Authors Olatz Martinez Aguado, Peter Garrett - Version 1.2 - Date 15.01.2025

Life Cycle Assessment

Of electricity production from an onshore V163-4.5 MW™ wind plant

Wind. It means the world to us.™

Key Sustainability Figures
V163-4.5 MW™

Wind plant specifications

Wind turbine model	V163-4.5 MW™
Power rating	4.5 MW
Lifetime	20 years
Hub height	98 metres
Wind Class	IEC S
Wind Speed	7.9 m/s
Annual Energy Production	22032 MWh
Foundation type	Low ground water level (LGWL)
Plant size	99 MW
Plant location	United States
Production location	Global average

Wind plant key figures

Wind plant carbon footprint (Global Warming Potential)

5.09

gCO2 e/kWh

Wind plant return on energy

39

Times

Wind plant return on energy

6

Months

Wind turbine key figures

Wind turbine carbon footprint per MW

374

tCO2 e/MW

Wind turbine recyclability of desgined 'as-built' turbine

98.5%

Percent of weight

Wind turbine recyclability after disassembly

98.1%

Percent of weight

Wind turbine recyclability after recycling treatment

94.6% to 85.3%

Percent of weight

For further details of the recyclability definitions refer to Section 5.3.5 and Annex A.4.

Note: actual recycling rates may vary, when considering project specific factors and regional waste management practices, which may lead to lower "real world" recyclability.

Wind turbine material breakdown

84.3%

Steel and iron materials

7.0%

Glass and carbon composites

5.6%

Polymer materials

1.1%

Electronics / electrics

0.9%

Aluminium and alloys

0.6%

Copper and alloys

0.4%

Lubricant and fluids

0.05%

Not specified

For detailed information refer to the corresponding LCA on vestas.com

Environmental Impact Summary

V163-4.5 MW™

The table presents the total potential environmental impacts associated with an onshore 100 MW wind power plant of V163-4.5 MW turbines, covering the entire power plant over the life cycle.

Whole-life environmental impacts of V163-4.5 MW by life cycle stage

Impact category	Unit	Total	Description
CML-impact indicators*			
Abiotic resource depletion (ADP elements)	mg Sb-e	0.10	Indication of the potential depletion (or scarcity) of non-energetic natural resources (or elements) in the earth's crust.
Abiotic resource depletion (ADP fossils)	MJ	0.06	Measure of the potential depletion (or scarcity) of non-renewable resources (except for nuclear power resources) that are non-living.
Acidification potential (AP)	mg SO2-e	14	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.
Eutrophication potential (EP)	mg PO4-e	1.9	Measure of nutrient enrichment in aquatic or terrestrial environments, which leads to ecosystem damage to those locations from over-enrichment.
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38	Measures the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil.
Global warming potential (GWP)	g CO2-e	5.09	Measures the warming effect of the earth's surface due to the release of greenhouse gases into the atmosphere.
Human toxicity potential (HTP)	mg DCB-e	1481	Measures the impact on humans, as a result of emissions of toxic substances to air, water and soil.
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	533	Measures the impact on marine water ecosystems, as a result of emissions of toxic substances to air, water and soil.
Photochemical oxidant creation potential (POCP)	mg Ethene	1.7	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.
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	30	Measures the impact on terrestrial ecosystems, as a result of emissions of toxic substances to air, water and soil.
Non CML-impact indicators			
Primary energy from renewable raw materials [1]	MJ	0.02	Provides a measure of the quantity of renewable energy consumed from hydropower, wind power, solar energy and biomass.
Primary energy from resources[2]	MJ	0.07	Provides a measure of the consumption of non-renewable energy over the life cycle, for example, from coal, oil, gas and nuclear energy.
AWARE water scarcity footprint[3]	g	Not assessed	Determines the water scarcity footprint based on available water remaining per unit area of watershed relative to the world average after water demand for human and aquatic ecosystems.
Blue water consumption	g	Not assessed	Indication of the net balance of water inputs and outputs of freshwater throughout the life cycle of the power plant.
Turbine circularity (not life cycle based, turbine only)[4]	Score range from 0 to 1. 1=max Circularity	0.66 to 0.70	Indicates 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).

[1] CML impact assessment method Version 2016

[2] Net calorific value

[3] Based on WUCLA model for water scarcity footprint that assesses available water remaining water (Boulay, 2018)

[4] Follows approach of Ellen Mc Arthur Foundation (EMF, 2015) with Granta Design and co-funded by LIFE, European Union's financial instrument. This scope is consistent with turbine Recyclability indicators (for details refer to Section 5.3.5 and Annex A.4).

Life Cycle Assessment of Electricity Production from an onshore V163-4.5 MW Wind Plant

January 2025

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Reference: Vestas, (2025). Life Cycle Assessment of Electricity Production from an onshore V163-4.5 MW Wind Plant – 15th January 2025. Vestas Wind Systems A/S, Hedeager 42, Aarhus N, 8200, Denmark.

Critical review

Life Cycle Assessment of Electricity Production from an onshore V163-4.5 MW Wind Plant

Commissioned by:	Vestas Wind Systems A/S Aarhus, 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 14071 (2024): Environmental management — Life cycle assessment — Critical review processes and reviewer competencies

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 1.2 received on 15th January 2025.

The analysis and the verification of individual datasets and an assessment of the life cycle inventory (LCI) model as well as the Annex A.4 Recyclability 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 19.12.2024. The reviewer provided 35 comments of general, technical and editorial nature to the commissioner by the 24.12.2024.

The feedback provided and the agreements on the treatment of the review comments were adopted in the finalisation of the study. A comprehensively revised report was delivered to the reviewer on 10.01.2025. There were still two editorial issues to be revised. The final version of the report was provided on 15.01.2025. All critical issues were resolved 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 complete the process. 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 26,000 components representing over 99.9% of the total mass of materials of the power plant. 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 90,000 wind turbines around the world, which covers 18% of current worldwide installed wind capacity.

As a result, the report is deemed to be representative for the studied product. 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 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.

Prof. Dr. Matthias Finkbeiner

24th January 2025

Contents

Figures

Tables

Executive summary

The present Life cycle assessment (LCA) is the final reporting for the electricity produced from a 100 MW[1] onshore wind power plant composed of twenty-two Vestas V163-4.5MW Mk4A turbines. 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 (2024) and 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.

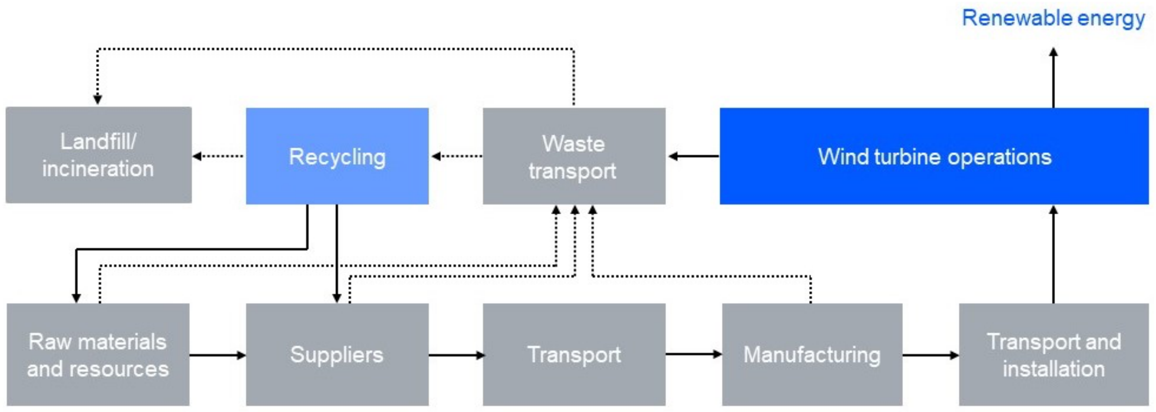
This LCA report presents the environmental performance of the latest V163-4.5MW turbine, which represents the serial-production model.

This LCA of the V163-4.5MW power plant has assessed the turbine's entire bill-of-materials accounting for around 26,600 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



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[1] See Table (page 17) for Turbine specification and wind plant details.

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	4.5
Generator type	-	Induction
Turbines per power plant	pieces	22
Plant size	MW	99*
Hub height	m	98
Rotor diameter	m	163
Wind class	-	Medium (IEC S)
Tower type	-	TST
Foundation type	-	Low ground water level (LGWL)
Production @7.9m/s	MWh per year	22032
Grid distance	km	20
Plant location	-	US**
Vestas production location	-	Global average

Note: The above figure for electricity production includes all losses, assuming an availability of 98.0%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

Note: IECS refers to “IEC Special” where the turbine is designed for special wind conditions for the low, medium or high IEC wind class. Refer to Annex E for further details of IEC wind classes.

** The plant size of 100MW is selected in this LCA to maintain consistency with previous LCAs. Furthermore, sales forecast for V163-4.5 turbines also indicates a similar average plant size (of around 100MW). To achieve nearest total power rating then 22 turbines of 4.5MW rating are selected, totalling to 99MW.*

*** US is the chosen plant location as this represents a significant market for the V163 turbine.*

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 100 MW 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 medium (IECS) wind conditions.

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[2].

The Vestas V163-4.5MW wind turbine has been designed to operate under medium (IECS) wind conditions and for this study, medium (IECS) wind conditions have been selected to evaluate environmental performance.

Environmental impacts

The table below presents the total potential environmental impacts of a 100 MW onshore wind power plant of V163-4.5MW 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, the operation & maintenance phase, and the plant setup phase to a lesser extent. Of production the foundations, tower, site cables, nacelle, and blades, contribute most significantly to all studied environmental impact indicators. Vestas factories contribute between <1% and 4% across all impact categories. Transport of the turbine components contributes between <1% and 14% across all impact categories, and 4% to the total global warming potential impacts[3].

Whole-life environmental impacts of V163-4.5MW plant (shown in g, mg or MJ per functional unit of 1kWh)

Environmental impact categories:	Unit	Quantity
Abiotic resource depletion (ADP elements)	mg Sb-e	0.10
Abiotic resource depletion (ADP fossils)	MJ	0.06
Acidification potential (AP)	mg SO2-e	14

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[2] 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, plant lifetime, etc.

[3] Transport refers to the aggregated impacts covering all transport stages in the life cycle, as far as they have been specifically modelled.

Eutrophication potential (EP)	mg PO4-e	1.9
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38
Global warming potential (GWP)	g CO2-e	5.1
Human toxicity potential (HTP)	mg DCB-e	1481
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	533
Photochemical oxidant creation potential (POCP)	mg Ethene	1.7
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	30

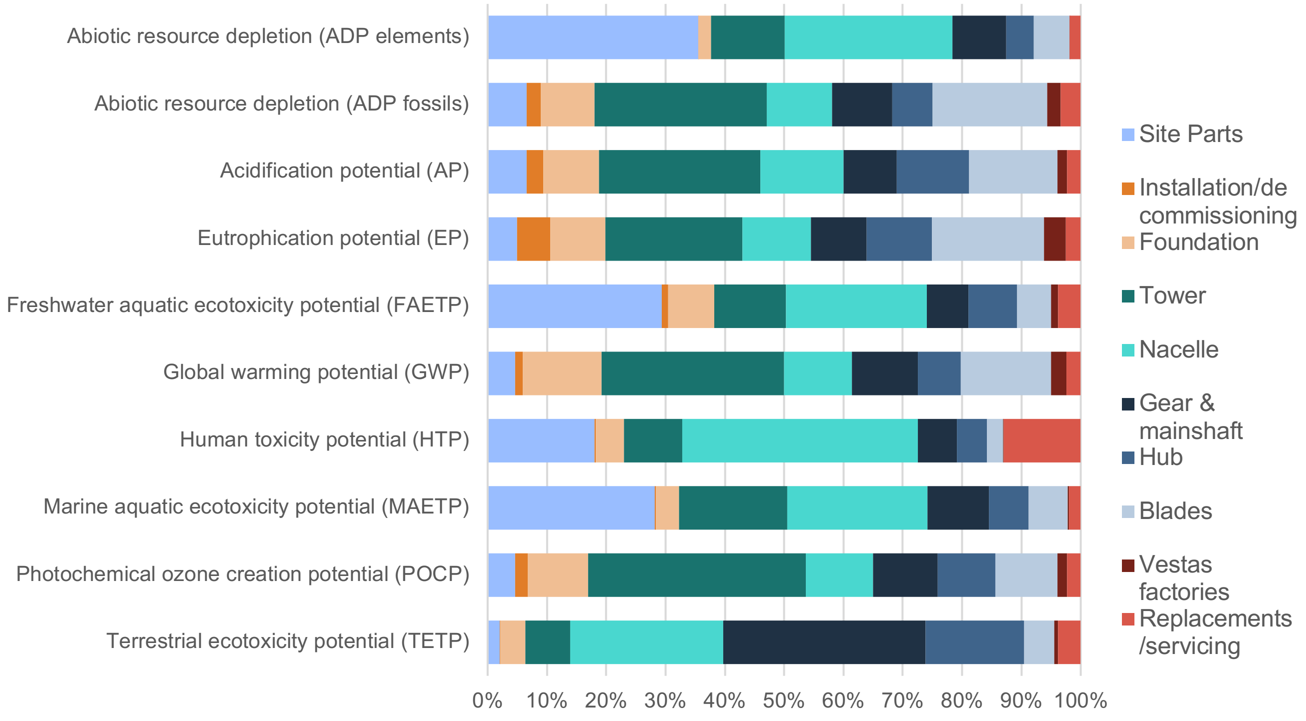
Note: impact indicators are based on CML impact assessment method Version 2016 (CML, 2016)

Increasingly Vestas customers and national authorities request a performance metric for total tonnes of CO_2-e per MW for a wind plant and wind turbine-only. For the V163-4.5MW, the results are the following over the full life cycle:

- Wind plant (full life cycle): 448 tonnes CO_2-e per MW
- Turbine only (full life cycle): 374 tonnes CO_2-e per MW

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

Production and use-phase environmental impacts of V163-4.5MW



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 100 MW wind power plant with the V163-4.5MW is 6.1 months for medium (IECS) wind conditions. This may be interpreted that over the life cycle of the V163-4.5MW wind power plant will return 39 times more energy back than it consumed over the plant life cycle.

The recyclability indicator represents the percentage mass of the wind turbine that is recyclable at end-of-life, considering recycling rates for the turbines components and material composition. For the V163-4.5MW LCA the recyclability method has been updated. In summary, the updated recyclability measure aims to provide greater transparency in measuring recyclability at each main stage of the of the end-of-life value-chain, as defined in this Section 5.3.5, with the final measure after EoL treatment being aligned with ISO 59000 series of standards for circular economy.

Additionally, a Material Circularity Indicator (MCI) provides a measure of the material flows of the turbine according to the circular economy method from the Ellen MacArthur Foundation (EMF, 2015). Refer to Section 5.3.6 for further description. For the V163-4.5MW turbine, this has been calculated between 0.66 and 0.70. This means that between 66% and 70% of the turbine product is managed according to the circular economy principles mentioned above, while 34% to 30% of the product has linear material flows.

It should be noted that non-impact indicators for water have been excluded due to an inconsistency in the dataset modelling for plate steel provided by worldsteel (2022) in the Sphera database (2024). As such, it has not been possible to evaluate the full life cycle results using the AWARE or Bluewater methods in the current LCA. These results are currently excluded from the report until further clarifications or dataset updates are completed.

Whole-life environmental indicators of V163-4.5MW (units shown in g or MJ per kWh)

Non-impact indicators:	Unit	Quantity
*Primary energy from renewable resources	MJ	0.02
*Primary energy from non-renewable resources	MJ	0.07
**AWARE water scarcity footprint	g	not assessed
Blue water consumption	g	not assessed
***Return-on energy	Number of times	39
****Turbine “Recyclability of designed ‘as-built’ turbine”	% (w/w)	98.5%
****Turbine Recyclability after disassembly”	% (w/w)	98.1%
****Turbine “Recyclability after recycling treatment”	% (w/w)	85.3 to 94.6%
*****Turbine circularity (not life cycle based, turbine only)	-	0.66 to 0.70

[*] *Net calorific value*
*** Based on WULCA model for water scarcity footprint that assesses available water remaining (Boulay, 2018)*
**** Based on 'Net energy' calculation defined in Section 6*
***** Rounded up or down to the nearest half percentage point and measure is* not life cycle based and turbine-only.
***** 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 onshore), and few turbines have ever been disposed, with some turbines reaching operational lives beyond their design lifetime, for other Vestas turbine models. Although variations occur, the design lifetime for this study of 20 years for a 'typical' plant, is considered reasonable. The sensitivity of this assumption is tested in the LCA.
- *Electricity production*: the electricity production per kWh is substantially affected 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 V163-4.5MW turbine assessed in this LCA is designed for the medium (IECS) wind class, which fairly reflects a 'typical' power plant.
- *Impacts of material production and recycling*: the turbine is constructed of around 85% 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). 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. 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 90,000 wind turbines around the world, correlating to over 185 GW total capacity. Vestas total installed capacity represented around 18 percent of the worldwide installed wind capacity in 2022 (GWEC, 2023a). 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. Most notably, there have been the following updates:

- The LCA reflects the complete bill-of-materials for the V163-4.5MW turbine;
- Vestas production data has been updated to reflect production in 2023;
- Environmental impact from Vestas employee air travel & accommodation globally has been included;
- Epoxy-infused blades are classified as 100% recyclable to reflect the latest development in technology related to the CETEC (Circular Economy for Thermosets Epoxy Composites) (Vestas, 2023b);
- LCA model updates use the latest Sphera LCA for Experts datasets updated to MLC Databases 2024.2 (Sphera, 2023).
- An updated recyclability method is applied to measure recyclability of the turbine at three stages in the end-of-life (EoL) value-chain and include all materials in the wind turbine (beyond metals-only which has been the scope considered in previous LCAs); and
- In alignment with the updated recyclability method, recycling credits at EoL are applied and adjusted, which are similar (in terms of percentage weight) compared to previous LCAs. However, in order to present conservative potential impact results, EoL crediting is only applied to metals, as in previous LCAs.

Conclusions and recommendations

Overall, the study represents a robust and detailed reflection of the potential environmental impacts of a 100 MW onshore wind power plant consisting of twenty-two V163-4.5MW 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 from considering the following:

- to assess the indicator for the AWARE water scarcity footprint and the indicator for ‘Blue water consumption;
- to include sensitivity analysis that reflect a wider range of scenarios, e.g. HGWL foundation, higher/lower distances to grid; and
- to account for crediting of blade raw materials at the end-of-life in baseline results scenario, which are currently excluded.

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
AWARE	Available water remaining
BOM	bill of materials
CML	Institute of environmental sciences (CML), Leiden University, The Netherlands.
CNC	computer numerical control
DCB	dichlorobenzene
DfX	DfX is a Sphera LCA for Experts 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
OEF	organisational environmental footprint
PCB	printed circuit board
PEF	product environmental footprint
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 substation) and site equipment (e.g. substation) 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.
WULCA	water use in life cycle assessment
w/w	weight for weight

1 Introduction

The present Life cycle assessment (LCA) is the final reporting for the electricity produced from a 100 MW[4] onshore wind power plant composed of twenty-two Vestas V163-4.5MW Mk4A 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 (2024) to assure the robustness and credibility of the results, conducted by Prof. Dr. Matthias Finkbeiner.

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.

This LCA report presents the environmental performance of the latest V163-4.5MW turbine.

The turbines are designed and 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 climate that it is operating within (i.e. low, medium or high wind conditions) is also a dominant factor.

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.

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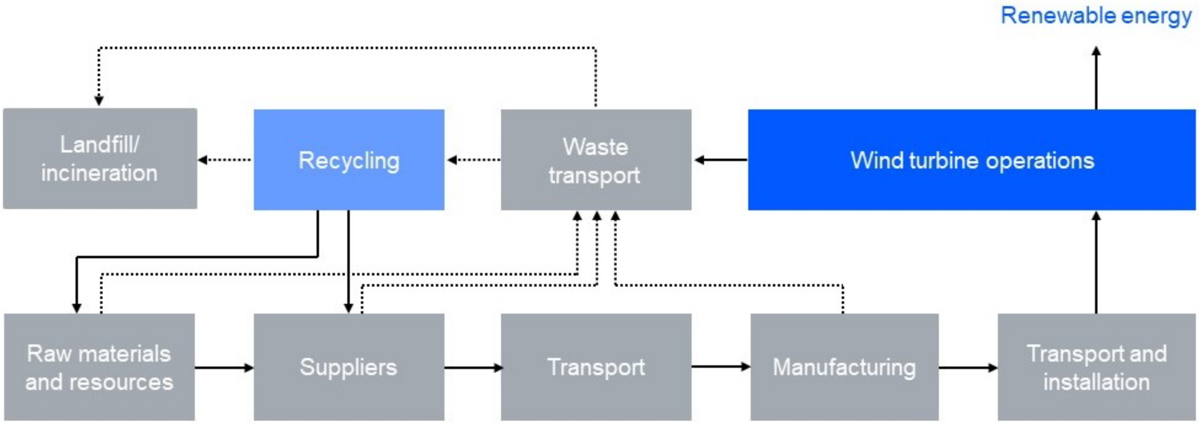
[4] See Table 1 (page 32) for Turbine specification and wind plant details.

