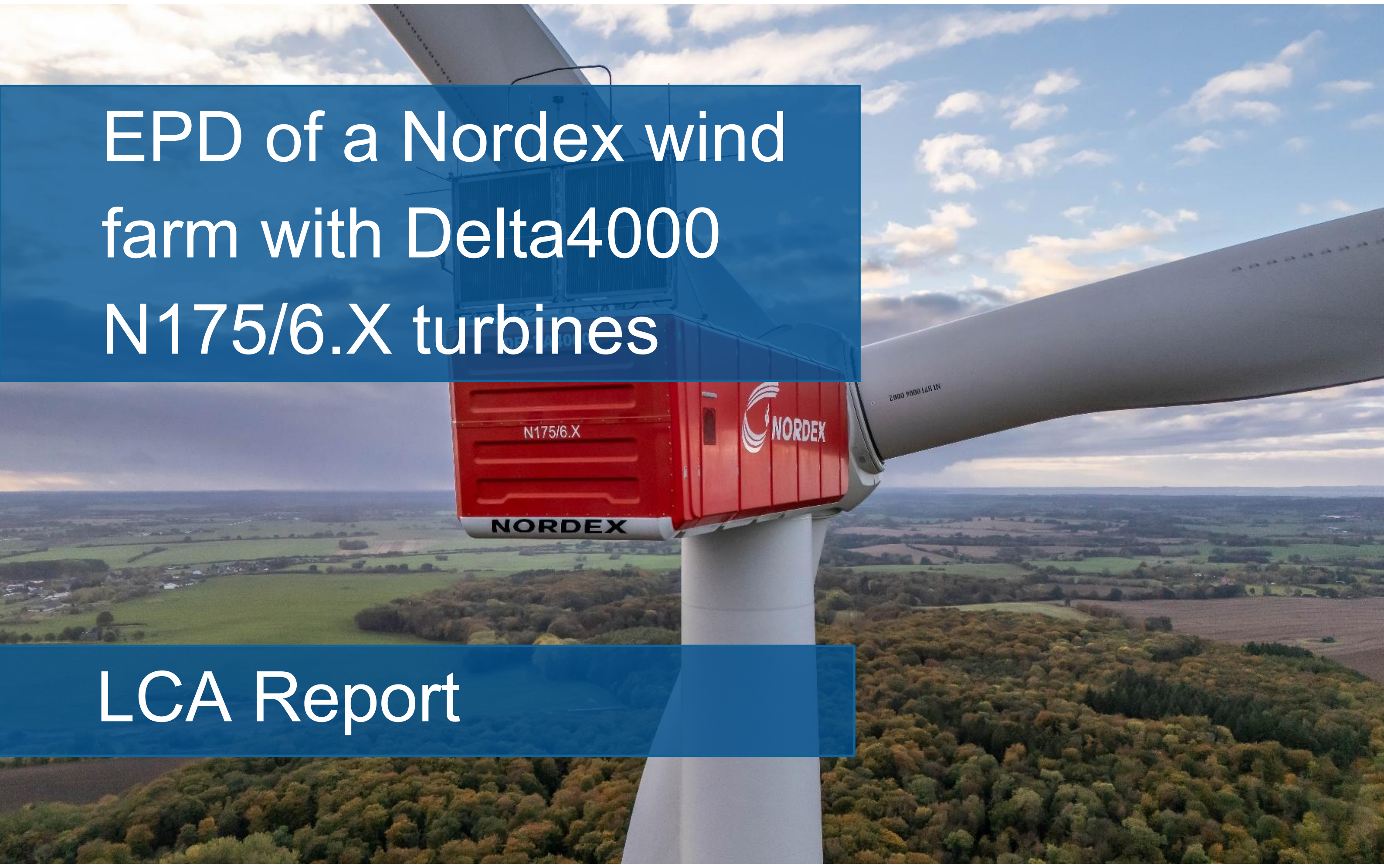

EPD of a Nordex wind farm with Delta4000 N175/6.X turbines

LCA Report

Title:	**EPD of a Nordex wind farm with Delta4000 N175/6.X turbines – LCA Report**
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List of Acronyms

AEP	Annual Energy Production
ADP	Abiotic depletion potential
AP	Acidification Potential
CML	Centre of Environmental Science at Leiden
EF	Environmental Footprint
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental product declaration
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
HV	High voltage
IEC	International Electrotechnical Commission
ILCD	International Cycle Data System
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCA FE	LCA For Experts modeling software (formerly known as GaBi)
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MV	Medium voltage
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone depletion potential
PCR	Product category rules
POCP	Photochemical ozone formation, human health
RSL	Reference service life
RoE	Return on Energy
VOC	Volatile Organic Compound
WDP	Water deprivation potential

Glossary

Life cycle

A view of a product system as “consecutive and interlinked stages … from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006, section 3.1). This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2)

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3)

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4)

Life cycle interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5)

Functional unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20)

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17)

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”

“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.” (ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it … and/or directly affected by decisions analysed in the study.” (JRC, 2010, p. 97) This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background system

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process … and/or those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good….” (JRC, 2010, pp. 97-98) As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45).

1. General aspects

1.1. Commissioner and practitioner of the study

This product EPD study on a ‘Delta4000 wind farm’ was commissioned by the Nordex SE. The Nordex Group is a world leading wind turbine manufacturer, renowned for its investment in R&D and the resulting technical excellence of its products. The wind turbine analysed in this study is part of the Delta4000 turbine series and the currently largest model. The product system assessed in this study is the N175/6.X.

Headquarter:	Nacelle production:	Wind farm location:
Langenhorner Chaussee 600 22419 Hamburg Germany	Rostock, Germany	Mahlsdorf, Germany

The underlying LCA study as well as the preparation of the EPD document were conducted internally by Nordex. The LCA model for the N175/6.X turbine type is based on the LCA model that had been prepared for our first LCA study of the turbine type N149/4.0-4.5 in 2020 and has accordingly been adapted to the turbine-specific and project-specific conditions. The first LCA model that serves as basis for all following, including the current LCA model, had been created by an external practitioner, Sphera. Sphera is a global sustainability, environmental health & safety software and consulting company. The basis model and documentation from 2020 have been externally verified by DEKRA.

1.2. EPD Requirements

This LCA/ EPD study has been conducted in accordance with the following standards and instructions:

- Regulations of the EPD Italy Programme, Revision 7.1;
- PCR EPDItaly013 – Wind turbines, Electricity produced by wind turbines, Rev. 1.1
- ISO 14040, Environmental management – Life cycle assessment – Principles and framework; (ISO, 2006)
- ISO 14044, Environmental management – Life cycle assessment – Requirements and guidelines; (ISO, 2006)
- ISO 14025, Environmental labels and declarations — Type III environmental declarations — Principles and procedures (ISO, 2006);

EPDs related to the same category of products but belonging to different programs may not be comparable.

1.3. Goal of the study

The intended use of this product EPD is to communicate environment-related information and LCA results for a specific Nordex's Delta4000 wind farm to support the assessment of the sustainable use of energy generation methods.

EPDs are mainly used for business-to-business communication. It is intended that this EPD will be published by the program operator “EPDItaly” where it will be made publicly available and therefore will also be accessible to the end consumer. As such, EPDs can also be used in business-to-consumer communication – Nordex can provide additional explanatory information should consumers request this; Nordex's contact phone number and email address will be stated in the EPD.

1.4. Purpose, content and availability of the project report

The purpose of a project report is to provide a systematic and comprehensive description of the project to support the verification of an EPD. It documents the information on which the LCA is based, whilst also ensuring the additional information contained within the EPD conforms to the requirements of the rule documents.

When the EPD is submitted for publication through the EPD System, the project report will be made accessible to the verifier under the conditions of confidentiality as specified by ISO 14025 (ISO, 2006).

1.5. Verification

This Environmental Product Declaration has been verified by the independent third party ICMQ (Michele Paleari).

This EPD will expire 5 years from the date of first issue.

2. Scope of the Study

The following sections describe the general scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function, functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System

This study and EPD evaluates a Nordex wind farm in Germany, which uses N175/6.X turbines that are part of the Delta4000 turbines series over its full life cycle, from cradle to grave. With the N175/6.X, Nordex designed a highly efficient wind turbine, our specialist for light-wind speeds. At typical low to medium-wind locations, the N175/6.X will achieve between 7 and 14 percent more yield compared to its sister models, the N163/5.X and N163/6.X due to its single-piece, newly designed 85.7-meter-long rotor blade and its above-average capacity factor. This additional yield is achieved particularly during times of lighter wind speeds with the turbine producing up to 22 percent more energy than its predecessors.

Figure 1: Product system – view of Delta4000 N175/6.X turbine

As part of the Delta4000 series, the high flexibility of site-dependent power modes are also applied to the N175/6.X, thus providing a wider range of options for increased suitability in terms of sound, load and power. The turbine can also be equipped with a bat module and on-demand night-time marking. A cold climate variant ensuring operation in environments of -30°C is also available.

A typical wind farm has a lifetime of around 20 to 25 years, depending on the local site conditions of the wind farm. A time period of 20 years has been used as the baseline for the EPD calculation.

The towers available offer various different hub heights (project and site-specific), however this study focuses on the 179 m hub height. The rotor sweep is 24,053 m^2 with a rotor blades diameter of 175 m.

2.2. Product Functions and Functional Unit

In LCA studies, the declared unit quantifies and describes the performance of a product system and is used as the basis for reporting results.

The function of a wind farm is to generate electricity by harnessing wind energy. As such, as defined by the PCR, the declared unit for this study is:

The generation of 1 kWh of electrical energy (net) considering the full lifetime of the wind farm (Delta4000 N175/6.X turbines), located in a German scenario and operating under special wind conditions (IEC wind class S), and thereafter distributed to a 115kV electrical grid.

The assessed wind farm design is a special wind site (IEC wind class S (Special)). The annual average wind speed is 6.5 m/s. Site-specific parameters for losses and uncertainties are considered using a net annual energy production (AEP) calculation.

The certified standard lifetime of Delta4000 turbines is 20 years. In principle, the lifetime of those turbines can be extended by 10 or even 15 years to a total lifetime of 30 or even up to 35 years, according to the method of lifetime extensions and the related advisory opinions by UL (UL, 2022). The applied lifetime of turbines in a wind farm follows site-specific conditions. The analysed wind farm in Germany was designed for an operational lifetime of 25 years with a lifetime extension assessment having been performed and expecting a lifetime of 30 years to be reached.

However, as specified by the PCR, the baseline assumption for the wind farm lifetime is 20 years. In LCAs on onshore wind turbines, the lifetime is often defined with 20 years as base case. To check the sensitivity on the results, a scenario with 25 years, but also with 30 years and 35 years lifetime is calculated.

The wind farm comprises 10 Delta4000 turbines. All turbines are operating with a nominal power of 6.8 MW, resulting in a total nominal power of the wind farm of 68.0 MW.

The resulting average nominal wind power density per turbine in the wind (based on 6.8 MW as average nominal power per turbine in the wind farm and a rotor sweep of 24,053 m^2).

