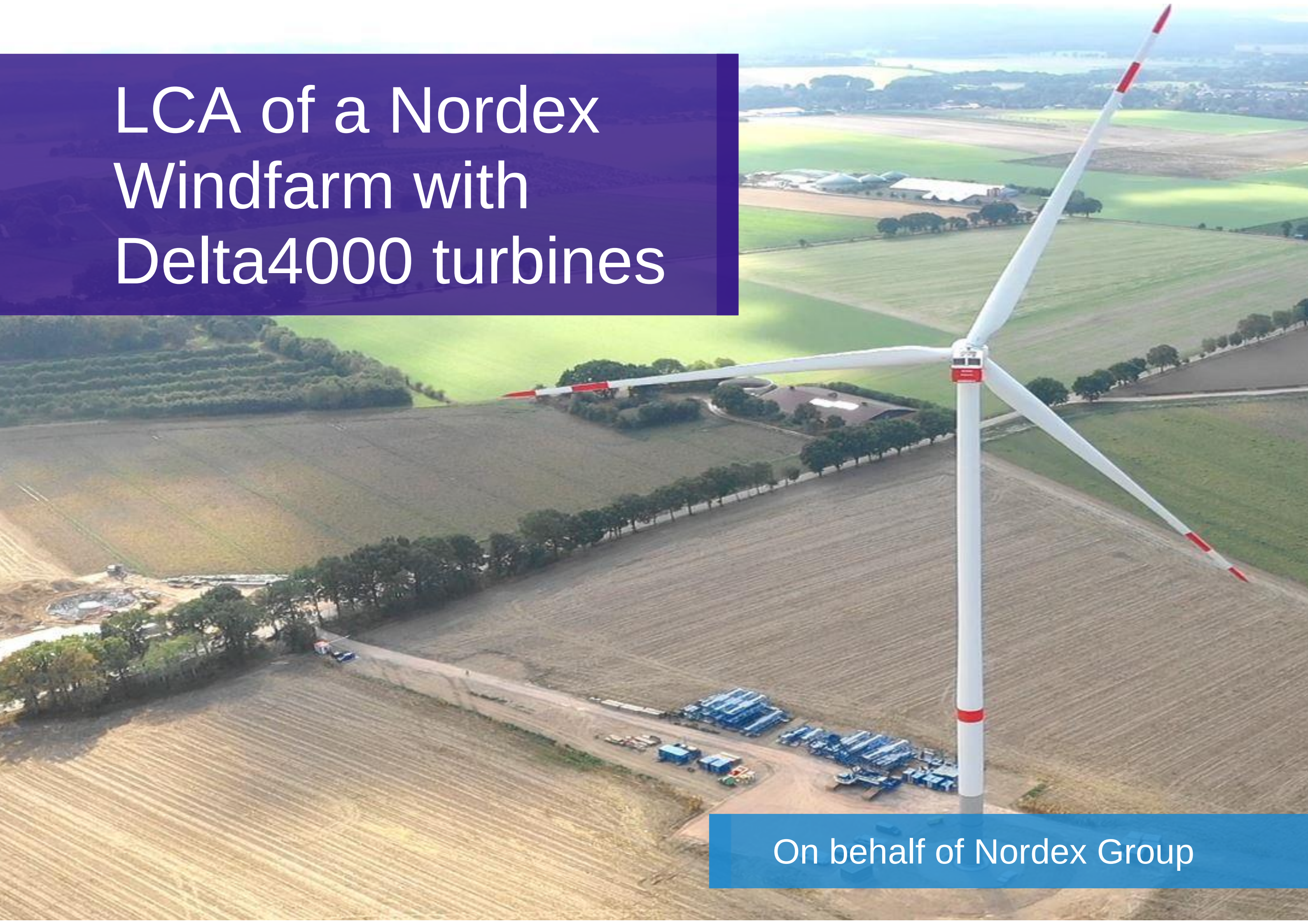

LCA of a Nordex Windfarm with Delta4000 turbines

On behalf of Nordex Group

Client: **Nordex Group**

Title: **Life Cycle Assessment of a Nordex Windfarm with Delta4000 turbines**

Report version: v2.1

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On behalf of Sphera Solutions, Inc., and its subsidiaries

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List of Acronyms

AEP	Annual Energy Production
AP	Acidification Potential
CML	Centre of Environmental Science at Leiden
EF	Environmental Footprint
EoL	End-of-Life
EP	Eutrophication Potential
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
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MV	medium voltage
NMVOC	Non-Methane Volatile Organic Compound
VOC	Volatile Organic Compound

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. Goal of the Study

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 to be analysed in this study is the newest turbine developed by Nordex, the Delta4000.

As well as producing technologically-leading products, Nordex is also concerned with minimising its impact on the environment and is seeking to better understand the sustainability performance of its products through a life cycle perspective.

The product system to be assessed in this study is the N149/4.0-4.5, the latest development of the successful Delta4000 series, which is the culmination of over 35 years of experience in the sector.

Nordex Group has commissioned Sphera, a sustainability, environmental health & safety software and consulting company, to carry out a life cycle assessment (LCA) of an exemplary Delta4000 windfarm.

The objectives of this LCA study are to:

- Develop Nordex's understanding of the environmental performance of the Delta4000 windfarm
- Identify environmental "hot spots" associated with the life cycle of the windfarm
- Inform design choices for future development of the Delta4000 and other wind turbine designs
- Assist the company with setting environmental targets.

The intended audience for the study is both internal and external to the Nordex Group (e.g. including employees, customers, investors, rating agencies, certifiers). The results of this study are not intended to be used in comparative assertions intended to be disclosed to the public.

This LCA has been conducted according to the requirements of ISO 14044 (ISO, 2006) and has undergone critical review by an independent reviewer.

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 evaluates an exemplary Nordex windfarm in Sweden, which uses N149/4.0-4.5 turbines that are part of the Delta4000 turbines series. The N149/4.0-4.5 turbine is one of the Nordex Group's highest yielding onshore turbine for light and medium wind regions and has an energy yield up to 28% higher than that of the company's previous N131/3600 model.

Figure 1: Product system – view of Delta4000 N149/ 4.0-4.5 turbine

The N149/4.0-4.5 turbine has a standard maximum output of between 4.0-4.5 MW, project-specific even up to 4.8 MW, and so is adaptable to the respective grid operator's individual requirements, along with local wind conditions and noise restraints. This allows for further optimisation when several of these turbines are deployed in a windfarm, where each turbine can adapt to its unique position to maximise the wind energy harnessed based on the local conditions.

A typical windfarm has a lifetime of around 20 years, depending on the local site conditions of the windfarm. This time period has been used as the baseline for this study. The towers available offer hub heights of 105, 125 and 164 metres, however this study focuses on the 105 m hub height. The rotor sweep is 17,460 m^2 with a blade diameter of 149.1 m. The turbine can be operated at sites with average temperatures in a “normal” climate range and is adaptable to temperatures as low as minus 20 degrees Celsius. In the cold climate variant, the turbine can be operated also down to minus 30 degrees Celsius.

The turbine is currently one of the quietest turbines on the market for its power rating of 4.0-4.5 MW and for the class of light wind sites. The maximum sound power level of the N149/4.0-4.5 lies between 103.6 dB(A) and 106.1 dB(A). In addition to this, at sites with lower permissible sound power requirements, the turbine has the potential to operate under a broader range of sound-optimising modes e.g. for just under 3 MW nominal power the sound power level lies at max. 96.5°dB(A).

2.2. Product Functions and Functional Unit

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

The function of a windfarm is to generate electricity by harnessing wind energy. As such, the functional unit for this study has been defined as:

The generation of 1 kWh of electrical energy (net) considering the full lifetime of the windfarm (Delta4000 turbines), located in an exemplary Swedish scenario and operating under low wind conditions (IEC wind class III), and thereafter distributed to a 110kV electrical grid.

The windfarm design is based on a predefined project landscape. The assessed site is a low wind site (IEC wind class III) which is defined as less than 7.5 m/s average wind speed at hub height (actual value applied in this study: average wind speed at hub height 6.8 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 years to a total lifetime of 30 years, according to the method of life time extensions and the related advisory opinions by TÜV Nord and TÜV Süd (TÜV Nord CERT, 2018) and (TÜV Süd Industrie Service, 2019). The applied lifetime of turbines in a windfarm follows site-specific conditions. For the assessed windfarm of this study, the CoE landscape for Sweden defines a lifetime of 25 years applying the method of lifetime extension by 5 years.

Thus, this functional unit allows for an average energy production to be determined based on-site-specific parameters for a location in Sweden. The baseline assumption for the windfarm lifetime is 25 years, but a reduced lifetime of 20 years and an extended lifetime of 30 years have been considered in a sensitivity analysis. In LCAs on onshore wind turbines, the lifetime is often defined with 20 years as base case.

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 for use and end-of-life stages, the use stage and the end-of-life stage including recycling and final disposal.

The local system boundary for the windfarm ends with the connection to the electricity grid. The turbines in the windfarm are connected via MV (medium voltage) cables to the substation. The substation transforms the electricity to 110kV (high voltage). The HV cable connects the windfarm 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 windfarm. Transport was also included from the windfarm to end-of-life processing.

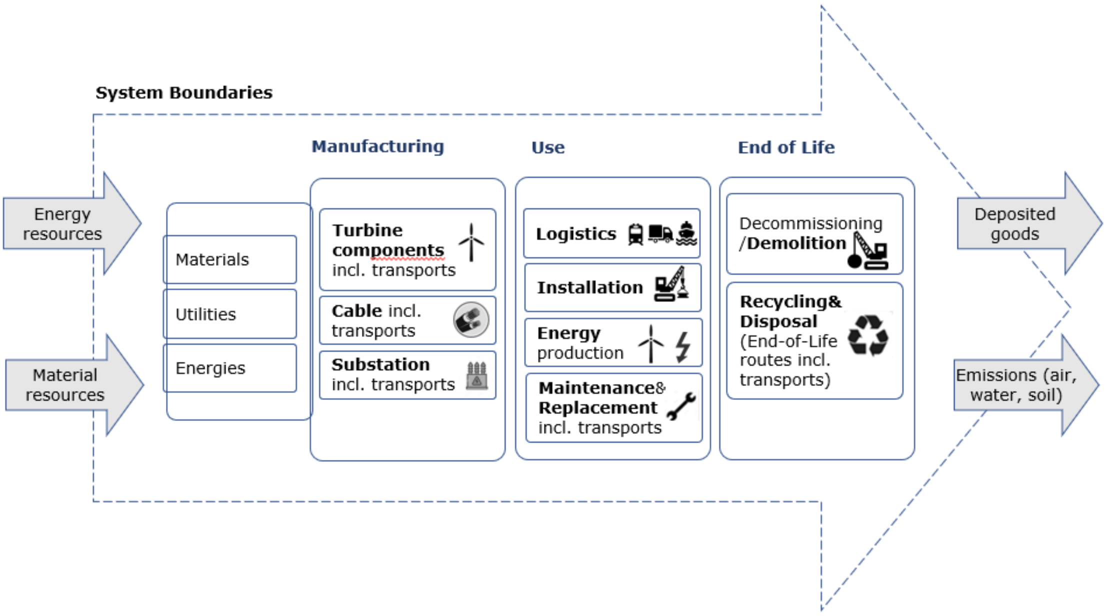


Figure 2: Overview of system boundaries

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

Table 1: System boundaries

Included	Excluded
✓ Raw material production ✓ Fabrication of raw materials into parts and components ✓ Manufacturing ✓ Installation, ✓ Associated infrastructure such as roads ✓ Operation ✓ End-of-life	× Employee commuting

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 windfarm have been included in the study. The boundary is taken to be the point at which the windfarm produces an equivalent of 1 kWh to be 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 windfarm (Delta4000 turbines) in 2019. 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 windfarm (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 windfarm (Delta4000 turbines) in Sweden. This is a light wind site with IEC wind class III, which is defined as having an average wind speed of less than 7.5 m/s at hub height.

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 GaBi 2019 databases is documented online (Sphera, 2019).

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 substitution approach has been selected as the baseline method in this study as we consider this to be most appropriate for the main materials used to construct wind turbines, where there is significant demand for recycled materials generated at end-of-life (e.g. steel). This follows the recommendations provided in the *GHG Protocol Product Life Cycle Accounting and Reporting Standard* (WRI, 2011) and in the LCI methodology report of the worldsteel association (worldsteel, 2017). Metals, especially steel, is the dominating material group for Delta4000 turbines. An explanation of how the substitution approach has been implemented in the LCA model is provided below.

The cut-off approach has been modelled in a scenario analysis and is also described below.

Short description of the substitution approach which has been selected as the baseline method in this study:

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.

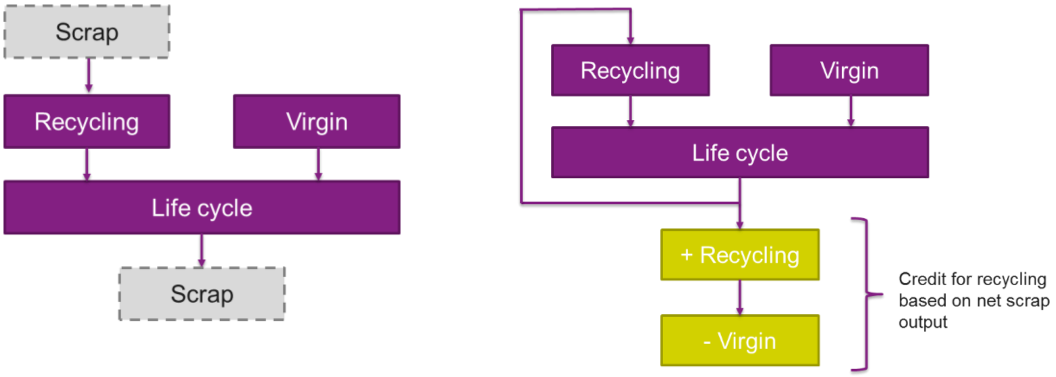
Energy recovery (substitution approach): In cases where materials are sent to waste incineration, they are linked to an incineration inventory dataset that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Credits are assigned for power 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.

Short description of the cut-off approach that has been modelled in a scenario analysis:

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): Any open scrap inputs into manufacturing remain unconnected. 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

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. 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. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2. The impact methodologies used to evaluate each impact category are a selection of those used in the European Commission's Product Environmental Footprint initiative (latest version, EF3.0, see (PEF METHOD 2019, 2019)) that are considered more relevant for the assessed product system. These are considered to be the most robust and up to date available for the respective impact categories.

Global warming potential was chosen because of its high public and institutional interest and being generally deemed to be the most pressing environmental issue of our time. The global warming potential impact category has been assessed based on the current IPCC characterisation factors taken from the 5th Assessment Report (IPCC, 2013) for a 100-year timeframe (GWP100) as this is currently the most commonly used metric [1]. In this study, the impacts covering the fossil related part of the climate change are considered. The biogenic and land use related parts are not considered. The global warming potential results related to the photosynthetically bound carbon (also called *biogenic carbon*) and the release of that carbon during the use or end-of-life phase as CO_2 and/or CH_4 is balanced out to zero as the complete life cycle of the system is analysed and relevant materials including biogenic carbon are thermally treated in end-of-life (so. no CH_4 emissions in EoL). Direct land use change is not considered for the foreground system of this study, so that part of GWP effects are not analysed. Indirect land use change has not been considered due to the high uncertainties in determining indirect effects.

Eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as NO_x, SO_2, VOC, and others.

