change to turbine design.
Energy production losses	Electrical: 2.5% Wake: 6.0% Availability: 3.0%	No change except for availability losses are 2% in 2016.	Increases AEP. No change to turbine design.

International Electrotechnical Commission standard (IEC)

H.2 Wind plant configuration

In order to make a more reliable evaluation of wind plant performance it is necessary to define a consistent wind turbine configuration and wind plant layout to allow fairer and transparent comparisons to be made. Section H.2 identifies the general parameters that affect turbine configuration and plant layout.

As defined in the Goal and Scope of the life cycle assessment, the wind plant layout includes all major components needed to construct a wind plant including: turbines, foundations, site cabling, site transformer and grid connection, but excludes transmission and distribution. All life cycle stages are included for raw materials, production, assembly, transport, site setup, site operation and maintenance, decommissioning and recycling and disposal.

H.2.1 Turbine configuration

When a new turbine platform is designed, generally a modular design approach is applied, which allows different turbine configurations and performance to be specified. For example, typical variations in configuration may include:

- rotor diameter (i.e. blade length);
- generator rating (MW);
- gearbox rating (torque, kNm);
- tower height (hub height in metres);
- foundation type (high- or low-ground water level); and
- optional extras (e.g. option kits), etc.

In general, previous Vestas life cycle assessments aim to select a typical turbine configuration and geographical region of high sales in order to make a representative evaluation of a typical wind plant layout. This is also the case for the new benchmark. For defining the tower configuration for each turbine, market specific requirements on the maximum tip height for the turbine is used. Thus, in the new benchmark, where relevant, a tip height restriction should be used to define the rotor/tower configuration when comparing different turbines in the same wind class. Refer to Table H2 for a summary of turbine configuration by wind class. Additionally, sensitivity analysis should be used for alternative hub heights and turbine configurations, where relevant.

Table H2: Turbine configuration

Parameter	Previous baseline	New baseline	Effect on performance
Tip height restriction	No direct consideration for tip height restriction in current baseline.	The new benchmark should align with market requirements for tip height restriction. For example, in high wind turbulence A (IEC1A) a tip height restriction of 135m or 150m may exist in certain regions.	The benchmark configuration will more closely align with market requirements.
Tower height	Based on typical turbine configuration and estimated highest annual sales.	Based on above tip height restriction, where relevant. Otherwise, no change.	The benchmark configuration will more closely align with market

			requirements.
Foundation type	Low ground water level foundation represents typical plant layout, with high ground water level as sensitivity.	No change.	No change.

H.2.2 Wind plant layout

The layout of a wind plant will vary from site to site and depend on the site specific conditions, plant requirements and the local topology, etc. As such, to make more reliable evaluation and fairer comparison of wind plant performance it is necessary to define a more standardised plant layout, as described in Table H4. In general, previous LCAs of Vestas wind turbines have assumed a relatively standard plant layout, however, this section aims to make this more transparent in terms of what parameters are considered. These include physical dimensions of the wind plant, plant location and lifetime of plant equipment and turbine.

Table H3 gives an indication of the global warming potential of various wind plant components, indicating their relative importance. Also, when also considering impacts per kWh, then other very important parameters are the turbine lifetime, electrical losses, wake losses and wind plant availability, which are not shown in Table H3, but contribute significantly to overall performance. For example, total losses account for around 10% of total plant energy production, while to impacts per kWh are directly proportional to plant lifetime , for instance, by extending plant lifetime by 10% will improve performance per kWh by around 10%.

Table H3: Contribution to global warming potential by wind plant component

Component	**Global warming potential impacts (percentage)**
Blades	15% to 25%
Tower	20% to 30%
Foundation	10% to 15%
Nacelle	10% to 15%
Gear and mainshaft	~10%
Hub	~5%
Replacement parts and servicing	~5%
Site cables	~5% to 10%
Switchgears	~1%
Installation	~1%
Decommissioning	~1%
Cooler top	~1%
Site transformer	~1%

Note: percentages include whole-life impacts of raw materials, manufacture, transport, service and disposal.