The average net annual energy production per turbine is 16,898 MWh per year (see chapter 3.2). With an assumed transmission loss of 2.1% (see also chapter 3.2) the actual amount of produced and delivered energy to the electricity grid is 16,543 MWh per year and turbine. For a realistic life-time of 25 years, the average total energy produced per turbine is 413.58 GWh (422.45 GWh without transmission loss). For the total number of 10 turbines, the total energy produced by the wind farm is 4.14 TWh.

2.3. System Boundary

The full life cycle of the turbine has been considered, from cradle-to-grave, i.e., from the point at which raw materials are extracted from the environment through to manufacturing, installation, operation and end-of-life.

An overview of the system boundaries of the study can be found in Figure 2. The study accounts for the whole product, including packaging. This includes the extraction and production of raw materials, the manufacturing of these materials into the finished product with packaging, the transportation and distribution of the product, the use stage and the end-of-life stage including recycling and final disposal.

The local system boundary for the wind farm ends with the connection to the electricity grid. The turbines in the wind farm are connected via MV (medium voltage) cables to the substation. The substation transforms the electricity to 115kV (high voltage, HV). The HV cable connects the substation at the wind farm to the grid.

Transport is included for inbound raw materials to the manufacturing sites and then distribution of the product system from the manufacturing site to the location of the wind farm. Transport was also included from the wind farm to end-of-life processing.

As detailed in section 3.3, the life cycle was split into the upstream, the core (infrastructure and processes) stage and the downstream stage. The two elements of the core stage are not separated in the visualisation of the system boundaries as the LCA results are presented as one value for the core stage and not broken down to the contributions of infrastructure and processes.

The assessed system ends at the connection point to the grid. The infrastructure and the electrical losses due to the transmission via HV (high voltage) cable between the wind farm and the connection point are considered in the core stage. The environmental impacts in the downstream stage are zero as no activity related to further transmission of the produced energy is considered as it is outside of Nordex control.

This approach is compliant with EPDItaly’s PCR where the system is looked at from an operator’s point of view and the EoL is part of the operator’s responsibility. While Nordex is the manufacturer of the wind turbines, the EoL is not in our scope, and is technically Nordex’ downstream process. However, to comply with the PCR, we allocate the EoL processes to the core section, as can be seen in Figure 2.

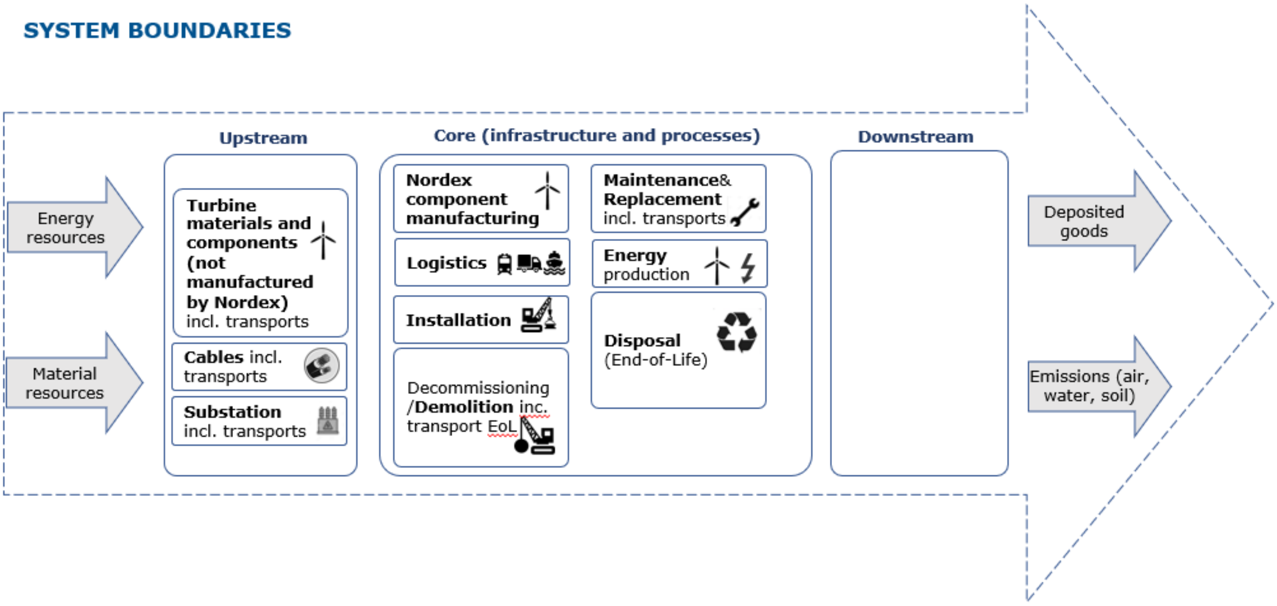


Figure 2: Overview of system boundaries

The system boundaries have been summarised in Table 1, detailing stages both included and excluded.

Table 1: System boundaries

Included	Excluded
✓ Raw material production	× Employee commuting
✓ Fabrication of raw materials into parts and components	× Research and Development
✓ Manufacturing	× Manufacturing of capital equipment utilised in the installation
✓ Installation	× Overhead (heating, lighting) of manufacturing facilities
✓ Associated infrastructure such as roads	× Warehousing
✓ Operation	
✓ End-of-life	

The boundary for the study is at the connection point to the grid. As such, electrical losses due to the voltage elevation in the substation as well as due to the distribution with the MV and HV cables inside and outside the wind farm have been included in the study. The boundary is taken to be the point at which the wind farm produces an equivalent of 1 kWh transmitted into the grid.

Impacts associated with employee commuting have been excluded as these are expected to be negligible for a manufactured product. However, all transports associated with the maintenance done by service teams and the replacement of parts during the service life of the turbines have been included.

The following sections describe the *intended* time, technology and geographical references that were aimed for at the start of the study. The actual data that were collected and used in the study are described in Chapter 3. How well these data match the requirements stated below is assessed in Chapter 5.

2.3.1. Time Coverage

The intended time reference for the study is to assess the operation of the Nordex wind farm (Delta4000 turbines) in 2024. At the time of the reference year, the wind farm was under construction. While the data was collected during 2025, the results of the study should remain valid until significant technological changes occur.

2.3.2. Technology Coverage

The study aims to assess the current technology and materials used to develop and operate the Nordex wind farm (Delta4000 turbines). The technology represented in the study is representative of some of the leading wind turbines available internationally.

2.3.3. Geographical Coverage

The study focuses on assessing the Nordex wind farm (Delta4000 turbines) in Germany. This is a special wind site with IEC wind class S. The EPD results could be adopted in principle also for wind farms outside of Germany in case the main wind site characteristics are comparable. However, the logistic data (transport distances and means) as well as other project-specific data might be different with the related influence on the overall results.

2.4. Allocation

2.4.1. Multi-output Allocation

No allocation has been necessary in relation to the foreground data used in this study as no co-products or by-products are generated.

Allocation within background data (energy and materials) from the Sphera Managed LCA Content (MLC) 2025.2 database is documented online (Sphera, 2025).

2.4.2. End-of-Life Allocation

End-of-life allocation follows the requirements of ISO 14044, section 4.3.4.3. These address the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems.

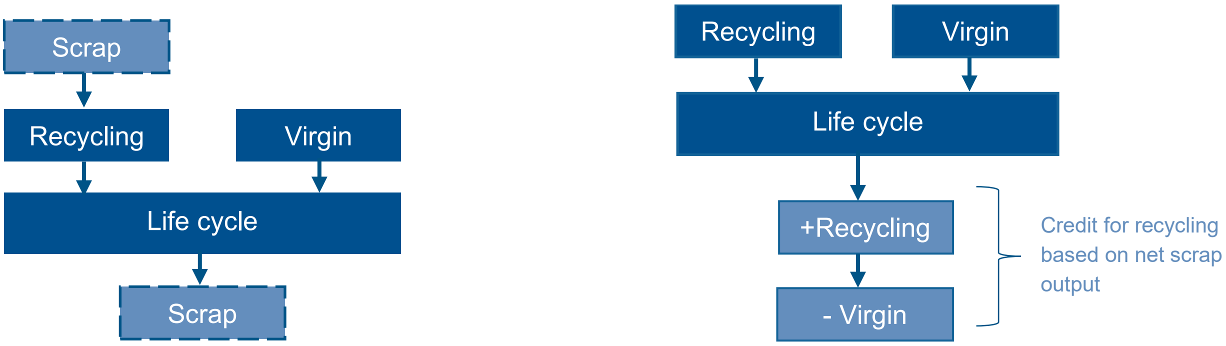
Two main approaches are commonly used in LCA studies to account for end-of-life recycling and recycled content.

- Cut-off approach – burdens or credits associated with material from previous or subsequent life cycles are not considered i.e., are “cut-off”. Therefore, scrap input to the production process is considered to be free of burdens but, equally, no credit is received for scrap available for recycling at end-of-life. Hence this approach rewards the use of recycled content but does not reward end-of-life recycling.
- Substitution approach – this approach is based on the perspective that material that is recycled at end-of-life will substitute for an equivalent amount of virgin material. A credit is given to account for the benefits of this substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. Hence this approach rewards end-of-life recycling but does not reward the use of recycled content.

The cut-off approach was utilised in this study as required by the PCR and regulations of EPD Italy. The following details a short description of the cut-off approach that has been modelled for this study:

Material recycling (cut-off approach): Any open scrap inputs into manufacturing remain unconnected. The system boundary at end-of-life is drawn after scrap collection to account for the collection rate, which generates an open scrap output for the product system. The processing and recycling of the scrap is associated with the subsequent product system and is not considered in this study.

Energy recovery & landfilling (cut-off approach): The system boundary includes the waste incineration and landfilling processes following the polluter-pays-principle. In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). No credits for power or heat production are assigned.



(i) Cut-off approach (scrap inputs and outputs are not considered)

(ii) Substitution approach (credit given for net scrap arising)

Figure 3: Schematic representations of the cut-off and substitution approaches

The substitution approach is considered for the additional environmental information in the EPD.

2.5. Cut-off Criteria

No cut-off criteria have been defined for this study. The system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, as much available energy and material flow data have been included in the model as possible, except for in a few cases where cut-off criteria have been applied in accordance with the PCR document. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Chapter 3.4. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in Chapter 5. For a small number of materials, data have been omitted entirely. The impact of these omissions is discussed in Chapter 5.

2.6. Interpretation to Be Used

The results from the study have been interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process steps, materials, and emissions contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations.

2.7. Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results. This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.
- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Chapter 5 of this report.

2.8. Type and format of the report

In accordance with the ISO requirements (ISO, 2006) this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.9. Software and Database

The LCA model was created using the LCA FE 10 Software system for life cycle engineering (software version 10.9.4.13), developed by Sphera Solutions Inc. The Sphera Managed LCA Content (MLC) 2025 LCI database is the basis for most of the life cycle inventory data for modelling the background system. Datasets from the database version 2025.2 are applied.