Resource use, energy carriers and minerals and metals were chosen as these often correlate closely with many other environmental impact categories and are directly relevant to issues relating to fuel supply, energy efficiency, choice of feedstocks and consumption of non-renewable resources. Similarly, resource use, minerals and metals were selected as wind turbines are heavily dependent on such materials.

Respiratory inorganic emissions have been included as there is increasing recognition of the significant disease burden posed by exposure to particulate matter both indoors and outdoors (Lim, 2012). The health effects of inhalable particulate matter include respiratory and cardiovascular

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[1] The climate change methodology used in PEF is based on the latest IPCC reports but also includes the effects of "climate-carbon feedback" which results in higher global warming potentials but is also associated with greater uncertainty. In this study we have used the more commonly-applied emission factors from the same report that exclude climate-carbon feedback effects.

effects, such as aggravation of asthma, respiratory symptoms and an increase in hospital admissions, as well as mortality from cardiovascular and respiratory diseases and from lung cancer.

The *Montreal Protocol on Substances that Deplete the Ozone Layer* was implemented in 1989 with the aim of phasing out emissions of ozone depleting gases. The protocol has been ratified by *all* members of the United Nations – an unprecedented level of international cooperation. With a few exceptions, use of CFCs, the most harmful chemicals have been eliminated, while a complete phase out of less active HCFCs will be achieved by 2030. As a result, it is expected that the ozone layer will return to 1980 levels between 2050 and 2070. In addition, no ozone-depleting substances are emitted in the foreground system under study. For these reasons, ozone depletion potential has not been considered in this study.

Water scarcity has not been analysed in this study as some of the most relevant background datasets for the assessed system from worldsteel do not have a closed water balance which leads to negative water scarcity results for the steel LCIs. Besides the LCI weakness concerning water, those worldsteel datasets are considered as highest quality LCI datasets for steel products as they represent up-to-date primary data from steel manufacturing sites around the globe.

All impact categories for toxicity and human health effects have not been analysed in this study because they are considered both as not scientifically robust and not relevant for the assessed system.

Land use has not been considered in this study. An exemplary windfarm in Sweden is analysed but not an actually installed windfarm. Impacts regarding land use or direct and indirect land use change (e.g. for climate change) are depending on site-specific conditions which have not been defined in that detail (e.g. soil quality) for this study.

Table 2: Impact category descriptions

Impact Category	Description	Unit	Reference
Climate change fossil (Global warming potential, GWP100)	A measure of greenhouse gas emissions, such as carbon dioxide (CO_2) and methane (CH_4). These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	(IPCC, 2013; Guinée, et al., 2002)
Eutrophication potential, freshwater, marine and terrestrial	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in freshwater, marine and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	Freshwater: kg P equivalent Marine: kg N equivalent Terrestrial: Mole of N equivalent	(Seppälä J., 2006; Posch, 2008; Struijs, 2009)

Acidification potential, terrestrial and freshwater	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H^+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	Mole of H+ equivalent	(Seppälä J., 2006; Posch, 2008)
Photochemical ozone formation, human health	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone O_3), produced by the reaction of VOC and carbon monoxide in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg NMVOC equivalent	(Van Zelm R., 441-453)
Resource use, energy carriers	A measure of the total amount of non-renewable primary energy extracted from the earth. Resource use is expressed in energy demand from non-renewable resources including both fossil sources (e.g. petroleum, natural gas, etc.) and uranium for nuclear fuel. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ	(Guinée, et al., 2002; van Oers, de Koning, Guinée, & Huppes, 2002)
Resource use, mineral and metals	The consumption of non-renewable resources leads to a decrease in the future availability of the functions supplied by these resources. Depletion of mineral resources and non-renewable energy resources are reported separately. Depletion of mineral resources is assessed based on ultimate reserves.	kg Sb equivalent	(van Oers, de Koning, Guinée, & Huppes, 2002)
Respiratory inorganics	Respiratory inorganics/ Particulate matter emissions and secondary aerosols formed in the atmosphere from NOx, NH_3 and SO_2 emissions contribute to human health impacts in the form of respiratory disease and related effects.	Disease incidences	(Fantke, 2016)

It shall be noted that the above-mentioned impact categories represent impact *potentials*, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually 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 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.

2.7. 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.

2.8. 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.

2.9. 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.

2.10. Software and Database

The LCA model was created using the GaBi 9 Software system for life cycle engineering (software version 9.2), developed by Sphera Solutions Inc. The GaBi 2019 LCI database is the basis for most of the life cycle inventory data for modelling the background system. Datasets from the database version with service pack status SP39 are applied.

2.11. Critical Review

A review, according to ISO 14044, section 6.2, has been carried out for this study. The Critical Review Statement can be found in Annex A.

Names and affiliations of reviewer:

Matthias Schulz
Accredited Reviewer on behalf of DEKRA Assurance Services GmbH

3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

Primary data were collected using customised data collection templates from Sphera, which were sent out by email to the respective data providers. Upon receipt, each data collection template was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. Where gaps, outliers, or other inconsistencies were found, Sphera engaged with the data provider to resolve these issues.

Various data providers were engaged within Nordex. The following experts indicated with their respective roles and functions have supported the data collection:

- Senior Expert Global Sustainability Mgmt.
- Senior Master Data & Process Manager
- Senior Engineer, Wind & Site Assessment
- Expert Engineer, Mechanical Drive
- Expert Engineer, Electrical Drive
- Expert Engineer, Blade Material & Design
- Expert Engineer, Tower & Foundation
- Expert Engineer, Mechanics, Tower & Loads
- Head of Design Mechanics, Design Mechanics
- Head of Repowering & Projects
- Group Lead PM (Project Management) Development
- Group Lead Sales Coordination Service
- Configuration Manager
- HSE Manager
- Facility Manager
- Energy Manager
- Project Manager

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

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

Delta4000 turbine

- Top-down approach: bill of material (BOM) for complete turbine (“digital twin”) with the respective configuration for the project design (windfarm in Sweden)
- Bottom-up approach: bill of materials (BOM) for single components and parts of the Delta4000 turbine collected from different expert engineers who are responsible for a part of a component or a complete component
- 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 sites for blades and nacelle in Germany– data collected for energies and utilities consumption, emissions, generated waste/wastewater and waste/wastewater treatment
- Majority of the data is measured; data uncertainties and gaps are closed with calculations and in few cases with estimations.

Cable connections and substation

- BOM for MV cable in windfarm
- BOM for HV cable as connection to grid
- BOM for substation
- Length of cable connections from PM experts
- Majority of the data is measured; data gaps are closed with calculations and estimations.

Logistics (transportation of all windfarm components, construction materials and machines to windfarm 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 based on the balance of plant (BoP) of the windfarm
- 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 windfarm 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 windfarm including cranes, excavators and trucks, the transport to a recycler or disposer depending on the material group.
- Data on rotor blade recycling is collected at neocomp.
- 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, 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.

3.2. Model Overview

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

Table 3 and Figure 4 show the LCA model created in GaBi for the windfarm analysed in this study. The model was split into 7 key life cycle sections which are further detailed in Section 3.3.

Table 3: Sub-plans used to build the GaBi model

Item number	Component	Life Cycle Stage
1	Delta4000 – N149/ 4.0-4.5	Raw materials / Manufacturing
2	Cables for windfarm	Raw materials / Manufacturing
3	Substation	Raw materials / Manufacturing
4	Logistics	Transport
5	Installation	Installation
6	Use Phase	Use
7	Decommissioning	End-of-life

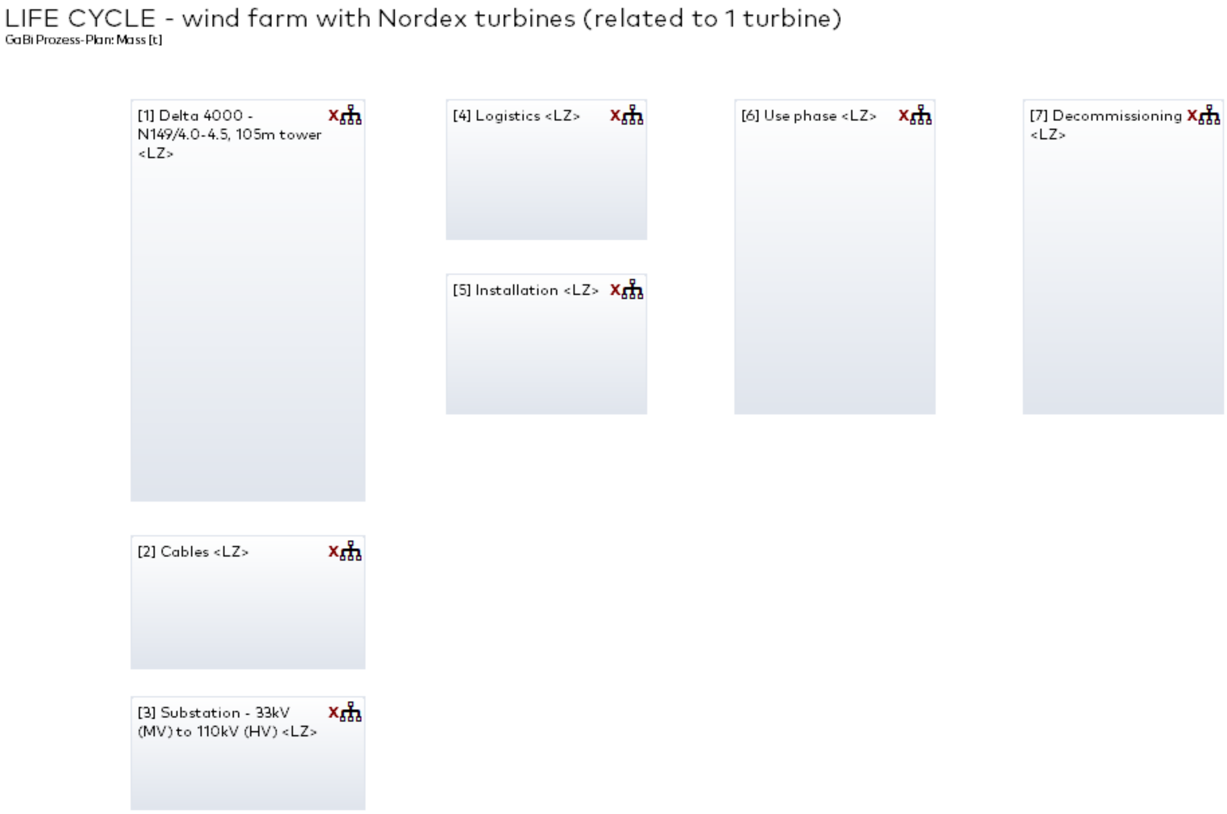

Figure 4: LCA model from GaBi

3.3. Delta4000 Wind farm

3.3.1. Overview of Product System

The Delta4000 pilot plant consists of 47 wind turbines however all foreground data is proportionally for the material composition and subsequent life cycle of 1 turbine with a hub height of 105 metres.

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

3.3.2. Delta4000 Turbine

Table 4 and Figure 5 detail the mass breakdown of the Delta4000 turbine components. The mass delta represents the difference between the total expected mass of the turbine and the sum of the components collected on a component by component basis. This difference was assumed to be steel sheet as a conservative estimation.

Table 4: Mass composition of turbine components required to fulfil functional unit

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

Figure 5: Composition breakdown by mass for the Delta4000 turbine

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

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

- 87.0% steel (carbon steel, stainless steel, cast steel)
- 9.1% glass fibre/carbon fibre reinforced plastics
- 1.5% polymers
- 0.6% operating fluids
- 0.5% electrics/electronics
- 0.5% aluminium
- 0.4% copper
- 0.4% others

The following sections detail the sub-plans for the different component parts within the Delta4000 Turbine plan shown in Figure 4.

Foundation

The baseline scenario for the study assumes a foundation for low ground water level conditions. The foundation for the turbine is approximately 93% 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 over 99% steel with less than 1% coating, and the interior construction – predominately composed of steel and aluminium.

Blades

The blades of the wind turbine are designed to efficiently capture the wind energy available onsite. These were designed and manufactured by Nordex. The key raw materials (by mass) used in manufacturing the blades of the wind turbine are glass fibre, carbon fibre, wood and the rest is a mixture of polymer parts, coatings and adhesives.

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 stainless steel.

Figure 6: Turbine electrical components in GaBi

Drivetrain

The drivetrain of the wind turbine is composed of the components required to produce electricity such as the gearbox and generator. The model split it into 19 sub-models, covering bearings, gears, drives, etc. Main material groups are steel, cast steel, copper, stainless steel and aluminium.

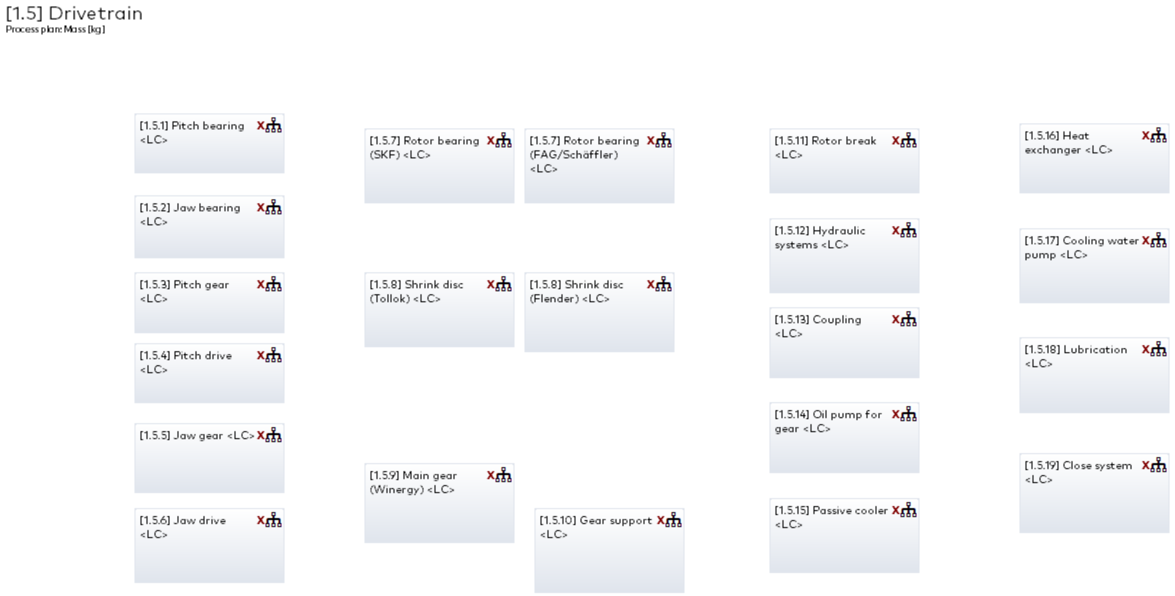

Figure 7: Drivetrain (incl. bearings, gears, etc.) for turbine in GaBi

Nacelle (including hub)

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 12 sub-plans along with the Nordex manufacturing process. Main material groups are cast steel, steel and glass fibre reinforced plastics.