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).

Environmental LCA is a comprehensive methodology to assess the environmental matters, nonetheless it requires additional environmental management techniques for a broader environmental understanding (e.g. noise and impacts on fauna), such as risk assessment, environmental performance evaluation and environmental impact assessment. Likewise, other tools may be used to address social and economic aspects which are not included in environmental LCA.

The LCA model has been developed in the Sphera LCA for Experts 10.9 software.

1.2.1 Goal and scope phase

In general terms, the goal and scope phase outline 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 Conditions for 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 climate 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).

If 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 and conditions 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 (i.e. for electricity delivered to grid).

1.2.4 Improvements

Several improvements were made in LCA for the V163-4.5MW, including:

Data improvements:

- *Sphera MLC Databases 2024.2* (including a software upgrade to LCA for Experts 10.9) are included as updates in the current LCAs. Overall, these updates cause relatively small increases or decreases in the inventory and impact assessment results.
- *Vestas production*: updates have been made to include Vestas production for year 2023 which represents production for the entire year. This includes energy use, raw materials, wastes, water and emissions but excludes consumables.
- *Turbine bill-of-materials*: the study assesses the latest turbine design for the V163-4.5MW, which includes all components within the turbine (i.e. around 26,600 lines in the product-tree).
- *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.

- *Turbine end-of-life*: During 2024, the recyclability of blades has been adjusted to reflect the latest development in technology related to the CETEC (Circular Economy for Thermosets Epoxy Composites – a novel chemical disassembly process that Vestas is currently focusing to scale up into a commercial solution), which Vestas spearheaded. This means that all epoxy-infused blades are classified as 100% recyclable, which increases the overall recyclability of the turbine (Vestas, 2023b).
- An updated recyclability method is applied to measure recyclability of the turbine at three stages in the end-of-life (EoL) value-chain and include all materials in the wind turbine (beyond metals-only which has been the scope considered in previous LCAs); and
- In alignment with the updated recyclability method, recycling credits at EoL are applied and adjusted, which are similar (in terms of percentage weight) compared to previous LCAs. However, in order to present conservative potential impact results, EoL crediting is only applied to metals, as in previous LCAs.

2 Goal of the study

The goal of this study is to evaluate the potential environmental impacts associated with production of electricity from a 100 MW onshore wind plant comprised of twenty-two (22) V163-4.5MW wind turbines from a life cycle perspective. A 100 MW plant represents a typical plant size for these turbines[5]. This assessment includes the production of raw materials, fabrication and assembly of the wind turbine by Vestas and its suppliers, site parts (e.g. sub-stations incl. transformers, switchgears, grid connections, cabling, etc.), use-phase repair and replacements, servicing and losses (e.g. transformer losses, etc.), end-of-life treatment and transport.

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-CML impact indicators, such as recyclability. These are listed in Section 3.8 and further explained in Annex A.

The study assesses a 'typical' onshore wind plant layout consisting of V163-4.5MW turbines 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. Accordingly, the results of the study will be used by Vestas to:

- inform management and employees involved in decision making processes;
- identify optimisation and improvement areas for technology and product development within Vestas;
- support environmental reporting at a product-level;
- develop a framework for product LCAs at Vestas to integrate environmental considerations in product design and procurement, target setting and decision making; and
- develop marketing materials to communicate 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 staff;
- 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 100 MW onshore wind power plant comprising of Vestas V163-4.5MW 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

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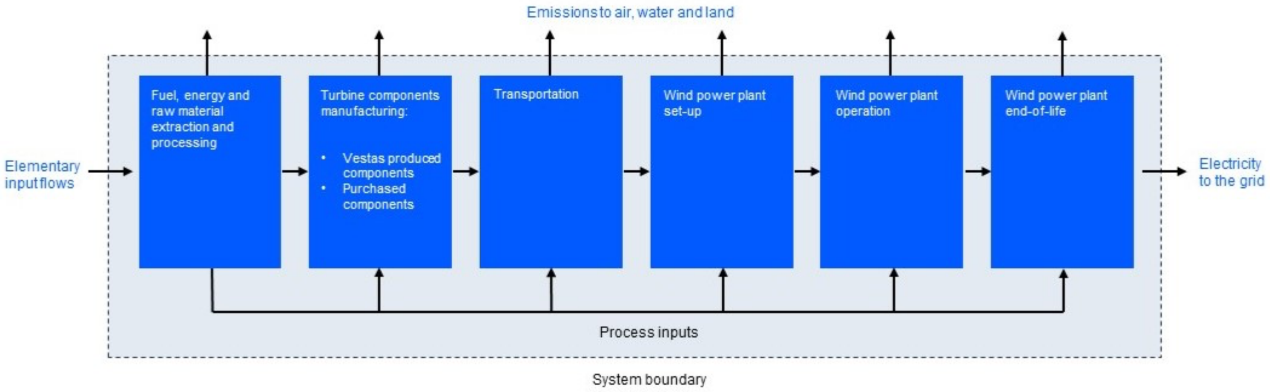
[5] The plant size of 100MW is selected in this LCA to maintain consistency with previous LCAs. Furthermore, sales forecast for V163-4.5 turbines also indicates a similar average plant size (of around 100MW)

(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 100 MW onshore wind power plant of V163-4.5MW 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 V163-4.5MW wind turbine has been designed to operate under medium (IECS) wind conditions which 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 8.7 TWh over a 20 year plant lifetime which results in a reference flow of $1.15*10^{-10}$ power plants per 1 kWh delivered.

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 medium (IECS) 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

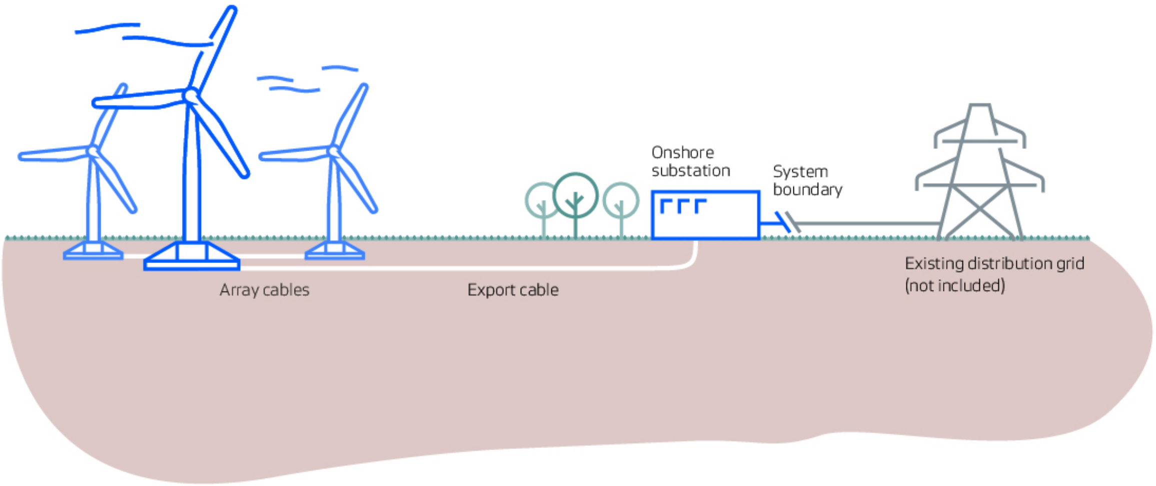


Table 1 gives an overview of the baseline wind power plant assessed in this life cycle assessment, which is further described in detail throughout Section 3.

Table 1: Baseline wind plant assessed

Description	Unit	Quantity
Lifetime	years	20
Rating per turbine	MW	4.5
Generator type	-	Induction
Turbines per power plant	pieces	22
Plant size	MW	99*
Hub height	m	98
Rotor diameter	m	163
Wind class	-	Medium (IEC S)
Tower type	-	TST
Foundation type	-	Low ground water level (LGWL)
Production @ 7.9 m/s	MWh per year	20032
Grid distance	km	20
Plant location	-	US**
Vestas production location	-	Global average

Note: The above figure for electricity production includes all losses, assuming an availability of 98.0%, total plant electrical losses up to grid of 2.5% and average plant wake losses of 6.0%.

Note: IECS refers to "IEC Special" where the turbine is designed for special wind conditions for the low, medium or high IEC wind class. Refer to Annex E for further details of IEC wind classes.

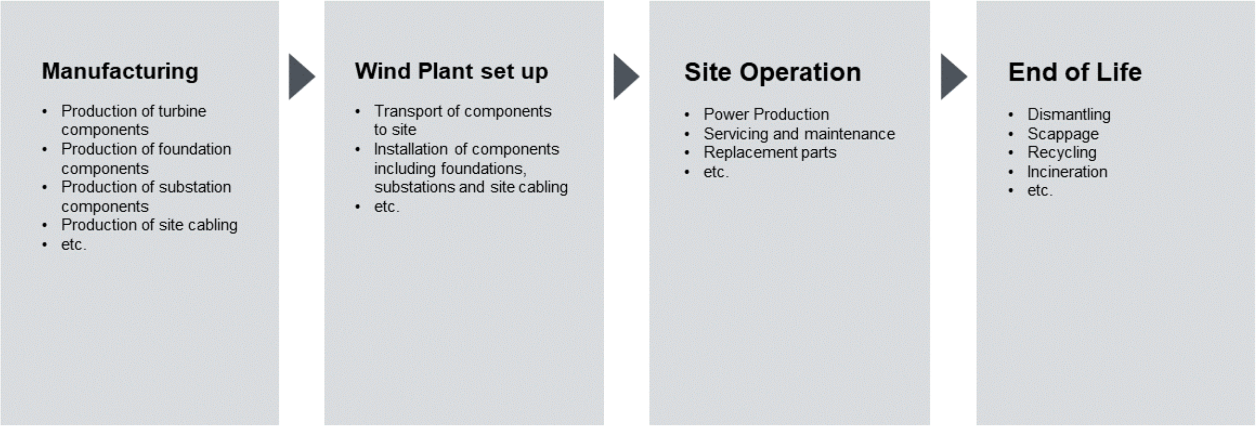
** The plant size of 100MW is selected in this LCA to maintain consistency with previous LCAs. Furthermore, sales forecast for V163-4.5 turbines also indicates a similar average plant size (of around 100MW). To achieve nearest total power rating then 22 turbines of 4.5MW rating are selected, totalling to 99MW.*

*** US is the chosen plant location as this represents a significant market for the V163 turbine.*

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



Manufacturing

- Production of turbine components
- Production of foundation components
- Production of substation components
- Production of site cabling
- etc.

Wind Plant set up

- Transport of components to site
- Installation of components including foundations, substations and site cabling
- etc.

Site Operation

- Power Production
- Servicing and maintenance
- Replacement parts
- etc.

End of Life

- Dismantling
- Scappage
- Recycling
- Incineration
- etc.

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 substations. 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), and adequately represents the plant configuration being assessed.

Transport to site for installation of the wind power plant includes transport by truck and by sea vessel, where specific data on fuel consumption (and vehicle utilisation) has been used. 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.

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 lifetime of the wind plant. The transport associated with operation and maintenance, to and from the turbines, is included in this phase and reflects estimated 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 7.2.7 presents a sensitivity analysis on this issue.

3.2.2 Technology coverage

This study assesses the production of the Vestas V163-4.5MW 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 2023 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 V163-4.5MW turbine represents the most recent model of onshore turbine. For turbine production at Vestas facilities a global production for the calendar year of 2023 is selected for this LCA study as it is deemed 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 project or site-specific 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 transport distances to site.

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

- the production of metals (iron, steel, copper and aluminium) of which the wind turbine is constituted around 85% metals uses datasets (such as those from worldsteel, Sphera, Eurofer, international copper association);
- datasets used for polymer and composites production include those from Plastics Europe and Sphera
- Sphera datasets are used for concrete; and
- end-of-life recycling also uses 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 2023; and
- turbine transport represents Vestas global average footprint for transport

The above 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 takes 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,b,c, 2013a,b, 2014a,b,c,d, 2015a,b,c, 2017a,b,c,d,e and 2022a). 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 methodology as well as the efficiencies.

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;
- 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;
- electrical losses in the entire power plant (for transformers, site cables and turbine electricity consumption, etc) from Vestas; and
- recycling rates of specific components/materials 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 Sphera (2024) and also include secondary sources from industry association, such as:

- worldsteel[6];
- Eurofer; 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 0.1% of the mass at a product-level, then it may be excluded, provided its environmental relevance is not of concern.t
- **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 V163-4.5MW turbine (i.e. covering all parts of the turbine-only, excluding foundation, site cables and site parts) have been accounted for, covering around 26,600 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

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[6] Note: Vestas identified an issue with the worldsteel dataset relating to EU/GLO structural steel plate. Essentially, for this dataset, one particular emission (for nickel to water) is negative net mass overall, which results in an overall negative freshwater aquatic ecotoxicity impact for LCIA results, which is an anomaly. In communication with worldsteel, Vestas has adjusted the nickel flow to previous database value and used this adjusted LCI for plate steel in the current LCA for results generation. Essentially, this removes an anomaly that exists for a single "outlier" plant where an industrial water input and emission of cooling water to the river miss a nickel emission factor.

their entirety for the complete wind power plant. As such, the LCA includes all materials and all components of environmental significance, with over 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 (Sphera 2024).

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 V163-4.5MW 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 their design lifetime. Additionally, other site components such as the site cabling and foundations may have a significantly longer useful lifetime. The effects of varying the lifetime of a wind plant on potential environmental impacts are discussed in Section 7.2.

3.4.2 Electricity production

A typical site for a V163-4.5MW turbine with a medium (IECS) wind of 7.9 m/s at an 98m hub height is assessed for the LCA, which represents, for example, a realistic US onshore site placement. Table 2 shows the electricity production from the power plant.

Based on medium (IECS) wind speed, the electricity production from a 100 MW onshore wind power plant of V163-4.5MW turbines is 8.7 TWh over 20 years (equivalent to 19788 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 20 km 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.

Table 2 shows the electricity production, as delivered to the grid, for the V163-4.5MW turbine.

Table 2: Electricity Production

Turbine	Wind class	Wind speed	Location	Grid distance	Per turbine per year (AEP)	Per 100 MW plant per 20 years
		ms^{-1}		km	MWh	TWh
V163-4.5MW	Medium (IECS)	7.9	Onshore	20	19788	8.7

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 0.5 ms^{-1} within the different wind classes and total electricity production is determined over the range of 0 ms^{-1} to 31 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 98.0%, 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 V163-4.5MW does not use rare earth elements in the generator magnets.

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 dismantled and recycled 98% recycled. Other major components, such as generator, gearbox, cables, and yaw system parts are 95% recycled. During 2024, the recyclability of blades has been adjusted to reflect the latest development in technology related to the CETEC (Circular Economy for Thermosets Epoxy Composites – a novel chemical disassembly process that Vestas is currently focusing to scale up into a commercial solution), which Vestas spearheaded (Vestas, 2023b). This means that all epoxy-infused blades are classified as 100% recyclable, which increases the overall recyclability of the turbine.

In alignment with the updated recyclability method (refer to Section 5.3.5), recycling credits at EoL are applied and adjusted, which are similar (in terms of percentage weight) compared to previous onshore LCAs. However, in order to present conservative potential impact results, EoL crediting is only applied to metals, as in previous LCAs. There are no credits applied to blade materials or polymers.

Table 3 shows the calculated average recycling treatment rates applied to the turbine. It is recognised that landfill and incineration treatment technology and mass flow may vary significantly in the future compared to the assumptions shown. However, the assumptions are used in the LCA to try to provide a reasonable estimate of a conservative case for future waste disposal (i.e. to not overestimate benefits of recycling or landfill/incineration). It is also recognised that the European wind industry has committed to avoid all composite blades materials being sent to landfill from 2025 onwards (WindEurope, 2022).

Table 3: End-of-life treatment of turbine material / components

32)		Treatment		Credited material datasets*
	Recycling credit	**Incineration**	**Landfill**	
Steel	93.2%	0%	6.8%	Value of scrap from worldsteel. No further distinction made between material grades.
Iron	97.4%	0%	2.6%	Value of scrap from worldsteel. No further distinction made between material grades.
Aluminium	94.7%	0%	5.3%	Aluminium ingot mix (2010). No further distinction made between material grades.
Copper	94.7%	%	5.3%	Copper mix (global) from Sphera. No further distinction made between material grades.
Blade materials	0%	0%	100%	No credit assigned
Polymers	0%	50%	50%	No credit assigned
Fluids	0%	100%	0%	No credit assigned
All other materials	0%	0%	100%	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*

Note: given the V163-4.5MW wind power plants will first be decommissioned in 20 years' time, and the recycling methods (specially for polymers and fluids) are expected to advance significantly during this time frame, the above assumptions for recyclability are considered conservative

The information for recycling rates of turbine components comes from the full recycling of a nacelle of a Vestas onshore turbine (Vestas and Averhoff, 2012), along with expert judgement and data obtained from previous LCA studies performed by Vestas.

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. Details of turbine recyclability can be found in Section 5.3.5.

However, it is also recognised that, from a scientific perspective, a 'recycled-content' approach for crediting may also be applied to wind turbines (Garrett, 2012). As such, Section 7.2.7 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 precisely 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 (23500 kg CO_2e) which is used in switchgears as an electrical insulator for medium- and high-voltage applications. The gas acts as an electrical insulator for the operation of the switchgear. Each turbine contains switchgears, 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 and site switchgears may potentially release up to 0.1% w/w of the sulphur hexafluoride per year, accounting for a potential 3% 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 7.2.6.

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 99% of all switchgears will be returned for reclamation at end-of-life. The remaining 1% 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:

- 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; and
- high groundwater level (HGWL): indicates a (maximum) groundwater level equal to the level of the terrain, which requires more concrete and steel reinforcement. A sensitivity analysis has been completed for a HGWL scenario in Section 7.2.5.

The size of the foundation will also vary depending on the turbine tower height and the wind class for the V163-4.5 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

Individual electronic components and printed circuit boards have been mapped on an individual part-by-part basis as they are designed in-house at Vestas. All controllers on the turbine were mapped specifically for component types, such as resistors, capacitors, integrated circuits, etc according to component size and specification.

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 covers the transport of the components from the supplier to Vestas' factories.

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

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

Component	Truck (km)	Ship (km)
Nacelle (including hub)	800	8000
Blades	1600	0
Tower	1100	0
Foundation	50	0
Site cables	600	0

Note: transport distances assume a US plant location and the supply chain distances are based on average distance to the respective component production locations. Foundations and other site parts are estimated distances by Vestas.

- **Transport associated with end-of-life recycling or disposal** assumed to be 200km to a regional recycling or disposal operator, except for onshore substation 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 1500km per plant per year.

- **Air transportation of Vestas personnel** for business purposes is included in the transport scenario. This is updated based on data for Vestas global business flights in 2023.

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 (Section 7.2.4.), assuming a likely best-case and worst-case approach.

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.

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 the physical material and energy flows[7].

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

The Sphera LCA for Experts software and databases together with its DfX software extension 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 (Sphera 2023).

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 V163-4.5MW turbine accounts for around 26,600 parts. Modelling this many components "conventionally" in LCA is not practicable. However, using Sphera 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 and balance-of-plant components 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 85%

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[7] 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.

metals), as well as other materials contained with the turbine and power plant, such a 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).

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

Environmental impact categories (based on CML):

- 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):

- Primary energy from renewable resources (net calorific value)
- Primary energy from non-renewable resources (net calorific value)
- 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 Sphera LCA for Experts 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. Furthermore, a recent study also confirmed that more recently published LCIA methods are not necessarily scientifically superior to CML as described by the paper titled: *Approach to qualify decision support maturity of new versus established impact assessment methods—demonstrated for the categories acidification and eutrophication* (Bach, Finkbeiner, 2017).

Also contained in Annex H the following additional results are presented:

- Impact assessment methods for EF 3.1.

It was intended to assess an indicator for water scarcity footprint in this environmental assessment called AWARE water scarcity footprint method (Boulay, 2018). This method supersedes the water use method used in previous LCAs (along with the 'Blue water consumption' indicator). This indicator shows the water scarcity footprint based on available water remaining per unit area of watershed relative to the world average after water demand for human and aquatic ecosystems. This method is in accordance with the ISO 14046 standard for water footprint and is recommended by the UNEP-SETAC life cycle assessment initiative, PEF/OEF programme of the European Commission and the international EPD system (UNEP, 2016).