Table H4: Wind plant layout

Parameter	Previous baseline	New baseline	Effect on performance
MW rating of total plant	Based on a typical plant size of the specific turbine. Typically total plant size is in the range of 50MW to 100MW.	No change.	No change.
Number of turbines per plant	Defined by total MW rating of the plant and turbine rating.	No change.	No change.
Plant location	Based on typical markets where the turbine is sold. Other plants locations are included as sensitivity analysis to test potential alternative transport scenarios.	No change.	No change.
Turbine lifetime	The lifetime should reflect the actual design life of the turbine. Typically design life is 20 years or more. This factor is extremely important when assessing impacts per kWh.	No change.	No change.
Repaired and replacement part lifetime	The lifetime should reflect the actual design life or failure rate of the component. Typically this relates to the gearbox, generator, yaw and blades.	No change.	No change.
Plant equipment lifetime	The lifetime should reflect the actual life of the plant component. Typically this relates to the site cables, transformer station and switchgears. Typically this is estimated to be in the range of 20 to 50 years.	No change.	No change.
Cable connection plant to grid (exit cable)	Typically 20km from plant to grid connection is assumed using 110kV PEX cables with aluminium conductor (630mm^2) and associated 2.5% electrical loss. Longer and shorter distances (10km with1.5% loss and 40km with 3.5% loss) are tested in sensitivity analysis.	No change.	No change.
Transformer station rating	The MVA rating of the transformer is governed by MW rating of the wind plant.	No change.	No change.
Cables connecting turbines (array cables)	Assumed an average of 1 km of 33 kV PEX cables per turbine with aluminium conductor. Cable length consists of various cables of 95mm2 (55%), 240mm2 (15%) and 400mm2 (30%).	No change.	No change.
Switchgears for site and turbine	Switchgears are included in the onsite equipment and turbine. Their specification accounts for typical rating, plant layout and number of panels.	No change.	No change.
Other electrical equipment	No further site equipment included in the LCA.	No change. But potentially this could be reviewed.	No change.
Electrical losses of plant	Electrical losses include losses for the turbine and complete plant with a	No change.	No change.

	20km grid cable, totalling an estimated 2.5%. Refer to Section 3.4.2 for details.		
Wake losses	Wake losses for plant size of 50MW to 100MW are estimated as 6.0%. Refer to Section 3.4.2 for details.	No change.	No change.
Plant availability	Wind plant availability is typically 97%. Refer to Section 3.4.2 for details.	No change. But as the fleet average plant availability improves with time, then this figure will also change.	No change.

H.3 Transport and supply chain

In general, the potential impacts of production from Vestas manufacturing should represent the year of production being assessed and for transport this should geographically represent the typical plant location, based on highest sales by region. The performance of Vestas production activities and the plant location will vary slightly from year to year depending on the specific supply chain and efficiencies. Additionally, Vestas has invested in its own wind power projects and retained credits to offset Vestas' own consumption of non-renewable electricity. These offsets are treated in sensitivity analysis.

As such, it would be valuable to update these data on an annual basis (or reasonable average) to represent year of operation. Table H5 presents a summary of transport and supply chain.

Table H5: Transport and supply chain

Parameter	Previous baseline	New baseline	Effect on performance
Transport distances	Based on a typical plant location in Europe (such as UK or Germany) and represents the supply chain setup for most recent year of turbine sale. Other plant locations are included as sensitivity analysis to test potential alternative transport scenarios. Refer to Section 3.4.8.	Regular update is required to represent year of operation and typical plant location.	The benchmark will more closely align with actual supply chain performance.
Transport emission factors	Transport reflects component-specific emissions and vehicle utilisation based on actual data for transporting blades, nacelle and towers by road and ship.	No change.	No change.
Vestas operations	Based on Vestas reported data for all global production units and business functions (such as sales), consisting of over 100 sites. This accounts for material, energy and fuel inputs, as well as product outputs, wastes and recycled materials. Data should represent most recent year of operations.	Should be assessed for representativeness and updated on a regular basis for year of operation.	The benchmark will more closely align with actual supply chain performance.
Vestas owned wind plants	Purchase of carbon dioxide credits is based on most recent year of operation and these offsets are included as a sensitivity analysis.	No change.	No change.

H.4 Installation and Servicing

The activities included to install the turbines and plant equipment include the usage of cranes, onsite vehicles, diggers and generators. Servicing and plant operation includes activities for: transport of staff; replacement of oil and filters; and replacement of major components, due to wear and tear. Table H6 presents a summary of Installation and servicing.