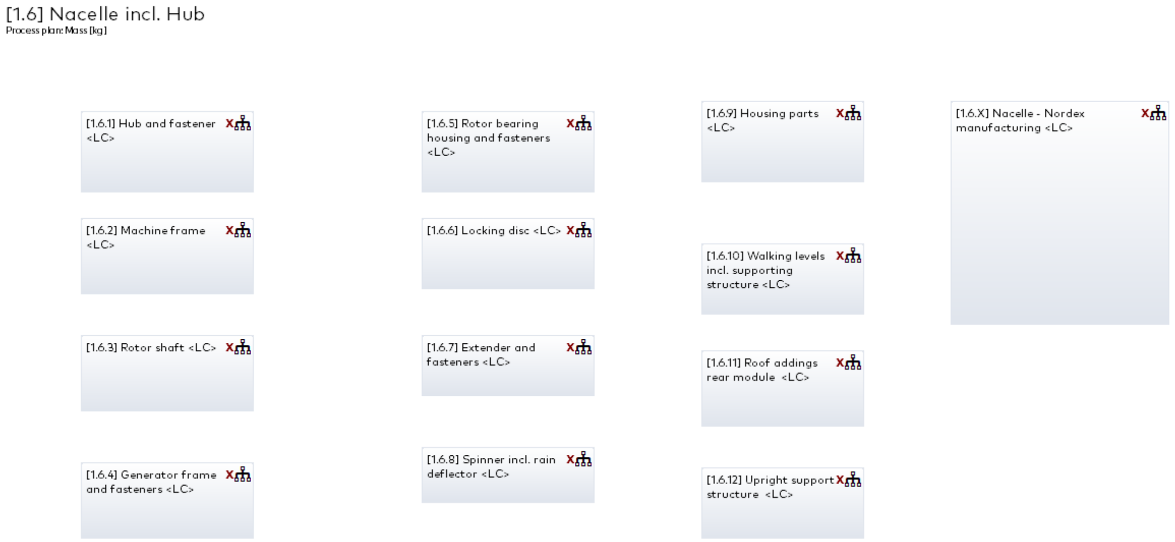

Figure 8: Nacelle wind turbine components in Gabi

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 windfarm is covered in the section on logistics.

3.3.3. Cables

MV cables (33kV)

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 (9%), aluminium (42%) and high-density crosslinked polyethylene, XLPE (50%). A cable weighs 3,155kg/km.

The average length of a MV cable per turbine in the assessed windfarm is 1.5km.

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%).

HV cables (110kV)

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 length of the HV cable which connects the windfarm to the grid is depending on site-specific conditions. For this study, a distance of 15km is estimated (which results in 0.32km cable length per turbine).

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%).

3.3.4. Substation

One substation is required on the site of the windfarm to transform the medium voltage of the windfarm from 33kV to the high voltage required for distribution at 110 kV.

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 weight of the substation is 392.5 t.

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%).

3.3.5. Logistics (distribution from manufacturing to site)

This section details the logistics required for the relevant components and infrastructure to reach the site of the windfarm. 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 data on t.km are provided in Annex B (confidential data).

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 50km for foundation materials up to 2,380km for the tower sections.

3.3.6. Installation

Table 5 describes all resources and materials required for the installation phase of the windfarm.

Table 5: 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. However, not all machines for e.g. excavated material are considered, so the diesel consumption is elevated with a factor of 1.3.

Further confidential data moved to Annex B.

3.3.7. Use phase

The use phase has been modelled considering the annual energy production of the windfarm and the lifetime for the baseline scenario, 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 windfarm was calculated using the following parameters:

- average wind speed at hub height: 6.8 m/s (IEC III – according to IEC 61400) – low wind site
- site-specific losses: 22.2%
- site-specific uncertainties for a 25-year lifetime: 12%

This resulted in a net AEP P75[1] value for 25y lifetime: 11,768 MWh per year.

The AEP value is representing an annual average. The applied values for losses and uncertainties are representative for the assessed windfarm. 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).

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

Further confidential data moved to Annex B.

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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 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 windfarm, 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 windfarm 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.

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.

Given the fact that the present study does not cover a specific site but an exemplary location in Sweden, the electrical losses that occur between the wind farm substation and the main electricity network, cannot be directly measured. Thus, an average value of 2.2% until a 110 KV network has been used to simulate these electrical losses, according to European Regulators Group for electricity and gas (ERGEG). This means that 2.2% of every generated kWh, is lost in the distribution network between the wind farm and the connection point to the grid.

Maintenance

During the 25-year lifetime it is assumed that 3.6 t of lubricants and 1 t of coolants will be required per turbine.

Replacement

An average value required for replaced parts and components was estimated for the 25-year lifetime based on statistics and experience within Nordex. In total, 8.2 t per turbine are expected to be replaced. Replaced components include rotor blades, main bearing, gearbox, generator and inverter.

Transport

The transport estimated for the service team during the lifetime was 15,000 km per turbine and the transport of replaced parts / components 8,200 t.km (1,000 km transport distance using a truck-trailer, Euro 0-6 mix, 34-40t gross weight / 27t payload capacity).

3.3.8. End-of-Life

The end-of-life of the windfarm is split into three key sections, the energy and resources required for the demolition itself, the transport required from the windfarm site to the disposal site and the final disposal of the windfarm through material recycling, thermal treatment and landfilling. These sections are further detailed below.

All components of the windfarm are dismantled. The HV cable outside the windfarm remains in the ground.

Demolition

The demolition stage of the end-of-life scenario uses various machines including cranes, lift trucks and excavators

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

Confidential data moved to Annex B.

Transport

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 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.

The data on t.km are provided in Annex B (confidential data).

Final disposal: material recycling, 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 die 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 windfarm 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.

The following materials groups / components are considered in end-of-life modelling which amount to 99.6% 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 foundation dominates the total mass of the turbine, so excluding foundation, the mass percentage of covered material groups in EoL modelling for the turbine amounts to 98.5%.

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).

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. SF6 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.

As SF_6 has a high impact on climate change (per kg emission, factor 26,100 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.

For the baseline scenario, it was assumed that all sulphur hexafluoride (SF_6) is fully recovered and recycled, hence there are no emissions. The influence of this assumption on the results has been assessed in a scenario analysis. 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.

3.4. Background Data

Documentation for all GaBi datasets can be found online (Sphera, 2019).

3.4.1. Fuels and Energy

National and regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2019 databases. Table 6: shows the most relevant LCI datasets used in modelling the product systems. Electricity consumption was modelled using national grid mixes that account for imports from neighbouring countries / regions.

Table 6: Key energy datasets used in inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year	Proxy?
Electricity	DE	Electricity grid mix	Sphera	2016	No
	SE	Electricity grid mix	Sphera	2016	No
	EU-28	Electricity grid mix	Sphera	2016	No
Renewables	DE	Electricity from hydro power	Sphera	2016	No
	EU-28	Lubricants at refinery	Sphera	2016	No
	DE	Lubricants at refinery	Sphera	2016	No
Compressed air	EU-28	Compressed air 7 bar (medium power consumption)	Sphera	2016	No
Thermal energy	EU-28	Thermal energy from natural gas	Sphera	2016	No
District heating	EU-28	District heating mix	Sphera	2018	No

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

3.4.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2019 database. Table 7 shows the most relevant LCI datasets used in modelling the product systems.

Table 7: Key material and process datasets used in inventory analysis

	Location	Dataset	Data Provider	Reference Year	Proxy?
Metals	EU-28	Fixing material screws galvanized (EN15804 A1-A3)	Sphera	2018	No
	GLO	Steel UO pipe	World Steel	2017	No
	EU-28	Concrete C35/45 (Ready-mix concrete) (EN15804 A1-A3)	Sphera	2018	No
	GLO	Steel rebar	World Steel	2017	No
	GLO	Steel UO pipe	Worldsteel	2017	No
	GLO	Steel wire rod	Worldsteel	2017	No
	EU-28	Fixing material screws galvanized (EN15804 A1-A3)	Sphera	2018	No
	EU-28	Primary aluminium ingot consumption mix (2015)	European Aluminium	2015	No
	EU-28	Aluminium extrusion profile (2015)	European Aluminium	2016	No
	GLO	Steel hot dip galvanised	Worldsteel	2017	No
	GLO	Steel electrogalvanized	Worldsteel	2017	Tech
	EU-28	Copper Sheet Mix (Europe 2015)	DKI/ ECI	2015	No
	EU-28	Copper Wire Mix (Europe 2015)	DKI/ ECI	2016	No

	DE	Copper wire (0.6 mm)	Sphera	2018	Geo
	EU-28	Steel forged component (EN15804 A1-A3)	Sphera	2018	No
	GLO	Special high grade zinc IZA	Sphera	2012	No
	DE	Lead (99,995%) ts	Sphera	2018	Geo
	EU-28	Stainless steel cold rolled coil (316)	Eurofer	2014	No
	GLO	Steel sections worldsteel	Worldsteel	2017	No
	EU-28	Stainless steel Quarto plate (304)	Eurofer	2014	No
	DE	Cast iron part (automotive)	Sphera	2018	No
	DE	Grey cast iron (GG) part (sand casting)	Sphera	2018	No
	GLO	Steel organic coated	Worldsteel	2017	No
	GLO	Steel Engineering steel	Worldsteel	2017	No
	EU-28	Brass (CuZn39Pb3)	Sphera	2018	No
	EU-28	DE: Zinc redistilled mix	Sphera	2018	No
	EU-28	Red brass	Sphera	2018	No
	EU-28	Stainless steel sheet (EN15804 A1-A3)	Sphera	2018	No
	DE	Cast iron component (EN15804 A1-A3)	Sphera	2018	Geo
Plastics	DE	Epoxy Resin (EP) Mix	Sphera	2018	Geo
	EU-28	Polyethylene, LDPE, granulate	Plastics Europe	2013	No
	DE	Styrene-butadiene rubber (S-SBR) mix	Sphera	2018	Geo
	EU-28	Polyethylene foam (EN15804 A1-A3)	Sphera	2018	No
	EU-28	Polypropylene / Ethylene Propylene Diene Elastomer Granulate (PP/EPDM, TPE-O) Mix	Sphera	2018	No
	EU-28	Plastic extrusion profile (unspecific)	Sphera	2018	No
	EU-28	Polyamide 6.6 Granulate (PA 6.6) Mix	Sphera	2018	No
	EU-28	Plastic Film (PE, PP, PVC)	Sphera	2018	No
	EU-28	PET, bottle grade, at plant	Plastics Europe	2015	No
	DE	Polypropylene granulate (PP) mix	Sphera	2018	Geo
	DE	Epoxy Resin (EP) Mix	Sphera	2018	Geo
	BE	Polyvinyl chloride granulate (Suspension, S-PVC)	Sphera	2018	Geo
	DE	Thermoplastic polyurethane (TPU, TPE-U) adhesive	Sphera	2018	Geo

	EU-28	Silicone sealing compound (EN15804 A1-A3)	Sphera	2018 No
	DE	Nitrile butadiene rubber (NBR, 33% acrylonitrile)	Sphera	2018 Geo
	DE	Polycarbonate Granulate (PC)	Sphera	2018 Geo
	DE	Polyester Resin unsaturated (UP)	Sphera	2018 Geo
	DE	Polymethylmethacrylate granulate (PMMA)	Sphera	2018 Geo
	RER	Polyvinylchloride pipe (PVC)	Plastics Europe	2005 Temp
	EU-28	Polyurethane flexible foam (PU) - TDI-based, no flame retardant, high density	EUROPUR	2013 No
Electronics	GLO	Average Printed Wiring Board with Signal-Power Electronics (DfX-Compatible)	Sphera	2018 Tech
	EU-28	Cable CAT 7 (EN15804 A1-A3)	Sphera	2018 No
Other materials	DE	Argon (gaseous)	Sphera	2018 Geo
	DE	Carbon dioxide (CO2) by-product ammonia (NH3) (economic allocation)	Sphera	2019 Geo
	EU-28	Kraftliner (2015) - for use in avoided burden EoL scenario cases	Sphera/ FEFCO	2018 No
	EU-28	Three-Layers laminated wood panel pine (EN15804 A1-A3)	Sphera	2018 No
	DE	Glass fibres	Sphera	2018 Geo
	EU-28	Carbon fiber (CF; PAN-based; HT) - 11	Fraunhofer	2018 No
	EU-28	Sand (grain size 0/2) (EN15804 A1-A3) (dried) ts	Sphera	2018 No
	DE	Drinking water mix ts	Sphera	2018 Geo
	EU-28	Process water ts	Sphera	2018 No
	EU-28	Sulphur (elemental) at refinery	Sphera	2018 Yes
	DE	Fluorine	Sphera	2018 Geo
	DE	Ethylene glycol	Sphera	2018 Geo
	EU-28	Tap water from groundwater	Sphera	2018 No

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

3.4.3. 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 GaBi 2019 database was used to model transportation. Transportation was modelled using the GaBi global transportation datasets. Fuels were modelled using the geographically appropriate datasets.

Table 8: Transportation and road fuel datasets

Process/material	Location	Dataset	Data Provider	Reference Year	Proxy?
Truck	GLO	Truck, Euro 0 - 6 mix, up to 7.5t gross weight / 2.7t payload capacity ts <u-so>	Sphera	2018	No
Truck	GLO	Truck, Euro 0 - 6 mix, up to 20-26t gross weight / 17.3t payload capacity ts <u-so>	Sphera	2018	No
Truck	GLO	Truck, Euro 0 - 6 mix, up to 34-40t gross weight / 27t payload capacity ts <u-so>	Sphera	2018	No
Diesel	DE	Diesel mix at refinery ts	Sphera	2016	No
Rail	GLO	Rail transport cargo - Diesel, average train, gross tonne weight, 1,000t/ 726t payload capacity	Sphera	2018	No
Ship	GLO	Container ship, 5,000 to 2000,000 dwt payload capacity, ocean going	Sphera	2018	No
Heavy fuel oil	EU-28	Heavy fuel oil at refinery	Sphera	2018	No

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

3.4.4. Waste treatment

Treatment of waste in production and at end-of-life is modelled using GaBi LCI data for landfill, incineration, recycling and composting processes. Table 9: shows the most relevant waste processing and treatment datasets used in modelling.

Table 9: Key waste treatment datasets used in inventory analysis

Process	Location	Dataset	Data Provider	Reference Year	Proxy?
Commercial waste incineration	EU-28	Commercial waste in municipal waste incineration plant	Sphera	2018	No
Inert waste on landfill	EU-28	Glass/inert waste on landfill	Sphera	2018	No
Municipal waste incineration	DE	Municipal waste in waste incineration plant	Sphera	2018	Geo
Municipal waste-water treatment	DE	Municipal wastewater treatment (agricultural sludge application)	Sphera	2018	Geo
Municipal waste-water treatment	DE	Municipal wastewater treatment (sludge incineration)	Sphera	2018	Geo
Paper incineration	EU-28	Paper / Cardboard in waste incineration plant	Sphera	2018	No
Plastic incineration	EU-28	Plastic packaging in municipal waste incineration plant	Sphera	2018	No
PA incineration	EU-28	Polyamide (PA) 6 in waste incineration plant	Sphera	2018	No
PU incineration	EU-28	Polyurethane (PU) in waste incineration plant	Sphera	2018	No
Wood incineration	EU-28	Wood (natural) in municipal waste incineration plant	Sphera	2018	No

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

3.5. 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 4.3 and 4.4 which cover aspects of the energy production during lifetime of the windfarm (AEP and lifetime), windfarm layout (MV cable length), ground conditions (type of foundation), tolerances defined by Nordex for suppliers and a risk assessment regarding SF6 emissions. Some of those parameters depend on site-specific conditions and thus, can vary.