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Based on the experience from the data collection for Nordex' first LCA study (see full report here: https://www.nordex-online.com/wp-content/uploads/sites/2/2022/03/LCA_N149_4.0-4.5_TS105.pdf), a new data collection procedure was set up internally for collecting (and/or updating) primary data. All primary data were collected using one integrated data collection template which was shared via a Microsoft Teams channel where all involved internal data providers had access to. Additionally, customer data was used for project-specific data collection. Once the template was filled, it was cross-checked by the Senior Technical Sustainability Specialist (Nordex' internal LCA expert) for completeness and plausibility using e.g. mass balance or internal and external benchmarking. Where gaps, outliers, or other inconsistencies were found, the LCA expert engaged with the data providers to resolve these issues.

Having one data collection template for the entire project lead to more transparency on the one hand, but also to better data consistency throughout the data collection process.

For each main component or life cycle stage of a turbine, a dedicated expert (potentially including his/her team) was engaged within Nordex. Named hereafter are the coordinating experts indicated with their respective roles and functions who have supported the data collection:

- Senior Environmental Technical Sustainability Specialist
- Senior Engineer Tower & Foundations
- Expert Engineer, Blade Material & Design
- Director Global Electrical Engineering
- Head of Mechanical Drives Global Engineering
- Engineer Machinery & Components
- Head of Design and Integration
- Project Manager Operations
- Project Logistics Manager
- Head of Global Commercial Service Sales

Most of the collected data is based on in-house expertise at Nordex as OEM of wind turbines and wind farm service provider for maintenance and repair. Some data is collected from tier 1 suppliers.

The data from Nordex' production facility originated from Nordex' environmental management tool, Quentic, which is used for environmental reporting – internally on a quarterly basis, and externally for the annual sustainability statement. For each production site, environmental data is entered on a quarterly basis in the tool and is stored there. In the course of publishing the annual sustainability statement (see respective report here: Nordex Integrated Annual Report 2024 E), the environmental data that had been entered in Quentic underwent an external audit by KPMG.

The main areas of data collection comprised the following components or life cycle phases:

Delta4000 turbine

- Components of the turbine are foundation, tower, blades, drivetrain, nacelle, E-module (electrics and electronics)

- Additional data collected per component: coatings, surface treatments, machining processes, connection of components (e.g. welding or bolts), specifications regarding material type and shape/design of parts, location of supplied materials and parts
- Nordex manufacturing site for drivetrain – data extracted from environmental management system (Quentic) for energy and utilities consumption, emissions, generated waste/wastewater and waste/wastewater treatment
- Production of nacelle, hub, blades and hybrid tower
- Majority of the data is measured; data uncertainties and gaps are closed with calculations and in few cases with estimations.

Cable connections and substation

- Length, weight and composition for MV cables in wind farm is taken from supplier's technical specifications
- Data for HV cable connection to grid is taken from previous LCA study using a conservative value for cable length per turbine
- Weight of substation components: Data taken from technical drawings of components
- Material composition of substation: Data taken from a previous LCA project
- Majority of the data is calculated and estimated.

Logistics (transportation of all wind farm components, construction materials and machines to wind farm site)

- Data on transport means and distances
- Data collection comprises all components of the turbine, cables, foundation materials, construction machines like cranes (main and auxiliary crane), infrastructure like lifting equipment and containers, construction materials for construction of drive-way and set-up area
- Majority of the data is calculated and estimated.

Installation

- Data collected and provided by customer of the wind farm
- Data collection comprises the cabling trenches excavation, the diesel consumption considering all construction machines like cranes, telehandler and working platforms, diesel consumption of aviation lights, consumption of construction materials for lifting areas and crane pads, waste and waste treatment of installation activities, construction and material consumption of wind farm access roads
- Majority of the data is calculated, some data is measured and estimated.

Use phase

- Data collection comprises net AEP, maintenance, replacement and related transports
- Majority of the data is measured, data gaps are closed with calculations and estimations

Decommissioning / End-of-Life

- Data collection comprises the demolition of the wind farm including cranes, excavators and trucks, the transport to a recycler or disposer depending on the material group.
- Data on rotor blade recycling had already been collected at Neocomp in the course of the first LCA study.
- Majority of the data is calculated, some data is measured and estimated.

Most of the data that is described in the following sections is confidential as it is sensitive primary industry data and is solely to be used for the critical review, but not to be published.

3.2. AEP and lifetime during use

The use phase has been modelled considering the annual energy production of the wind farm and the lifetime, the maintenance required throughout the lifetime operation, any replacement materials or equipment required and the associated transport.

Annual Energy Production and Lifetime

The net annual electricity production (AEP) for the wind farm was calculated using the following parameters:

- average wind speed at hub height: 6.5 m/s (IEC S – according to IEC 61400-1)
- site-specific losses: 19.8%

This resulted in a net AEP P75[1] value for 30y lifetime of 16,898 MWh per turbine per year.

The AEP value is representing an annual average. The applied values for losses and uncertainties are representative for the assessed wind farm. The losses are explained in more detail below, they determine the difference between gross and net AEP. The uncertainties are used in the calculation of probabilities as coefficient of variation (CoV). Thus, the percentiles (p75 applied as base case percentile for the AEP in this study) result as statistical values applying the uncertainties in combination with the standard distribution (Gauss).

Important parameters for the AEP calculation are the factors A and k concerning the Weibull distribution and the shear wind parameter. Factor A ranges between 5.3 and 9.1 m/s and factor k ranges between 2.19 and 2.73 for the 10 turbines of the wind farm. The parameter for shear wind (Hellman index) ranges between 0.32 and 0.34. The air density is set to 1.209 kg/m³.

Concerning the stability and mechanical loads, the turbines are designed for the turbulence class S according to IEC 61400.

The AEP losses originate from the following aspects:

- wake effect – a group of turbines generate less energy per turbine than a stand-alone turbine. So, the wake effect is the aggregated influence on the energy production of the wind farm, which results from the changes in wind speed caused by the impact of the turbines on each other.
- availability – shutdown of turbines, so unavailable to produce electricity because of maintenance or unavailability of the grid over which power can be exported
- environmental – shutdown of turbines due to icing, nature protection (e.g. respecting flying times of bats)
- curtailment – some or all of the turbines within a wind farm may need to be shut down to mitigate issues associated with turbine loading, or certain planning conditions. Two main issues: wind sector management (issue with wind direction) and wind velocity management (issue with wind speed)
- electrical – distribution losses in cables, losses in substation and transformers inside the turbine
- turbine performance – adjustment of site-specific issues, which may mean that for a specific site the wind turbine will not perform in accordance with the supplied power curve.

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[1] A value of "P75" describes the annual value of power production from an intermittent resource, such as wind power, with a probability of 75%.

The by far biggest effect on AEP losses is caused by the wake effect.

The AEP uncertainties origin from the following aspects:

- wind measurement
- long term correction
- future wind availability
- modeling
- performance and losses

The biggest effect on AEP uncertainties is caused by the wind measurement.

The electrical losses that occur between the wind farm substation and the main electricity network were not directly measured, but an average value of 2.1% has been used to simulate these electrical losses. This means that 2.1% of every generated kWh, is lost in the distribution network between the wind farm and the connection point to the grid.

Most of the data that is described in the following sections is confidential as it is sensitive primary industry data, so it was transferred to the Annex B. The confidential Annex B was part of the report version used for the critical review, but it is not part of the published report.

3.3. Life Cycle Stages

3.3.1. Overview of Product System

The Delta4000 wind farm consists of 10 wind turbines however all foreground data is proportionally for the material composition and subsequent life cycle of 1 turbine with a hub height of 179 metres.

The product system detailed in this section includes the Delta4000 wind turbine, the MV cable required for operation on the wind farm and the substation in the wind farm, the transportation of materials, parts and components to manufacturing sites for the equivalent of one turbine.

The product system is split into three life cycle stages: Upstream, core (process and infrastructure) and downstream.

3.3.2. Upstream Module

As defined by the PCR, the upstream module includes all relevant processes of the supply chain including the extraction of raw materials including waste recycling and the production of semi-finished products and auxiliary items, as well as the packaging of products and semi-finishing products. Transport of raw materials to the manufacturing company (the wind turbine parts manufacturing sites and final manufacturing/ assembly site).

Delta4000 Turbine overview

Table 2 and Figure 4 detail the mass breakdown of the Delta4000 turbine components.

Table 2: Mass composition of turbine components required to fulfil functional unit

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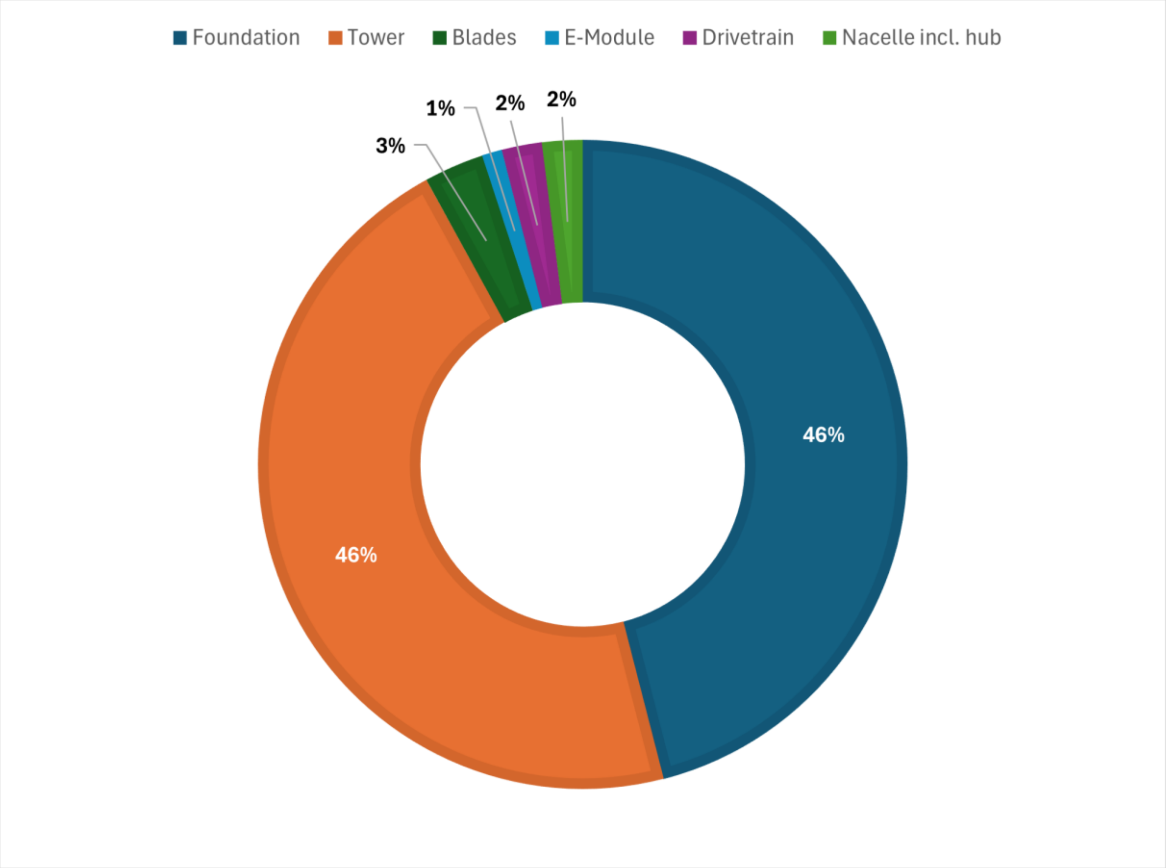

Figure 4: Composition breakdown by mass for the Delta4000 turbine

Overall, the material mix for the Delta4000 turbine excluding the mass-dominant foundation is:

- 66.9% Concrete
- 27.8% Steel (carbon steel, stainless steel, cast steel, iron)
- 2.7% Glass fibre/ Carbon fibre reinforced plastics
- 1.9% Polymers
- 0.1% Operating fluids
- 0.02% Electrics / Electronics
- 0.1% Aluminium
- 0.2% Copper
- 0.2% Others

The following sections detail the sub-plans for the different component parts within the Delta4000 turbine plan shown in Figure 9.