Additionally, it was also intended to assess ‘Blue water consumption’ which refers to water withdrawn and returned to ground water and surface water bodies. The blue water inventory includes all freshwater inputs and outputs but excludes rainwater. The water input flows refer to total water use. To quantify total freshwater consumption, all freshwater input flows and output flows are summed up. For impact assessment, only blue water (i.e. surface and groundwater) is considered. Sea water and rain water is also excluded from the aggregation.

However, due to an inconsistency in the dataset modelling for plate steel provided by worldsteel (2022) in the Sphera database (2024), then it has not been possible to evaluate the full life cycle results for both AWARE and blue water. These results are currently excluded from the report until further clarifications are completed and will be included in an update to the report.

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 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 footprinting and greenhouse gas (GHG) accounting and verification.

Also, the Vestas developed 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 (Environdec,

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, it 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. Annex H presents the results for whole-life modelling in alignment with the EPD approach for electricity delivered to the grid.

3.9 Interpretation

The interpretation stage of the LCA has been carried out in accordance with the main steps defined in ISO 14044 (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 2023 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:

1. variation in wind power plant lifetime: ± 4 years;
2. variation in frequency of parts replacement;
3. variation in hub height: 113m;
4. varying the transport distances for components to wind plant erection site;
5. high ground water level type foundations;
6. incidence of a potential turbine switchgear blow-out; and
7. potential effects of method used for crediting recycling of metals.

Additionally, the major conclusions and recommendations for improvement have been identified (refer to Section 8). The study limitations are highlighted throughout the report, where relevant.

As part of the interpretation of the study, reference has also been made to 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 14071:2024 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[8] 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 datasets.

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[8] The reviewer acts and was contracted as an independent expert, not as a representative of his affiliated organisation.

4 Material breakdown of V163-4.5MW wind power plant

Table 6 (per wind plant total) and Table 7 (per kWh delivered to grid) present the material breakdown for the complete onshore 100 MW wind power plant of V163-4.5MW 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 by mass 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 are shown in Annex G, divided into substance flows and reported per main life cycle stage.

Figure 5: Material breakdown of V163-4.5MW turbine-only (% mass)

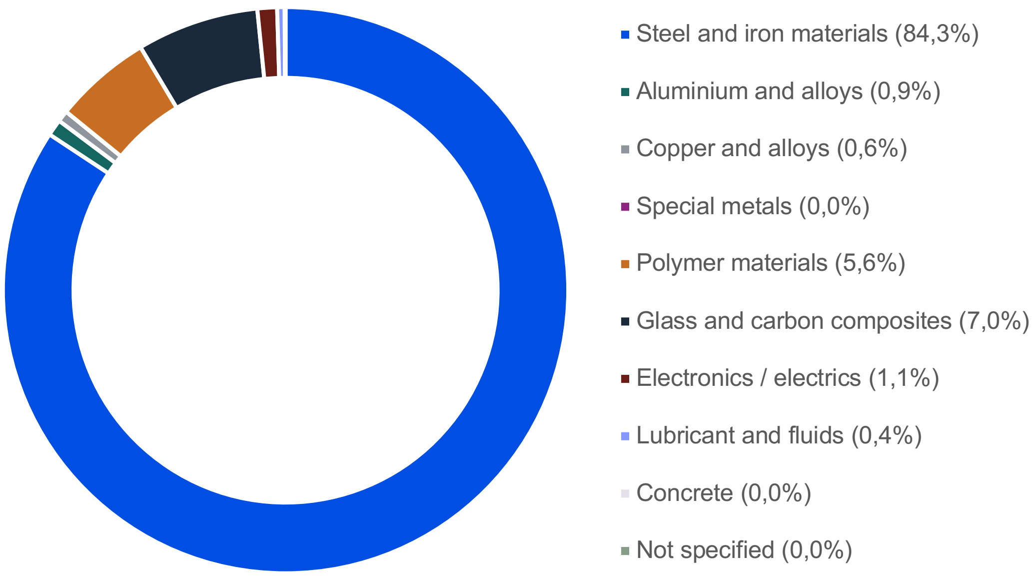


Figure 6: Material breakdown of 100 MW power plant of V163-4.5MW turbines (% mass)

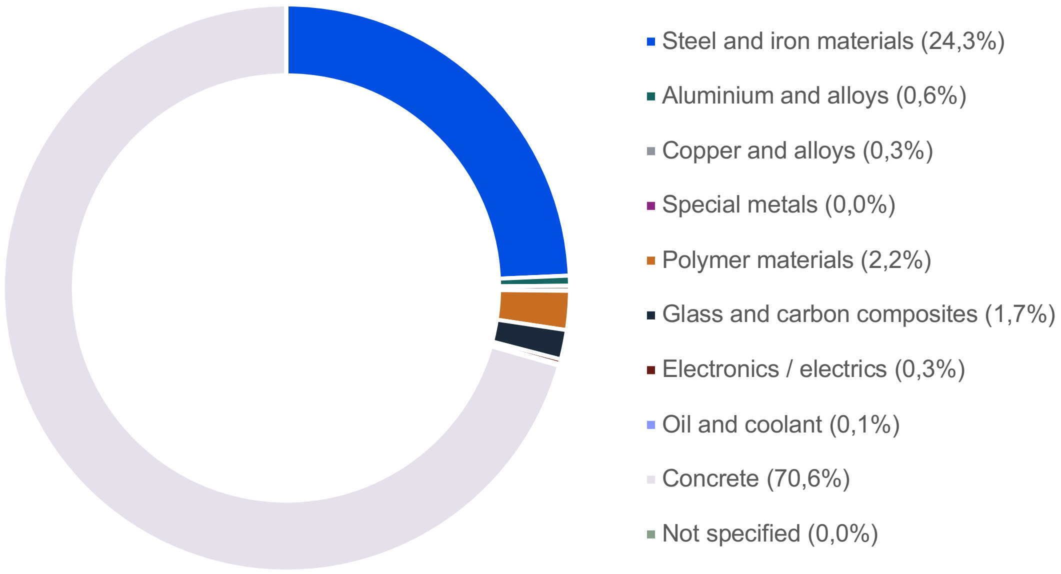


Table 6: Material breakdown of 100 MW power plant of V163-4.5MW turbines (units shown in kg or tonne per total wind plant)

Material classification	Unit	Turbines	Foundations	Site Cables	Site transformer	Site switchgears
Steel and iron materials (total)	tonne	9092	1738	0	110	5
Unalloyed, low alloyed	tonne	6919	1738	0	0	0
Highly alloyed	tonne	550	0	0	0	5
Cast iron	tonne	1623	0	0	0	0
Lights alloys, cast and wrought alloys (total)	tonne	101	2	154	0	0
Aluminium and aluminium alloys	tonne	101	2	154	0	0
Nonferrous heavy metals, cast and wrought alloys (total)	tonne	70	1	39	17	2
Copper	tonne	54	1	39	17	2
Copper alloys	tonne	11	0	0	0	0
Zinc alloys	tonne	5	0	0	0	0
Special metals	kg	85	0	0	0	0
Silver	kg	3	0	0	0	0
Solder paste	kg	82	0	0	0	0
Polymer materials (total)	tonne	600	16	341	41	0
Other materials and material compounds (total)	tonne	752	31780	1	2	0

Material classification	Unit	Turbines	Foundations	Site Cables	Site transformer	Site switchgears
Modified organic natural materials	tonne	2	0	0	2	0
Ceramic / glass	tonne	748	0	1	0	0
Other materials and material compounds	tonne	0	0	0	0	0
Concrete	tonne	0	31780	0	0	0
Magnets	tonne	2	0	0	0	0
SF6 Gas	kg	180	0	0	0	48
Electronics / electrics (total)	tonne	121	0	0	0	0
Electronics	tonne	25	0	0	0	0
Electrics	tonne	96	0	0	0	0
Lubricants and liquids (total)	tonne	46	0	0	0	0
Lubricants	tonne	34	0	0	0	0
Coolant / other glycols	tonne	12	0	0	0	0
Other fuels and auxiliary means	tonne	0	0	0	0	0
Not specified	tonne	5	0	0	0	0
Total mass	tonne	10789	33537	535	170	7

Material classification	Unit	Turbines	Foundations	Site Cables	Site transformer	Site switchgears
Total number of pieces	tonne	22	22	1	1	1
Mass of piece	tonne	490	1524	535	170	7

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 100 MW power plant of V163-4.5MW turbines (units shown in mg per MWh)

Material classification	Unit	Turbines	Foundation	Site Cable	Site Trafo	Site Switchgear
Steel and iron materials (total)	mg per MWh	1044	200	0	13	1
Unalloyed, low alloyed	mg per MWh	795	200	0	0	0
Highly alloyed	mg per MWh	63	0	0	0	1
Cast iron	mg per MWh	186	0	0	0	0
Lights alloys, cast and wrought alloys (total)	mg per MWh	12	0	18	0	0
Aluminium and aluminium alloys	mg per MWh	12	0	18	0	0
Nonferrous heavy metals, cast and wrought alloys (total)	mg per MWh	8	0	5	2	0
Copper	mg per MWh	6	0	5	2	0
Copper alloys	mg per MWh	1	0	0	0	0
Zinc alloys	mg per MWh	1	0	0	0	0

Material classification	Unit	Turbines	Foundation	Site Cable	Site Trafo	Site Switchgear
Special metals	mg per MWh	0	0	0	0	0
Silver	mg per kWh	0	0	0	0	0
Solder paste	mg per kWh	0.009	0	0	0	0
Polymer materials (total)	mg per MWh	69	2	39	5	0
Other materials and material compounds (total)	mg per MWh	86	3650	0	0	0
Modified organic natural materials	mg per MWh	0	0	0	0	0
Ceramic / glass	mg per MWh	86	0	0	0	0
Other materials and material compounds	mg per MWh	0	0	0	0	0
Concrete	mg per MWh	0	3650	0	0	0
Magnets	mg per MWh	0.224	0	0	0	0
SF6 Gas	mg per MWh	0.021	0	0	0	0.006
Electronics / electrics (total)	mg per MWh	14	0	0	0	0
Electronics	mg per MWh	3	0	0	0	0
Electrics	mg per MWh	11	0	0	0	0
Lubricants and liquids (total)	mg per MWh	5	0	0	0	0

Material classification	Unit	Turbines	Foundation	Site Cable	Site Trafo	Site Switchgear
Lubricants	mg per MWh	4	0	0	0	0
Coolant / other glycols	mg per MWh	1	0	0	0	0
Other fuels and auxiliary means	mg per MWh	0	0	0	0	0
Not specified	mg per MWh	1	0	0	0	0
Total mass	mg per MWh	1239	3852	61	19	1
Total number of pieces	pcs	22	22	1	1	1
Mass of piece	mg per MWh	56	175	61	19	1

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 100 MW wind power plant of V163-4.5MW 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 V163-4.5MW plant (units shown in g, mg or MJ per kWh)

Environmental impact categories:	Unit	Quantity
CML-impact indicators:		
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	14
Eutrophication potential (EP)	mg PO_4-e	1.9
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	38
Global warming potential (GWP)	g CO_2-e	5.1
Human toxicity potential (HTP)	mg DCB-e	1481
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	533
Photochemical oxidant creation potential (POCP)	mg Ethene	1.7
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	30
Non CML-impact indicators:		
*Primary energy from renewable raw materials	MJ	0.02
*Primary energy from non-renewable resources	MJ	0.07
***Return-on energy	Number of times	39
****Turbine “Recyclability of designed ‘as-built’ turbine”	% (w/w)	98.5%
****Turbine “Recyclability after disassembly”	% (w/w)	98.1%
****Turbine “Recyclability after recycling treatment”	% (w/w)	85.3 to 94.6%
*****Turbine circularity (not life cycle based. turbine only)	-	0.66 to 0.70

* *Net calorific value*

*** Based on WULCA model for water scarcity footprint that assesses available water remaining (Boulay, 2018).*

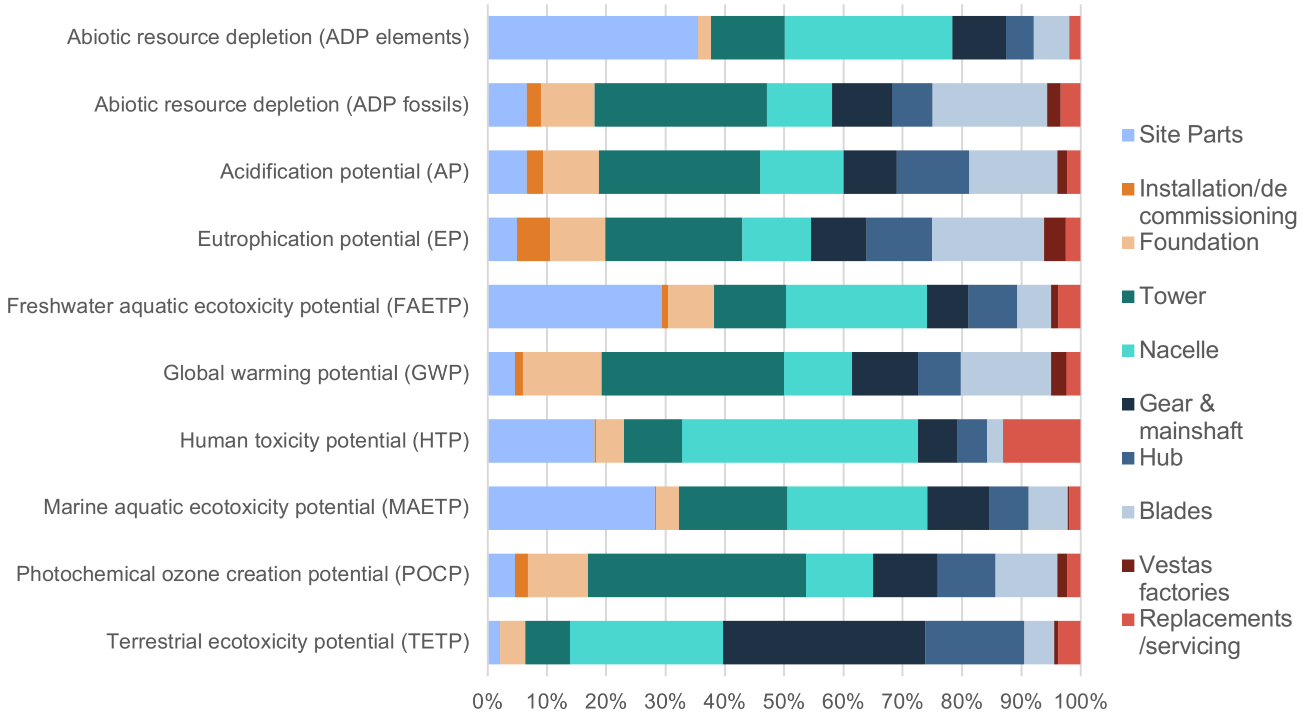
**** Based on ‘Net energy’ calculation defined in Section 6*

**** *Rounded up or down to the nearest half percentage point and measure is* not life cycle based and turbine-only.

***** *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 tower, nacelle and the blades contribute most significantly to all environmental impact indicators. Out of the site components, the foundations and the site cables are very significant. Vestas factories contribute around <1% and 4% 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 V163-4.5MW



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 V163-4.5MW by life cycle stage (units shown in g, mg or MJ per kWh)

Impact category	Unit	Manu-facture	Plant setup	Opera-tion	End-of-life	Total
CML-impact indicators:						
Abiotic resource depletion (ADP elements)	mg Sb-e	0.16	0.00	0.00	-0.06	0.10
Abiotic resource depletion (ADP fossils)	MJ	0.08	0.00	0.00	-0.02	0.06
Acidification potential (AP)	mg SO_2-e	19	0	0	-6	14
Eutrophication potential (EP)	mg PO_4-e	2.1	0.1	0.1	-0.3	1.9
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	39	0.2	2	-3	38
Global warming potential (GWP)	g CO_2-e	7.02	0.04	0.14	-2.13	5.09
Human toxicity potential (HTP)	mg DCB-e	1791	2	266	-579	1481
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	1031	1	20	-520	533
Photochemical oxidant creation potential (POCP)	mg Ethene	2.6	0.0	0.1	-1.0	1.7
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	28	0.0	1.1	0.3	30
Non CML-impact indicators:						
*Primary energy from renewable resources	MJ	0.01	0.00	0.00	0.00	0.02
*Primary energy from resources	MJ	0.09	0.01	0.03	-0.019	0.12
**AWARE water scarcity footprint	g	not assessed	not assessed	not assessed	not assessed	not assessed
Blue water consumption	g	not assessed	not assessed	not assessed	not assessed	not assessed

** Net calorific value*

*** Based on WUCLA model for water scarcity footprint that assesses available water remaining (Boulay, 2018)*

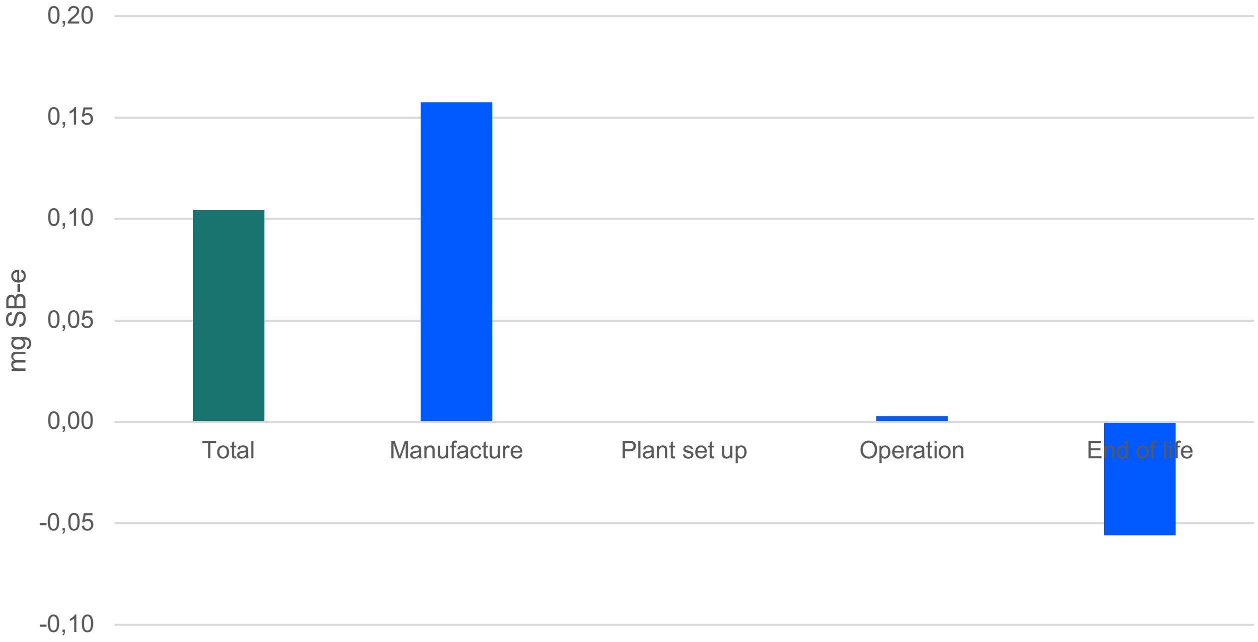
5.2.1 Abiotic resource depletion (elements)

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 gold (22.1%), silver (21.6%), copper (18.8%), and lead (17.4%). This potential impact mainly relates to the use of high-alloy steels in the nacelle parts, such as generator and gearbox, etc. Colemanite ore consumption is driven by the manufacture of the glass fibre in the blades of the turbine. The end-of-life phase also has a contribution, providing an environmental credit for the recycling of metals (around -35%), where production of these materials is avoided.

The end-of-life stage is dominated by the recycling of steel. The impact from operation relates primarily to replacement parts over the lifetime of the turbine.