Key parameters / assumptions are:

- Configuration of Delta4000 – N149/4.0-4.5: 105m hub height, one-piece NR74.5 rotor blade
- Windfarm design: exemplary windfarm in Sweden with 47 turbines and 1 substation
- Wind conditions: IEC wind class III (low wind site)
- Lifetime of windfarm: 25y
- Net AEP: 11,768 MWh (p75)

Further relevant assumptions are:

- Average MV cable length per turbine in windfarm: 1.5km
- HV cable length as connection of windfarm to grid: 15km
- Low ground water level resp. good ground conditions which requires a lighter version of the turbine foundation (usually 2 types of gravity foundation applied: a lighter version for low ground water level and a heavier version for high ground water level)
- No SF6 emissions during use and EoL (normal operation mode)
- 2.2% electrical losses per generated kWh due to HV cable connection to grid

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

<u>Data proxies</u> 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
- Balsa wood → laminated wood panel as proxy (similar density)
- 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

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
- HV cable is not dismantled and remains underground – no effort for demolition and no credits for recycled materials (mainly aluminium and copper as recycled goods and plastic as waste-to-energy)

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

- “Midel 7131” – synthetic ester (*further confidential data moved to Annex B)*
- Silver (*further confidential data moved to Annex B)*
- Pultrusion process (production step for CFRP parts, mainly electricity consumption)
- Magnets
- Li-ion battery
- Special resin in 100kV transformer
- Various coatings for metal parts

The effect of those data gaps was tested on the overall GWP results if possible: the estimated contribution of Midel (synthetic ester) is +0.4% to the overall GWP result, the estimated contribution of silver is +0.0004% to the overall GWP result. The difference between an estimated lead battery and lead metal on the overall GWP result is the following: 0.005% due to the battery and 0.007% due to lead metal.

4. LCIA Results

This chapter contains the results for the impact categories and additional metrics defined in section 2.6. 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.

4.1. Overall Results

The overall life cycle results for the product system are presented in Table 10 and the relative contribution to each impact potential per life cycle stage is displayed in Figure 9.

Table 10: Impact potentials for the full life cycle of the product system per functional unit, production of 1 kWh of electricity

Impact category	TOTAL	[1] Delta4000 - N149/4.0-4.5, 105m tower	[2] Cables in windfarm (MV)	[3] Substation - 33kV (MV) to 145kV (HV)	[4] Logistics	[5] Installation	[6] Use phase	[7] De-commissioning
Acidification terrestrial and freshwater [Mole of H+ eq.]	**2.9E-05**	2.9E-05	9.5E-07	4.5E-07	3.1E-06	6.7E-07	5.7E-07	-5.5E-06
Climate Change fossil [kg CO2 eq.]	**6.5E-03**	8.3E-03	2.0E-04	1.0E-04	3.0E-04	7.0E-05	1.7E-04	-2.6E-03
Eutrophication freshwater [kg P eq.]	**1.6E-08**	1.4E-08	2.7E-10	1.7E-10	1.1E-09	3.7E-10	6.6E-10	-4.9E-10
Eutrophication marine [kg N eq.]	**6.6E-06**	5.5E-06	1.6E-07	7.5E-08	8.5E-07	3.2E-07	1.2E-07	-4.5E-07
Eutrophication terrestrial [Mole of N eq.]	**7.1E-05**	5.9E-05	1.7E-06	8.0E-07	9.4E-06	3.5E-06	1.3E-06	-3.8E-06
Photochemical ozone formation [kg NMVOC eq.]	**2.1E-05**	1.9E-05	5.2E-07	2.4E-07	2.2E-06	9.2E-07	4.8E-07	-2.6E-06
Resource use, energy carriers [MJ]	**7.9E-02**	9.7E-02	2.9E-03	1.1E-03	3.9E-03	5.9E-04	3.2E-03	-3.0E-02
Resource use, mineral and metals [kg Sb eq.]	**5.3E-08**	8.5E-08	5.8E-09	1.1E-08	1.8E-11	4.0E-12	3.8E-10	-4.9E-08
Respiratory inorganics [Disease incidences]	**3.42E-10**	3.2E-10	1.4E-11	8.4E-12	4.6E-11	2.1E-11	5.8E-12	-7.9E-11

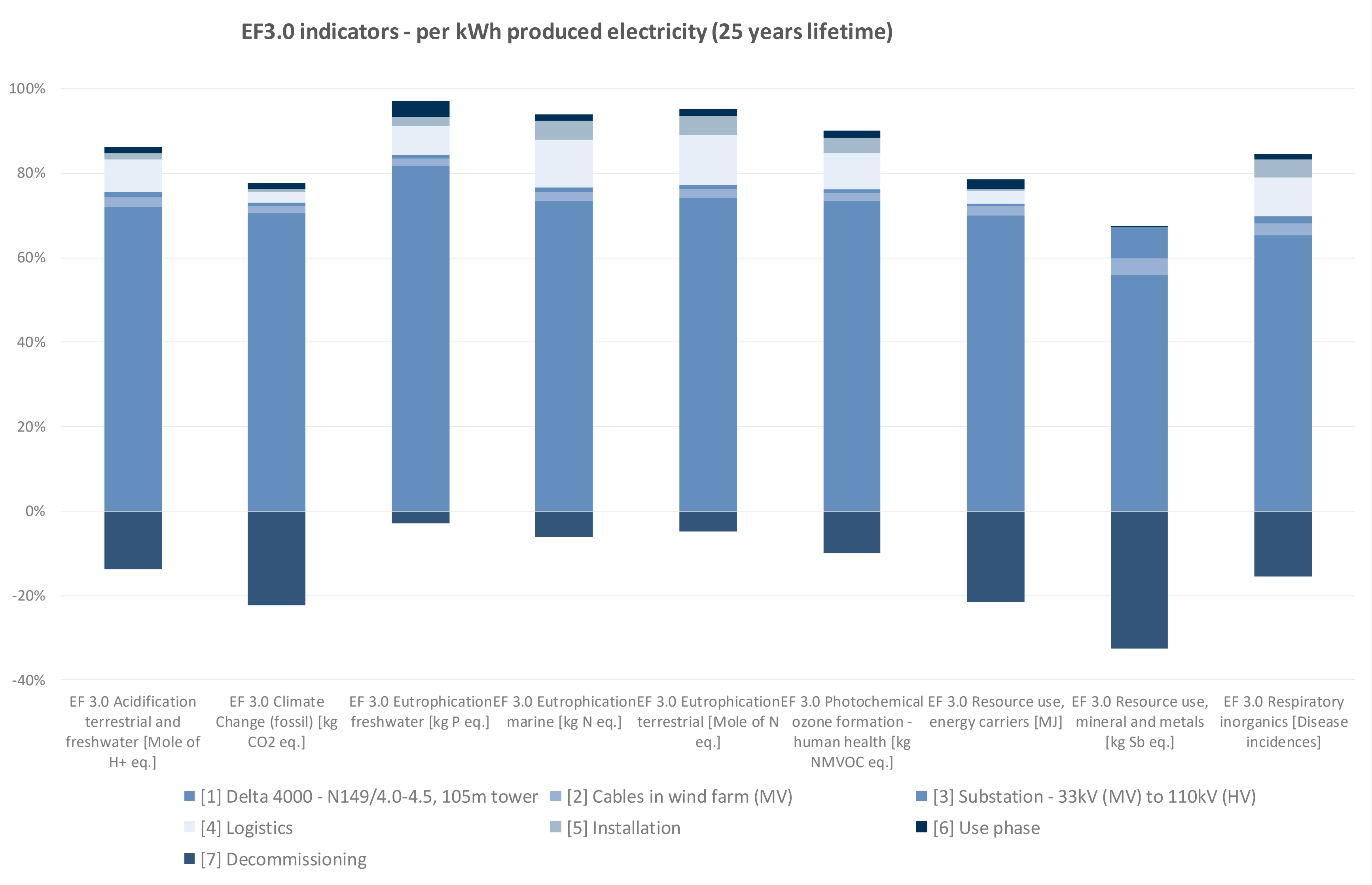

Figure 9: Relative impact potentials for the full life cycle per functional unit, production of 1 kWh electricity

4.2. Detailed Results

Results are presented for each key impact and inventory metric in the following section for the baseline scenario of the product system.

All results are reported for the functional unit of the production of 1 kWh of electricity over a lifetime of 25 years.

4.2.1. Climate change (fossil)

The indicator for climate change (fossil) is representative of a wide range of effects resulting from increases in heat-trapping greenhouse gas in the atmosphere. Increased atmospheric temperature causes higher evaporation of water, leading to greater frequency of extreme weather events (storms, flooding), wildfires and droughts, as well as the melting of polar ice, which, along with thermal expansion of the oceans, causes sea levels to rise. Increased concentration of atmospheric CO_2 also increases ocean acidity, which has been identified as a primary cause of a global die-off of coral reefs, as lower seawater pH interferes with calcium carbonate formation, critical for many varieties of marine life. The environmental effects of climate change also have social and political consequences, e.g. longer and more frequent droughts can lead to potential political instability, migration and conflict over water resources. A lower result for climate change indicates a lower potential to cause these effects and therefore better environmental performance.

Life cycle

Figure 10 presents the overall life cycle results for climate change, showing the breakdown by windfarm component and life cycle stage.

The total climate change potential for the life cycle of the windfarm is 6.5 g CO2 eq/kWh electricity produced. Phase 1, which represents the raw materials and manufacturing required to produce the turbine, the Delta4000 – N149/ 4.0-4.5, shows strong dominance for climate change at 8.3 g CO2 eq/kWh. Phase 7, the decommissioning phase is the second largest contributor to climate change potential whereby due to the recovery of steel assumed at end-of-life, has a negative climate change impact of -2.6 g CO2 eq/kWh electricity produced (90% impact in phase 7 from steel recycling).

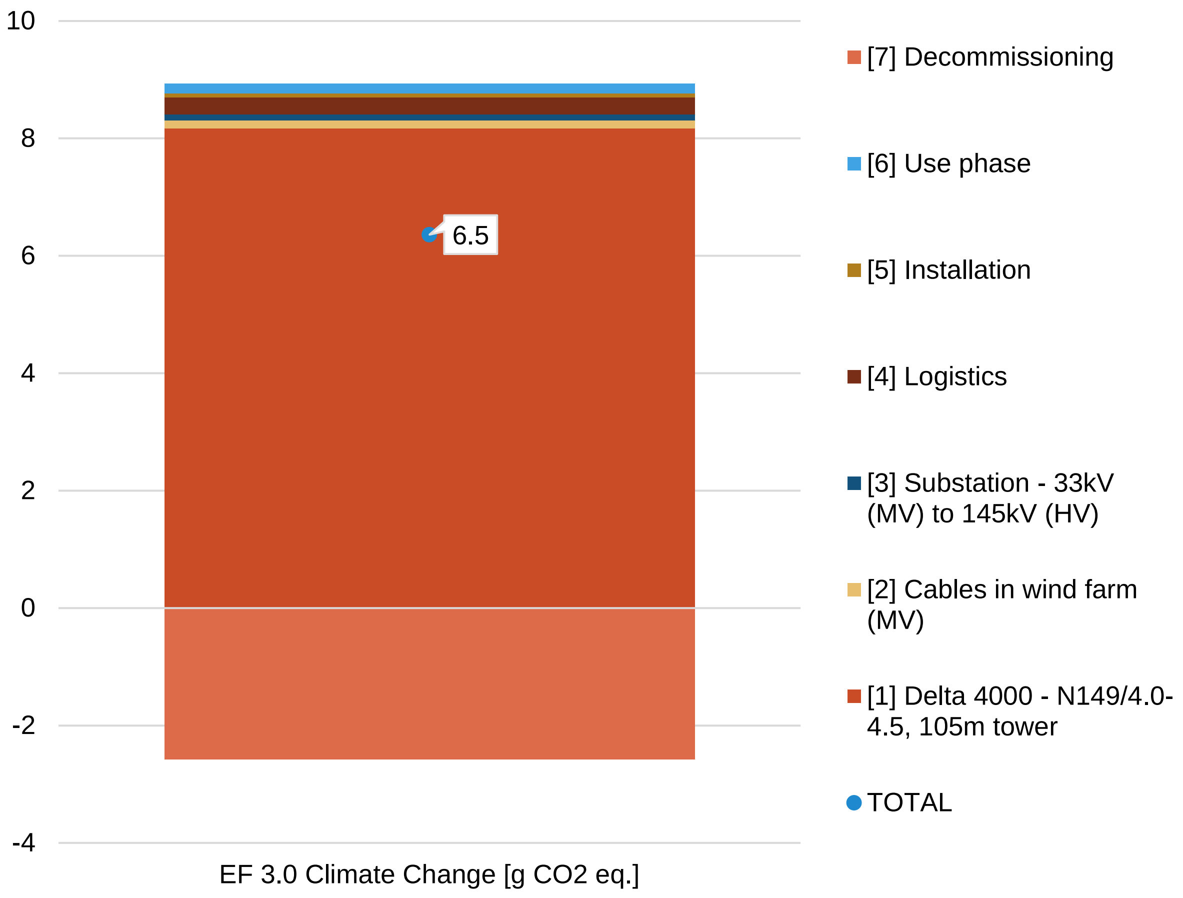

Figure 10: Life cycle climate change (g CO2 eq.) per functional unit

Wind turbine breakdown

The raw materials and manufacturing of the Delta4000 wind turbine dominate the impacts of the life cycle for climate change potential. Figure 11 shows the breakdown of the impacts from the different components of the turbine itself.

The tower is the largest contributor to the impact of the turbine; the tower supporting structure is composed of more than 98% steel which, as a material, has a substantially larger impact than concrete which is the majority material utilised for the foundation. Hence, despite the foundation being the largest component by weight (73%), the climate change potential for the foundation is approximately 50% that of the tower structure.

The blades are the second largest contributor to climate change potential at around 21% of the total turbine contribution whereby the carbon fibre component is approximately 10%, the resin is approximately 5% and the glass fibre 3%.

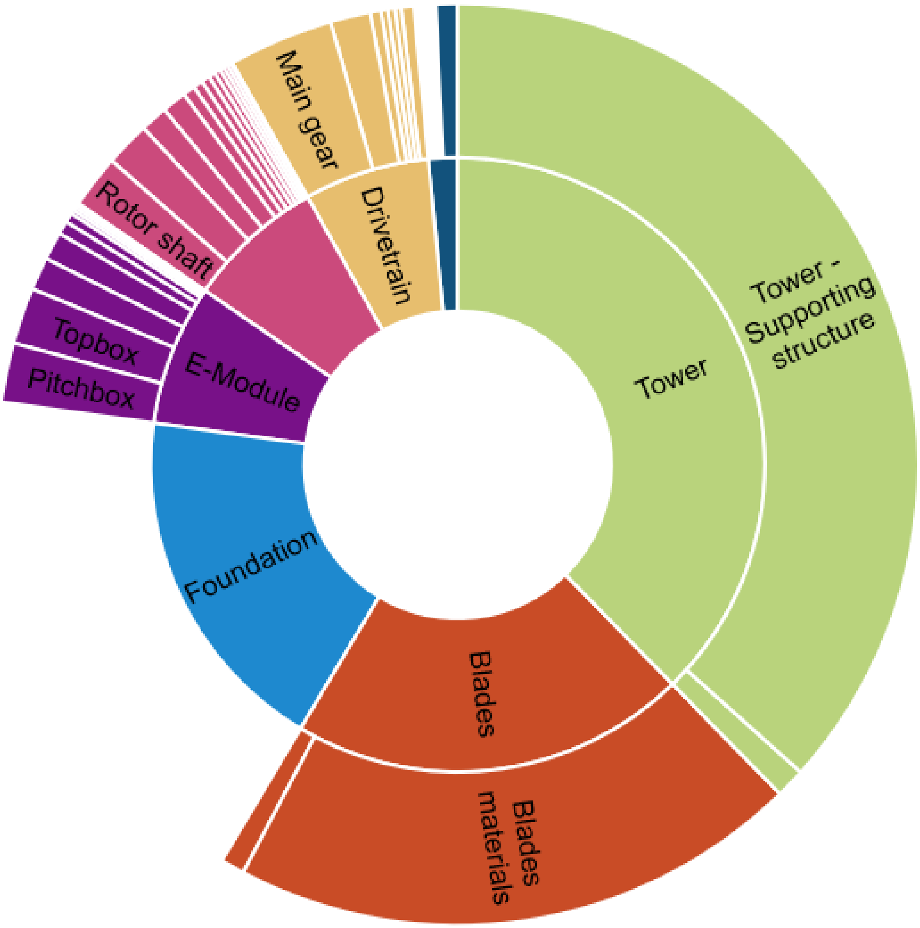

Figure 11: Delta4000 Turbine impact breakdown - climate change (8.3 g CO2 eq.)