Table H6: Transport and supply chain

Parameter	Previous baseline	New baseline	Effect on performance
Installation activities	Installation impacts are based on typical impacts for these activities.	No change. But potentially this could be reviewed.	No change.
Service transport	Transport impacts are based on typical service vehicle, service frequency and distance driven.	No change. But potentially this could be reviewed.	No change.
Repaired and replacement parts and servicing	The replacement rate of components is based on specific turbine type and design.	The new baseline also now accounts for major components that are repaired.	No change.

H.5 Decommissioning and End-of-life treatment

The end-of-life treatment of materials includes options for: recycling; incineration with energy recovery; component reuse; and deposition to landfill. The LCA model for disposal accounts for specific recycling rates of different components, depending on their material purity and ease of disassembly, based upon industry data. Additionally, sulphur hexafluoride (SF_6) gas is collected and reclaimed from switchgears to assure the safe disposal. Table H7 shows the specific recycling and disposal rates for all components and materials.

Table H7: End-of-life treatment

Component	Previous baseline	New baseline	Effect on performance
Decommissioning activities	Installation impacts are based on typical impacts for these activities.	No change. But potentially this could be reviewed.	No change.
Large metal components that are primarily mono-material e.g. tower sections, cast iron frame in nacelle, etc (metal composition only).	Disposal efficiency based on nacelle disassembly study and GaBi processes for metal recycling losses. Turbine dismantling efficiency is: • 98% recycled • 2% landfilled	Should be assessed for representativeness and updated for year of operation.	No change.
Other major components e.g. generator, gearbox and yaw system (metal composition only).	Disposal efficiency based on nacelle disassembly study and GaBi processes for metal recycling losses. Turbine dismantling efficiency is: • 95% recycled	Should be assessed for representativeness and updated for year of operation.	No change.

	• 5% landfilled		
Cables (metal composition only).	Disposal efficiency based on nacelle disassembly study and GaBi processes for metal recycling losses. Turbine dismantling efficiency is: • 95% recycled • 5% landfilled	Should be assessed for representativeness and updated for year of operation.	No change.
Foundations (metal composition only).	Disposal efficiency based on nacelle disassembly study and GaBi processes for metal recycling losses. Turbine dismantling efficiency is: • 92% recycled • 8% landfilled	Should be assessed for representativeness and updated for year of operation.	No change.
Remaining turbine components (metal composition only).	Disposal efficiency based on nacelle disassembly study and GaBi processes for metal recycling losses. Turbine dismantling efficiency is: • 92% recycled • 8% landfilled	Should be assessed for representativeness and updated for year of operation.	No change.
Polymers	Disposal efficiency based on assumed disposal as follows: • 0% recycled • 50% landfilled • 50% incinerated	Should be assessed for representativeness and updated on a regular basis for year of operation.	No change.
Lubricants	Disposal efficiency based on assumed disposal as follows: • 0% recycled • 0% landfilled • 100% incinerated (without credit for energy recovery)	Should be assessed for representativeness and updated for year of operation.	No change.
Sulphur hexafluoride (SF6) gas	Disposal efficiency based on industry data and assumed recycling rates. Turbine dismantling efficiency is: • 95% recycled • 5% release to air	No change.	No change.
All other materials (including concrete)	Disposal efficiency based on assumed disposal as follows: • 100% landfilled	Should be assessed for representativeness and updated for year of operation.	No change.
Method adopted for giving recycling credits	An ‘avoided impacts approach’ (or closed-loop) is adopted. This gives credit for end-of-life recycling and also assigns a burden to input scrap for raw materials. A ‘recycled-content’ approach is applied in sensitivity analysis.	No change.	No change.

H.6 Inventory datasets, impact methods and LCA assumptions

In order to maintain consistency with the most recent datasets and environmental impact assessment methods it is necessary to continually update the LCA models to utilise the most recent and scientifically valid data available. However, by constantly updating background datasets and impact methods, as well as other background assumptions, then this can cause complications when comparing wind turbine performance over a longer time period.