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



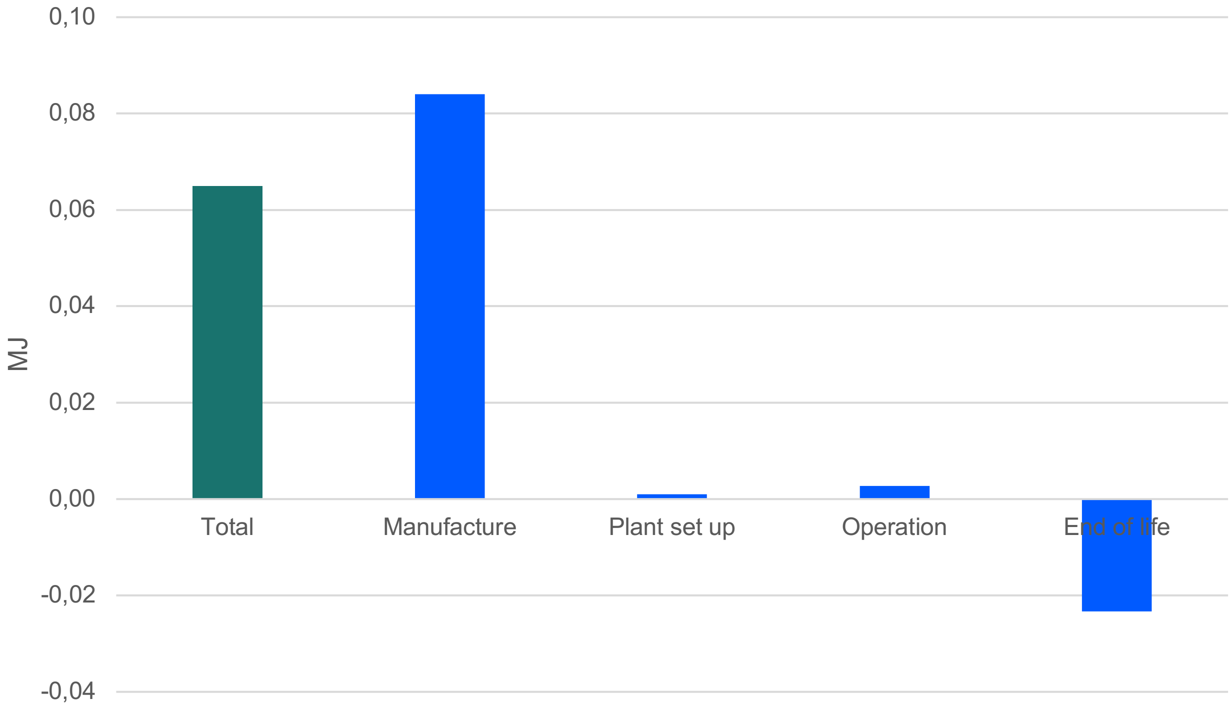
5.2.2 Abiotic resource depletion (fossil)

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 driven by production of the turbine (74%), followed by the foundations (7.5%) and site cables (5.4%). Within production, the tower, nacelle and blades contribute most significantly to this impact category. The second most significant life cycle phase is operation followed by plant set up.

Overall, the impacts relate to the consumption of coal (45.6%), natural gas (19.2%), and oil (16.5%%) for the production of metals and polymers. End-of-life recycling of metals also provides environmental credits relating to avoided potential depletion of resources (of around -26%).

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



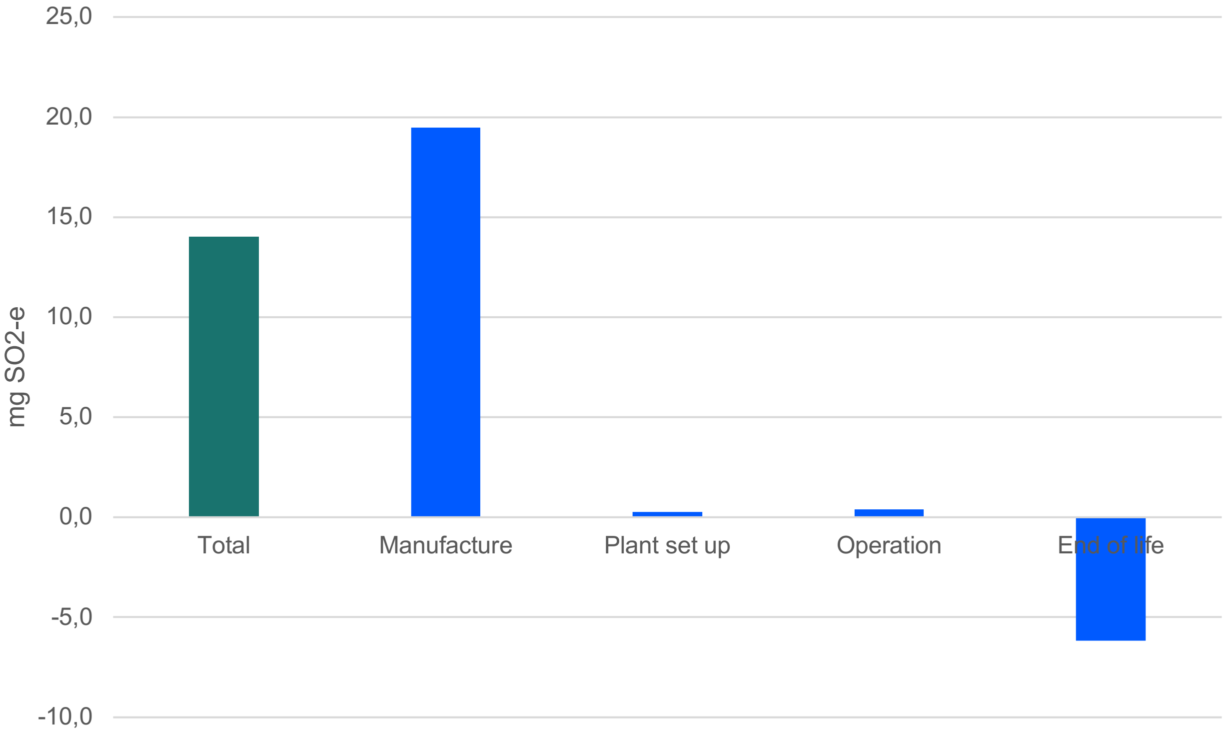
5.2.3 Acidification potential

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 (35%), blades (21%), nacelle (17%), hub (15%), foundations (11%), and site cables (7%), The emissions to air of sulphur dioxide (61%) and nitrogen oxides (33%) are associated with the production of iron and steel and with glass fibres in the blades.

The end-of-life phase also has an overall contribution, providing an environmental credit (of around -30%) 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

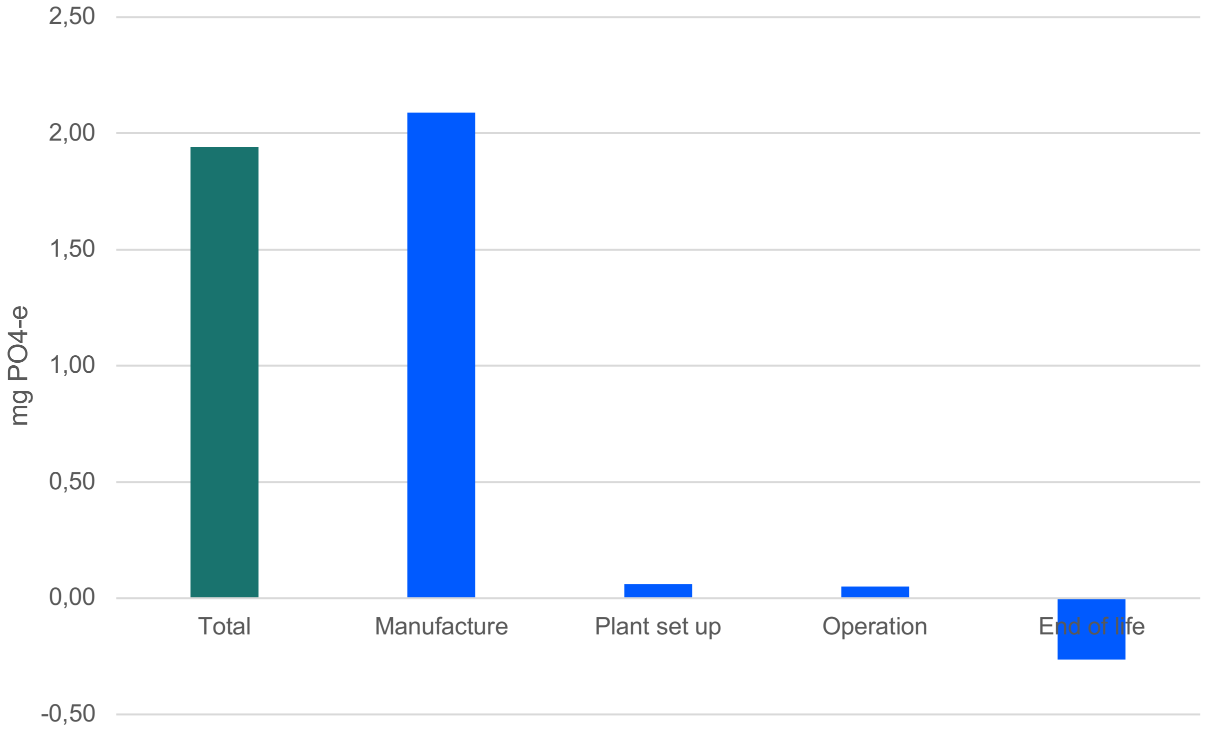
In general terms, eutrophication potential provides a measure of nutrient enrichment in aquatic or terrestrial environments, which leads to ecosystem damage to those locations from over-enrichment and is measured in mass of phosphate equivalents.

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. Over the complete life cycle, the primary substances contributing to eutrophication are the emissions to air of nitrogen oxides (78%), and inorganic emissions to fresh water (9%).

The principal turbine components contributing to eutrophication potential are the tower (23%), blades (18%), nacelle (11%), and foundation (9%). Additionally, the site parts, including the site cables, contribute around 5%. The eutrophication impacts in the nacelle and tower are mainly due to the transportation associated with the same. In the blades, the contribution to eutrophication potential is from the manufacture of glass fibre; concrete in the foundations and aluminium contributes to eutrophication potential in the site cables.

The nitrous oxide emissions are driven mainly by the manufacture of the glass fibre used in the turbine blades. The end-of-life phase also has a relatively low overall contribution, providing an environmental credit (of around -12%). 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

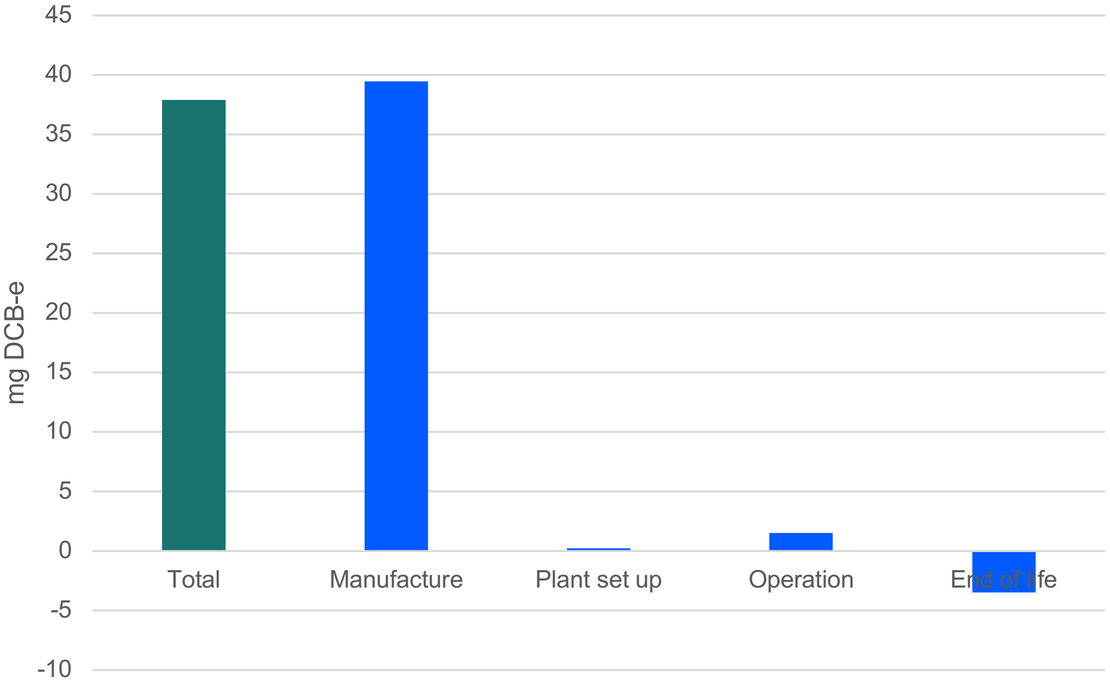


5.2.5 Freshwater aquatic ecotoxicity potential

Freshwater aquatic ecotoxicity potential, in general terms, refers to the impact on freshwater 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 (29%), nacelle (23%), tower (12%), foundation (8%), hub (8%), gear and mainshaft (7%), and blades (6%). 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. While other contributing substances relate to the release of heavy metals (49%) to water and to air, such as nickel, vanadium and barium. These heavy metal releases result from the production processes for metals used in the turbine. The environmental credit for end-of-life is also associated with the avoidance of heavy metal release to air and water (around -8%) 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 (31%), foundations (13%), blades (15%), gear and mainshaft (11%), nacelle (11%), and cables (5%), being the primary components contributing to this impact category. Vestas production and operations contribute around 2% of the global warming impacts. The end-of-life phase also has a significant contribution (-30%), providing environmental credits associated with avoided metal production of iron, steel, copper and aluminium.

The emission to air of carbon dioxide (91.5%) is the primary contributing substance, which results from the combustion of fuels in production of the turbine raw materials, as well as methane (8%) resulting from glass fibre and steel production. Other lesser contributing substances to global warming potential include the release of sulphur hexafluoride gas to air (0.0007%) from improperly disposed switchgears, and nitrous oxide (0.4%) 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

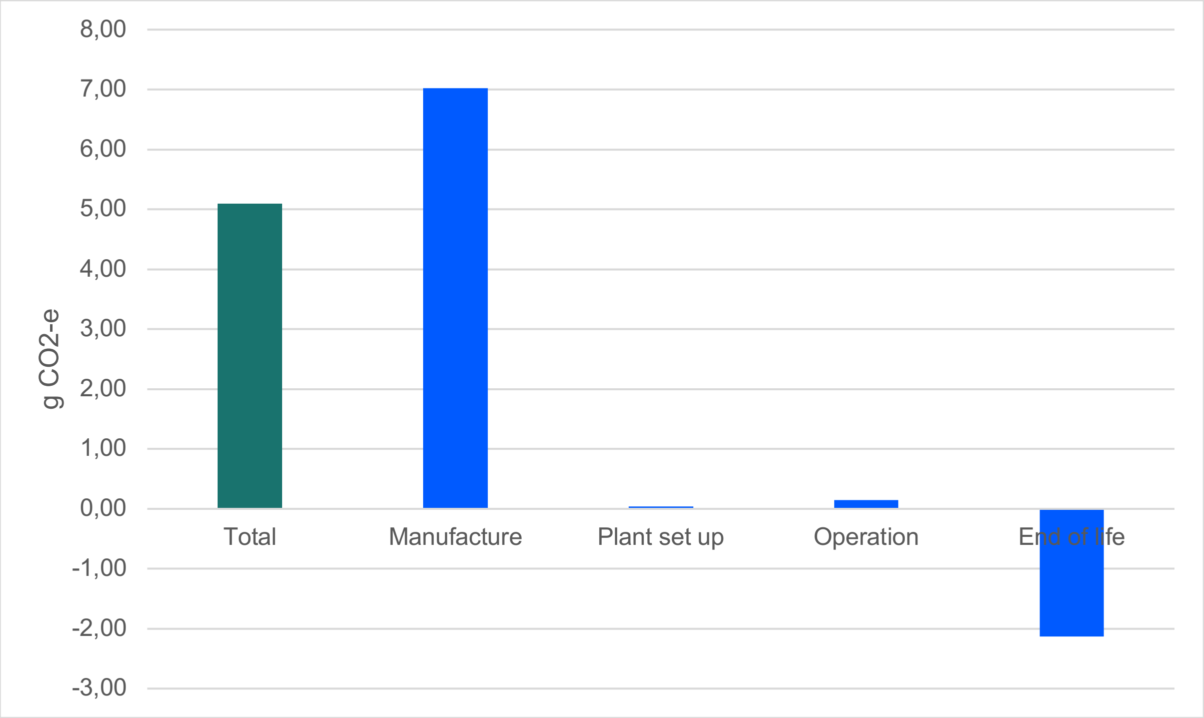


Table 10 presents the total tonnes of CO_2-e per MW for the V163-4.5MW total wind plant and wind turbine-only. This is included in the LCA report because, increasingly, Vestas customers and national authorities request this as a performance metric for the wind turbine and plant.

Table 10: Whole-life Global Warming Potential of V163-4.5MW by life cycle stage (units shown tonnes CO2e per MW)

Component scope	Unit	Manu-facture	Plant setup	Opera-tion	End-of-life	Total
Full wind plant	tonnes CO2-e per MW	618	4	13	-187	448
Turbine only	tonnes CO2-e per MW	505	4	13	-147	374

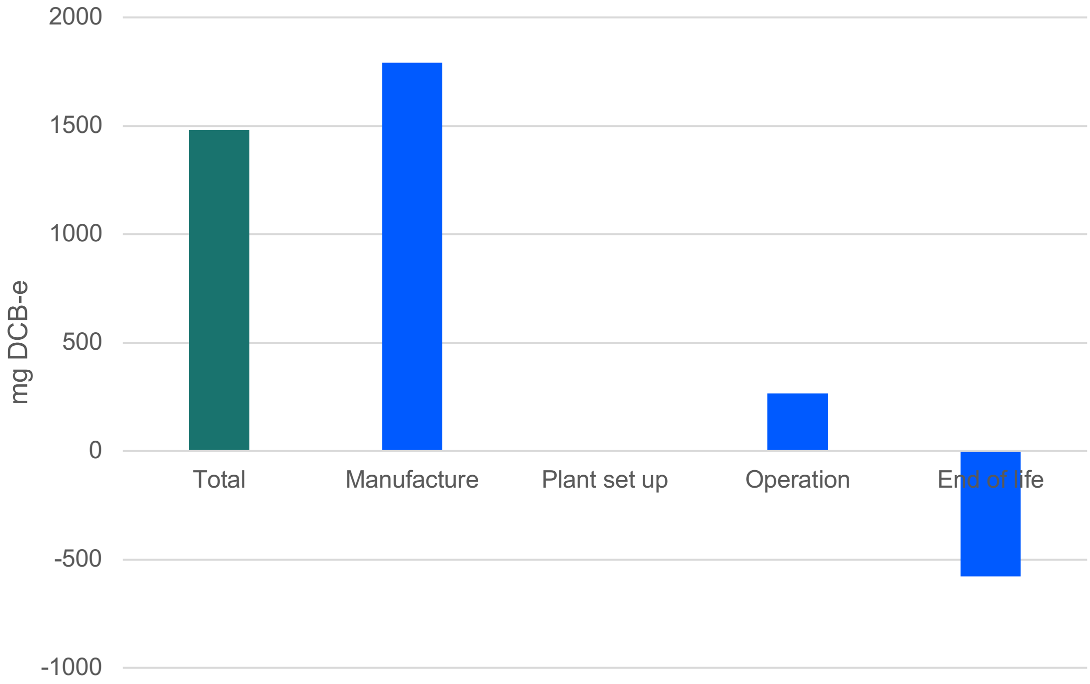
5.2.7 Human toxicity potential

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 nacelle (40%), site parts (18%), tower (10%), and gear and main shaft (7%) being the principal contributing components. The end-of-life phase also provides a large environmental credit (around -28%) from the recycling of metals.

The release of heavy metals to air (14%), like nickel and arsenic and the emission of non-methane volatile organic compounds (72.6%) are the main contributors to the human toxicity potential. The non-methane volatile organic compounds are released primarily from the manufacture of aluminium from the site cables and glass fibre from the blades.

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



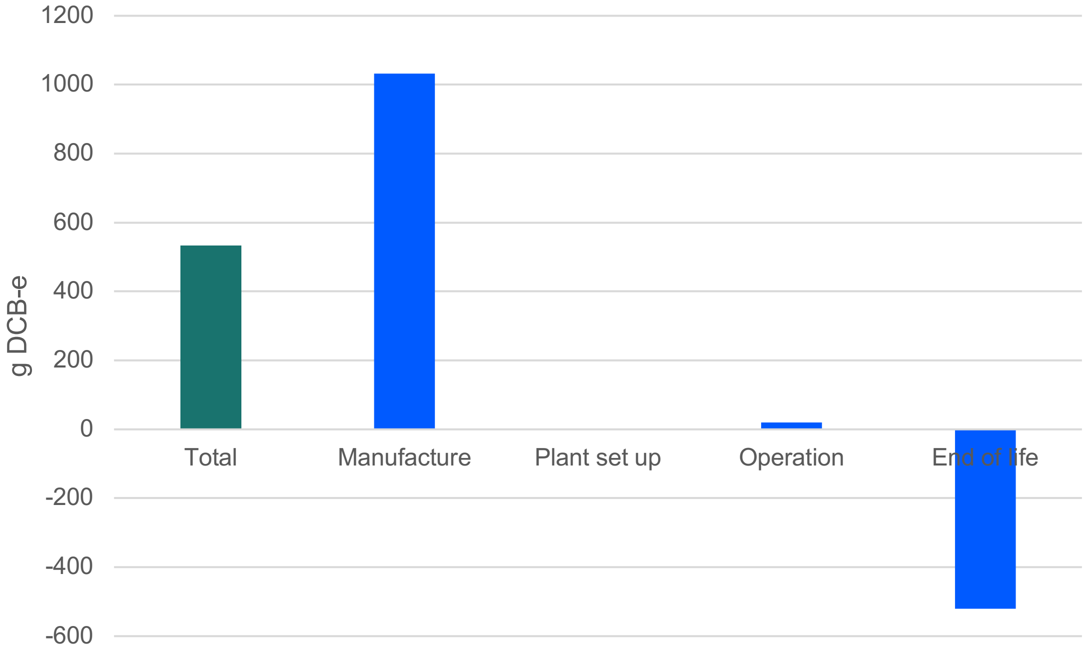
5.2.8 Marine aquatic ecotoxicity potential

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 in the LCA, 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 (93.1%) from both aluminium and steel production processes, used in the site cables, tower, nacelle, and many parts of the turbine.