Foundation

The foundation for the turbine is approximately 94% concrete by weight, the remaining mass is composed of steel rebar, pipe and screws.

Tower

The tower is formed of two main parts: the supporting structure – composed of around 22% steel and around 78% concrete, and the interior construction – predominately composed of aluminium and plastics.

Blades (materials only)

The blades of the wind turbine are designed to efficiently capture the wind energy available onsite. The key raw materials (by mass) used in manufacturing the blades of the wind turbine are glass and carbon fibres, epoxy resin, steel and the rest is a mixture of coatings, wood and other polymers.

The gross weight of the blades is considered in the model as a relatively high share of the applied material is lost during the manufacturing steps. Related waste treatment processes are considered.

E-Module

The E-Module includes all the electrical components of the wind turbine required to generate electricity. The model is composed of 10 sub-plans (generator, transformer cables etc.). Main material groups are steel, copper, electrics/electronics and cast iron.

[1.4] E-Module (E-Technik) p
Process plan: Mass [kg]
The names of the basic processes are shown.

Figure 5: Turbine electrical components in LCA FE

Drivetrain

The drivetrain of the wind turbine is composed of the components required to produce electricity such as the gearbox and generator. The model is split into 20 sub-models, covering bearings, gears, drives, etc. Main material groups are steel, cast iron, copper, stainless steel and aluminium.

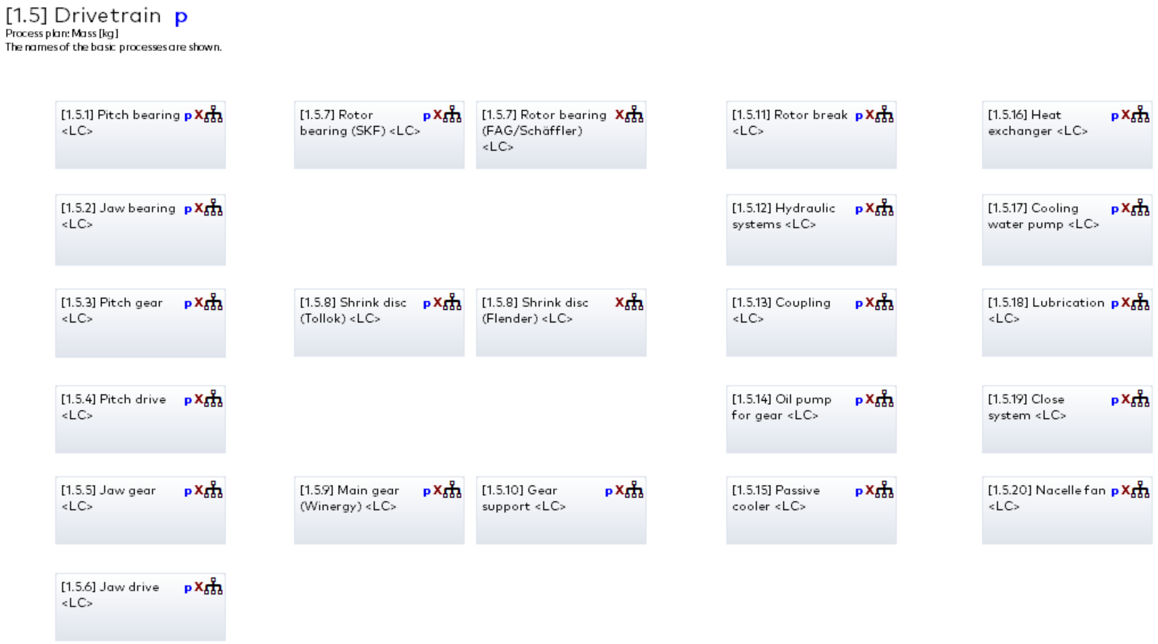

Figure 6: Drivetrain (incl. bearings, gears, etc.) for turbine in LCA FE

Nacelle, including hub (materials only)

The nacelle of the turbine is the housing for the electrical and other generating components to the wind turbine. In the model this is split into 13 sub-plans. Main material groups are cast iron, steel and glass fibre reinforced plastics.

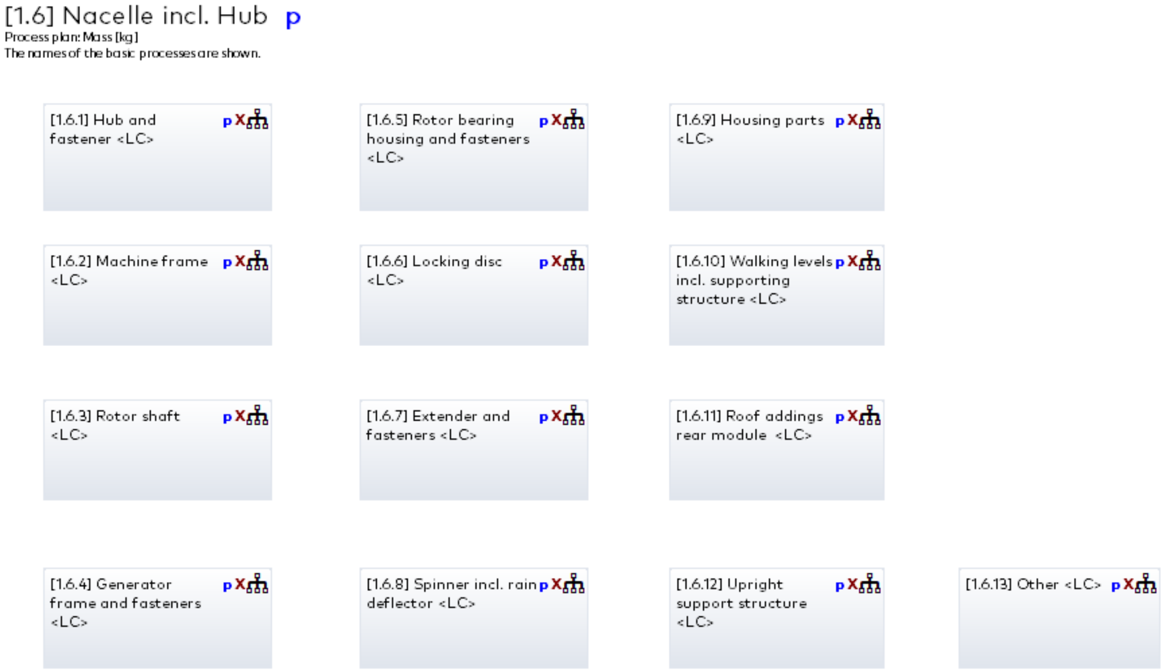

Figure 7: Nacelle wind turbine components in LCA FE

Transports

The transportation of all materials and components from suppliers to Nordex is estimated with an average transport distance of 1,000km with a share concerning means of transport of 50% truck-trailer (up to 40t gross weight, utilisation by mass: 50%) and 50% rail transport (diesel driven, utilisation by mass: 40%).

The transport of the foundation materials to the wind farm is covered in the section on logistics.

Cables

MV cables (30kV)

The key considerations for the cables in the wind farm are the raw materials required and the associated manufacturing along with inbound transport of raw materials to the manufacturing site. The cables are – on average – composed of copper (10%), aluminium (51%) and high-density crosslinked polyethylene, XLPE (38%). Different cable systems are used with cable weights ranging from 1550kg/km to 5070kg/km. The effort for the manufacturing step of the cables is estimated with a factor of 1.1 on the material mix. The transportation of all materials for cable manufacturing is estimated with an average transport distance of 1,000km with 100% truck-trailer (up to 40t gross weight, utilisation by mass: 50%).

The average length of a MV cable per turbine in the assessed wind farm is 24,420m.

HV cables (115kV)

The key considerations for the cables are the raw materials required and the associated manufacturing along with inbound transport of raw materials to the manufacturing site. The cables are composed of copper (4%), aluminium (34%) and high-density crosslinked polyethylene, XLPE (62%). A cable weighs 7,150kg/km. The effort for the manufacturing step of the cables is estimated with a factor of 1.1 on the material mix. The transportation of all materials for cable manufacturing is estimated with an average transport distance of 1,000km with 100% truck-trailer (up to 40t gross weight, utilisation by mass: 50%).

The length of the HV cable which connects the wind farm to the grid is depending on site-specific conditions. For this study, a distance of 1.41km cable length per turbine was assumed. All data has been taken from a previous LCA study (N149/5.X). As the cable connection to the grid for this project was already existing, only the share of the new turbines (10/18) was allocated to this project.

Substation

One substation is required on the site of the wind farm to transform the medium voltage of the wind farm to the high voltage required for distribution.

The substation model considers the raw materials required and the associated manufacturing, along with inbound transport of raw materials to the manufacturing site. The substation is composed of copper, aluminium and steel.

The effort for the manufacturing step of the substation is neglected. The transportation of all materials for substation manufacturing is estimated with an average transport distance of 1,000km with 100% truck-trailer (up to 40t gross weight, utilisation by mass: 50%).

Overview – upstream module

The following table details the mass breakdown of the different components required to construct the wind turbine, cables and substation. The data were provided in German and translated to English.

Table 3: Mass breakdown of turbine, cables and substation components required per functional unit

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3.3.3. Core (infrastructure)

Nordex component manufacturing

Manufacturing of the nacelle is carried out by Nordex and hence is included within the core infrastructure life cycle stage. While the blades are manufactured by a third-party, the production effort is estimated with Nordex data as it should not differ significantly from our own production. Consumption of energy and water, internal transports (fuel consumption and emissions), emissions into air from manufacturing processes and waste treatment is considered.

Logistics (distribution from manufacturing to site)

This section details the logistics required for the relevant components and infrastructure to reach the site of the wind farm. This includes turbine components, foundation materials, cranes, materials for construction of the driveway into the site and the area required for set-up of the installation site.

The following is relevant for one turbine and constitutes a total of 5,489,872 t.km.

- 2,834,745 t.km with large trucks (up to 40t gross weight) per turbine
- 71,582 t.km with medium trucks (up to 26t gross weight) per turbine
- 626,615 t.km with special trucks (more then 40t gross weight trucks or oversize parts like rotor blades) per turbine.
- 2,150,333 t.km with ships (cargo and inland vessel) per turbine.

The diesel consumption and related emissions for special transports due to oversize parts is estimated with a factor of 1.2 on the specification of large trucks.

The partly calculated and partly estimated transport distances vary between ~30-200 km for foundation materials up to ~9,300 km for the nacelle and hub.