4.2.2. Photochemical Ozone Formation

Figure 12 presents the overall life cycle results for photochemical ozone formation, showing the breakdown by windfarm component and life cycle stage.

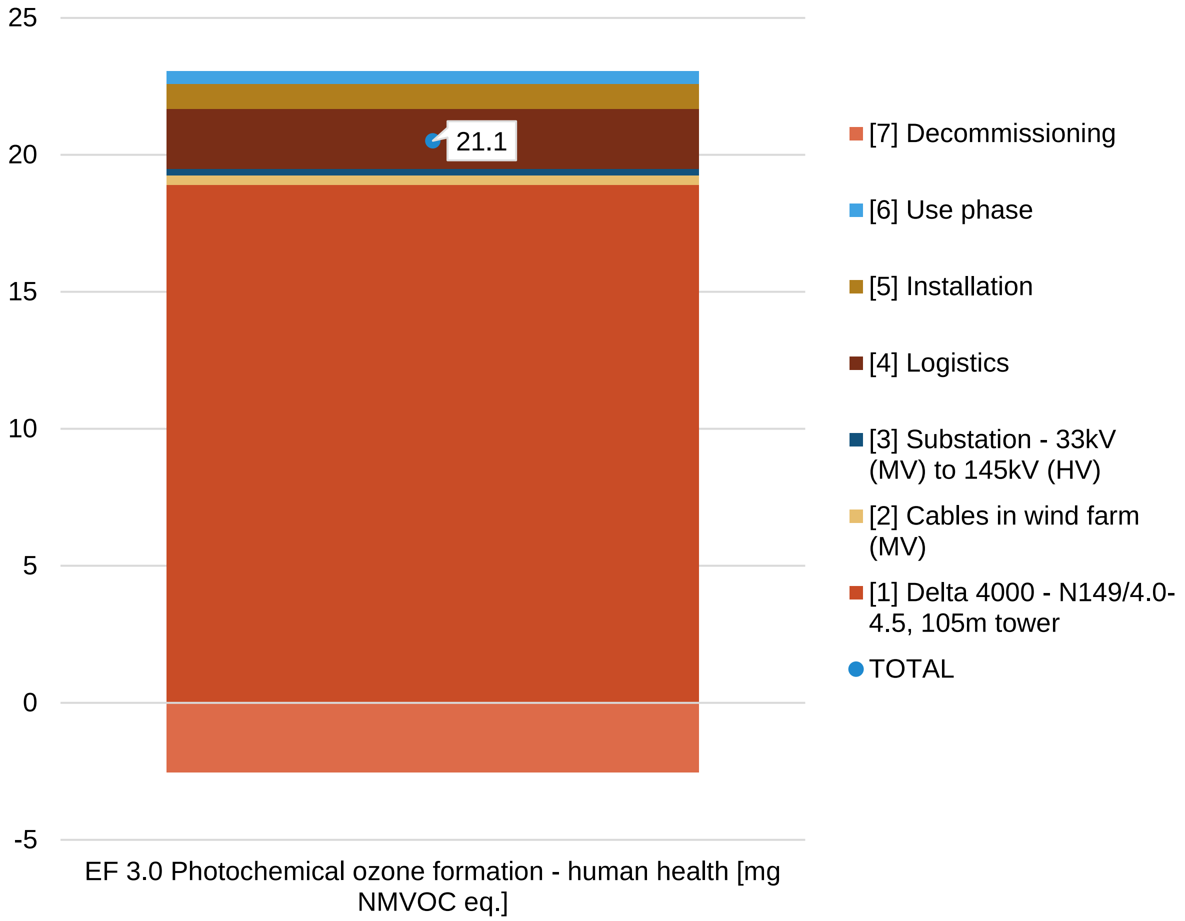

Figure 12: Life cycle photochemical ozone formation – human health (mg NMVOC eq.) per functional unit

Despite playing a protective role in the stratosphere, at ground-level ozone is classified as a damaging trace gas. Photochemical ozone formation in the troposphere can damage vegetation and high concentrations are toxic to humans. In the presence of both nitrogen oxides and hydrocarbons (including VOCs), radiation from the sun drives complex chemical reactions that generate aggressive reaction products, one of which is ozone. Hydrocarbon emissions can occur from incomplete fuel combustion, and fuel handling (storage, turnover, refuelling etc.) or from solvents.

The high contribution from the manufacturing stage of the Delta4000 is due to the electricity and raw materials required to produce the wind turbine. This is also the greatest component of the windfarm by mass, so there are additional contributions from fuel use to transport the raw materials to the manufacturing site.

The logistics stage of the life cycle is more significant for PCOP than climate change potential. Again, this is due to the direct emissions related to fuel use for transport via truck and ship.

4.2.3. Acidification potential, terrestrial and freshwater

Figure 13 presents the overall life cycle results for acidification potential, showing the breakdown by windfarm component and life cycle stage.

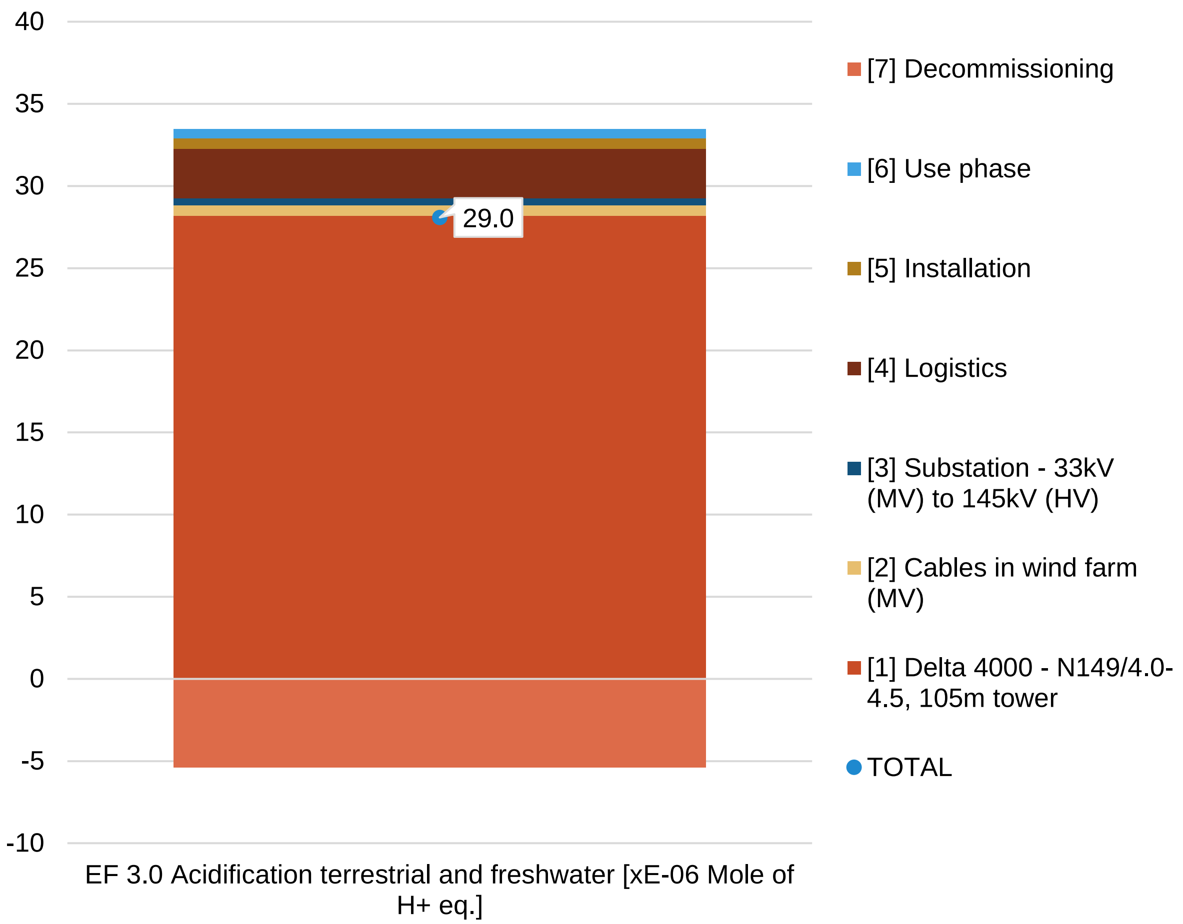

Figure 13: Life cycle acidification, terrestrial and freshwater (x10^{-6} moles of H+ eq.) per functional unit

Acidification of soils and waters mainly occurs through the transformation of air pollutants into acids. This leads to a decrease in the pH-value of rainwater from 5.6 to 4 or lower. Sulphur dioxide, nitrogen oxides and their respective acids (H_2SO_4 and HNO_3) are major contributors to environmental acidification.

As well as the direct damaging effect of acids on ecosystems there are also indirect effects such as the washing of nutrients out of soils and the increased solubility of metals into soils. Buildings and building materials can also be damaged, especially limestone, marble and other calcium carbonate-based rocks.

The life cycle breakdown of contribution to acidification potential is similar to that of photochemical ozone potential, as both are largely linked to energy combustion and emissions of NO_x gases.

4.2.4. Eutrophication, Freshwater

Figure 14 presents the overall life cycle results for eutrophication freshwater potential, showing the breakdown by windfarm component and life cycle stage.

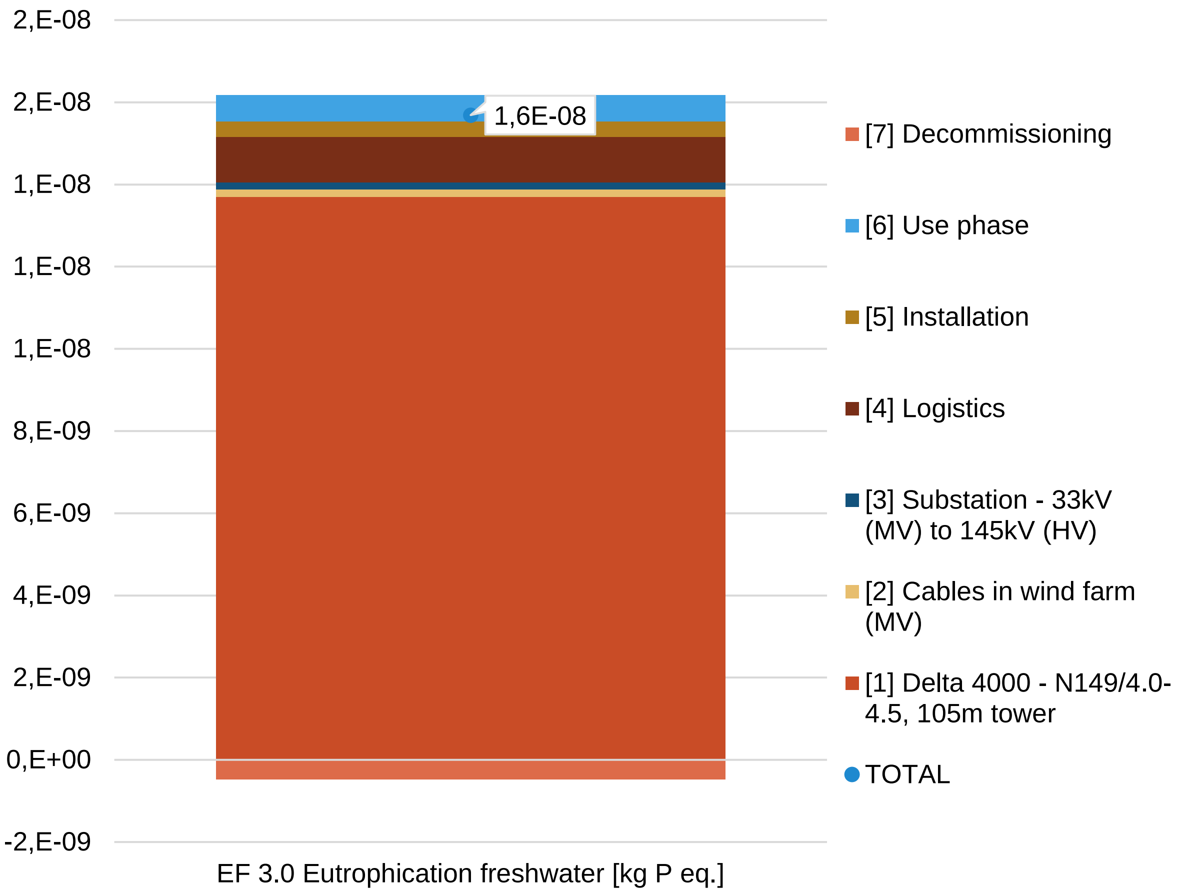

Figure 14: Life cycle eutrophication freshwater (kg P eq.) per functional unit

Eutrophication is the excessive enrichment of nutrients (N and P) within an ecosystem. Air pollutants, wastewater and production and application of fertilisers all contribute to eutrophication. In water this can result in accelerated algae growth that prevents sunlight from reaching the lower depths. This decreases photosynthesis and reduces oxygen production. Further deoxygenation occurs as dead algae decompose. This can lead to fish die-off and to anaerobic decomposition that can produce extremely toxic hydrogen sulphide, further damaging the ecosystem

Eutrophication of freshwater ecosystems is driven by phosphate emissions as phosphorus is usually the key limiting nutrient in these environments.

Eutrophication potential follows a similar pattern of life cycle impacts as seen for photochemical ozone formation and acidification, this is due to the significant impact of the raw materials and energy related to acquiring and manufacturing the wind turbines. The use phase is more dominant for freshwater eutrophication than for other impact categories, this is due to burdens from the replacement parts required for the turbine (mainly from the blades replacement).

4.2.5. Eutrophication, Marine

Figure 15 presents the overall life cycle results for eutrophication marine potential, showing the breakdown by windfarm component and life cycle stage.