The remaining impacts primarily result from emissions of heavy metals to air (3.4%) and fresh water (0.6%), which result, for example, from the production of stainless-steel materials. The end-of-life stage also offers substantial environmental credits (around -49%), which is mainly associated with the aluminium and steel production.

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



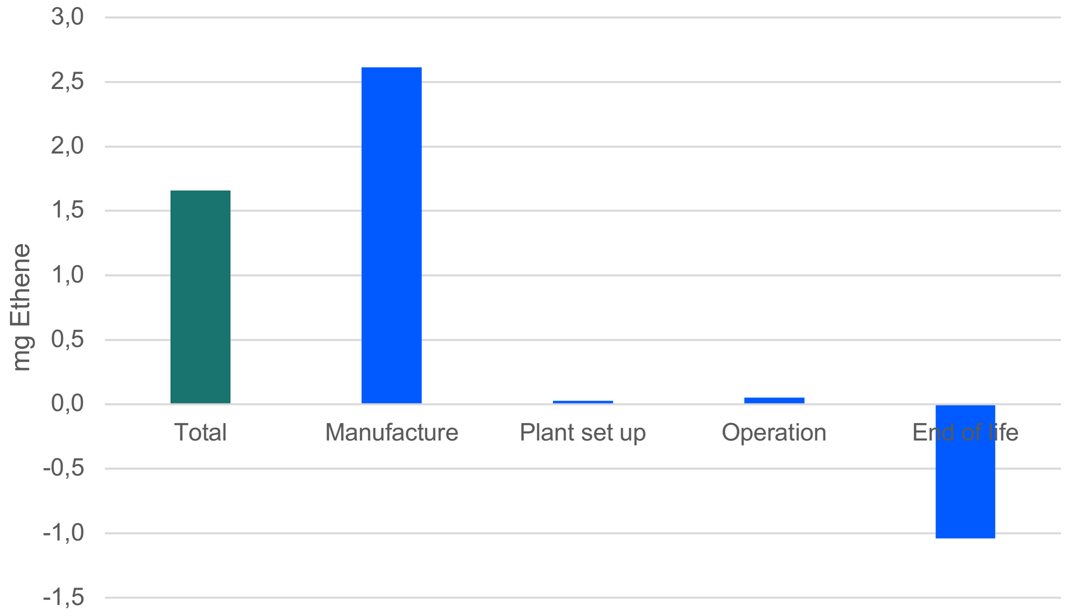
5.2.9 Photochemical oxidant creation potential

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 (37%), gear and main shaft (11%), nacelle (11%), blades (11%) and foundation (10%). The main contributing substances are carbon monoxide (42%), sulphur dioxide (18%), nitrogen oxides (13%), methane (4.6%) non-methane volatile organic compounds (4.1%), and VOCs (4.5%) from steel, aluminium, copper, and glass fibre production processes.

Transport contributes 2% to photochemical oxidant creation which is primarily from shipping operations. End-of-life recycling provides a credit of around -38% of potential impacts. Vestas' production and operations contribute about 2% overall to this impact category.

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



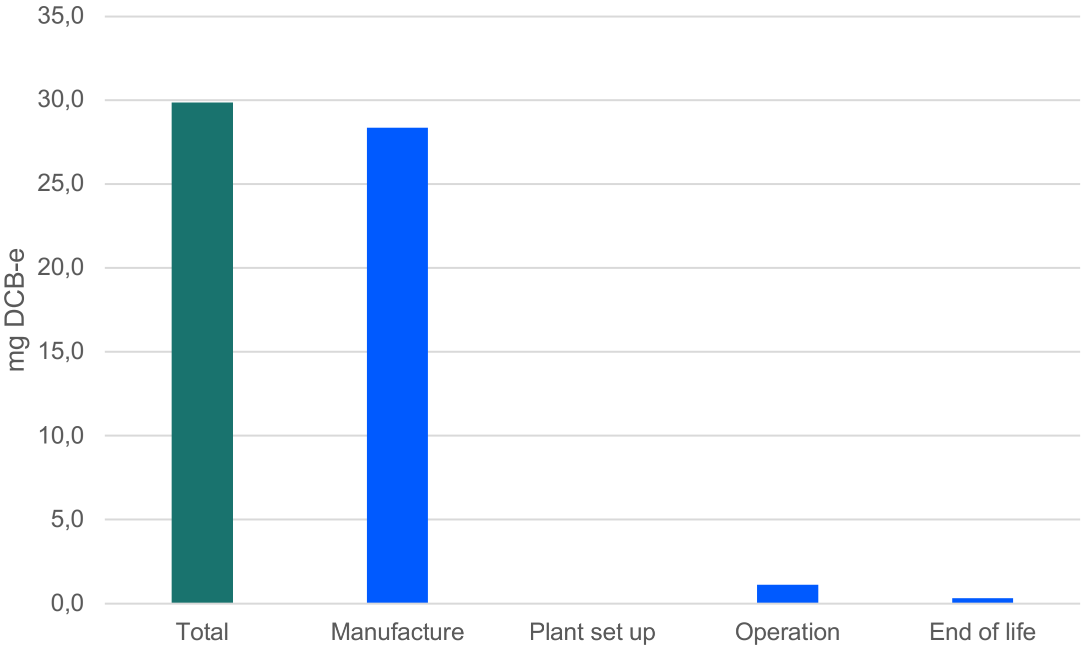
5.2.10 Terrestrial ecotoxicity potential

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 (85%), as well as heavy metal emissions to soil (11%). The heavy metals relate mainly to chromium, and mercury. These emissions mainly result from the production of metals used in the turbine, particularly production of, cast iron, steel, and stainless steels and in the gear and main shaft (34%), nacelle (26%), hub (17%), tower (8%), and blades (5%).

End-of-life recycling provides a negative credit (of around +1%). This is due to a discrepancy in values of the steel dataset and the steel scrap dataset due to the steel recycling scrap value which causes an overall detrimental impact. Vestas' production and operations contribute around 1% 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 CML-impact indicators

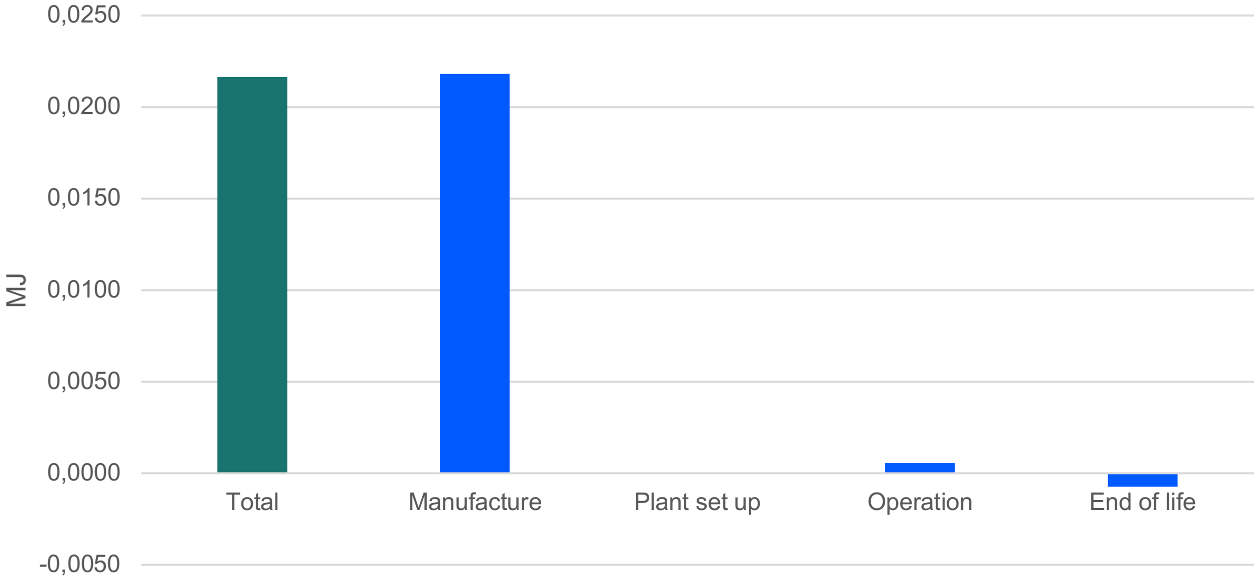
This section provides an analysis of the non-CML impact related indicators for the life cycle assessment.

5.3.1 Primary energy from renewable resources (net calorific value)

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

Figure 18 shows the consumption of primary energy from renewable resources per kWh of electricity produced by the power plant. As with other results in the LCA, the manufacturing stage dominates the life cycle. Within the manufacturing stage, the most significant components are gear and mainshaft (18%), tower (18%), blades (16%), nacelle (13%), hub (10%), site cables (5%), foundations (3%). Vestas' production contributes with 14% to this indicator. The end-of-life provides a negative 3% credit due to discrepancy in the steel scrap and steel plate datasets from renewable sources like hydropower. The contributions to this indicator mainly arise from wind energy, hydropower and solar energy.

Figure 18: Contribution by life cycle stage to Primary energy from renewable resources (net calorific value) per kWh



5.3.2 Primary energy from non-renewable resources (net calorific value)

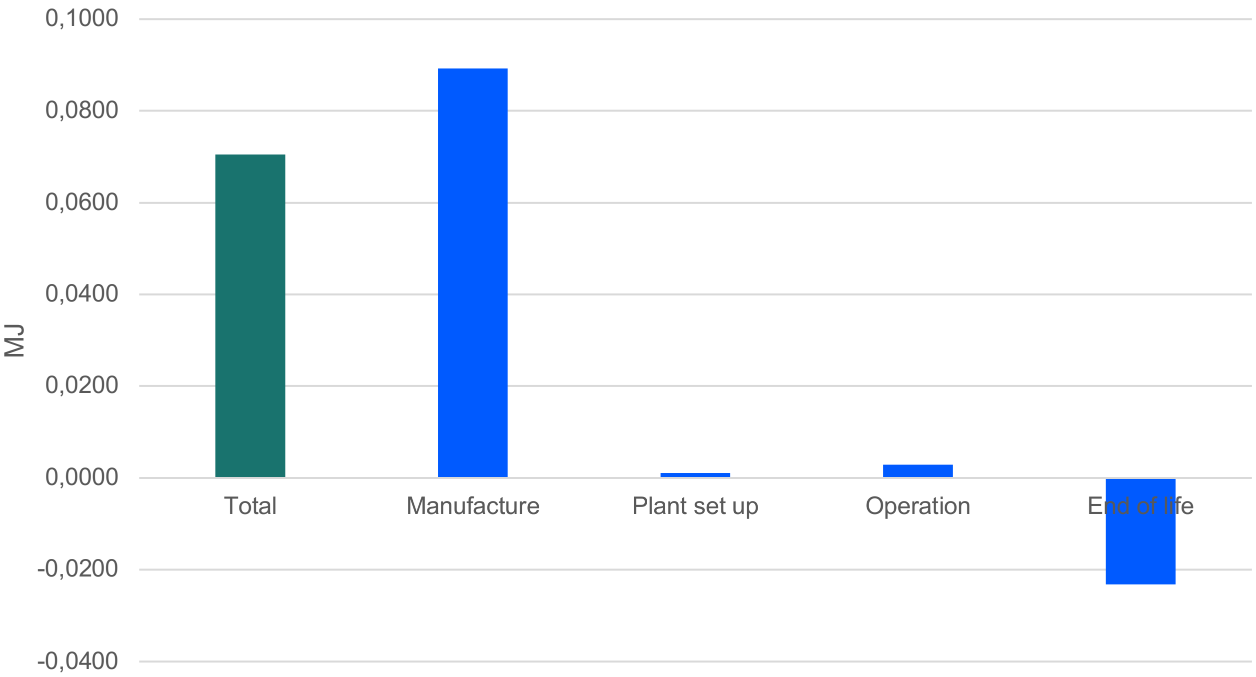
Primary energy from resources provides a measure of the consumption of non-renewable energy over the life cycle, for example, from coal, oil, gas and nuclear energy, measured in MJ.

Figure 19 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, followed by the operation stage and the plant set-up stage, with end-of-life also providing a credit for this indicator.

Within the manufacturing stage, the most significant components are tower (28%), blades (20%), nacelle (11%), foundation (9%), hub (7%), site cables (7%). The end-of-life phase provides a credit of -25%.

Vestas' production contributes <1% to the total life cycle. The contributions to this indicator mainly arise from coal (43%), natural gas (24%), oil (10%), and uranium (5%).

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



5.3.3 AWARE water scarcity footprint

The AWARE water scarcity footprint method (Boulay, 2018) determines the water scarcity footprint based on available water remaining per unit area of watershed relative to the world average after water demand for human and aquatic ecosystems. This method is in accordance with the ISO 14046 standard for water footprint.

This section is currently not included in the report due to an inconsistency in the dataset modelling for plate steel provided by worldsteel (2019) and cast iron in the Sphera database (2024). where it has not been possible to evaluate the full life-cycle results in the current LCA. These results are excluded from the report until further clarifications or updates are completed.

5.3.4 Blue water consumption

Blue 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.

This section is currently not included in the report due to an inconsistency in the dataset modelling for plate steel provided by worldsteel (2019) and cast iron in the Sphera database (2024), where it has not been possible to evaluate the full life-cycle results in the current LCA. These results are excluded from the report until further clarifications or updates are completed.

5.3.5 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 method Vestas applies to calculate product recyclability has been updated and expanded to better capture all wind turbine material fractions and to provide greater transparency in the reporting of recyclability at different stages in the end-of-life (EoL) value-chain. Additionally, the goal is to be aligned with latest recyclability and circular economy methods and standards (ISO, 2024b,c,d).

In order to assess recyclability in the context of circular economy and Vestas Circularity roadmap, a more extensive procedure has been developed and applied in the LCA that also measures the recyclability of the non-metal fraction and to more transparently reflect recyclability at different stages in the value-chain, where those actors in the value-chain have responsibility to deliver highly recyclable/recycled secondary raw materials (Vestas, 2024).

5.3.5.1 Recyclability of turbine

The recyclability of V163-4.5MW turbine is evaluated using an updated method in this LCA report compared to previous published ISO LCAs, which considers recyclability in the context of product disassembly rates, material separation and material recycling treatment rates assigned to each material/component in the turbine. Input data for recyclability are based on 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; as well as recyclability rates from European reports, industry associations, scientific literature, etc.

Additional details and industry data sources utilised are summarised in Annex A.4. Table 11 presents the recyclability rates for the complete turbine.

Table 11: Recyclability by life-cycle stage (not life cycle based, turbine only)

	Recyclability by life-cycle stage		
	1. “Recyclability of designed ‘as-built’ turbine”	**2. “Recyclability after disassembly” of turbine**	**3. “Recyclability after recycling treatment” of turbine**
V163-4.5MW turbine-only	98.5%	98.1%	94.6 to 85.3%

Note: actual recycling rates may vary, when considering project specific factors and regional waste management practices, which may lead to lower “real world” recyclability.

In relation to previous published LCAs, then the recyclability for the V163-4.5 MW turbine comparable to previous onshore wind turbine. The previous measure of “recyclability” only included metal fraction of the turbine (in 2023 and earlier), while in LCAs published in 2024 onwards, then blade recycling technology was also included. The range in “recyclability” results is most closely comparable to the measure “3. Recyclability after recycling treatment” compared to results reported in previous LCAs.

Furthermore, the percentage range shown in “3. Recyclability after recycling treatment” (of 85.3% to 94.6%) is presented as a range to also reflect the range in recyclability efficiency ranges of recycling treatment technologies, for example, where steel recycling could potentially range from around 92% to 98%. Other materials fractions also consider different ranges in potential recycling rates.

In reporting performance, Vestas aims to show a reasonable or conservative case and do not intend to overstate performance. As such, and where possible a range in results for recyclability has been reported which aims to account for potential “high” and “low” recyclability rates, according to industry and published data gathered, as shown in Table 11. It is expected that as technology improves and process losses also improve, along with advances in end-of-life treatment and further investment circular economy initiatives, then recyclability will increase over time.

Furthermore, it is important to note that actual recycling rates may vary when considering project specific factors and regional waste management practices, etc. which may lead to lower “real world” recyclability values when comparing to the calculated recyclability.

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

This section presents an indicator to measure the Circularity of the present V163-4.5MW turbine. 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, which 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); and
- making more intensive use of products (e.g. via service or performance models).

Indicators covering these principles 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 needs to be evaluated in the context of other potential environmental impacts,

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; and
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 formula has been developed (EMF, 2015) which provides a score ranging from 0 to 1, where 1 indicates a maximum Circularity. For this wind turbine, the indicator has been calculated for the turbine-only and excludes site parts, such as the foundations, site cables and substations, as well as the other upstream and downstream elements of the product system according to LCA. This limited scope is consistent with turbine *Recyclability* indicators (shown in Section 5.3.4).

5.3.6.1 Circularity indicator results

By applying the formula, further explained in Annex A.4, the Circularity score for the V163-4.5MW turbine ranges between 0.66 and 0.70. Accordingly, between 66% and 70% of the turbine's materials are managed in a closed-loop way, while the remaining 30% to 34% of materials act in a linear manner.

The calculation of Circularity index of the V163-4.5MW turbine has been carried out in as shown in Table 12. The applies the recycling credit rates shown in Table 3, Section 3.4.4.

Table 12: Circularity index of the V163-4.5MW turbine

Name	Variable	Unit	Formula	Value
Turbine weight	M	tonne		10769
Virgin feedstock	V	tonne	$(M - \mathrm{FR.M} - \mathrm{FU.M})$	6935
Recycled feedstock	$F_R.M$	tonne	$\mathit{Scrap\ content\ of\ metal\ proportion\ of\ the\ turbine}$	3834
Components reused	$F_U.M$	tonne	$\mathit{Not\ included}$	0
Components collected for reuse	$C_U.M$	tonne	$\mathit{Not\ included}$	0

Material collected for recycling	$C_R.M$	tonne	*100% of the turbine is collected for recycling*	10769
Material going to landfill/energy recovery	W_O	tonne	$M - metal\ content\ and\ blade\ mass\ of\ the\ turbine$	145
Waste from recycling process	W_F	tonne	$M * \frac{(1-EF)FR}{EF}$ *Fraction of feedstock from recycled sources. FR:0.34* *Efficiency of recycling process used to produce recycled feedstock for a product. EF:0.97*	246
Utility	X		$\frac{lifetime\ (20\ years)}{industry\ average\ lifetime\ (20\ years)}$	1
Unrecoverable waste from recycling	W_C	tonne	$(1 - EF) * metal\ content\ of\ the\ turbine$	566
Total waste	W	tonne	$W_O+W_F+W_C$	958
Linear flow index	LFI		$\frac{(V+W)}{2.M+\frac{WF-WC}{2}}$	0.37
Material Circularity Index	MCI		$\left(1 - LFI * \left[\frac{0.9}{X}\right]\right)$	0.67

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 Sphera MLC Databases 2024.2. This gives a recycled input of around 36% 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, polymers, electronics, electrics parts and fluids which is based on the same scope as the *Recyclability* indicator (see Section 5.3.4) which estimates recycling efficiency and losses by major turbine component. This indicates that between 85.3% and 94.6% of the turbine total weight is usefully recycled at end-of-life. The wind turbine lifetime is evaluated to be equal to the industry average of 20 years design lifetime.

Turbine components having a high metal content, for example towers and large iron castings also have a high Circularity score because of their high recyclability rate at end-of-life, as well as a proportion of recycled-content input raw material; however, components heavy with polymers or electronics are generally low in Circularity score, due to higher proportion of virgin material inputs and may not always have viable recycling processes at end-of-life, depending on local infrastructure and technology at time of disposal. Several strategies could be implemented in order to close the loop, thus improving the circularity of the product:

- 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 both efficiency and viability of recycling processes.

Data availability would also need to be improved if improvements are to be measured; suppliers' specific data for recycled content would be needed, rather than using industry average datasets, as currently. Additionally, recycled material quality should be considered further, in general, from a wider circular economy perspective.

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, therefore, should not be evaluated in isolation.

Based on the method outlined hereabove, the Circularity score for the V163-4.5MW turbine ranges between 0.66 and 0.70 depending on the recyclability efficiency after the recycling treatment. As such, this estimates that between 66% and 70% of the product's materials are managed in a restorative or circular nature, while the remaining 34% to 30% of materials act in a linear manner.