Installation

Table 4 describes all resources and materials required for the installation phase of the wind farm.

Table 4: Data for resources/ processes required for installation stage

**** moved to Annex B (confidential data) ****

The partly measured and partly calculated diesel consumption considers most of the installation activities.

GWP due to Land Use and Land Use Change (GWP LULUC)

The analysed Nordex wind farm comprises 10 wind turbines of the specification Delta4000 N175/6.X. The affected area is dominated by planted forest for harvesting wood. The following table illustrates land use before and after the installation of the wind farm in more detail:

Table 5: Land use before and after installation

CORINE LAND COVER CLASSES	BEFORE (m²)	AFTER (m²)
1 Artificial surfaces		
1.2 Industrial, commercial and transport units	0	111492
2 Agricultural areas		
3 Forests and seminatural areas		
3.1 Forest	150000	0
3.2 Shrub and/or herbaceous vegetation associations	0	38508
4 Wetlands		
5 Water bodies		
TOTAL	**150000**	**150000**

A total of 15.0 ha have been affected and modified by the installation and operation of the wind farm. The occupied areas are mainly used for:

- Foundations
- Roads and crane pads
- Cable trenches
- Substation

The resulting affected area per turbine is 1.5 ha. The calculation of the GWP LULUC effects are done based on (IPCC, 2019). The main assumptions for the calculations are:

- Removed above-ground biomass and dead organic matter (dead wood and litter) is considered, changes in soil organic carbon (SOC) stocks are not considered.
- Changed areas were assumed to be the areas for foundations, substations, roads, and cable trenches. No additional buffer zone or temporal additional areas were added, as the total cleared vegetation area was assumed to already cover these areas. Shrub and/or herbaceous vegetation associations is the land use category used for "after windpark construction", given the assumption that forest area is cut back, but regrowth occurs.
- Carbon content of biomass (dry matter): 50%
- Ratio of total area affected by construction of wind park is 74% (i.e. total study site area = cleared vegetation area over the permanently changed areas after wind park construction)

The resulting GWP LULUC effect is 300.02 t CO_2 per ha which means 450.03 t CO_2 per turbine.

Primary data for the land use before construction at the study site are GoogleEarth and the Corine Land Cover map.

Figure 8: Satellite image of the (already existing) wind park showing also the location for Mahlsdorf before land use change

**** moved to Annex B (confidential data) ****

Demolition

All components of the wind farm that are considered in the study are dismantled.

The demolition stage of the end-of-life scenario uses various machines including cranes, lift trucks and excavators. For a 4.X turbine it was estimated that the diesel required to operate these machines would be 6.8 t per turbine (in the first LCA study). As no real data was available for this specific project, this value is used again here.

The diesel consumption for the demolition is higher than that required for installation due to activities such as deconstructing the foundation using an excavator.

Transport to End-of-Life

Transportation at end-of-life includes the transportation of the decommissioned components of the turbine, cables and substation, the machines for demolition and the driveway and set-up area utilized. This resulted in an estimated 397,633 t.km per turbine using a truck-trailer, Euro 0-6 mix, 34-40t gross weight/ 27t payload capacity. The assumed average transport distance is 100km.

Final disposal: thermal treatment and landfill

The waste treatment route for final disposal depends upon the material type.

The recycling recovery rate for all material types was assumed to be 95% after demolition. According to Nordex experts, the demolition of a turbine can be done with almost no losses. However, 5% losses were set as conventional assumption, this amount was landfilled.

The recycling recovery rate for steel used in the wind farm was modelled as being 96.5%. The remaining steel that could not be recycled was assumed to be landfilled. The slightly higher recovery rate for steel is because of the tower steel sections. They can be unbuilt with almost no losses (99% recovery), so the 96.5% is a weighted average of the total steel in the turbine including the tower sections. This share is taken from the first LCA study.

The following materials groups / components are considered in end-of-life modelling which amount to 99.1% related to mass of the turbine (incl. foundation and incl. replacement parts): steel, stainless steel, copper, aluminium, concrete, plastics/polymers, rotor blades. 100% of materials related to mass were covered in EoL for the MV cables and the substation. The foundation is fully dismantled and recycled.

The following EoL models were applied for the various material groups:

- All metals: landfill is considered. Recycling and material credits due to substitution of primary materials is not considered
- Concrete: landfill is considered. Recycling and material credits due to substitution of primary materials is not considered.

- Plastics: these are disposed of to waste incineration with energy recovery. However, no credits (thermal / electrical) are provided for the cut-off EoL allocation approach.
- Rotor blades: End-of-life technology provided by Neocomp (https://www.neocomp.eu/) has been applied (thermal recovery - partial material recycling in cement plant not considered).

SF_6 is applied in the MV switchgear in the turbine and the substation. This material is used in the electrical industry as a gaseous dielectric medium for high-voltage circuit breakers, switchgears, and other electrical equipment, often replacing oil filled circuit breakers (OCBs) that can contain harmful PCBs. SF_6 gas under pressure is used as an insulator in gas insulated switchgear (GIS) because it has a much higher dielectric strength than air or dry nitrogen.

Confidential data moved to Annex B.

However, as SF_6 has a high impact on climate change (per kg emission, factor 39,700 compared to CO_2), an emission during use or EoL needs to be discussed. Nordex turbines apply technical solutions to avoid a leakage, so under usual operational conditions, there is no emission of SF_6 – neither during the use phase nor at decommissioning phase.

It was assumed that all sulphur hexafluoride (SF_6) is fully recovered and recycled, hence there are no emissions. The recycling step itself is not modelled.

The end-of-life of the following material groups were neglected: used oil (in most cases, used oil is thermally treated), magnets (unclear EoL), electronics (in most cases, electronics are shredded and partly recycled), carbon fibre parts (unclear EoL) and coolant (no dataset available for EoL process). As those material groups are below 1% of the total mass on the system, the expected environmental effects of EoL is seen as very limited. Therefore, those material groups are cut off from EoL modelling.

3.3.4. Core (process)

Maintenance and Replacement

During the 20-year lifetime it is assumed that 35 kg of lubricants and 148 kg of coolants will be required per turbine per year.

An average value required for replaced parts and components was estimated for the 20-year lifetime based on statistics and experience within Nordex. Replaced components include rotor blades, main bearing, gearbox, generator and inverter.

Further confidential data moved to Annex B.

Transport – maintenance (process)

The transport estimated for the service team during the lifetime was 10,672 km per turbine and the transport of replaced parts / components 4,346 t.km (1,000 km transport distance using a truck-trailer, Euro 0-6 mix, 34-40t gross weight / 27t payload capacity).

3.3.5. Downstream stage

No activities considered in the downstream stage, as the system boundary of this study ends at the connection with the grid.

3.3.6. Additional environmental information in EPD - material substitution at End-of-Life

As a scenario calculated for the additional environmental information section in the EPD, the material credits are considered. The cut-off approach from the base case of the LCA and EPD is replaced by the substitution approach which is typically applied for products including recyclable metals. A short description of the substitution approach (net-scrap calculation) follows:

Material recycling (substitution approach): Open scrap inputs from the production stage are subtracted from scrap to be recycled at end-of-life to result in the net scrap output from the product life cycle. This remaining net scrap is sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary material to scale the substituted primary material, i.e., applying a credit for the substitution of primary material so as to distribute burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.

Energy recovery (substitution approach): In cases where materials are sent to waste incineration, they are linked to an incineration inventory dataset that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the avoided burden.

Landfilling (substitution approach): In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix.

The following EoL models were applied for the various material groups:

- All metals: secondary materials are recycled and substituted for primary materials. A kilogram of secondary material is assumed to substitute for 1 kg of virgin material. For aluminium, a value-correction factor has been applied such that 1 kg recycled aluminium substitutes for only 0.6 kg virgin aluminium. Secondary aluminium has a lower quality than primary aluminium. The exact quality loss depends on the application case, so a conventional assumption with a relatively high-quality loss of 40% was assumed.
- Concrete: secondary material is recycled and substitutes for gravel.
- Plastics: these are disposed of to waste incineration with energy recovery.
- Rotor blades: End-of-life technology provided by Neocomp (https://www.neocomp.eu/) has been applied (thermal recovery and partial material recycling in cement plant).

3.4. Model Overview

This section provides an overview of the LCA model developed in LCA FE. Each life cycle stage was modelled separately to allow for analysis and identification of hot spots throughout the life cycle.

Table 6 and Figure **Fehler! Verweisquelle konnte nicht gefunden werden.**9 show the LCA model created in LCA FE for the wind farm analysed in this study. The model was split into 7 key life cycle sections.

Table 6: Sub-plans used to build the LCA FE model

Life Cycle Stage	Item number	Component	Life Cycle Stage
Upstream/ Core	1	Delta4000 turbine (main components incl. foundation)	Raw materials / Nordex Manufacturing
Upstream	2	Cables for wind farm	Raw materials / Manufacturing
Upstream	3	Substation	Raw materials / Manufacturing
Upstream	4	Logistics	Transport
Core	5	Installation	Installation
Core	6	Use Phase	Use
Core/ Downstream	7	Decommissioning	End-of-life

Figure 8 shows the top-level plan of the life cycle model in LCA FE.

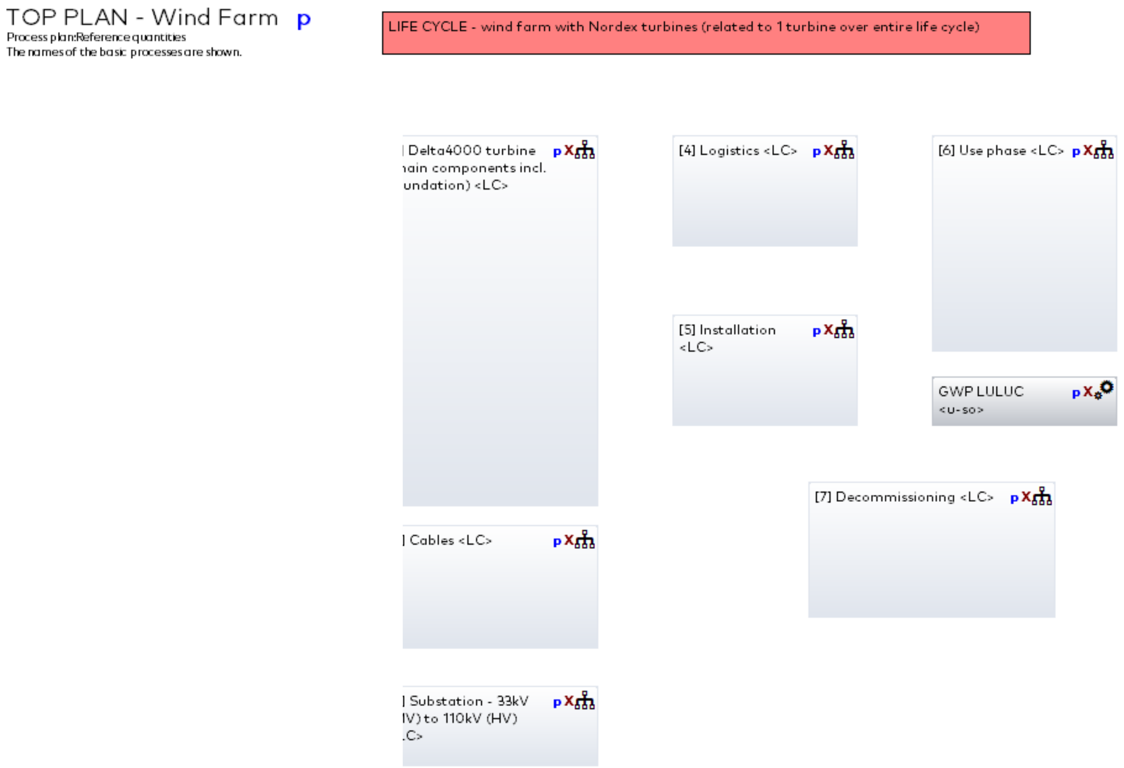

Figure 9: LCA model from LCA FE

3.5. Background Data

Documentation for all Sphera Managed LCA Content (MLC) datasets can be found online (Sphera, 2025). Contribution analysis has been utilised to quantify the contribution of datasets to the results of the EPD, and subsequently to justify their inclusion within the dataset documentation (>0.01% contribution to EF 3.1 Climate Change - total results). All datasets with a lower contribution have been cut-off based on their negligible contribution to the overall results.