Thus, to determine how much a product has improved in environmental performance it is necessary to clearly distinguish between actual product improvements (e.g. which result from design optimisation and environmentally-led initiatives, for example), and those changes in performance led by data updates which cannot be attributed to product improvement.

Additionally, it is important that there is consistent application of assumptions when a LCA study is updated or knowledge of the product improves and is included in the assessments.

There are two examples where updating of data has caused an issue when making a comparison between old and new LCA studies:

- Life cycle inventory dataset updates: the original V112-3.0 MW (Mark 0) was conducted with GaBi (2006) datasets and since 2011 these datasets have been updated on an annual basis. However, in comparison to older 2006 datasets, for example, there were some significant changes relating to:
    - metal and cast iron production changed significantly in terms of the scrap input as part of the production dataset. For consistency in results, the original 2006 dataset for cast iron has been used in all subsequent LCA studies. However, the newer cast iron dataset has been used in this study as it is more representative temporally and technologically.
    - the assumptions relating to the accounting of water flows changed significantly whereby water inputs and outputs are aggregated, as well as inclusion of some nomenclature changes. This has had the effect to dramatically increase water consumption per kWh generated by the wind plant. In the current LCAs, adjustments have been made to remove both lake water and river water from the ‘non-impact’ indicator for water-use (refer to Section 5.3), as well as being removed from the complete power plant inventory, shown in Annex G. These adjustments aim to give consistency with previous LCAs using the 2006 GaBi databases, which reflect similar results as previous LCA studies.

In order to maintain consistency and fair comparison with previous results it is necessary to update the studies being compared to maintain the same assumptions, datasets and impact methods. As such, when new datasets and impact methods become available then these will be used, where possible, in the new benchmark.

In the current LCA, recyclability is a measure of the proportion of the turbine weight that can be usefully recycled at end-of-life. It measures the useful material output from recycling, accounting for the losses in dismantling and recycling/reuse activities.

A new indicator called *Product Waste* is introduced in this LCA which indicate the amount of material that is not recyclable (or reusable) at turbine end-of-life. The indicator is quantified as grams of (non-recyclable) material per kWh. It relates to the turbine-only. In relation to product improvement the indicator encourages more efficient utilisation of materials per kWh, as well as selection of more recyclable materials.

Table H8 shows a summary for the datasets, environmental impact methods and briefly indicates the other related assumptions for data collection and quality, etc.

Table H8: Datasets, impact methods and study quality

Parameter	Previous baseline	New baseline	Effect on performance
Life cycle inventory datasets	Utilises following: • GaBi 2014 datasets • Vestas production in 2012	The most recent and representative datasets should be used and updated for year of operation.	The benchmark will more closely align with actual supply chain performance.
Dataset selection	It is important that dataset selection being applied consistently across LCA studies. For example, that a cast and machined component received the correct raw material dataset and fabrication steps.	No change.	No change.
Impact assessment method	CML (2013)	Method ~~should be~~ updated to most recent version of CML. Additionally, results should be presented using the Product Environmental Footprint (EC, 2013).	The benchmark will more closely align with scientific best practice. Generally, changes from CML (2013) to CML (2016) have minor impact on results.
Impact assessment for water	Refer to Section 3.8 for details.	No change. The datasets for water accounting are not considered reliable and transparent in the GaBi inventory. Therefore a manual adjustment still exists in the new benchmark. However, this may be further investigated and reviewed.	No change.
Turbine recyclability	Refer to Section 5.3.4 for details.	This will be reported along with a new indicator for turbine *Product waste*	The benchmark will provide greater transparency and clarity.
Product waste	Refer to Section 5.3.5 for details.	Not used in previous LCAs. The new indicator supersedes Recyclability and was introduced to avoid the conflict Recyclability has with other impacts per kWh.	No change.
Return-on energy	Refer to Section 6 for details.	No change.	No change.
Data collection	Refer to Section 3.2.5 for details.	No change.	No change.
Data quality	Refer to Section 3.9 for details.	No change.	No change.
Allocation	Refer to Section 3.5 for details.	No change.	No change.
Cut-off criteria	Refer to Section 3.3 for details.	No change.	No change.

Review	An external review according to ISO14040 Section 6.2 shall be conducted for reports that are made public.	No change.	No change.