In order to improve Circularity performance the following example was applied:

- increasing the recycled-content of steel to 60% (from 36% baseline) would improve the Circularity score quite significantly from 0.70 to 0.77.

6 Return-on-energy from V163-4.5MW 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:

   $$\text{Net energy payback (months)} = \frac{\text{life cycle energy requirement of the wind plant (MJ)}}{\text{electrical energy output from the wind (MJ)}} \times 360$$

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:

   $$\text{Primary energy payback (months)} = \frac{\text{life cycle energy requirement of the wind plant (MJ)}}{\text{primary energy input of EU average grid (MJ)}} \times 360$$

Following the net-energy approach, as defined above, the breakeven time of the onshore V163-4.5MW wind plant is 6.1 months for medium (IECS) wind. This may be interpreted that over the life cycle of the V163-4.5MW wind power plant, the plant will return 39 times more energy back than it consumed over the plant life cycle.

The results of the second approach estimate 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 V163-4.5MW wind plant of 2-3 months for medium (IECS) wind conditions, for this indicator when assessing example electricity mixes for United States and Brazil. 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 for this 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-two V163-4.5MW 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 V163-4.5MW 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.

The impacts of transport of the turbine from Vestas production locations to the wind plant erection site are also reasonably significant (between <1% and 14% depending on impact category). Transport includes specific fuel use (and vehicle utilisation) data for the transport of specific turbine components (for towers, hub, 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, in different geographies based on their supply chain, results in reasonably significant life cycle impacts.

In general, the parts of the wind power plant 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 foundations, site cables, turbine tower, nacelle, and blades. Previous LCA studies of Vestas turbines (PE, 2011, Vestas 2011a,b,c, Vestas 2013a,b, Vestas 2014a,b,c,d, 2015a,b,c, 2017a,b,c,d,e and 2022a) have shown similar results.

When considering Vestas production facilities only, the results show that the impacts of fuels and electricity contribute around <1% to 4% of all potential environmental impacts. This is similar in scale to previous LCA studies of Vestas turbines. The LCA is temporally representative of 2023.

The contribution of specific substance releases to and extractions from the environment are not listed specifically here (refer to Section 5.2); however, the consumption of iron, steel, aluminium, and copper (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 operate under (i.e. low wind class) 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 medium (IECS) wind speed has been chosen for the wind-class, which represents a typical ‘virtual’ power plant and is a reasonable assumption. 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 turbine’s 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 over 20 years, 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 90.000 wind turbines around the world, equivalent to around 185 GW 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.

The current assessment does not consider the potential impacts of land use change, for example, of the clearance of vegetation when erecting onshore equipment to connect the wind plant to the electricity grid.

Overall, this assessment provides a robust indication of the environmental impacts per 1kWh for the V163-4.5MW wind plant.

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 scenarios:

1. variation in wind power plant lifetime: ± 4 years;
2. variation in frequency of parts replacement;
3. variation in hub height: 113m;
4. varying the transport distances for components to wind plant erection site;
5. high ground water level type foundations;
6. incidence of a potential turbine switchgear blow-out; and
7. potential effects of method used for crediting recycling of metals.

These scenarios represent the most significant assumptions made in the LCA study.

7.2.1 Wind plant lifetime

The design lifetime of the V163-4.5MW turbine is 20 years; however, this may vary depending on the specific conditions of operation and could be up to 30 years lifetime or over. 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 7.2.3 to indicate the significance of that assumption.

Table 13 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 13: 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)
CML-impact potential impacts:				
Abiotic resource depletion (ADP elements)	mg Sb-e	0.13	0.10	0.09
Abiotic resource depletion (ADP fossils)	MJ	0.08	0.06	0.05
Acidification potential (AP)	mg SO_2-e	17	14	12
Eutrophication potential (EP)	mg PO_4-e	2.4	1.9	1.6
Freshwater aquatic ecotoxicity potential (FAETP)	mg DCB-e	47	38	31
Global warming potential (GWP)	g CO_2-e	6.36	5.09	4.24
Human toxicity potential (HTP)	mg DCB-e	1851	1481	1234
Marine aquatic ecotoxicity potential (MAETP)	g DCB-e	665	533	444
Photochemical oxidant creation potential (POCP)	mg Ethene	2.1	1.7	1.4
Terrestrial ecotoxicity potential (TETP)	mg DCB-e	37	30	25
Non CML-impact indicators:				
*Primary energy from renewable resources	MJ	0.03	0.02	0.02
*Primary energy from non-renewable resources	MJ	0.09	0.07	0.06
AWARE water scarcity footprint	g	not assessed	not assessed	not assessed
Blue water consumption	g	not assessed	not assessed	not assessed

* *Net calorific value*

7.2.2 Repair and replacement parts

There may be variation in the level of maintenance and the need for repair or replacement parts for any particular wind turbine power plant. Based on both monitored and calculated data, a typical rate for the repair or replacement of parts is included in the LCA for the V163-4.5MW turbine.

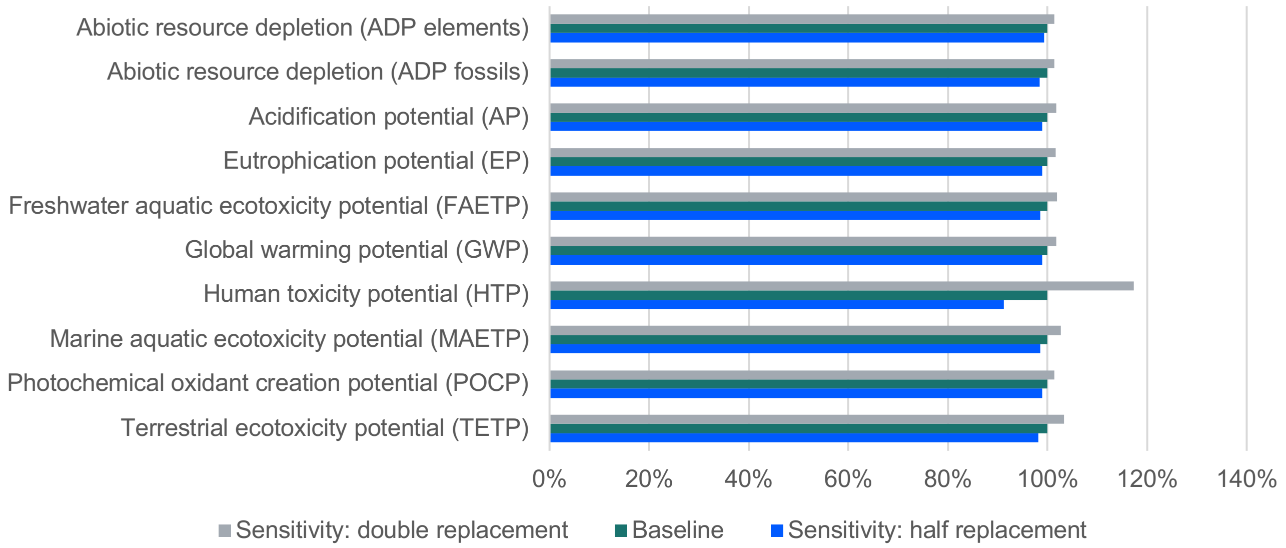
This sensitivity analysis evaluates the effects of doubling the frequency of repaired/replaced parts, which represents an extremely conservative estimate, as well as halving repaired/replaced parts.

Figure 20 shows the results of the sensitivity analysis which shows that doubling of replacement parts has the effect of increasing all impact categories, being human toxicity the most affected category (17.4%), while all other impacts increase by around 1.3% to 3.4%. For abiotic resource depletion elements, the increase generally relates to increased use of high alloy steels and copper, relating to the alloying elements such as molybdenum and chromium, lead, and silver.

Halving the replacement parts has the effect of reducing all impacts, being human toxicity potential the most affected category (8.7%), other categories decrease between -0.7% to -1.8%.

Overall, the result of this sensitivity shows that the V163-4.5MW onshore wind plant is not very sensitive to changes in the frequency of repaired/replaced parts.

Figure 20: Whole-life sensitivity assessment of doubling or halving replacement parts



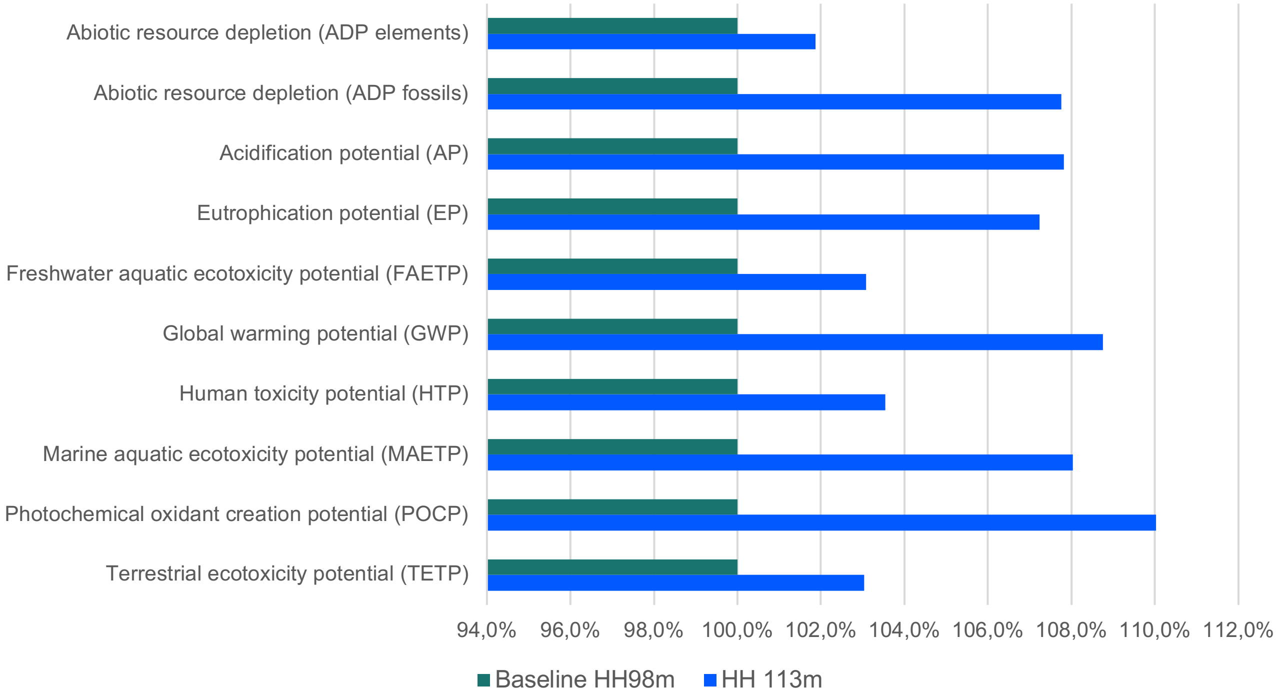
7.2.3 Variation in hub height: 113m

There are different options for height of tower when configuring a turbine for a specific wind plant location. In general, high wind turbines tend to have lower tower heights, while low wind turbines tend to operate on higher towers. The tower height and loading depending on the wind class and site conditions, will affect the amount of steel needed to construct the tower.

This sensitivity analysis evaluates the effect of a 113 metre in medium (IECS) wind condition. This has the effect to increase tower mass by approximately 30%, as well as to increase the foundation weight.

Figure 21**Error! Reference source not found.** shows that increasing the hub height from 89 to 113 metres, considering the same wind speeds and energy production, will increase all potential environmental impacts being assessed. Being Photochemical oxidant creation potential (POCP) indicator the most affected impact category, by increasing a 10%, and Abiotic resource depletion (ADP elements) indicator the less affected impact category, with an increase of 2%.

Figure 21: Whole-life sensitivity analysis of hub height variation to 113m



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 2024 for a US based wind power plant site location.

This sensitivity analysis evaluates the significance of the transport of the wind turbine components from their production locations to the wind plant erection site. To test the sensitivity of the model to a change in transport distances, a Brazil based scenarios has been considered based on the expected sale for this turbine.

Both Brazil and US primarily have all production facilities within that region. It should be noted that this sensitivity does not account for changing any datasets to be region-specific (e.g. for the production of materials or electricity mixes), but only transport distances are adjusted to represent that particular region and supply of parts.

Table 14 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 t.km for the transport of turbine parts compared to the Sphera LCA for Experts default containerised transport datasets.

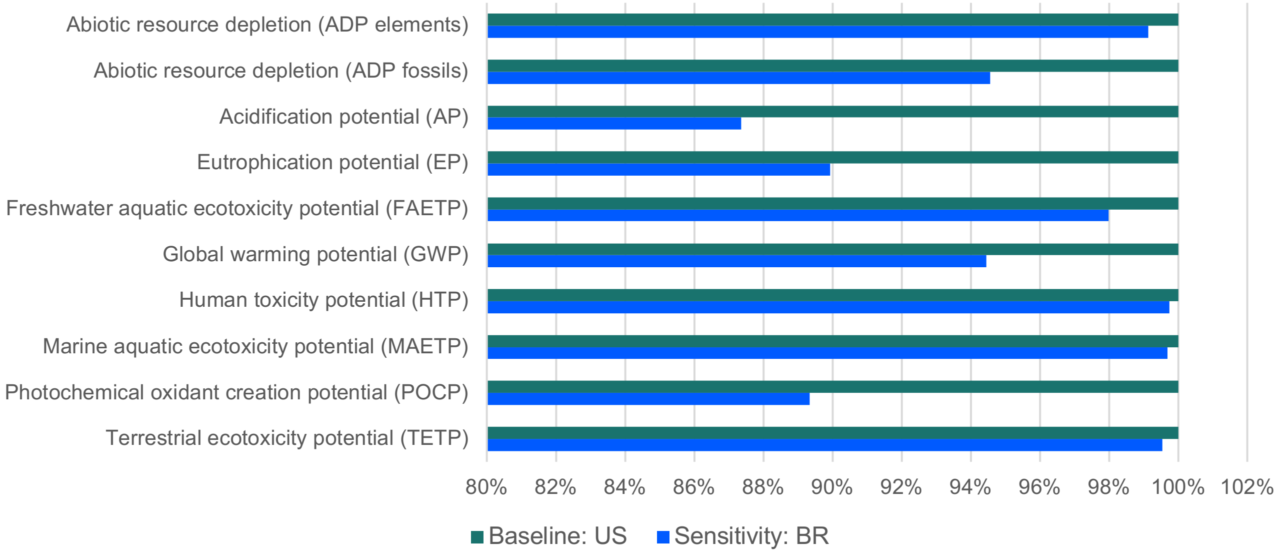
Based on the sensitivity analysis, the baseline scenario represents a conservative assumption.

Table 14: Transport distances for sensitivity analysis of wind plant components

Component	Baseline: US		Sensitivity: BR	
	Truck (km)	Ship (km)	Truck (km)	Ship (km)
Nacelle	2000	0	650	0
Hub	800	8000	650	0
Blades	1600	0	800	0
Tower	1100	0	800	0
Foundation	50	0	50	0
Other site Parts	600	0	50	0

Figure 22 shows the results of the scenario analysis which indicates that for the Brazil sensitivity case study, the results decrease by ~5% compared to the baseline. This is primarily due to shorter distances required for supply chain on the Brazil scenario to transport a good, e.g. reduced shipping of the hub in the particular assumption for supply. As such, the greatest decrease is coming from Acidification potential category, with a decrease of 12.6%.

Figure 22: Whole-life sensitivity analysis of transport distances

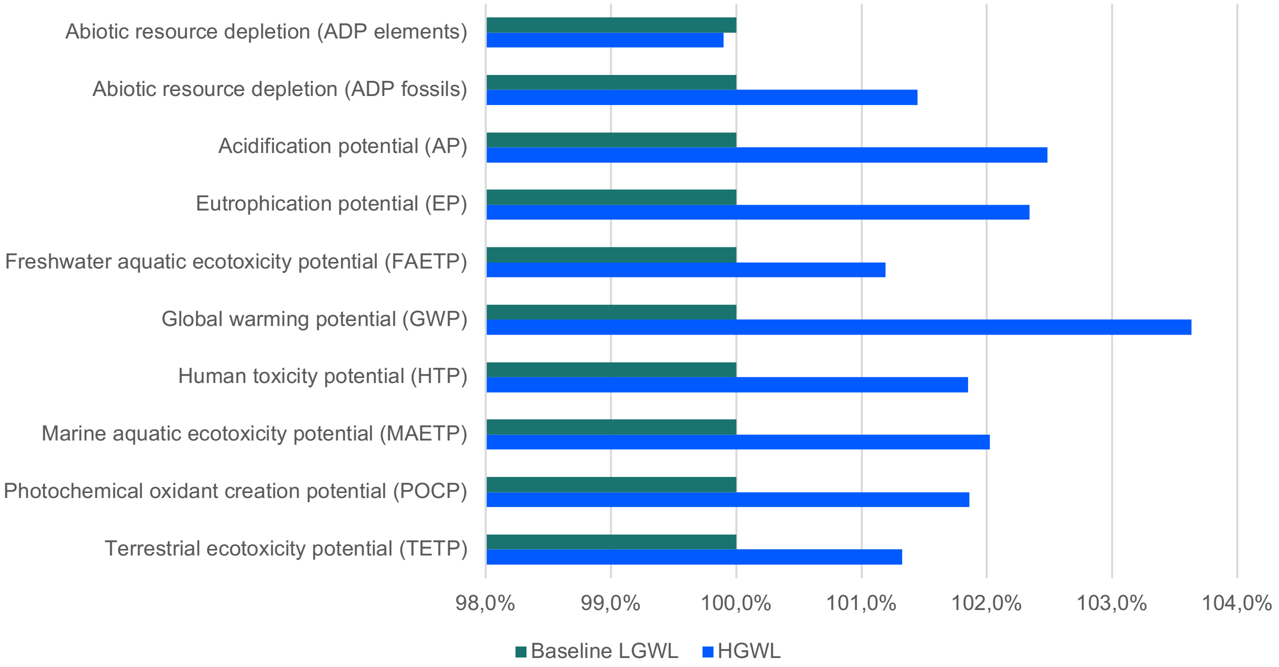


7.2.5 High ground water level type foundations

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 23Figure 23. Whole-life impacts for changing from LGWL to HGWL foundation shows the results of the analysis for the use of the high groundwater level foundation, where the potential impacts increase between 1% and 4% (except for ADP elements, that has a negligible reduction of 0.1%), which indicates that this does not significantly change the environmental impacts. The increase in potential impacts directly correlates to the increased use of steel and concrete for this foundation type.

Figure 23. Whole-life impacts for changing from LGWL to HGWL foundation



7.2.6 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. This corresponds to 0.00025 blow outs over a period of 20 years, which is the lifetime of the wind plant assessed. For a power plant containing twenty-two V163-4.5MW turbines, this would result in a release of approximately 114g of SF_6 over the lifetime, which equates to below 0.01% of the total global warming potential impacts.

7.2.7 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.

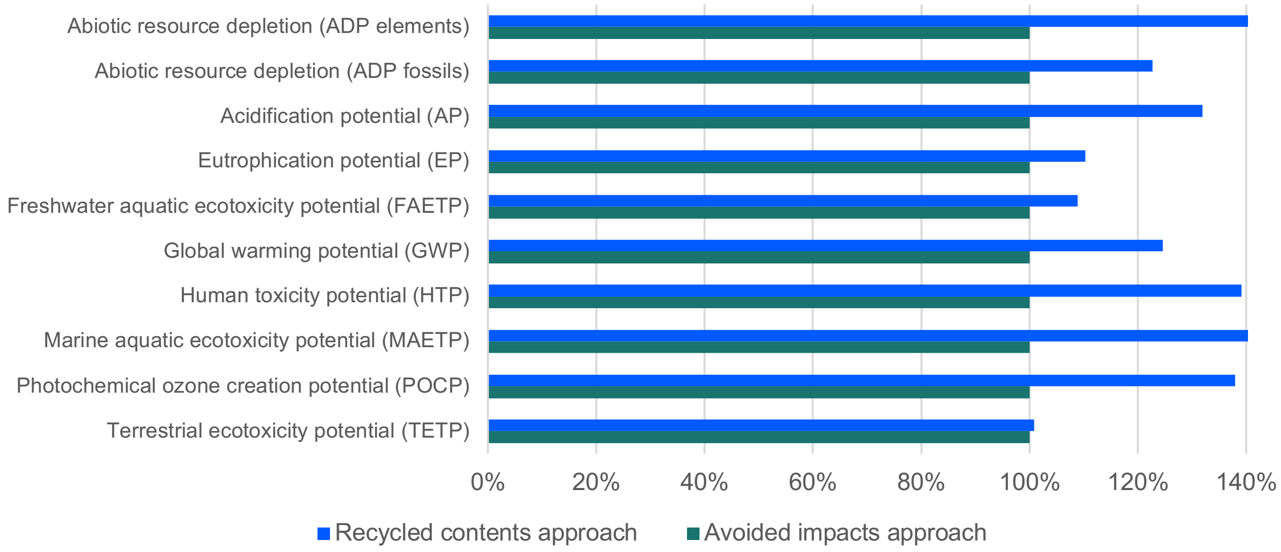
An alternative approach is to use a *recycled-content approach*, whereby environmental credits are received for the incoming raw-materials used to manufacture the wind-plant based upon the actual recycled material content of the wind turbine. For this approach no credit is given at end-of-life but received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

Around 85% of the wind-turbine itself is constructed from metal components (primarily iron and steel, as well as copper and aluminium) and of the wind-plant components around 93% are constructed from metal components, of which 56% is removed at end-of-life for recycling (in baseline scenario). 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 24 shows the results of the assessment which indicate that across all impact categories these increase between 5% and 29% compared to the baseline, with the exception of terrestrial ecotoxicity potential (-2%). The global warming potential increases by 22%.