3.5.1. Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the Sphera managed LCA Content (MLC) 2025.2 database. Table 7: shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using residual grid mixes that account for imports from neighbouring countries / regions (consumption mix).

Table 7: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	RER	Electricity grid mix 1kV-60kV	Sphera	2021	No
	DE	Electricity grid mix 1kV-60kV	Sphera	2021	No
	CN	Electricity grid mix	Sphera	2021	No

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Thermal energy	DE	Thermal energy from natural gas	Sphera	2021	No
	RER	Thermal energy from natural gas	Sphera	2021	Geo
	DE	Thermal energy from hard coal (credit)	Sphera	2021	Geo
	DE	Thermal energy from lignite (credit)	Sphera	2021	Geo
	CN	Thermal energy mix	Sphera	2021	No
	RER	District heating mix	Sphera	2021	No
Diesel	RER	Diesel mix at refinery	Sphera	2021	No
	RAS	Diesel mix at refinery	Sphera	2021	No
		Diesel combustion in construction machine	Sphera	2018	No

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.5.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the Sphera Managed LCA Content (MLC) 2025 database. Table 8: shows the most relevant LCI datasets used in modelling the product systems.

Table 8: Key material and process datasets used in inventory analysis

	Location	Dataset	Data Provider	Reference Year	Proxy?
Metals	RER	Fixing material screws galvanized (EN15804 A1-A3)	Sphera	2024	No
	RER	Fixing materials screws stainless steel (EN15804 A1-A3)	Sphera	2024	No
	GLO	Steel UO pipe	Worldsteel	2022	No
	GLO	Steel welded pipe	Worldsteel	2022	No
	GLO	Steel rebar	Worldsteel	2022	No
	RER +EFTA	Primary aluminium ingot mix consumed in Europe (2021-2023)	European Aluminium	2021	No
	RER +EFTA	Aluminium extrusion production (2021) European Aliminium	European Aluminium	2021	No
	GLO	Steel hot dip galvanised	Worldsteel	2022	No
	GLO	Steel electrogalvanized	Worldsteel	2022	Tech
	RER	Copper Sheet Mix (Europe 2015)	DKI/ ECI	2015	Temp
	RER	Copper Wire Mix (Europe 2015)	DKI/ ECI	2015	Temp
	RER	Steel forged component (EN15804 A1-A3)	Sphera	2024	No
	RER	Stainless steel cold rolled coil (316)	Eurofer	2014	Temp

	Location	Dataset	Data Provider	Reference Year	Proxy?
	RER	Stainless steel sheet (EN15804 A1-A3)	Sphera	2024	No
	GLO	Steel sections	Worldsteel	2022	No
	RER	Stainless steel Quarto plate (304)	Eurofer	2014	Temp
	RER	Stainless steel white hot rolled coil (304)	Eurofer	2014	Temp
	DE	Grey cast iron (GG) part (sand casting)	Sphera	2024	Geo
	DE	Cast iron component (EN15804 A1-A3)	Sphera	2024	Geo
	RER	Steel hot dip galvanised	Worldsteel	2022	No
	GLO	Steel organic coated	Worldsteel	2022	No
	GLO	Steel Engineering steel	Worldsteel	2022	No
	RER	Brass (CuZn39Pb3)	Sphera	2024	No
	RER	Red brass	Sphera	2024	No
Plastics	RER	Polyethylene foam (EN15804 A1-A3)	Sphera	2024	No
	RER	Polyethylene, LDPE, granulate	Plastics Europe	2013	Temp
	DE	Polypropylene / ethylene propylene diene elastomer granulate (PP/EPDM, TPO, TPE-O) mix	Sphera	2024	Geo
	DE	Polyamide 6.6 granulate (PA 6.6) Mix	Sphera	2024	Geo
	RER	PET, bottle grade, at plant	Plastics Europe	2015	Temp
	DE	Polypropylene granulate (PP) mix	Sphera	2024	Geo
	BE	Polyvinyl chloride granulate (S-PVC)	Sphera	2024	Geo
	DE	Polyvinyl chloride granulate (S-PVC) mix	Sphera	2024	No
	DE	Thermoplastic polyurethane (TPU, TPE-U) adhesive	Sphera	2024	Geo
	DE	Epoxy resin (EP) mix	Sphera	2024	Geo
	DE	Styrene-butadiene rubber (S-SBR) mix	Sphera	2024	No
	DE	Polymethyl methacrylate granulate (PMMA)	Sphera	2024	No
	DE	Nitrile butadiene rubber (NBR, 33% acrylonitrile)	Sphera	2024	No
Electronics	GLO	Average Printed Wiring Board with Signal-Power Electronics (DfX-Compatible)	Sphera	2024	Tech
	RER	Cable CAT 7 (EN15804 A1-A3)	Sphera	2024	Geo

	Location	Dataset	Data Provider	Reference Year	Proxy?
Other materials	RER	Kraftliner 2021; by-products: tall oil, turpentine; substitution EoL; [mass allocation]	Sphera/ FEFCO	2024	No
	DE	Glass fibres	Sphera	2024	Geo
	DE	Carbon fiber yarn (CF; from PAN; intermediate strength)	Sphera	2022	Geo
	RER	Solid construction timber (softwood) (EN15804 A1-A3) (15% moisture; 13% H2O content) 1m^3	Sphera	2024	Geo
	RER	Sand 0/2	Sphera	2024	No
	RER	Gravel 2/32	Sphera	2024	No
	RER	Concrete C35/45 (Ready-mix concrete) (EN15804 A1-A3)	Sphera	2024	No
	RER	Concrete C80 (Ready-mix concrete) (Nordex adapted)	Sphera / Nordex	2023	No
	RER	Silicone sealing compound (EN15804 A1-A3)	Sphera	2024	No
	DE	Ethylene glycol (via O2/ methane; price allocation)	Sphera	2024	No
	RER	Tap water from groundwater	Sphera	2024	No
	RER	Lubricants at refinery	Sphera	2021	No

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

The data on steel products from worldsteel are the best available data as they represent the global average production based on primary industry data. However, the water consumption data is partly not consistent as the water balance is not closed for all products and for all steel plants participating at the global data collection of worldsteel. So, for this study, the water data for the products rebar, sections and UO pipe had to be manually adapted as the total water consumption was negative in the original datasets. A conservative assumption of about 10kg blue water consumption per kg steel product was chosen as baseline and the three products were adapted accordingly.

3.5.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to production and assembly facilities.

The Sphera Managed LCA Content (MLC) 2025 database was used to model transportation. Transportation was modelled using the MLC global transportation datasets. Fuels were modelled using the geographically appropriate datasets.

Table 9: Transportation and road fuel datasets

Process/material	Location	Dataset	Data Provider	Reference Year	Proxy?
Truck	GLO	Truck, Diesel, Euro mix, 20 - 26t gross weight	Sphera	2023	No

Process/material	Location	Dataset	Data Provider	Reference Year	Proxy?
	GLO	Truck-trailer, Euro 0-6 mix, 34 - 40t gross weight / 27t payload capacity – modified (special transport)	Sphera	2018	No
Diesel	RER	Diesel mix at refinery	Sphera	2021	Geo
Fuel oil	RER	Heavy fuel oil at refinery (1.0wt.% S)	Sphera	2021	Geo
Ship	GLO	Container ship, 5,000 to 200,000 dwt payload capacity, deep sea	Sphera	2023	No
Passenger car	GLO	Passenger car, average, Euro 3-5, engine size from 1.4l up to >2l	Sphera	2022	No
Excavator	GLO	Excavator, 100 kW, construction	Sphera	2023	No

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.5.4. Waste treatment

Treatment of waste in production and at end-of-life is modelled using Sphera Managed LCA Content (MLC) 2025.2 database LCI data for landfill, incineration, recycling and composting processes. Table 10: shows the most relevant waste processing and treatment datasets used in modelling.

Table 10: Key waste treatment datasets used in inventory analysis

Process	Location	Dataset	Data Provider	Reference Year	Proxy?
Commercial waste incineration	RER	Commercial waste in municipal waste incineration plant	Sphera	2024	Geo
Inert waste on landfill	RER	Inert matter (Glass) on landfill	Sphera	2024	Geo
Municipal waste incineration	DE	Municipal waste in waste incineration plant (38.6% H_2O content)	Sphera	2024	Geo
Wood incineration	RER	Untreated wood in waste incineration (10% H_2O content)	Sphera	2024	Geo
Plastic incineration	RER	Plastic packaging in municipal waste incineration plant	Sphera	2024	Geo

*Proxy legend: Geo = Geographical, Tech = Technology, Temp = Temporal

3.6. Data assumptions and data gaps

The study includes a wide range of different kind of data and parameters. Key parameters are further analysed in section 4.4 which cover aspects of the energy production during lifetime of the wind farm (AEP and lifetime) and the chosen end-of-life scenario. Some of those parameters depend on site-specific conditions and thus, can vary.

Key parameters / assumptions are:

- Configuration of Delta4000 – N175/6.X: 179m hub height, one-piece NR85.7 rotor blade
- Wind farm design: wind farm in Germany with 10 turbines and 1 substation
- Wind conditions: IEC wind class S
- Lifetime of wind farm: up to 30y (baseline for EPD: 20 years)
- Net AEP: 16,898 MWh (p75)

Further relevant assumptions are:

- Average MV cable length per turbine in wind farm: 24.42km
- No SF6 emissions during use and EoL (normal operation mode)

Assumptions are taken during modelling on mainly 2 levels – selection of dataset proxies and modelling assumptions. Both are listed below.