H.7 Product Environmental Footprint (2013) impact assessment

Section H.7 presents the impact assessment results for the V112-3.45 MW Mark 3 wind plant using the alternative LCIA method for Product Environmental Footprint (2013) impact recommendations. Tables H9 show the overall impact results by life cycle stage.

Table H9: Whole-life environmental impacts of V112-3.45 MW by life cycle stage (units shown in g, mg or MJ per kWh) using Product Environmental Footprint (2013) impact assessment

Impact category	Unit	Manufacture	Plant setup	Operation	End-of-life	V112-3.45 MW Mk3a: New benchmark
Acidification midpoint (v1.09)	Mole of H+ eq.	3.20E-02	5.53E-04	3.45E-04	-7.65E-03	2.53E-02
Ecotoxicity freshwater midpoint (v1.09)	CTUe	1.09E+00	4.00E-02	3.67E-02	-1.87E-02	1.15E+00
Eutrophication freshwater midpoint (v1.09)	mg P eq	1.59E-05	2.78E-07	4.19E-07	4.04E-06	2.06E-05
Human toxicity midpoint, cancer effects (v1.09)	CTUh	5.50E-08	1.91E-09	1.37E-09	1.67E-10	5.84E-08
Human toxicity midpoint, non-cancer effects (v1.09)	CTUh	4.21E-07	9.54E-09	9.48E-09	5.70E-09	4.46E-07
Ionizing radiation midpoint, human health (v1.09)	kg U235 eq	2.16E-01	9.15E-04	5.09E-03	-3.09E-03	2.19E-01
Climate change midpoint, excl biogenic carbon (v1.09)	g CO2-Equiv.	7.47E+00	7.51E-02	9.57E-02	-2.40E+00	5.24E+00
Climate change midpoint, incl biogenic carbon (v1.09)	g CO2-Equiv.	7.47E+00	7.37E-02	9.51E-02	-2.39E+00	5.24E+00
Eutrophication marine midpoint (v1.09)	mg N-Equiv.	6.56E-03	1.89E-04	7.69E-05	-5.73E-04	6.25E-03
Ozone depletion midpoint (v1.09)	kg CFC-11 eq	2.86E-08	1.45E-12	6.37E-10	5.79E-08	8.71E-08
Particulate matter/Respiratory inorganics midpoint	kg PM2,5-Equiv.	2.81E-03	1.62E-05	6.70E-05	-4.22E-04	2.47E-03
Photochemical ozone formation midpoint, human health (v1.09)	kg NMVOC	2.20E-02	5.78E-04	2.65E-04	-4.32E-03	1.85E-02
Resource depletion, mineral, fossils and renewables, midpoint (v1.09)	kg Sb-Equiv.	5.94E-04	7.53E-08	2.19E-05	-1.61E-04	4.54E-04
Eutrophication terrestrial midpoint (v1.09)	Mole of N eq.	7.17E-02	2.06E-03	8.07E-04	-9.63E-03	6.49E-02
Resource depletion water, midpoint (v1.09)	kg	1.23E-02	5.50E-05	3.90E-04	-1.22E-03	1.15E-02

Annex J. Benchmarking of V112-3.45 MW (Mk3)

Annex J presents the results of the V112-3.45 MW (Mark 3a) turbine in context with the previous Mark 2c turbine operating in high wind class (IEC1A), which, in this case, relates to the V105-3.3 MW (Mark 2c).

The purpose of including Annex J is to demonstrate product design improvements, per IEC wind class, as Vestas develops new and optimised wind turbines and value chains.

As part of Vestas' Sustainability strategy, global product environmental improvement targets have been set for the period 2016 to 2020, as follows:

- 'CO₂ footprint' reduction of -5%
    - Baseline: 6.9 grams CO_2 per kWh
    - Period: 5 year target from 2016 to 2020
    - Update frequency: aligned with turbine mark release schedule

- 'Product Waste' reduction of -3%
    - Baseline: 0.20 grams Waste per kWh
    - Frequency: 5 year target from 2016 to 2020
    - Update frequency: aligned with turbine mark release schedule

The targets are based on average weighting by wind class for low, medium and high wind, as depicted in Figure J1 below, which shows the turbine configurations by hub height and wind class. The configurations and results are established according to the description in Annex H.