Figure 24: Whole-life impacts using a recycled-content approach for metal recycling credits



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 2023, 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.

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 26.600 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[9], Eurofer, Plastics Europe, as well as (Sphera 2024) generated datasets. These are, in general, considered to be of good or high quality. The updated Sphera datasets seem generally to be in alignment also with previous datasets.

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 for 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, hub, 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.

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[9] Note: Vestas identified an issue with the worldsteel dataset relating to EU/GLO structural steel plate. Essentially, for this dataset, one particular emission (for nickel to water) is negative net mass overall, which results in an overall negative freshwater aquatic ecotoxicity impact for LCIA results, which is an anomaly. In communication with worldsteel, Vestas has adjusted the nickel flow to previous database value and used this adjusted LCI for plate steel in the current LCA for results generation. Essentially, this removes an anomaly that exists for a single “outlier” plant where an industrial water input and emission of cooling water to the river miss a nickel emission factor.

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 100 MW wind power plant consisting of V163-4.5MW 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:

- to assess the indicator for the AWARE water scarcity footprint and the indicator for ‘Blue water consumption;
- to include sensitivity analysis that reflect a wider range of scenarios, e.g. HGWL foundation, higher/lower distances to grid; and
- to account for crediting of blade raw materials at the end-of-life in baseline results scenario, which are currently excluded.

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Annex A Impact category descriptions

A.1 Impact category descriptions

The following impact categories, as used by CML (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)
- Terrestrial ecotoxicity potential (TETP)

Non CML-impact indicators:

- Primary energy from renewable resources (net calorific value)
- Primary energy from non-renewable resources (net calorific value)
- AWARE water scarcity footprint
- Blue water consumption
- Turbine recyclability (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 resources. 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 freshwater 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 CML-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.
- The indicator for water scarcity footprint has been introduced in this environmental assessment called AWARE water scarcity footprint method (Boulay, 2018). This method supersedes the water use method used in previous LCAs (along with the 'Blue water consumption' indicator). This indicator determines the water scarcity footprint based on available water remaining per unit area of watershed relative to the world average after water demand for human and aquatic ecosystems.
- 'Blue water consumption' is assessed which refers to water withdrawn from ground water or surface water bodies. The blue water inventory includes all freshwater inputs but excludes rainwater. The water input flows refer to total water use. To quantify total freshwater use, all freshwater input flows are summed up. For impact assessment, only blue water (i.e., surface and groundwater) is considered. Sea water and rainwater is also excluded from the aggregation.
- Turbine recyclability (not life cycle based, turbine only) – refer section 5.3.4 and Annex A.4 for detail on turbine recyclability.
- Turbine circularity (not life cycle based, turbine only) – refer Annex A.5 for detail on turbine circularity.

A.4 Recyclability (not life cycle based, turbine only)

This Section A.4 explains in more detail the recyclability indicators. As mentioned in Section 5.3.5, 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 method Vestas applies to calculate product recyclability has been updated to a more extensive, transparent and aligned with both Vestas Circularity roadmap and with international standards.

A.4.1 Alignment with international best practice

It should be noted that, in accordance with ISO 59020:2024 (ISO, 2024c). the '**3. Recyclability rate after recycling treatment'** defined above aligns with the '**percent design recyclability rate of the outflow'** measure under ISO 59020:2024. It is important to note that actual recycling rates may vary when considering project specific factors and regional waste management practices, etc. which may lead to lower "real world" recyclability values when comparing to the calculated recyclability.

The updated method measures the 'practical recyclability' rather than 'real recyclability' and as such, the proposed method does not intend to align with the ISO 59020:2024 (ISO, 2024c) measure '**percent of actual recycled material derived from outflow'.** This measure will account for site specific and regional waste management systems, etc. and is more appropriately applied by a Vestas customer or local recycling contractor to measure 'real' recyclability.

The text below provides further description of the updated method for measuring recyclability in the context of circular economy, including some of the concepts applied and data sources for calculations.

A.4.2 Circular economy

In 2024, the ISO 59000 family of standards was published which is designed to foster a shift towards a circular economy. These standards aim to help organisations contribute to the United Nations Agenda 2030 for Sustainable Development by facilitating the transition to circular use of resources. They set out key terms and concepts, a vision for a circular economy, core principles and practical guidance for delivering on sustainability goals (ISO, 2024b,c,d).

According to ISO 59004:2024 in Circular Economy (ISO, 2024b) recyclability is one of the elements of organisations activities that interacts with the circular economy. Measuring recyclability helps to determine the circularity performance of an organisation and its products.

Relating to recyclability measurement, ISO 59020:2024 defines two distinct product outflow metrics, as listed below:

1. the percent of actual recycled material derived from outflow; and
2. the percent designed recyclability rate of the outflow.

The updated Vestas recyclability method (Vestas, 2024) is ultimately aligned with the second metric listed above; but further introduces the concept of value-chain stages (or actor responsibility) in its definition to measure recyclability at different points in the value-chain, as described further.

A full method document (including definitions and concepts, benchmarking various best practice and international standards and updated method definition) is defined in the Vestas report "*Updated Method to Assess Recyclability of Vestas Wind Turbines* (Vestas, 2024)" and forms the primary definition of the Vestas updated method.

A.4.3 End of life value-chain phases/actors

In order to measure recyclability of Vestas' wind turbines it is important to understand and define the end-of-life treatment value-chain.

In 2020, WindEurope launched a Task Force for wind turbine Dismantling and Decommissioning to produce guidelines for sustainable decommissioning, with the aim of elaboration into an international standard through the International Electrotechnical Commission (IEC/TS, 2023). In general accordance with these documents, there are the following main stages occurring at end-of-life of a wind plant:

1. **Dismantling / disassembly:** involving a set of activities of demounting and disintegrating waste wind turbine components by a manual or mechanical way for the convenience of treatment.
2. **Preparation for recycling:** disassembled wind turbine components should be collected and stored according to different materials.
3. **Separation, storage and transport:** dismantled equipment components and materials/waste are classified and collected according to functions and storage requirements, as well as hazardous waste, for onward transport to final treatment.
4. **Treatment to perform recycling, refurbishment or reuse**: considering methods according to the waste hierarchy.

Each actor in the end-of-life value-chain is responsible to efficiently minimise waste and maximise recovery of all materials and resources at each stage for the activities they are responsible to perform.

From a manufacturer perspective, Vestas is responsible to design, manufacture and deliver a product to our customers that can be considered fully recyclable. Vestas' customers purchase and own the wind turbine asset and are responsible for initiating the end-of-life decommissioning and subsequent treatment.

At end-of-life, the wind-plant site will be dismantled/disassembled (typically by contractors) into components/materials and sent for onward treatment to material/waste processing contractors for recycling, recovery or reuse.

In order for Vestas to adequately measure recyclability of wind turbine products, we need to distinguish the responsibilities in the end-of-life value-chain; and therefore, where the recyclability measurement should begin and end, whilst also accounting for practical recyclability.

At each stage in the value-chain, a different actor has a different responsibility (which is ultimately to minimise losses) to achieve 100% recyclability, as follows:

1. **Manufacturer:** perform activity to design and manufacture a turbine product that can be disassembled into components/materials that are technically and commercially recyclable;
2. **Dismantler/disassembler:** perform activity to dismantle/disassemble components/materials into separate fractions with minimal losses to be sent for onward treatment (for reuse, recycling or refurbishment); and
3. **Treatment handler/recycler:** to receive components/materials and perform the reuse, recycling or refurbishment of these for next use, with minimal loss.

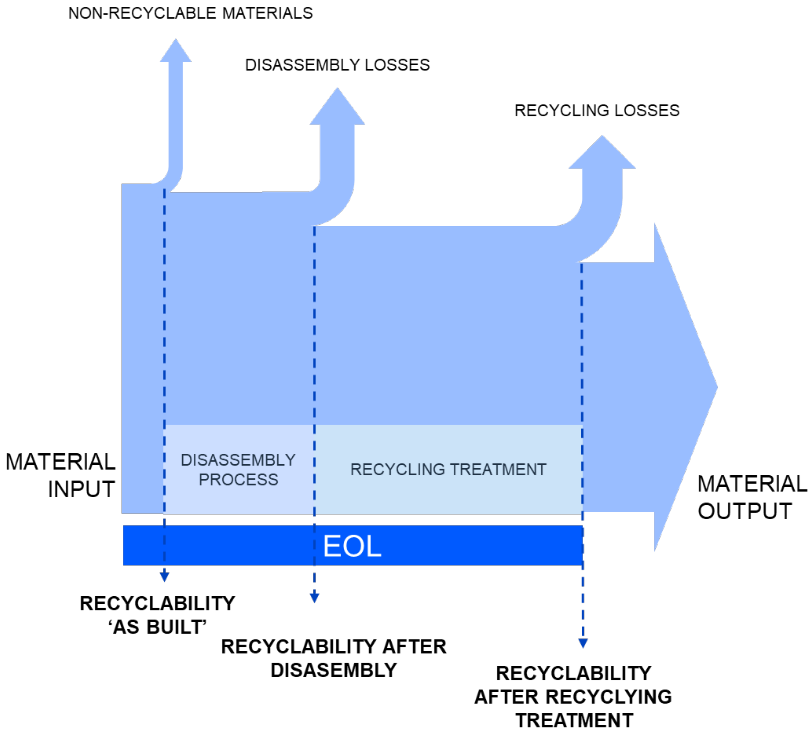
Each stage encompasses consecutive and interlinked steps from when the product is designed and manufactured through to the EoL stage for dismantling/disassembly through to final treatment.

Figure A 1 depicts and distinguishes three phases in the end-of-life value-chain to measure recyclability of the wind turbine according to the different main phases of activity (and those actors responsible for each phase); therefore, defining where the recyclability measurement should begin and end for each actors' activities in the EoL value-chain.

It should be noted, that the end-point of the recyclability measurement (i.e. after recycling treatment) shown in Figure A 1 aligns with the definition of the 'percent designed recyclability rate of the outflow' under ISO standards for circular economy (ISO, 2024c).

In summary, Vestas aims to provide transparency in measuring recyclability at each main stage of the of the end-of-life value-chain, as defined in this section, with the final measure after EoL treatment being aligned with ISO standard for circular economy; however, in relation to the Vestas' global targets for recyclability (e.g. 100% rotor recyclability), then recyclability will be measured at the value-chain stage of the "as-built turbine" at the factory gate.

Figure A 1. Measurement of recyclability at different life-stages in the end-of-life value-chain



A.4.4 Calculation definition

The calculation of the recyclability involves of two main steps for each of the three value-chain stage measures:

1. prepare the component and material breakdown of the wind turbine; and
   a. define turbine configuration for evaluation of recyclability
   b. based on LCA model:
      i. compile BoM of wind turbine configuration
      ii. map material composition to at least 99.5% (by weight) of components in BoM

    c. develop raw material breakdown of the blade, hub, nacelle and tower
2. apply the recyclability rates for each material or component

The updated method evaluates recyclability at three different levels of the EoL (as presented Figure A 1. Measurement of recyclability at different life-stages in the end-of-life value-chain):

1. **Recyclability of designed “As-built Turbine” and “As-built Rotor”**: Recyclability is assessed at the point where the end-of-life begins (or essentially based on the as-built product BoM). Materials or components are applied a binary figure of 0% or 100%, based on disassembly and recyclability principles.

Equation 1

$$\text{Recyclability ‘as-built’ (\%)} = [\text{sum for all part materials}]\ \frac{\text{recyclability factor (\%)} \times \text{total material/component mass (kg)}}{\text{Total material/component mass (kg)}}$$

2. **Recyclability after Disassembly:** Recyclability is assessed after wind turbine components are dismantled and disassembled into materials and components. Material losses during disassembly are applied from a range of 0% to 100%, based on disassembly principles and data.

Equation 2

$$\text{Recyclability after disassembly (\%)} = [\text{sum for all part materials}]\ \frac{\text{recyclability factor (\%)} \times \text{disassembling rate (\%)} \times \text{total material/component mass (kg)}}{\text{total material/component mass (kg)}}$$

3. **Recyclability after Recycling treatment:** Recyclability is evaluated after recycling treatment processes are complete. Material losses during recycling (and any further material separation) are applied from a range of 0% to 100%, based on principles e.g. technology readiness level and data for treatment rates.

Equation 3

$$\text{Recyclability after recycling treatment (\%)} = [\text{sum for all part materials}]\ \frac{\text{recyclability factor(\%)} \times \text{disassembling rate(\%)} \times \text{recycling efficiency(\%)} \times \text{total material/component mass (kg)}}{\text{total material/component mass (kg)}}$$

A.4.5 Input data

Currently, the information for disassembly rates of metal 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.

The material separation and material recycling treatments are assigned to each material/component based on standards, European reports, industry associations, scientific literature, etc. Further details are included in Vestas method document and templates (Vestas, 2024).

During 2024, the recyclability of blades has been adjusted to reflect the latest development in technology related to the CETEC (Circular Economy for Thermosets Epoxy Composites – a novel chemical disassembly process that Vestas is currently focusing to scale up into a commercial solution), which Vestas spearheaded. This means that all epoxy-infused blades are classified as 100% recyclable.

In reporting performance, we do not wish to overstate performance. As such, where assumptions in data are applied, then these should be based on a conservative approach; therefore, where possible a range in results for recyclability has been reported.

Again, it is important to note that actual recycling rates may vary when considering project specific factors and regional waste management practices, etc. which may lead to lower “real world” recyclability values when comparing to the calculated recyclability.

Additionally, it is expected that data inputs for calculations should be updated periodically to represent when a new wind turbine product is released or updates in technology readiness, etc.

A.5 Circularity Indicator

Section A.5 presents the formula developed by Ellen McArthur Foundation (EMF, 2015) for the calculation of the circularity indicator, present in this report in section 5.3.6, which quantitatively measures the degree of a closed/open loop of the material flows into a product/system.

The formula provides a score ranging from 0 to 1, where 1 indicates a maximum Circularity. 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 indicator (shown in Sections 5.3.4).

Circularity formula

The Material Circularity Indicator (MCI) is calculated using the following formula as described below and in Figure A 2.

Figure A 2 Diagrammatic view of the Material Circularity Indicator based on Ellen Mc Arthur Foundation (2015)

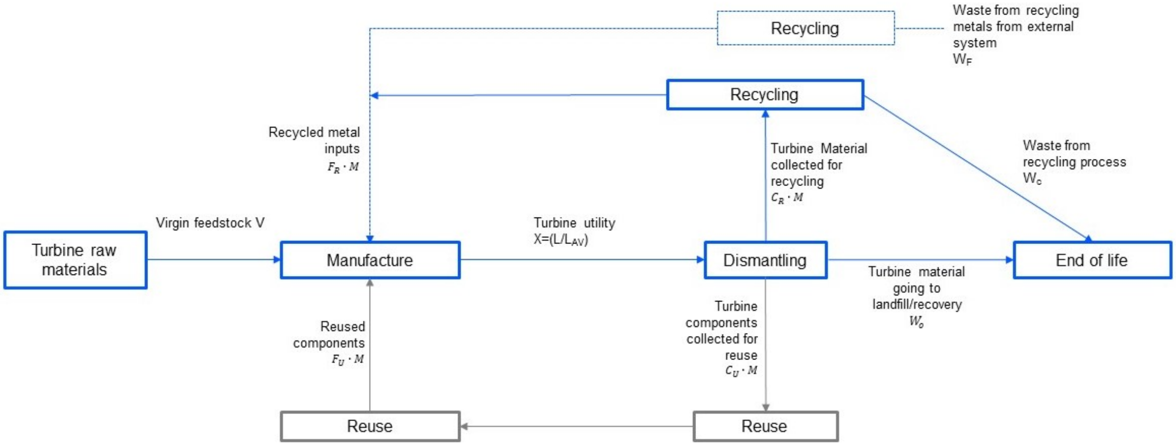


Figure A 2 identifies the basic product flows which are:

- 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; and
- 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 which indicates materials that 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 intensity 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.

Annex B General description of wind plant components

A wind turbine is constructed of around 26,600 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 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 V163-4.5MW gearbox is based on complete bill of materials of the product available with Vestas. The gearbox is composed of cast iron and steel and is modelled by specific grades of these metals.

B1.2 Generator

The generator mainly consists of steel, cast iron and copper. The complete bill-of-materials has been used to model the generator.

B1.3 Nacelle foundation

The nacelle foundation is made from cast iron and produced by suppliers to Vestas (prior to 2013 Vestas owned its own casting and machining facilities, which were then divested).

B1.4 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 produced at Vestas' or outsourced blades factories. Each blade comprises of two structural shell sections and web design. 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 fibrereinforced 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 98 m high and is built for medium (IECS) wind conditions. Other tower heights are available for other site-specific wind conditions for the turbine. Towers are designed for different heights to suit different wind speeds and local site conditions and physical loading.

All towers for Vestas' turbines are purchased from sub-suppliers. In this LCA. data from towers manufactured by Vestas up to the year 2021 has been used.

Towers are manufactured primarily of structural steel. The steel is delivered 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. Subsequently, surface treatment (i.e. sandblasting) and painting of towers is performed.

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 two transformers in the V163-4.5MW turbine 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. 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 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 specifications; however, typically these can be specified by the wind plant developer/Vestas customer.

B.10 Site cables

22 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 wind plant transformer. This cable length consists of various cables with differing aluminium conductor area of 95mm2 (12.1km), 240mm2 (3.3km) and 400mm2 (6.6km), 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.

20 km of high voltage 110kV PEX cables with aluminium conductor (630mm2) 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

There are two 60 MVA transformer has been included in the wind plant. The transformer is modelled from an EPD from Hitachi on a Power transformer 40 MVA and scaled up to 60 MVA (based on MVA rating). These data are updated in the V163 LCA model from previous studies.

Annex C Manufacturing processes

Vestas emissions for manufacturing of turbines is reported on a quarterly basis from each of the more than 100 sites which include all operations and 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.

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 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 15% mass of the turbine itself. Different cast grades are used, such as EN GJS 400 18 LT. EN GJS 500-14 and EN GJS 400.	Steel is primarily used in the tower, nacelle, hub & nose cone (comprising about 69% of the turbine mass), as well as the turbine monopile 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 used in the site cables (around 30%) and the turbine nacelle and tower 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: concrete grades(C12/15,C30/37,C40/50) used Sphera (2024) datasets.
LCI dataset used (where applicable)	-	Datasets include: DE: Cast iron component (EN15804 A1-A3) Sphera	Datasets include: GLO: Steel plate worldsteel GLO: Steel hot dip galvanized worldsteel RER: Fixing material screws stainless steel (EN15804 A1-A3) Sphera DE: Steel billet (42Cr4) Sphera RER: Stainless steel cold rolled coil (304) Eurofer GLO: Steel rebar worldsteel	Datasets include: RER: Aluminium ingot mix - consumption mix Sphera	Datasets include: RER: Concrete C12/15 (Ready-mix concrete) (EN15804 A1-A3) Sphera RER: Concrete C30/37 (Ready-mix concrete) (EN15804 A1-A3) Sphera
Time-related coverage	Data should represent the situation in 2024 and cover a period representing a complete calendar year.	Sphera datasets published in 2024 have been used	Sphera datasets published in 2024 have been used.	Sphera datasets published in 2024 have been used.	Sphera datasets published in 2024 have been used.

Parameter	Requirement	Production LCI datasets for iron	Production LCI datasets for steel	Production LCI datasets for aluminium	Production LCI datasets for concrete
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 infrastructure. Due to geographical availability, the dataset has been considered representative for a US case.	Primarily worldsteel[10], Eurofer and Sphera datasets have been used. These datasets used are considered the most comprehensive and representative available.	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 European infrastructure. Due to geographical availability, the dataset has been considered representative for a US case.	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 European infrastructure. Due to geographical availability, the dataset has been considered representative for a US case.
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 Sphera datasets have been used in the LCA which represent Global averages.	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	A comparison has not been made with other datasets, as these were not readily	Comparison have been made with european worldsteel sources of data, which show lower overall potential impacts. These datasets	In general, comparisons have not been made with other sources of data. Datasets available relate only to	Comparisons have not been made with other sources of data, as only datasets for Europe were available.