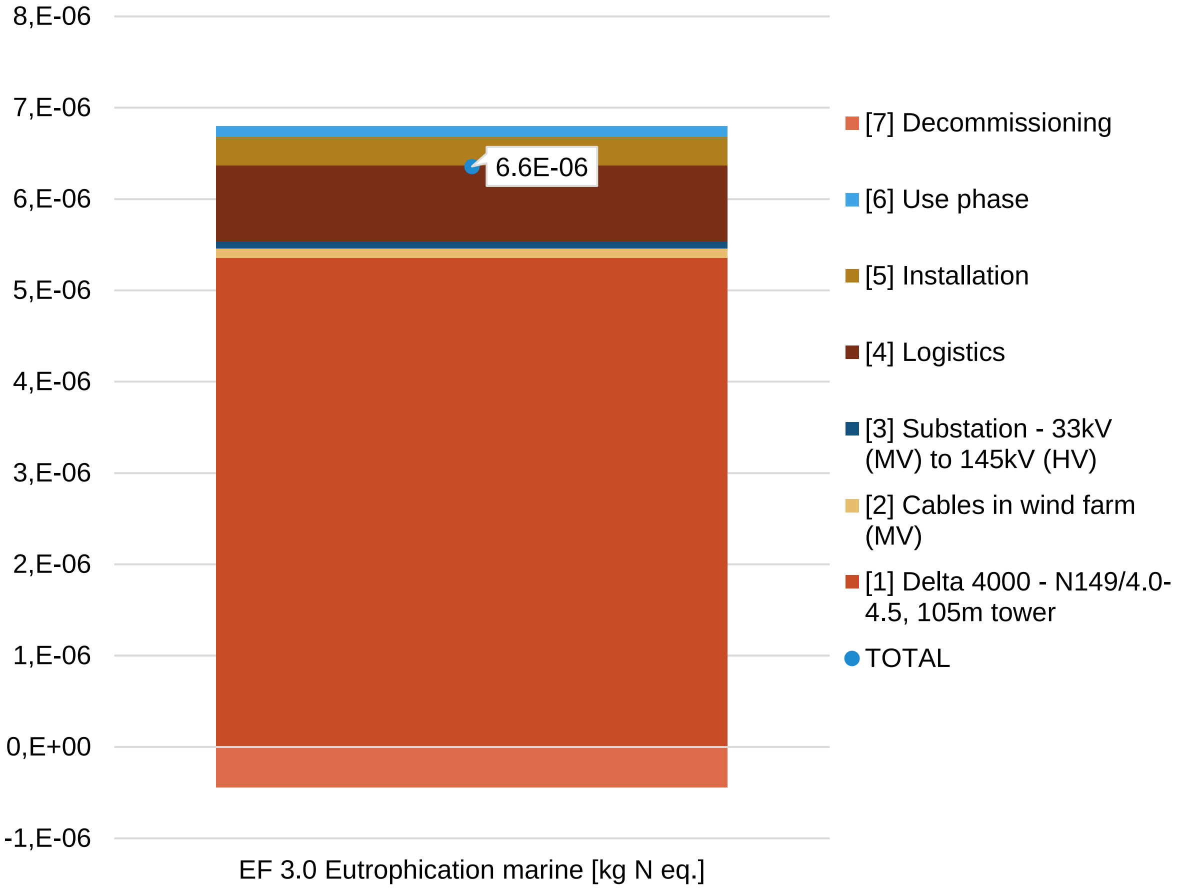

Figure 15: Life cycle eutrophication marine (kg N eq.) per functional unit

Eutrophication of marine ecosystems is driven by nitrogen emissions, as nitrogen is usually the key limiting nutrient in these environments.

Marine eutrophication potential follows a similar pattern to eutrophication freshwater potential however the logistics stage is more significant. This is due to the use of heavy fuel oil associated with shipping, directly entering the marine environment.

4.2.6. Eutrophication, Terrestrial

Figure 16 presents the overall life cycle results for eutrophication terrestrial potential, showing the breakdown by windfarm component and life cycle stage.

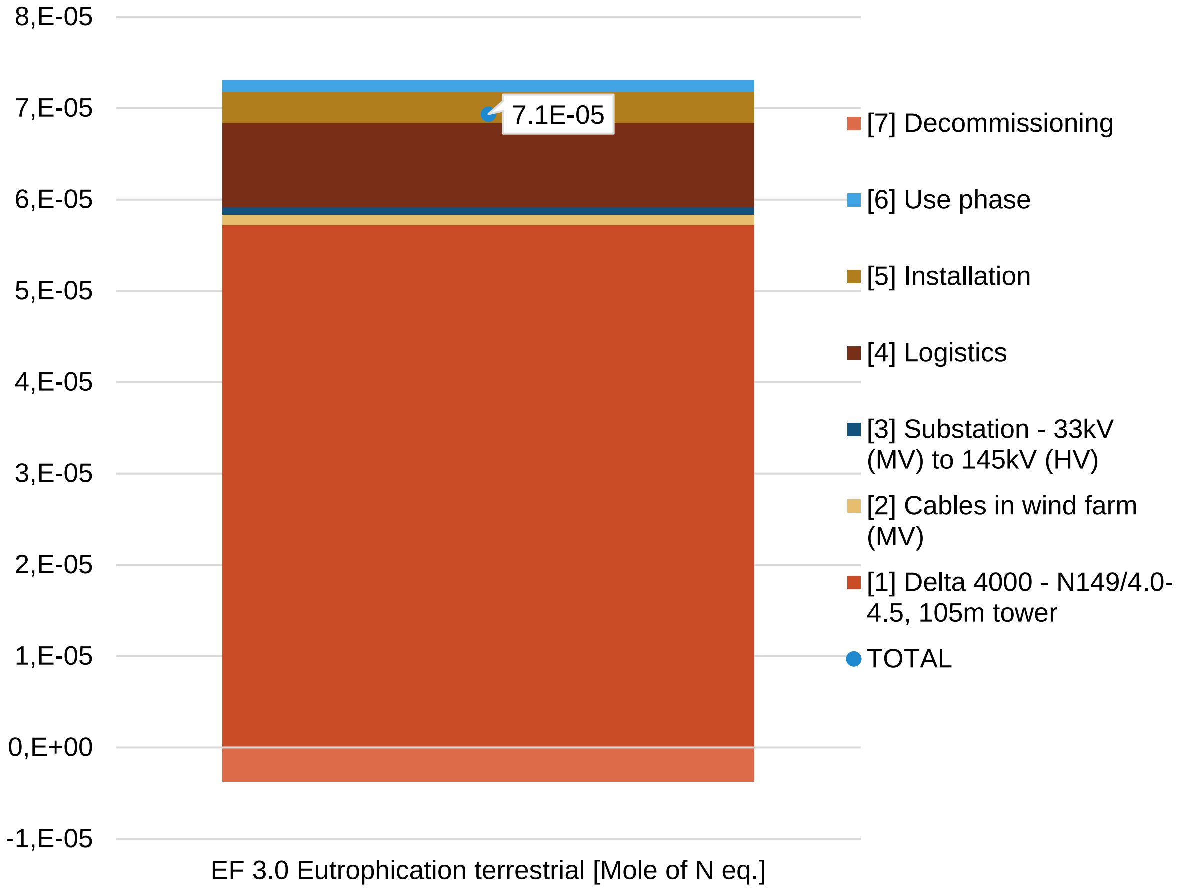

Figure 16: Life cycle eutrophication terrestrial (Mole of N eq.) per functional unit

Eutrophication is the excessive enrichment of nutrients within an ecosystem. Overly nutrient-enriched soils may increase the susceptibility of plants to diseases and pests and degrade plant stability, thereby damaging ecosystems. Eutrophication of terrestrial ecosystems is driven by nitrogen emissions, as nitrogen is usually the key limiting nutrient in these environments.

Terrestrial eutrophication potential follows a similar pattern to eutrophication freshwater and marine potential, driven largely by raw materials, manufacturing and the logistics associated with transporting the components of the windfarm to site via ship and truck.

4.2.7. Resource use, energy carriers

Figure 17 presents the overall life cycle results for resource use, energy carriers, showing the breakdown by windfarm component and life cycle stage.

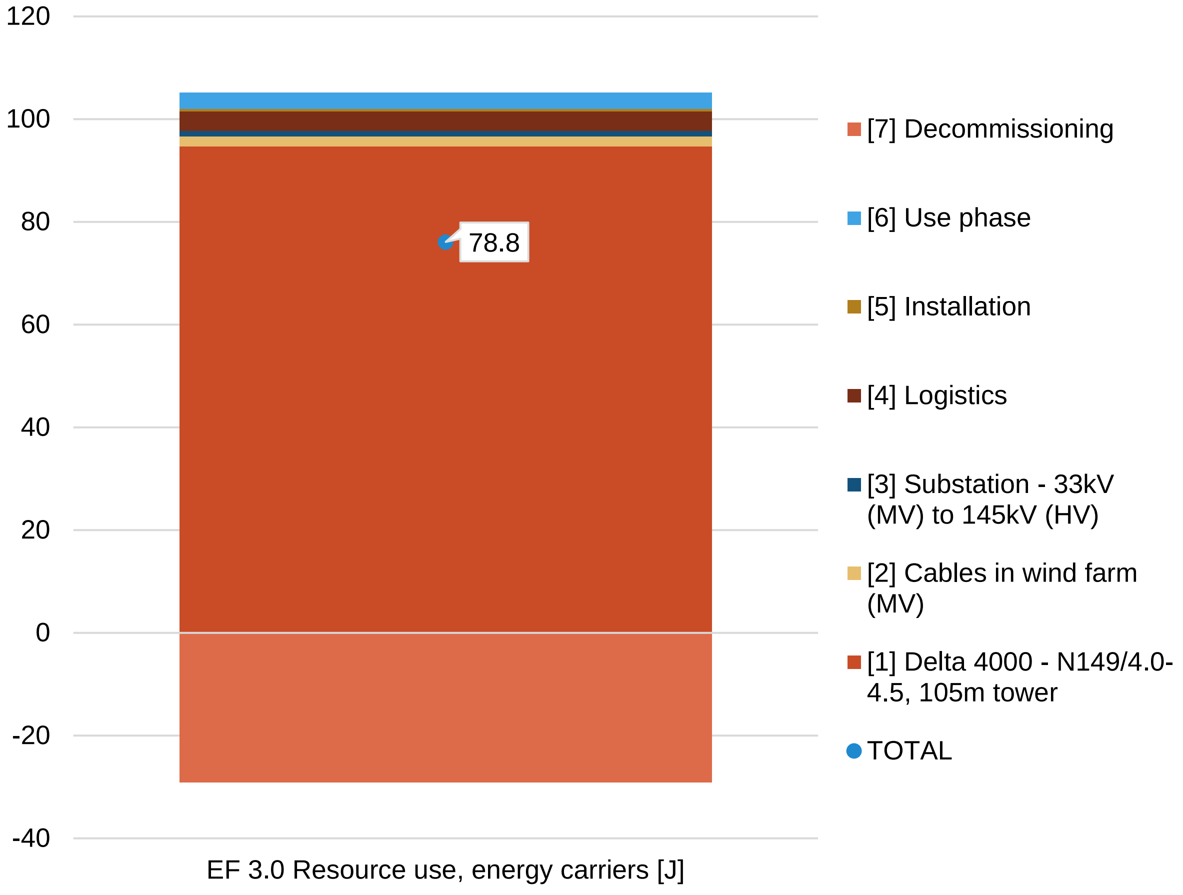

Figure 17: Life cycle resource use, energy carriers (J) per functional unit

Resource use, energy carriers, is representative of the non-renewable resource use/ energy directly taken from the environment.

The cradle-to-gate stage of the wind turbine life cycle is the most dominant for resource use, energy carriers, in line with the other impact categories due to raw materials and resource use during manufacturing. There is a substantial credit awarded to the material recycling due to the energy content of the substituted materials.

4.2.8. Resource use, minerals and metals

Figure 18 presents the overall life cycle results for resource use, minerals and metals, showing the breakdown by windfarm component and life cycle stage.

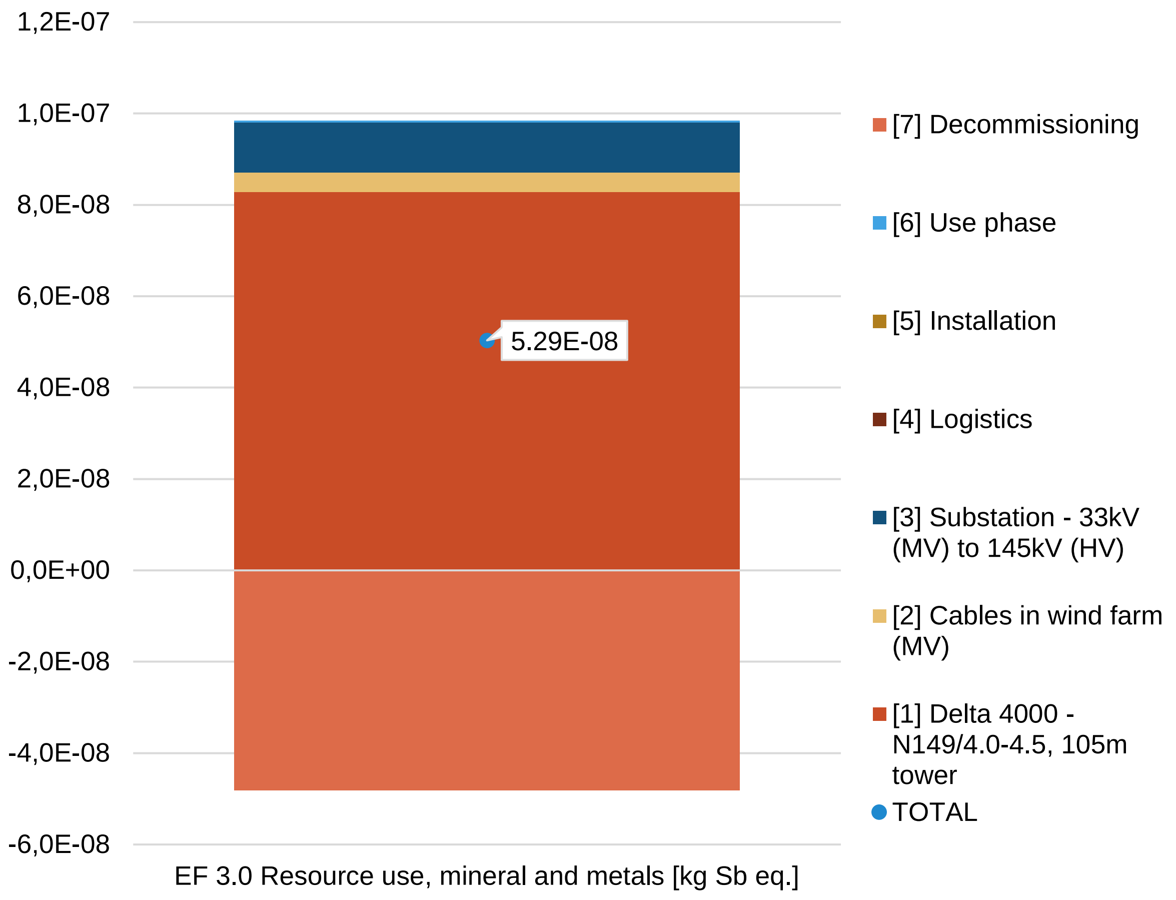

Figure 18: Life cycle resource use, mineral and metals (kg Sb eq.) per functional unit

Resource use, minerals and metals, represents the utilisation of non-renewable minerals and metals across the life cycle.

Wind farms generally have a significant contribution to this category due to the large amount of infrastructure required. The turbine manufacturing stage is the most significant due to the quantity of steel and other components used – the highest contribution is due to the dataset proxy for electronic parts (contains gold). Equally the decommissioning stage is more dominant for this impact category than others as it is directly related to the relatively large amount of material recycling at end-of-life.

4.2.9. Respiratory inorganics

Figure 19 presents the overall life cycle results for respiratory inorganics, showing the breakdown by windfarm component and life cycle stage.