Data proxies applied for

- Various alloyed metal parts modelled with proxies (e.g. steel, cast steel, stainless steel, aluminium) – reality (thousands of metal products) vs. model (hundreds of metal datasets available). This is true for nearly all material groups (but metals are by far the most relevant material group in the assessed system) and is implicitly the nature of LCA modelling.
- Electrical steel → electro-galvanized steel as proxy
- Lead battery → lead metal as proxy (*further confidential data moved to Annex B)*
- Forming processes for plastic or metal parts → partly modelled with proxies
- Submerged arc welding → gas metal arc welding as proxy
- Various electronic parts (partly not differentiated in detail during data collection as masses are relatively small) → average printed wiring board with signal-power electronics as proxy
- Geographical reference modelled with proxies – steel as main material is always modelled as globally produced industry average as the Nordex sourcing uses different steel suppliers located all around the world

Qualitative assessment of the relevance of data proxy application related to main environmental indicators:

- The simplification of the modelling of alloyed metal parts has a low impact on environmental indicators. The variety of metal products is huge, but the range in shares of alloying elements is in most cases relatively low.
- Electrical steel has a minor contribution compared to other steel products in the overall mass of the product. So, the relevance of the selected data proxy is considered small.
- Lead batteries have a very minor contribution compared to other components in the overall mass of the product. So, the relevance of the selected data proxy is considered very small.
- Forming processes for plastic or metal parts are of minor relevance compared to the actual materials that are formed. So, the relevance of the selected data proxy is considered very small.
- Various electronic parts are modelled conservatively with electronic datasets that represent miniature electronics. So, the environmental impacts due to electronics in the product is most likely overestimated based on the selected data proxy.
- The geographical reference for steel products has a certain relevance for the overall results as steel is the main material in the product. Especially the recycled content varies from region to region. The selected global production mix of steel products is considered as the most representative choice as Nordex doesn´t have a specific supplier for steel and it is produced and traded globally.

Modelling assumptions

- Cable models with +10% material consumption assumed to account for manufacturing and gross material consumption
- Special transports (applied in logistics) with +20% of diesel consumption and emissions of large trucks
- Production of SF6 → estimated as material mix of sulphur and fluorine
- Manufacturing of aluminium wires → adaptation of dataset for copper wire manufacturing
- Estimated average transport distance for raw materials, part, components from suppliers for manufacturing of turbine, cables and substation → 1,000km
- Estimated average transport distance for dismantled parts at EoL → 100km

For a few materials, no LCI dataset was available. So, no LCI data was applied for:

- “Midel 7131” (ca. 1,650kg per turbine) – synthetic ester
- Silver (less than 10g per turbine)
- Magnets
- Li-ion battery
- Special resin in 100kV transformer
- Various coatings for metal parts

The effect of those data gaps – which are the same as in Nordex’ previous LCA studies – has already been tested on the overall GWP results in the course of the first LCA: the estimated contribution of Midel (synthetic ester) was +0.4% to the overall GWP result, the estimated contribution of silver was +0.0004% to the overall GWP result. The difference between an estimated lead battery and lead metal on the overall GWP result was the following: 0.005% due to the battery and 0.007% due to lead metal. It is therefore assumed that the data gaps for the current LCA are within a very similar range.

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks. The results for each impact are presented in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

4.1. Indicators for the LCIA

As required by the PCR and EN 15804:2012+A2:2019, the environmental impact assessment categories listed in Table 11 are reported in this EPD. The method indicated in EN15804:2012+A2:2019 is EF 3.1 characterisation factors (Hauschild M, 2011) with the latest 3.1 update.

It should be noted that LCIA results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins or risks.

The results of ADPE, ADPF, and WDP impact indicator shall be used with care as the uncertainties on these results are high or as there is limited experienced with the indicator.

Table 11: Categories of life cycle impact assessment inventory on output flows

Category	Abbr.	Unit
Climate change - total	GWP	kg CO_2 equivalent
Climate change, fossil	GWP fossil	kg CO_2 equivalent
Climate change, biogenic	GWP biogenic	kg CO_2 equivalent
Climate change, land use and land use change	GWP LULUC	kg CO_2 equivalent
Ozone depletion	ODP	kg CFC 11 equivalent
Eutrophication, freshwater	EP	kg P equivalent
Acidification	AP	moles of H+ equivalent
Photochemical ozone formation, human health	POCP	kg NMVOC equivalent
Resource use, mineral and metals	ADPE	kg Sb equivalent
Resource use, fossils	ADPF	MJ, net calorific value

Category	Abbr.	Unit
Water use	WDP	m^3 equivalent

4.2. Indicators for the LCI

The environmental parameters shown below describe the use of renewable and non-renewable material resources, renewable and non-renewable primary energy and water and are based on data from the averaged LCI results.

Table 12: Resource consumption descriptive parameters

Indicator	Abbr.	Unit
Use of non-renewable primary energy excluding non-renewable primary energy resources used as raw material	PENRE	MJ, net calorific value
Use of renewable primary energy excluding renewable primary energy resources used as raw material	PERE	MJ, net calorific value
Use of non-renewable primary energy as raw materials	PENRM	MJ, net calorific value
Use of renewable primary energy as raw materials	PERM	MJ, net calorific value
Total use of non-renewable primary energy resources (primary energy and primary energy resources used as raw materials)	PENRT	MJ, net calorific value
Total use of renewable primary energy (primary energy and primary energy resources used as raw materials)	PERT	MJ, net calorific value
Net use of fresh water	FW	kg
Use of secondary material	SM	kg
Use of renewable secondary fuels	RSF	MJ, net calorific value
Use of non-renewable secondary fuels	NRSF	MJ, net calorific value

Table 13: Waste production descriptive parameters

Indicator	Abbr.	Unit
Hazardous waste disposed	HWD	kg
Non-hazardous waste disposed	NHWD	kg
Radioactive waste disposed	RWD	kg
Materials for recycling	MFR	kg
Materials for energy recovery	MER	kg
Components for reuse	CRU	kg
Exported thermal energy	EET	MJ
Exported electrical energy	EEE	MJ

4.3. Overall Results

The overall life cycle results for the product system are presented in Table 14.

Table 14: EN15804+A2 Impact potentials for the full life cycle of the product system per functional unit, production of 1 kWh of electricity

Impact indicator	Unit	TOTAL	Upstream	Core	Downstream
GWP- total	kg CO_2 equivalent	1,70E-02	1,05E-02	6,41E-03	0,00E+00
GWP, fossil	kg CO_2 equivalent	1,28E-02	1,05E-02	2,34E-03	0,00E+00
GWP, biogenic	kg CO_2 equivalent	2,73E-03	3,73E-05	2,69E-03	0,00E+00
GWP, LULUC	kg CO_2 equivalent	1,38E-03	6,59E-06	1,37E-03	0,00E+00
ODP	kg CFC 11 equivalent	6,47E-14	6,05E-14	4,20E-15	0,00E+00
EP, freshwater	kg P equivalent	3,40E-08	1,86E-08	1,53E-08	0,00E+00
AP	moles H+ equivalent	4,77E-05	3,85E-05	9,17E-06	0,00E+00
POCP	kg NMVOC equivalent	3,58E-05	2,29E-05	1,29E-05	0,00E+00
ADP, minerals + metals	kg Sb equivalent	1,50E-07	1,49E-07	3,70E-10	0,00E+00
ADP, fossil	MJ, net calorific value	1,56E-01	1,31E-01	2,43E-02	0,00E+00
WDP	m^3 equivalent	1,64E-03	1,51E-03	1,38E-04	0,00E+00

Table 15: Impact potentials for the full life cycle of the product system per functional unit, production of 1 kWh of electricity

Impact indicator	Unit	TOTAL	Upstream	Core	Downstream
PENRE	MJ, net calorific value	1,56E-01	1,31E-01	2,43E-02	0,00E+00
PERE	MJ, net calorific value	3,64E-02	3,30E-02	3,37E-03	0,00E+00
PENRM	MJ, net calorific value	0,00E+00	0,00E+00	0,00E+00	0,00E+00
PERM	MJ, net calorific value	0,00E+00	0,00E+00	0,00E+00	0,00E+00
PENRT	MJ, net calorific value	1,56E-01	1,31E-01	2,43E-02	0,00E+00
PERT	MJ, net calorific value	3,64E-02	3,30E-02	3,37E-03	0,00E+00
FW	kg	3,64E-04	1,93E-04	1,70E-04	0,00E+00
SM	kg	5,56E-06	5,56E-06	0,00E+00	0,00E+00
RSF	MJ, net calorific value	0,00E+00	0,00E+00	0,00E+00	0,00E+00
NRSF	MJ, net calorific value	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Table 16: Impact potentials for the full life cycle of the product system per functional unit, production of 1 kWh of electricity

Impact indicator	Unit	TOTAL	Upstream	Core	Downstream
HWD	kg	4,31E-08	4,25E-08	6,82E-10	0.00E+00
NHWD	kg	2,61E-03	9,75E-04	1,64E-03	0.00E+00
RWD	kg	3,60E-06	3,35E-06	2,55E-07	0.00E+00
MFR	kg	1,16E-02	6,43E-06	1,16E-02	0.00E+00
MER	kg	1,41E-04	0,00E+00	1,41E-04	0.00E+00
CRU	kg	0,00E+00	0,00E+00	0,00E+00	0.00E+00
EET	MJ	8,02E-03	0,00E+00	8,02E-03	0.00E+00
EEE	MJ	4,45E-03	0,00E+00	4,45E-03	0.00E+00

4.4. Results for additional environmental information

ALTERNATIVE CASE 1 - System expansion with substitution approach (including material credits

Substitution approach – this approach is based on the perspective that material that is recycled at end-of-life will substitute for an equivalent amount of virgin material. A credit is given to account for the benefits of this substitution. However, this also means that burdens equivalent to this credit should be assigned to scrap used as an input to the production process, with the overall result that the impact of recycled granulate is the same as the impact of virgin material. Hence this approach rewards end-of-life recycling but does not reward the use of recycled content.

Short description of the substitution approach which has been selected as alternative method for the additional environmental information:

> *Material recycling (substitution approach):* Open scrap inputs from the production stage are subtracted from scrap to be recycled at end-of-life to result in the net scrap output from the product life cycle. This remaining net scrap is sent to material recycling. The original burden of the primary material input is allocated between the current and subsequent life cycle using the mass of recovered secondary material to scale the substituted primary material, i.e., applying a credit for the substitution of primary material so as to distribute burdens appropriately among the different product life cycles. These subsequent process steps are modelled using industry average inventories.
>
> *Energy recovery (substitution approach):* In cases where materials are sent to waste incineration, they are linked to an incineration inventory dataset that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate of the avoided burden.
>
> *Landfilling (substitution approach):* In cases where materials are sent to landfills, they are linked to an inventory that accounts for waste composition, regional leakage rates, landfill gas capture as well as utilisation rates (flaring vs. power production). A credit is assigned for power output using the regional grid mix.

The following EoL models were applied for the various material groups:

- All metals: secondary materials are recycled and substituted for primary materials. A kilogram of secondary material is assumed to substitute for 1 kg of virgin material. For aluminium, a value-correction factor has been applied such that 1 kg recycled aluminium substitutes for only 0.6 kg virgin aluminium. Secondary aluminium has a lower quality than primary aluminium. The exact quality loss depends on the application case, so a conventional assumption with a relatively high-quality loss of 40% was assumed.
- Concrete: secondary material is recycled and substitutes for gravel.
- Plastics: these are disposed of to waste incineration with energy recovery.
- Rotor blades: End-of-life technology provided by Neocomp (https://www.neocomp.eu/) has been applied (thermal recovery and partial material recycling in cement plant).