Figure J1: 3MW platform benchmark by wind class, hub height and turbine type

	IEC1a	IEC2a	IEC3a
Tip height	150m	175/180m	200m
HH **Mk2c**	V105 97,5	V117 116,5	V126 137
Mk3a/b	V112 94	V126 117	V136 132

J.1 Wind plant specification (IEC1A)

Table J1 outlines the wind plant specification assessed for the benchmark performance for high wind (IEC1A) for the Mk3a and Mk2c turbines.

Table J1: Wind plant specification for benchmark in IEC1A

Description	Unit	V112	V105
Mark version	-	Mk3a	Mk2c
Wind climate for target setting	-	High IEC1A	High IEC1A
Lifetime	years	20	20
Nominal rating	MW	3.45	3.3
Generator type	-	Induction	Induction
Turbines per power plant	pieces	29	30
Plant output	MW	100	100
Tip height	m	150	150
Hub height	m	94	97.5
Rotor diameter	m	112	105
Wind class [brackets show other wind classes available but not used for baseline results]	-	IEC1A	IEC1A
Tower type	-	Standard	Standard
Foundation type		LGWL	LGWL
Production @ 7.5 m/s, k=2.0* [at 100% without losses]	MWh pa	-	-
Production @ 8.5 m/s, k=2.0* [at 100% without losses]	MWh pa	-	-
Production @ 10.0 m/s, k=2.0* [at 100% without losses]	MWh pa	15725 [17508]	14268 [16049]
Grid distance	km	20	20
Plant location	-	Europe	Europe
Vestas production location	-	Global	Global
Project transport	-	Global	Global

Note: The above figures for electricity production include all losses, assuming and availability of 98%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

** The V105 hub height at 97.5m is not a tower for sale, but was created for the purpose of target setting, in order to maintain tip height with the Mk3a platform and future potential turbines.*

J.1 Benchmark results

When benchmarking performance it is important to distinguish between updates relating to data (which cannot be counted as product improvements), such as background dataset changes, and updates that are driven from design, such as design optimisation or increased turbine energy production. As mentioned, in Section 1.2.3 when benchmarking a wind turbine performance from turbine to another it is important that this is made on an equivalent functional basis, and should only be compared within the same wind class. Hence, the benchmark results presented here compare equivalent turbines within the IEC1A wind class for the Mk3a.

Table J2 provides the benchmark results for the following two indicators:

- *$CO_{2\text{-}e}$ Footprint* (g CO2-e per kWh)
- *Product waste* (g waste per kWh)

The results indicate the performance improvement of 3MW Mk3a has improved 7.2% for *CO_2-e Footprint* and 10.9% for *Product waste*. The primary reason for improvement is due to increased generator rating from 3.3MW to 3.45MW, as well as the wind turbine increasing in wind class with a larger rotor diameter. This has significantly increased turbine energy production. Additionally, the 3MW Mk3a turbines have further optimised design which results in reduced material consumption per kWh, within the wind class.

In order to distinguish between data and model changes versus product design changes, the previous LCA model was compared to the current model for changes to individual turbine modules (or main assemblies), such as the rotor and blade assembly, tower, foundation, powertrain, etc . The design changes were identified in terms of material type, weight and production process differences, as well as differences to turbine energy production. The remaining changes were identified which relate to updates to data and cannot be counted as design improvements, for example, material production inventories, transport assumptions and others, such as changes to LCIA characterisation factors. These were aggregated to both turbine and wind-plant level to identify overall improvements that were due to design and due to data changes.

Table J2: Benchmark results for IEC1A wind class

Description	**Unit**	**High**	**Improvement**
IEC climate	-	IEC1A	
Turbine	-	Baseline: V105 Update: V112	
Tip height	m	150	
Carbon footprint (grams CO_2-e per kWh)			
	2016 baseline	5.91	
	2017 update	5.26	
	Design improvements	-0.43	
	Data change	-0.22	
	% design improvement versus 2016 baseline		**-7.2%**
Product waste (grams waste per kWh)			
	2016 baseline	0.18	
	2017 update	0.16	
	Design improvements	-0.02	
	Data change	0.00	
	% design improvement versus 2016 baseline		**-10.9%**

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