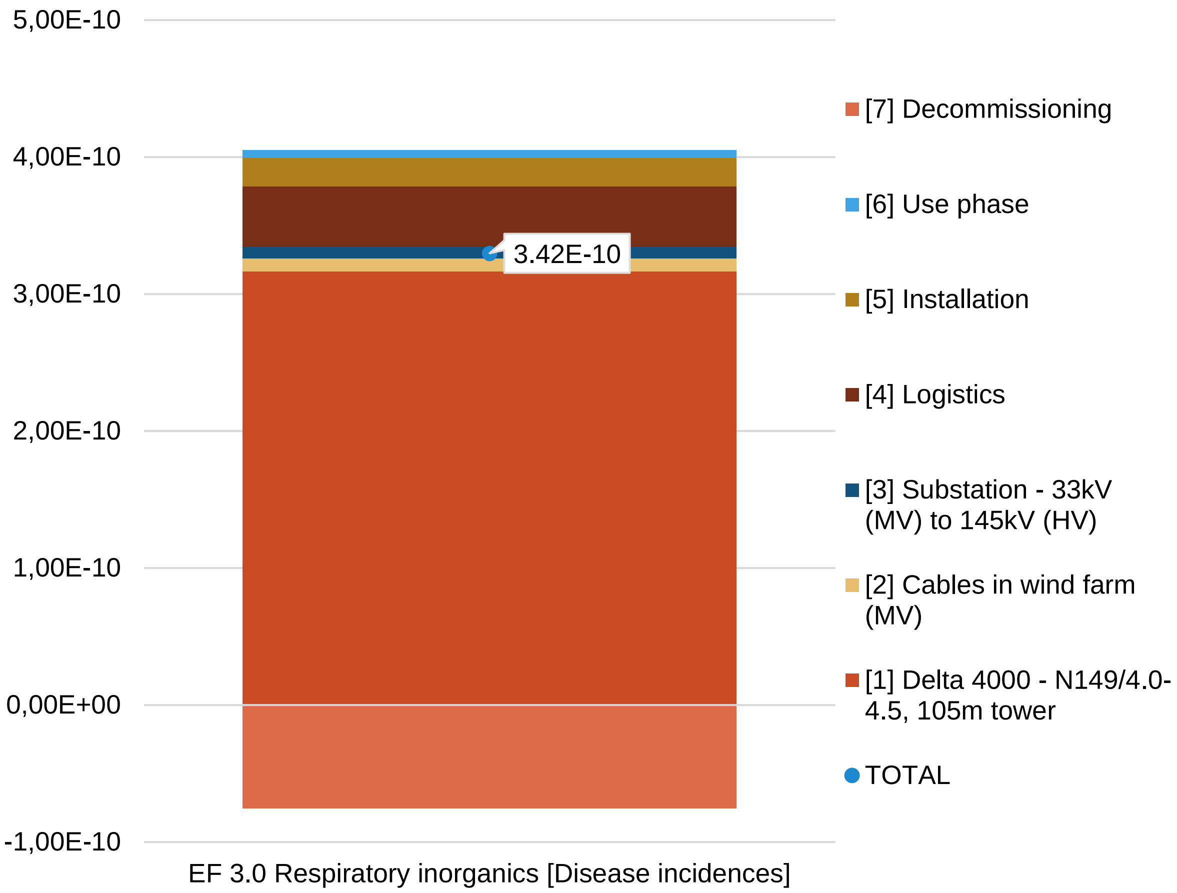

Figure 19: Life cycle respiratory inorganics (disease incidences) per functional unit

Respiratory inorganics accounts for the burdens associated with particulate matter released throughout the life cycle, directly impacting quality of air, which is directly related to disease incidences.

Following a similar pattern to other impact categories, the turbine stage is dominant. The logistics stage is also relatively significant due to the burning of diesel and heavy fuel oils for transport via ship and truck – these are associated with large amounts of particulate emissions.

4.3. Sensitivity Analysis

Sensitivity analyses test the sensitivity of the final results towards variations in parameter values. A sensitivity analysis was conducted for the baseline scenario with two considerations: the life time of the wind turbines and the average cable length deployed at the windfarm. Both parameters were analysed in isolation at +/- 20% the baseline values used in the study. The results are displayed in Figure 20.

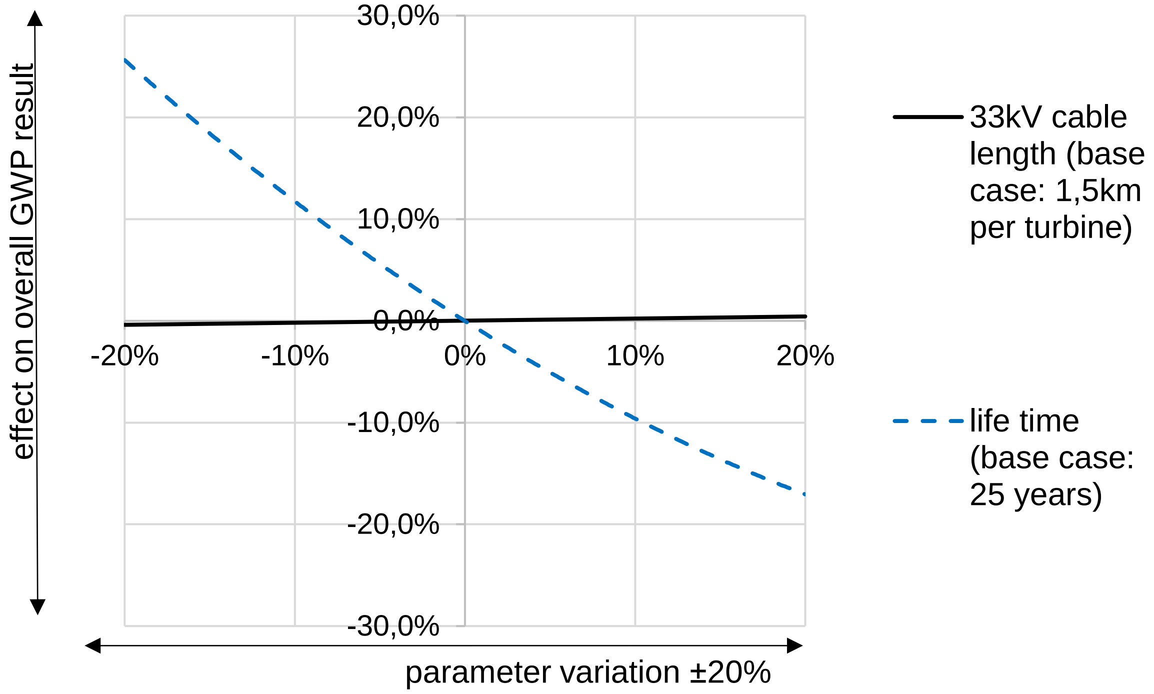

Figure 20: Sensitivity analysis on parameters (cable length and windfarm life time)

The results showed that variation in the cable length onsite by +/- 20% was not relevant to the results for climate change potential. However, the variation of the lifetime of the windfarm had a significant impact on the climate change potential of the windfarm. Decreasing the lifetime by 20% resulted in a climate change potential 25% higher than the baseline scenario (8.18 vs. 6.54 g CO2 eq/kWh), while increasing the lifetime by 20% reduced the climate change potential by 17% (5.45 vs. 6.54 g CO2 eq/kWh).

4.4. Scenario Analyses

Scenario analyses compare results among discrete sets of parameter settings or modelling choices. The following scenarios analysed for this study were identified as being most significant design choices for the windfarm pilot plant.

As Nordex rate climate change as the most important impact category for their business, the results of the scenario analyses presented here focus on this indicator only.

4.4.1. Lifetime and net AEP value (scenario 1)

The baseline scenario in this study presented a net annual energy production (AEP) of 11,768 MWh per annum (P75) and a 25-year lifetime. The following scenarios were analysed to determine the importance of variations in the AEP and lifetime of the windfarm.

- Scenario 1.1 - optimistic: net AEP of 12,675 MWh per annum (P50) for a 25-year lifetime
- Scenario 1.2 - pessimistic: net AEP of 10,457 MWh per annum (P95) for a 20-year lifetime

The results are presented in Figure 21.

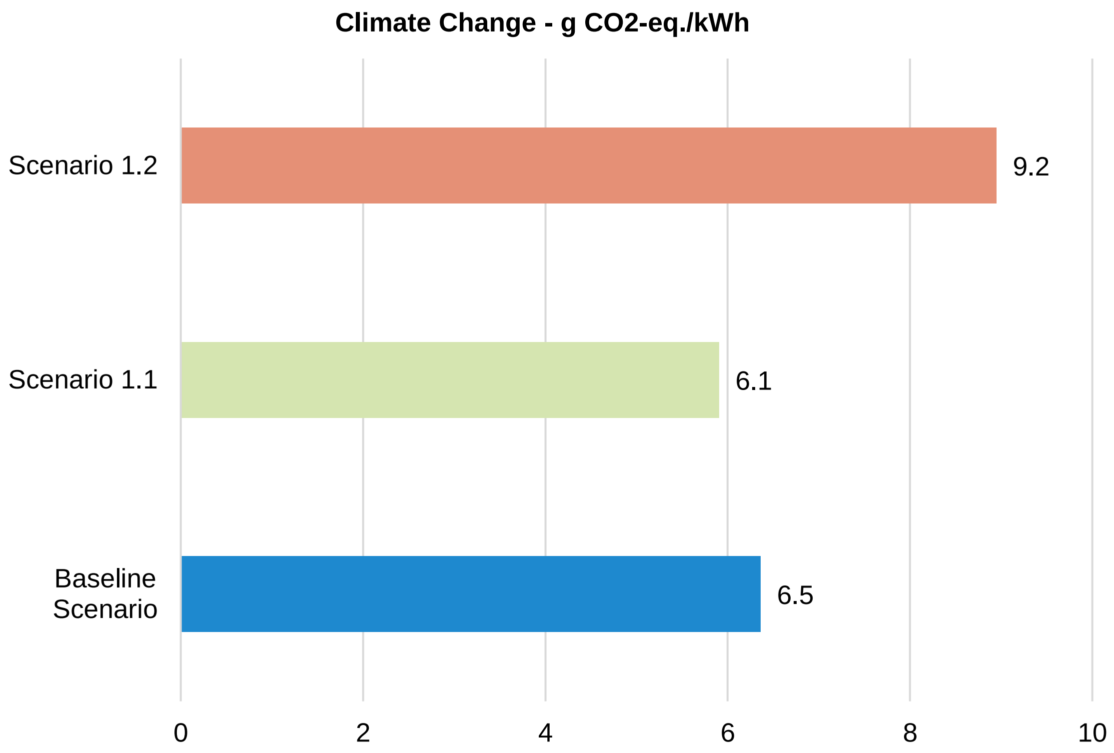

Figure 21: Climate change for scenarios 1.1 and 1.2 (Lifetime and net AEP)

The results showed the pessimistic scenario 1.2 to have a greater impact in varying the climate change potential of the life cycle of the windfarm, increasing it by 41%. The optimistic scenario 1.1 reduced the climate change potential by 7% showing the reduction of the lifetime of the windfarm to be most significant.

4.4.2. Foundation with high ground water level (scenario 2)

The baseline scenario for the study assumes a foundation that has a low ground water level, the scenario comparison considers a foundation with a high ground water level. A high ground water level requires an increase in foundation material including steel and concrete by a mass of approximately 17%.

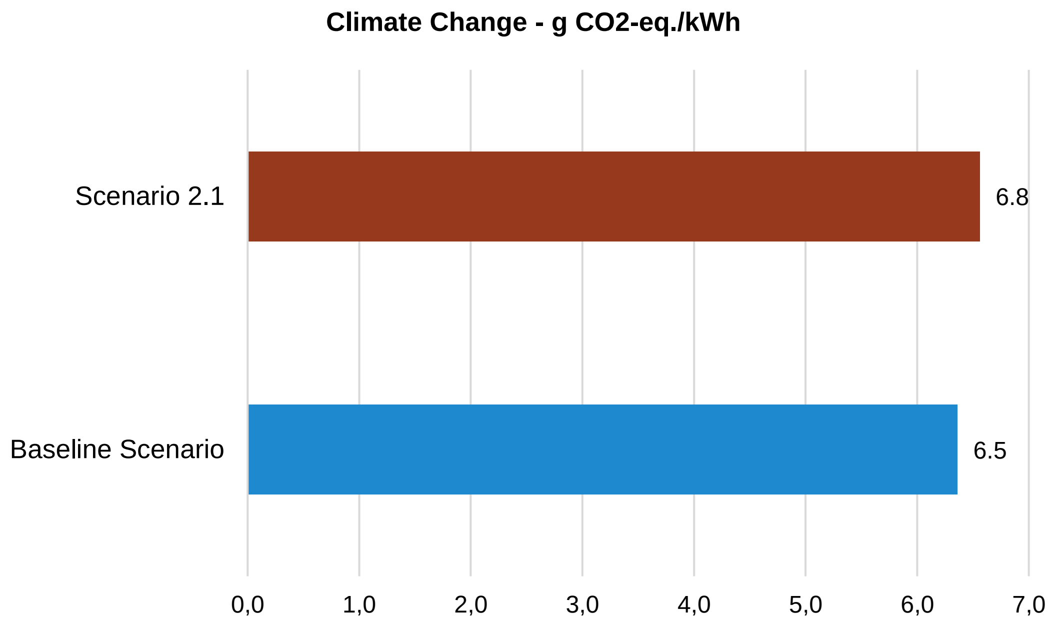

Figure 22: Climate change for scenario 2.1 (Foundation ground water level)

4.4.3. End-of-life allocation (scenario 3)

The baseline scenario for this study uses the substitution approach for modelling the end-of-life of the windfarm. This scenario analysis compares substitution with the cut-off methodology that is discussed in section 2.4.2.

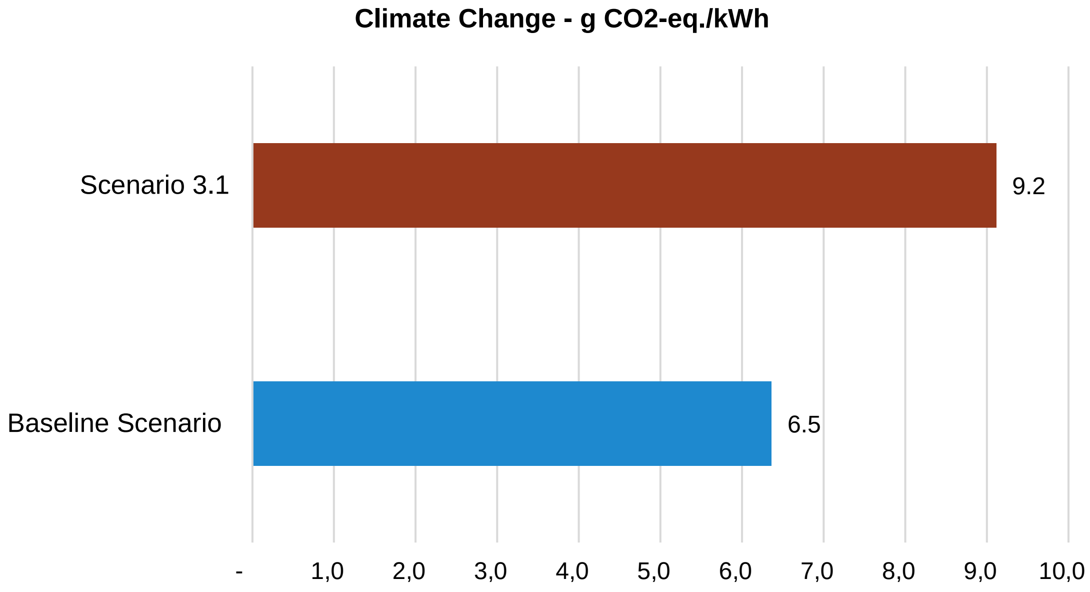

Figure 23: Climate change for scenario 3.1 (end-of-life allocation)

The results from this scenario analysis show a considerable increase in climate change potential by shifting to the cut-off allocation method whereby credits aren't rewarded for material recycling at end-of-life. The major elements of the turbine, including steel were assumed to have a recovery rate of over 95% hence, the life cycle climate change potential increasing by approximately 42% of the baseline scenario.