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[10] Note: Vestas identified an issue with the worldsteel dataset relating to EU/GLO structural steel plate. Essentially, for this dataset, one particular emission (for nickel to water) is negative net mass overall, which results in an overall negative freshwater aquatic ecotoxicity impact for LCIA results, which is an anomaly. In communication with worldsteel, Vestas has adjusted the nickel flow to previous database value and used this adjusted LCI for plate steel in the current LCA for results generation. Essentially, this removes an anomaly that exists for a single “outlier” plant where an industrial water input and emission of cooling water to the river miss a nickel emission factor.

Parameter	Requirement	Production LCI datasets for iron	Production LCI datasets for steel	Production LCI datasets for aluminium	Production LCI datasets for concrete
	databases, where applicable.	available in Sphera LCA for Experts 10.9 (for cast iron).	used are considered the most comprehensive and representative available.	European average and Germany. The datasets used are considered the most comprehensive and representative 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 analysis.	Dataset is considered internally consistent across the Sphera 2024 database of inventories.	Dataset is considered internally consistent across Sphera 2024 database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across Sphera 2024 database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the Sphera 2024 database of inventories which are generally applied 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 Sphera 2024 and considered accessible to reproduce.	Dataset is published by Sphera 2024 and considered accessible to reproduce.	Dataset is published by Sphera 2024 and considered accessible to reproduce.	Dataset is published by Sphera 2024 and considered accessible to reproduce.
Sources of the data	Data will be derived from credible sources and databases.	Dataset is published by Sphera 2024 and considered credible source.	Dataset is published by Sphera 2024 and considered credible source. Original data sources include: Worldsteel Life Cycle Inventory Study for Steel Industry Products, 2017, and Eurofer publications.	Dataset is published by Sphera 2024 and considered credible source. Original data sources include: European Aluminium Environmental Profile Report, 2018	Dataset is published by Sphera 2024 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 and the site cables for the wind power plant, along with other plant components. The copper grade may vary according to the application in the wind plant.	Polymers are mainly used in the turbine (around 6%), excluding blades, along with the site cables for the plant (64%). The polymer type varies according to the application in the wind plant. But generally, a representative dataset from PlasticsEurope or PE 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 PE 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 of the V163-4.5MW turbine; however few turbines have ever been disposed, reaching operational beyond their design lifetime for other Vestas turbine models.
LCI dataset used (where applicable)	Datasets include: GLO: Copper mix (99.999% from electrolysis) Sphera RER: Copper sheet (A1-A3) Sphera	Datasets include: RER: Polyethylene high density granulate ELCD/PlasticsEurope RER: Polyvinylchloride injection moulding part (PVC) PlasticsEurope DE: Polyethylene Cross-Linked (PEXa) Sphera DE: Ethylene Propylene Diene Elastomer (EPDM) Sphera	Datasets include: RER: Epoxy resin PlasticsEurope DE: Glass fibres Sphera DE: Carbon Fiber (CF; from PAN; standard strength) Sphera	Not relevant.
Time-related coverage	Sphera datasets published in 2024. Technology considered representative for 2024.	Sphera datasets published in 2024.	Sphera datasets published in 2024.	Representative of specific turbine being assessed in reference time period.
Geographical coverage	The GLO: Copper mix dataset is a global dataset and represents consumption mix at consumer. The RER: Copper sheet and RER: Brass component is a European average and represents a technology mix. Due to geographical availability, the	Generally, the dataset represents an average production mix for European infrastructure. Datasets available relate only to European average and Germany. The datasets used are considered the most comprehensive and representative available.	Generally, the dataset represents an average production mix for European infrastructure Datasets available relate only to European average and Germany. The datasets used are considered the most comprehensive and representative available.	Representative of specific turbine being assessed for geographical coverage.

Parameter	Production LCI datasets for copper	Production LCI datasets for polymers	Production LCI datasets for composites	Power plant lifetime
	dataset has been considered representative.			
Technology coverage	The dataset represents a technology mix for primary production. The technology is considered representative.	The datasets represents a technology mix that is considered representative.	The datasets represents a 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	In general, comparisons have not been made with other sources of data. Sphera datasets are the most up-to-date, valid datasets and are therefore considered the most representative available.	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 of the V163-4.5MW is a 20 years which is the standard design lifetime of previous onshore turbine generations.
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 Sphera (2024) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the Sphera (2024) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the Sphera (2024) database of inventories which are generally applied throughout the LCA.	Not relevant.
Reproducibility	Dataset is published by Sphera (2024) and considered accessible to reproduce.	Dataset is published by Sphera (2024) and considered accessible to reproduce.	Dataset is published by Sphera (2024) and considered accessible to reproduce.	Not relevant.
Sources of the data	Dataset is published by Sphera (2024) and considered credible source.	Dataset is published by Sphera (2024) and considered credible source. Original data sources include: PlasticsEurope, Association of Plastics Manufacturers, Brussels.	Dataset is published by Sphera (2024) and considered credible source.	Vestas wind turbine specifications.

Parameter	Production LCI datasets for copper	Production LCI datasets for polymers	Production LCI datasets for composites	Power plant lifetime
		and Boustead LCI database: Boustead model, Horsham, UK 2005.		

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 affected 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 medium 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: GLO: Value of scrap worldsteel EU28+EFTA: Primary aluminium ingot consumption mix (2015) European Aluminium GLO: Copper mix (99.999% from electrolysis) Sphera	Not relevant.
Time-related coverage	Representative of specific turbine being assessed in reference time period.	Sphera datasets published in 2024. Technology considered representative for 2024.	Sphera datasets published in 2024. Technology considered representative for 2024.	The CML (2016) baseline characterisation factors are considered representative for 2024.

Parameter	Power plant electricity production	Transport datasets	End-of-life crediting method and LCI datasets used for crediting	Coverage of LCIA characterisation factors.
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 US 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 represent a European and Asian technology mix that is considered representative.	The datasets represent 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 EF 3.1 impact assessment (2024) and considered reasonably similar for this study compared to CML. Similar components dominate the life cycle impacts, although often different

Parameter	Power plant electricity production	Transport datasets	End-of-life crediting method and LCI datasets used for crediting	Coverage of LCIA characterisation factors.
				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 average low wind conditions.	Dataset in general considered representative for time-related, geographical and technological scope.	The datasets in general considered representative for time-related, geographical and technological scope.	The datasets in general considered representative for time-related, geographical and technological scope.
Consistency	Not relevant.	Dataset is considered internally consistent across the Sphera (2024) database of inventories which are generally applied throughout the LCA.	Dataset is considered internally consistent across the Sphera (2024) 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 Sphera (2024) and considered accessible to reproduce.	Dataset is published by Sphera (2024) 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 Sphera 2024 and considered a credible source. Modified datasets for turbine component transport are specific data from Vestas suppliers.	Dataset is published by Sphera 2024 and considered a credible source. Includes on following reference: European Aluminium Association, worldsteel and Sphera database (2024).	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 assumed at the following wind speeds. This represents the top-end of 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.

It should be noted that, increasingly within the wind industry, turbines are designed for IEC Special wind class, where the average wind speeds may vary slightly from the standard IEC definition, but fall within the IEC range for wind speed. This allows for better optimisation of turbine design to meet market conditions and also improve performance and business-case; as such, the IEC conditions are denoted as "IEC Special" or "IECS" in each low, medium or high wind class.

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 and offshore turbines which are each suited to specific conditions and requirements; Table E2 shows the various wind turbines and their wind classes.

Table E2: Vestas 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)
V90-3.0 MW	X	X		Yes (2012)
2MW Platform				
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)
V110-2.0 MW			X	Yes (2015)
V116-2.0 MW		X		Yes (2018)
V120-2.0 MW			X	Yes (2018)
4MW Platform				
V105-3.3 MW	X			Yes (2014)
V105-3.45 MW	X			Yes (2017)
V112-3.0 MW		X	X	Yes (2011)
V112-3.3 MW	X	X		Yes (2015)
V112-3.45 MW	X			Yes (2017)

Turbine Class	IEC I High Wind	IEC II Medium Wind	IEC III Low Wind	Published LCA of turbine completed (year)
V117-3.3 MW		X	X	Yes (2014)
V117-3.45 MW	X	X		Yes (2017)
V117-4.2 MW	X			Yes (2019)
V126-3.3 MW			X	Yes (2014)
V126-3.45 MW		X		Yes (2017)
V136-3.45 MW		X	X	Yes (2017)
V136-4.2 MW		X		Yes (2022)
V150-4.2 MW			X	Yes (2022)
V163-4.5MW		X		Yes (2025)
EnVentus				
V150-5.6 MW		X		Yes (2022)
V150-6.0MW		X		Yes (2022)
V162-5.6MW	X			Yes (2022)
V162-6.0MW	X			Yes (2022)
V162-6.2MW	X			Yes (2022)
V162-7.2MW			X	No
V172-6.5MW			X	No
V172-6.8MW			X	No
V172-7.2MW			X	No
Offshore				
V164-9.5MW	X			No
V174-9.5MW	X			No
V236-15MW	X			Yes (2024)

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 Sphera DfX software was used to assess the wind turbine production down to the level of individual components. The BOM used contained around 31,800 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 Sphera (2024). The datasets have not been adjusted for any allocation procedures made. Lastly, allocation is also applied to the site transformers, based on MVA rating, which has been scaled up from 40MVA to 60MVA to represent the requirements of the 100 MW wind plant (two pieces per 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. Recycling credits are only applied for metal parts.

F.5 Impact assessment

Uncertainty is also introduced in the impact assessment phase of the LCA, which will vary according to 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 V163-4.5MW 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 100 MW power plant of V163-4.5MW turbines (units shown in mg per kWh)

Flow	Unit	Turbine	Foundation	Site Parts	Plant set up	Replacements/ servicing	End of life	Total
Energy resources	mg per kWh	2,29E+06	2,75E+05	1,68E+05	2,58E+04	8,55E+04	-9,21E+05	1,93E+06
Non renewable energy resources	mg per kWh	2,28E+06	2,72E+05	1,68E+05	2,58E+04	8,51E+04	-8,92E+05	1,94E+06
Crude oil (resource)	mg per kWh	2,94E+05	3,39E+04	6,97E+04	2,28E+04	3,27E+04	1,12E+04	4,64E+05
Hard coal (resource)	mg per kWh	1,28E+06	2,02E+05	3,92E+04	2,46E+02	2,62E+04	-9,17E+05	6,33E+05
Lignite (resource)	mg per kWh	2,18E+05	1,27E+04	1,01E+04	4,10E+01	8,55E+03	8,32E+03	2,58E+05
Natural gas (resource)	mg per kWh	4,85E+05	2,41E+04	4,91E+04	2,70E+03	1,76E+04	6,94E+03	5,85E+05
Material resources	mg per kWh	6,45E+11	3,29E+08	4,37E+09	1,86E+06	1,70E+08	-2,89E+09	6,47E+11
Renewable resources	mg per kWh	6,45E+11	3,22E+08	4,37E+09	1,85E+06	1,69E+08	-2,88E+09	6,47E+11
Water	mg per kWh	6,45E+11	3,21E+08	4,37E+09	1,84E+06	1,69E+08	-2,88E+09	6,47E+11
Deposited goods	mg per kWh	1,52E+07	2,46E+06	1,58E+06	2,46E+03	5,31E+05	-1,01E+07	9,65E+06
Stockpile goods	mg per kWh	1,52E+07	2,46E+06	1,58E+06	2,45E+03	5,31E+05	-1,01E+07	9,65E+06
Overburden (deposited)	mg per kWh	1,34E+07	1,73E+06	1,06E+06	2,11E+03	4,51E+05	-8,56E+06	8,14E+06
Spoil (deposited)	mg per kWh	4,49E+04	5,24E+05	2,33E+04	1,72E+02	9,16E+02	1,77E+04	6,11E+05
Waste (deposited)	mg per kWh	6,80E+04	1,06E+05	8,56E+04	5,54E+01	1,24E+03	3,96E+05	6,57E+05
Emissions to air	mg per kWh	6,10E+07	4,57E+06	4,16E+06	5,68E+05	1,90E+06	-3,10E+06	6,91E+07
Inorganic emissions to air	mg per kWh	4,71E+07	3,77E+06	3,48E+06	5,62E+05	1,49E+06	-4,37E+06	5,21E+07
Carbon dioxide	mg per kWh	5,19E+06	9,14E+05	3,03E+05	4,29E+04	1,54E+05	-2,05E+06	4,55E+06

Carbon dioxide (biotic)	mg per kWh	3,12E+05	1,67E+04	4,41E+03	7,57E+01	1,08E+04	1,21E+04	3,56E+05
Water (evapotranspiration)	mg per kWh	1,90E+06	4,42E+05	5,10E+05	9,55E+05	8,55E+05	3,33E+07	3,32E+07
Water vapour	mg per kWh	9,30E+05	2,73E+06	8,47E+03	3,63E+05	-3,16E+06	1,36E+07	1,36E+07
Organic emissions to air (group VOC)	mg per kWh	2,00E+04	1,62E+03	1,49E+03	2,17E+02	8,03E+02	-4,97E+03	1,91E+04
Methane	mg per kWh	1,73E+04	1,48E+03	1,20E+03	8,89E+01	6,69E+02	-5,04E+03	1,57E+04
Other emissions to air	mg per kWh	1,38E+07	7,94E+05	6,82E+05	5,53E+03	4,10E+05	1,28E+06	1,70E+07
Exhaust	mg per kWh	9,27E+06	3,35E+05	6,28E+05	4,48E+03	2,66E+05	1,68E+06	1,22E+07
Emissions to fresh water	mg per kWh	6,12E+09	2,78E+08	4,37E+09	1,40E+06	1,64E+08	-2,65E+09	8,28E+09
Other emissions to fresh water	mg per kWh	6,01E+09	2,70E+08	4,36E+09	1,31E+06	1,60E+08	-2,65E+09	8,15E+09
Radioactive emissions to fresh water	mg per kWh	1,07E+08	7,73E+06	1,09E+07	9,25E+04	3,44E+06	2,20E+06	1,32E+08
Radium (Ra226)	mg per kWh	1,07E+08	7,73E+06	1,09E+07	9,25E+04	3,44E+06	2,20E+06	1,32E+08
Emissions to sea water	mg per kWh	1,98E+07	2,14E+06	2,55E+06	1,82E+04	3,34E+05	-1,23E+07	1,26E+07
Other emissions to sea water	mg per kWh	1,98E+07	2,14E+06	2,55E+06	1,76E+04	3,33E+05	-1,23E+07	1,26E+07
Cooling water to sea	mg per kWh	1,49E+07	1,61E+06	1,48E+06	1,73E+04	2,61E+05	-8,61E+06	9,71E+06
Processed water to sea	mg per kWh	4,84E+06	5,22E+05	1,06E+06	3,16E+02	7,24E+04	-3,65E+06	2,85E+06
Emissions to agricultural soil	mg per kWh	7,93E+00	9,06E-01	6,35E-02	9,73E-03	1,68E-01	-3,08E+00	6,00E+00
Heavy metals to agricultural soil	mg per kWh	6,26E-01	1,53E-01	1,34E-02	8,66E-03	-2,01E-02	-4,12E-01	3,70E-01
Chromium (+III)	mg per kWh	4,30E-01	1,36E-02	2,72E-03	2,66E-03	4,13E-03	1,38E-04	4,53E-01
Iron	mg per kWh	6,13E-01	6,51E-02	4,12E-03	9,05E-05	1,58E-02	-2,35E-01	4,63E-01
Inorganic emissions to agricultural soil	mg per kWh	7,29E+00	7,53E-01	5,00E-02	1,08E-03	1,88E-01	-2,67E+00	5,61E+00
Aluminium	mg per kWh	9,29E-01	1,29E-01	4,82E-03	1,38E-04	2,44E-02	-5,20E-01	5,67E-01
Potassium	mg per kWh	6,04E+00	5,67E-01	4,42E-02	8,89E-04	1,55E-01	-1,91E+00	4,90E+00

Emissions to industrial soil	mg per kWh	5,92E+01	9,68E-01	3,05E+00	4,59E-02	1,94E+00	1,25E+02	1,90E+02
Inorganic emissions to industrial soil	mg per kWh	5,64E+01	1,16E+00	2,68E+00	4,58E-02	1,85E+00	1,21E+02	1,83E+02
Calcium	mg per kWh	1,29E+01	2,05E-01	1,73E-01	1,17E-02	2,57E-01	1,87E+01	3,22E+01
Chloride	mg per kWh	7,44E+00	5,15E-01	5,08E-01	1,16E-02	1,94E-01	7,54E+01	8,41E+01
Sulphate	mg per kWh	1,98E+01	5,37E-03	1,72E-02	3,08E-04	6,80E-01	7,94E-01	2,13E+01

*Regionalised water flows are not included in the table.

Annex H Additional Life cycle impact assessment results

Section H presents the impact assessment results for the V163-4.5MW wind plant using the alternative LCIA method EF 3.1. Table H1 shows the overall impact results by life cycle stage.

Table H1: Whole-life environmental impacts of V163-4.5MW by life cycle stage (units shown per kWh) using the EF 3.1 impact assessment

Environmental impact categories:	Unit	Manufacture	Plant set up	Operation	End of life	Total
Acidification	Mole of H+ eq.	2,30E-05	3,93E-07	4,63E-07	-7,05E-06	1,68E-05
Climate Change - total	g CO2-Equiv.	7,10E+00	4,57E-02	1,47E-01	-2,16E+00	5,13E+00
Climate Change. biogenic	g CO2-Equiv.	1,21E-02	1,47E-05	4,76E-04	3,30E-04	1,29E-02
Climate Change. fossil	g CO2-Equiv.	7,08E+00	4,56E-02	1,46E-01	-2,16E+00	5,11E+00
Climate Change. land use and land use change	g CO2-Equiv.	7,94E-03	2,39E-05	1,85E-04	-5,25E-04	7,63E-03
Ecotoxicity. freshwater - total	CTUe	3,37E-02	4,39E-04	1,66E-03	-1,82E-03	3,40E-02
Ecotoxicity. freshwater inorganics	CTUe	3,34E-02	4,35E-04	1,65E-03	-1,78E-03	3,37E-02
Ecotoxicity. freshwater organics	CTUe	3,28E-04	3,37E-06	1,06E-05	-4,38E-05	2,98E-04
Eutrophication. freshwater	mg P eq	1,83E-02	2,17E-04	7,43E-04	6,49E-04	1,99E-02
Eutrophication. marine	mg N-Equiv	5,20E+00	1,77E-01	1,00E-01	-7,79E-01	4,70E+00
Eutrophication. terrestrial	Mole of N eq.	5,57E+01	1,94E+00	1,10E+00	-6,90E+00	5,18E+01
Human toxicity. cancer - total	CTUh	2,90E-11	7,47E-15	4,43E-12	7,29E-13	3,41E-11
Human toxicity. cancer inorganics	CTUh	9,81E-13	7,04E-15	5,22E-14	-1,01E-14	1,03E-12
Human toxicity. cancer organics	CTUh	2,80E-11	4,32E-16	4,38E-12	7,39E-13	3,31E-11
Human toxicity. non-cancer - total	CTUh	3,68E-11	1,72E-13	1,31E-12	-1,15E-12	3,71E-11

Environmental impact categories:	**Unit**	**Manufacture**	**Plant set up**	**Operation**	**End of life**	**Total**
Human toxicity. non-cancer inorganics	CTUh	3,57E-11	1,66E-13	1,28E-12	-9,03E-13	3,62E-11
Human toxicity. non-cancer organics	CTUh	1,11E-12	6,63E-15	3,43E-14	-2,45E-13	9,05E-13
Ionising radiation. human health	kBq U235 eq.	3,93E-04	1,23E-07	7,00E-06	1,25E-05	4,13E-04
Land Use	Pt	1,34E-02	1,09E-04	3,92E-04	-9,02E-04	1,30E-02
Ozone depletion	mg CFC-11 eq	1,11E-05	5,39E-12	2,71E-07	-5,01E-06	6,33E-06
Particulate matter	Disease incidences	4,57E-10	1,18E-12	6,08E-12	-7,52E-11	3,89E-10
Photochemical ozone formation. human health	mg NMVOC	1,66E+01	5,07E-01	3,37E-01	-3,30E+00	1,41E+01
Resource use. fossils	MJ	8,93E-02	1,06E-03	2,85E-03	-2,31E-02	7,00E-02
Resource use. mineral and metals	mg Sb-Equiv.	1,49E-01	5,71E-06	2,45E-03	-5,63E-02	9,48E-02
Water use	m³ eq.	1,74E-03	2,62E-06	4,30E-05	-1,94E-04	1,60E-03

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