Two indicators are shown in the EPD related to the adapted EoL stage (GWP total and GWP fossil). Including the substitution approach with material credits for the net amounts of recyclable material instead of the cut-off approach the results are the following:

Applying the substitution approach with an assumed 25-year lifetime:

- **GWP total** – upstream, core, downstream: 11.53g CO2eq / kWh
- GWP fossil – upstream, core, downstream: 8.00g CO2eq / kWh

ALTERNATIVE CASE 2 – Lifetime extension to 25, 30 and 35 years

According to the technical design of the Delta4000 N175/6.X the lifetime is expected to be 30 years according to a lifetime extension assessment. For the sake of comparability and to follow the requirements of the PCR, the base case in this LCA takes 20 years lifetime as a basis. This sensitivity analysis checks the influence of the extended lifetime on two result parameters. 25% longer lifetime results in 25% more energy produced. The result parameters related to AEP, namely GWP, are reduced accordingly.

For 25 years lifetime:

- **GWP total** – upstream, core, downstream: 13.58g CO2eq / kWh
- GWP fossil – upstream, core, downstream: 10.29g CO2eq / kWh

For 30 years lifetime:

- **GWP total** – upstream, core, downstream: 11.33g CO2eq / kWh
- GWP fossil – upstream, core, downstream: 8.58g CO2eq / kWh

For 35 years lifetime:

- **GWP total** – upstream, core, downstream: 9.71g CO2eq / kWh
- GWP fossil – upstream, core, downstream: 7.37g CO2eq / kWh

5. Interpretation

5.1. Identification of Relevant Findings

This report presents the results for the environmental impact from the life cycle assessment study of a Delta4000 wind farm composed of 10 turbines of the type N175/6.X, located in Germany.

In summary, the study is modelled with the assumption that the wind farm is based in Germany at a special wind site (IEC wind class S conditions; average wind speed at hub height in this study is 6.5 m/s).

The results are presented in a heat map in The installation phase contributes around 17.0% to the total GWP.

Table 17, showing the relative contribution from cradle to end-of-life. The decommissioning stage is considered here as part of the “Core” module.

It can be seen from the results, presented per declared unit, that across the majority of impact categories, the upstream module (raw material and manufacturing stages not carried out by Nordex) of the turbine is, by far, the most dominant contributor across the whole life cycle of the wind farm. This is due to the raw material procurement and upstream manufacturing associated with the wind turbine.

The share of the foundation by mass is 45.6% of the turbine. However, as it is composed of approximately 94% concrete, the impact potential across all impact categories is significantly lower than that of the components that are composed of metals and other higher impact materials. The foundation contributes to approximately 6.6% of the total GWP over the full life cycle. The entire tower accounts for 46.3% of the mass of the turbine, similar to that of the foundation. However, due to the quite large amount of steel that contributes to the tower structure, as well as the bottom part out of concrete, the GWP is approximately 19.6% of the full life cycle, showing it to be more significant than the foundation. Similarly, despite the blades only contributing 2.6% of the mass of the turbine, they are significant contributors in several impact categories and represent 13.4% of the total GWP making them the second largest contributor out of the turbine components.

With the relatively high amount of MV cables used in the wind farm, their overall contribution to the total GWP is around 14.6%. Transportation of materials and components to the wind farm site account for approximately 5.7% of the total GWP, as quite some components are manufactured or assembled in China and transported to the wind farm location in Germany. The installation phase contributes around 17.0% to the total GWP.

Table 17: Heat map for environmental impact potentials

Abbr.	Unit	TOTAL	Upstream	Core	Downstream
GWP - total	kg CO_2 equivalent	1,70E-02	1,05E-02	6,41E-03	0,00E+00
GWP fossil	kg CO_2 equivalent	1,28E-02	1,05E-02	2,34E-03	0,00E+00
GWP biogenic	kg CO_2 equivalent	2,73E-03	3,73E-05	2,69E-03	0,00E+00
GWP LULUC	kg CO_2 equivalent	1,38E-03	6,59E-06	1,37E-03	0,00E+00
ODP	kg CFC 11 equivalent	6,47E-14	6,05E-14	4,20E-15	0,00E+00
EP, freshwater	kg PO_4 equivalent	3,40E-08	1,86E-08	1,53E-08	0,00E+00
AP	moles H+ equivalent	4,77E-05	3,85E-05	9,17E-06	0,00E+00
POCP	kg NMVOC equivalent	3,58E-05	2,29E-05	1,29E-05	0,00E+00
ADP metals + minerals	kg Sb equivalent	1,50E-07	1,49E-07	3,70E-10	0,00E+00
ADP, fossil	MJ, net calorific value	1,56E-01	1,31E-01	2,43E-02	0,00E+00
WDP	m^3 equivalent	1,64E-03	1,51E-03	1,38E-04	0,00E+00

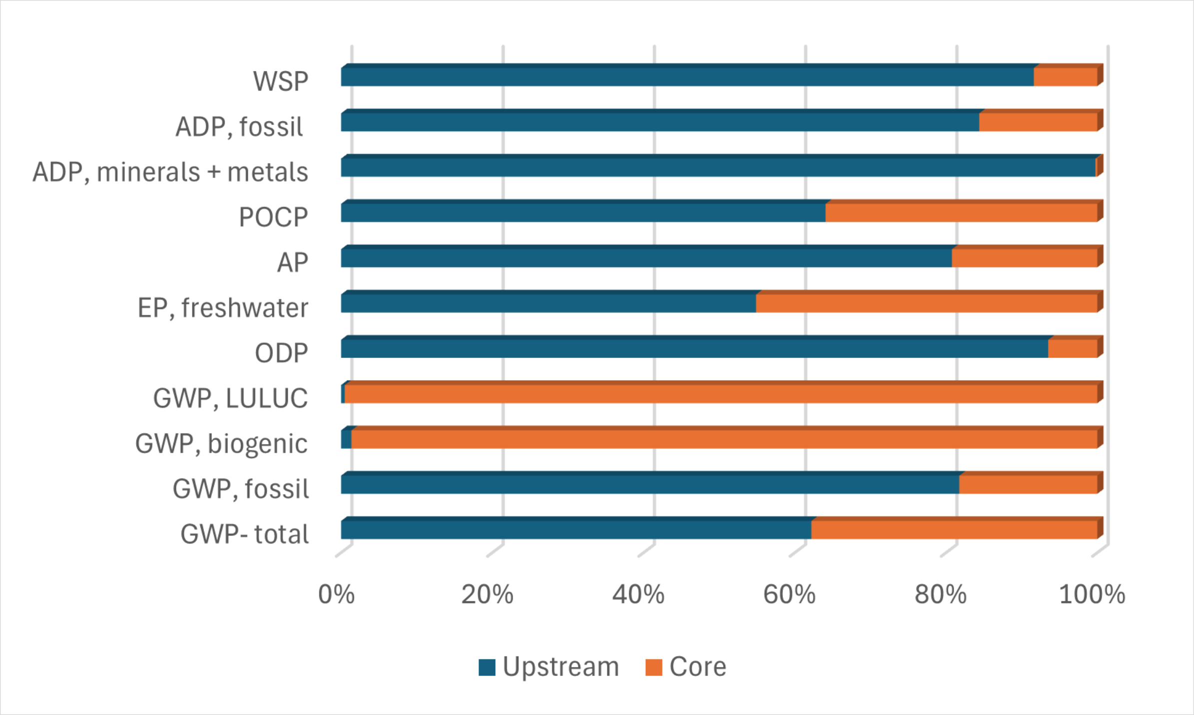

Figure 10: Percentage contribution from different life cycle modules to the total impact of the Nordex Delta4000 wind farm

5.2. Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand industry data in combination with consistent background LCA information from the Sphera Managed LCA Content (MLC) 2025 database were used. The LCI datasets from the Sphera Managed LCA Content (MLC) 2025 database are widely distributed and used with the LCA FE 10 Software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science.

5.2.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources provided by the Nordex Group, precision is considered to be high. Seasonal variations/variations across different manufacturers were balanced out by using yearly averages. Most background data are sourced from Sphera Managed LCA Content (MLC) databases with the documented precision.
- ✓ **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. Some data points were omitted as documented earlier in this report. Nevertheless, completeness of foreground unit process data is considered to be high. Most background data are sourced from Sphera Managed LCA Content (MLC) databases with the documented completeness.

5.2.2. Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while most background data were sourced from the Sphera Managed LCA Content (MLC) databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third party should be able to approximate the results of this study using the same data and modelling approaches.

5.2.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2024. Most secondary data come from the Sphera Managed LCA Content (MLC) 2025 databases and are representative of the years 2022-2027. As the study intended to compare the product systems for the reference year 2024, temporal representativeness is considered to be moderate/high.
- ✓ **Geographical:** All primary and secondary data were collected specific to the countries under study. Where country-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be moderate.
- ✓ **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Where technology-specific data were

unavailable, proxy data were used. Technological representativeness is considered to be high.

5.3. Model Completeness and Consistency

5.3.1. Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.3.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimised by predominantly using LCI data from the Sphera Managed LCA Content (MLC) 2025 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.4. Conclusions, Limitations, and Recommendations

5.4.1. Conclusions

This study has evaluated the environmental performance of the Nordex Delta4000 wind farm situated in Germany, in a special wind site with an IEC wind class S, and 6.5 m/s average wind speed at hub height.

For a 20-year wind farm lifetime and net annual energy production (AEP) of 16,898 MWh per annum (P75) per turbine, the total climate change impact of the electricity generated was found to be 16.9g CO_2 eq./kWh including land use change. For comparison, the average climate change burden of electricity from the German electricity production is 329g CO2 eq./kWh[2]. Large reductions were also seen for other impact categories assessed in this study. This demonstrates the significant improvements in environmental performance that can be achieved through increasing the proportion of electricity generated using wind power.

The impacts associated with the wind farm are dominated by the upstream life cycle stage – this accounts for 55-100% of the total cradle-to-use burden across all impact categories apart from Climate change related to land use and land use change and Climate change through biogenic CO2 emissions, where the core stage dominates the impact potential accounting for 100% and 99%, respectively. This is typically due to the raw materials required for the turbines and manufacturing that occurs upstream to Nordex onsite processes. Other life cycle stages, such as installation, logistics, other wind farm infrastructure, etc. have a smaller contribution in comparison, hence the core stage is not as significant.

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[2] Public Electricity Generation 2024: Renewable Energies cover more than 60 Percent of German Electricity Consumption for the First Time - Fraunhofer ISE (152 Mio t CO2eq / 462 TWh = 329g CO2eq / kWh)

A more detailed look at the turbines themselves shows that for this turbine type most of the burdens are associated with the tower materials and manufacturing, although the blades, foundation and electronics also have noticeable contributions in specific impact categories.

5.4.2. Limitations

This study reflects a wind farm comprising Delta4000 wind turbines, which is operated in Germany under specific wind conditions. It may not be valid to extrapolate these results to wind farms in other regions or operating under different conditions. Some materials used in the construction of the turbines have been omitted from the study, such as the magnets and batteries amongst others.

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