4.4.4. Tolerances for thickness of steel pipes for tower sections (scenario 4)

The alternative tolerances for thickness of steel pipes assessed in this scenario analysis are - 1.9% and + 4.9%. Altering the thickness of the steel pipes by -1.9%/+4.9% results in a difference in climate change potential of -0.4%/ +1.1% respectively.

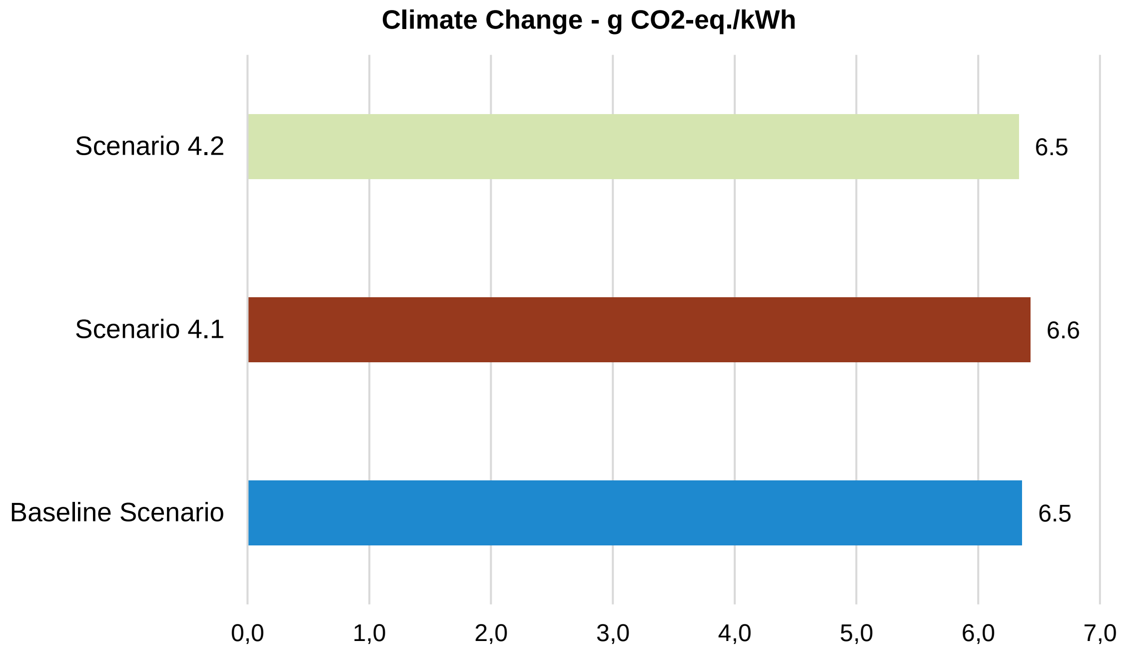

Figure 24: Climate change for scenarios 4.1 and 4.2 (steel pipe thickness)

The results for this scenario analysis show that altering the tolerances for the thickness of the steel pipes is relatively insignificant compared to the overall impact of the life cycle of the windfarm.

4.4.5. Risk assessment for sulphur hexafluoride gas in switchgears (scenario 5)

The baseline scenario assumes that no sulphur hexafluoride (SF_6) gas that is utilised in the switchgears leaks into the atmosphere; scenario 5.1 assumes that 100% of the SF6 gas utilised throughout the life cycle leaks into the atmosphere. Considering the little mass of SF6 gas per turbine, it shows how potent it is as a greenhouse gas.

Further confidential data moved to Annex B

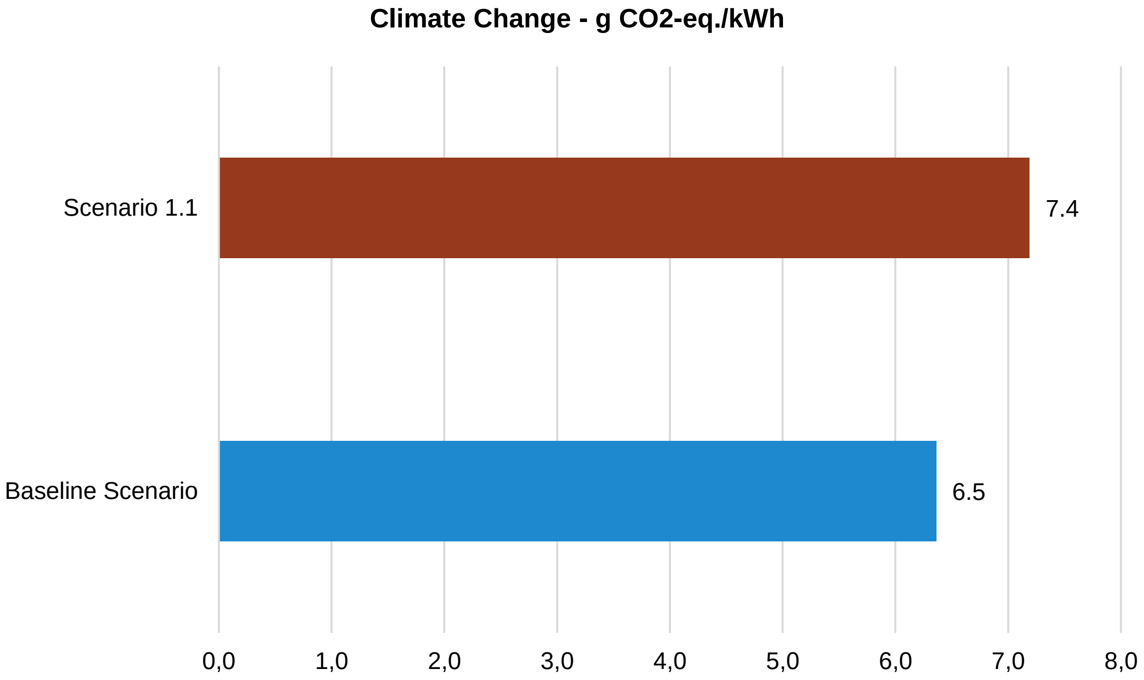

Figure 25: Climate change for scenario 5.1 (% of SF_6 gas leak)

As can be seen in Figure 25, scenario 5.1 whereby 100% SF6 gas is released has a 13% increase in climate change potential for the entire life cycle.

4.5. Return on Energy (RoE)

The RoE parameter is an estimation of energy efficiency of the windfarm compared to the energy required to produce the windfarm. It is measured in years and represents the running time required for the turbine to produce the amount of energy consumed for its complete life cycle.

There are no specific standards about how to calculate this indicator. RoE can be expressed in various units; the unit adopted in this study is an amount of time expressed in years. Computation occurs as follows:

$RoE= E\_invested\ /\ E\_produced{,}year\ [y]$

E_invested = Total amount of total primary energy (thermal and electric; total non-renewable + total renewable energy) required to manufacture the wind turbine starting from primary components and including all the necessary fuels.

E_produced, year = Total amount of net electricity generated per year by the wind turbine

The result for RoE is 0.64 years, which equals to 7.7 months.

5. Interpretation

5.1. Identification of Relevant Findings

Summary of baseline scenario

This report presents the results for the environmental impact from the life cycle assessment study of a pilot Delta4000 windfarm composed of 47 turbines, located in Sweden.

In summary, the baseline scenario is modelled with the assumption that the windfarm is based in Sweden at a light wind site (less than 7.5 m/s average wind speed on hub height; actual average wind speed at hub height in this study is 6.8 m/s). The system boundary ends at the substation hence there is no direct connection to the grid and no distribution of electricity considered.

The results for the baseline scenario are presented in a heat map in Table 11, showing the relative contribution from cradle to use phase as 100% of the impacts and the decommissioning stage a percentage of that, as decommissioning was a negative impact across all impact categories.

It can be seen from the results, presented per functional unit, that across all impact categories, the raw material and manufacturing stage of the turbine is, by far, the most dominant contributor across the whole life cycle of the windfarm.

The second largest contributor across the majority of impact categories is the decommissioning whereby the credit for material recycling is significant. This is dependent on a high recycling rate for high impact materials, predominantly steel used in the infrastructure of the turbine. The largest credit can be seen for climate change potential and resource use, minerals and metals, (see Table 13).

The substation contributes to 11% of the cradle-to-use phase impact for both resources use, metals and minerals. This is due to the substation composition of steel, copper and aluminium.

The logistics stage is not a dominant contributor for climate change potential however is of greater significance for acidification, eutrophication (all water bodies), photochemical ozone formation potential and respiratory inorganics. These categories are directly related to the burning of heavy fuel oil for shipping parts as well as transport via truck.

Table 11: Heat map of full life cycle for baseline scenario (100% = cradle through to the use phase, Decommissioning = % of cradle to use phase)

	[1] Delta4000 – N149/4.0-4.5, 105m tower	[2] Cables in windfarm (MV)	[3] Substation – 33kV (MV) to 145kV (HV)	[4] Logistics	[5] Installation	[6] Use phase	[7] De-commissioning
Acidification terrestrial and freshwater	84%	2%	1%	9%	2%	2%	-16%
Climate Change (fossil)	91%	1%	1%	3%	1%	2%	-29%
Eutrophication freshwater	85%	1%	1%	7%	2%	4%	-3%
Eutrophication marine	79%	2%	1%	12%	5%	2%	-6%
Eutrophication terrestrial	78%	2%	1%	13%	5%	2%	-5%
Photochemical ozone formation – human health	82%	1%	1%	10%	4%	2%	-11%
Resource use, energy carriers	90%	2%	1%	4%	1%	3%	-28%
Resource use, mineral and metals	84%	4%	11%	0%	0%	0%	-49%
Respiratory inorganics	78%	2%	2%	11%	5%	1%	-19%

Delta4000 Turbine summary

As the production of the Delta4000 turbine was identified as the dominant contributor from the life cycle of the windfarm for all impact categories, it is important to understand the breakdown of the components of the turbine and their relative contribution to each impact category. The percentage contribution is detailed in Table 12.

The foundation of the turbine by mass, is 73% of the turbine however, as it is composed of approximately 93% 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 tower accounts for 13% of the of the mass of the turbine however due to the large amount of steel that contributes to the infrastructure, the impact is generally much larger than that of the foundation of the turbine.

Similarly, despite the blades only contributing 3% of the mass of the turbine, they are significant in several impact categories. Freshwater eutrophication potential is the highest for the blades, this is largely due to the polymer parts, resin glass fibres and electricity required to manufacture the blades.

The E-module is the most significant contributor to resource use, metals and minerals which is due to the electronics present in the top-box and pitch-box (dataset proxy for electronics contains gold).

Table 12: Heat map for Delta4000 component contribution across all impact categories

	Foundation	Tower	Blades	E-Module	Drivetrain	Nacelle	Delta	Transport
Mass % of Turbine	73%	13%	3%	1%	3%	7%	0%	-
Acidification terrestrial and freshwater	18%	36%	17%	14%	9%	4%	1%	1%
Climate Change (fossil)	19%	38%	21%	7%	7%	7%	1%	1%
Eutrophication freshwater	7%	13%	55%	10%	5%	7%	0%	3%
Eutrophication marine	20%	32%	22%	10%	7%	5%	1%	4%
Eutrophication terrestrial	21%	31%	22%	10%	7%	5%	1%	4%
Photochemical ozone formation	18%	33%	26%	9%	6%	5%	1%	3%
Resource use, energy carriers	13%	33%	31%	8%	7%	6%	1%	1%
Resource use, mineral and metals	1%	8%	3%	81%	2%	3%	2%	0%
Respiratory inorganics	20%	34%	13%	16%	12%	4%	1%	1%

Normalisation

The normalisation of results supports the identification of the most relevant impact categories in the study. The global normalisation factor per person equivalent was utilised in this study, based on data provided from the Product Environmental Footprint initiative.

The normalisation factors represent the total impact of a reference region for a certain impact category (e.g. climate change, eutrophication, etc.) in a reference year (Serenella Sala, 2017). For the environmental footprint, due to the international nature of supply chains, the use of global normalisation factors is recommended.

Table 13: PEF 3.0 Normalisation of Nordex windfarm and German and Swedish Grid mix

PEF 3.0 Normalised Results	Nordex windfarm per kWh	German grid mix per kWh	Wind farm % of German grid mix	Sweden grid mix per kWh	Wind farm % of Swedish grid mix
Acidification terrestrial and freshwater	5.05E-07	1.77E-05	3%	2.26E-06	22%
Climate Change (fossil)	7.91E-07	7.19E-05	1%	4.72E-06	17%
Eutrophication freshwater	9.74E-09	1.50E-06	1%	4.63E-07	2%
Eutrophication marine	3.26E-07	1.41E-05	2%	2.34E-06	14%
Eutrophication terrestrial	3.92E-07	1.62E-05	2%	2.28E-06	17%
Photochemical ozone formation – human health	5.04E-07	1.70E-05	3%	2.49E-06	20%
Resource use, energy carriers	1.17E-06	1.11E-04	1%	5.41E-05	2%
Resource use, mineral and metals	7.91E-07	3.42E-06	23%	6.89E-07	115%
Respiratory inorganics	5.54E-07	1.22E-05	5%	1.80E-06	31%

The results for normalisation of the windfarm baseline scenario of this study show the resource use, energy carriers impact category to have the most significance compared to the reference. Climate change and resource use, mineral and metals are also significant; these are all interlinked and driven by the raw material use in manufacturing the Delta4000 turbine.

Comparing the impact of generating 1 kWh from the windfarm to the 1 kWh from the German grid mix, it can be seen that the windfarm has much lower impacts for all assessed impact categories.

Compared to the Swedish grid mix, the advantages of the Nordex windfarm are lower than in comparison to the German grid mix, but still very significant for most impact categories. However, for resource use, minerals and metals, the windfarm burdens are slightly higher. This is due to the large amount of steel and electronics required for the windfarm, as detailed earlier in the interpretation.

5.2. Assumptions and Limitations

It was not always possible to obtain an exact match between desired and available background datasets. In such cases, proxy data were usually used to fill data gaps. In most instances, these proxy data related to geographical region (i.e. background dataset may have specified a different region to that actually used in the study). It is not expected that this difference will have too great an impact on the results of the study as the same technology is applied in both cases, although some differences may arise due to variations in e.g. electricity grid mixes between regions.

Section 3.5 gives a detailed overview on the assumptions and data gaps. The effect of some assumptions and gaps could be quantified – partly in the sensitivity and scenario analysis (discussed below). The key assumptions/parameters have a significant impact on the overall results, the data gaps have a very limited effect (in case the effect could be quantified).

5.3. Results of Sensitivity and Scenario Analysis

5.3.1. Sensitivity Analysis

Sensitivity analyses were performed to test the influence on the result of uncertainties in input parameter values.

Cable length on site and lifetime of windfarm

The analyses showed that varying the cable length onsite resulted in no significant change to the overall climate change impacts of the windfarm. However, varying the operating lifetime of the windfarm +/- 20%, resulted in a change in climate change of -17% (for 20% increase in lifetime) and +25% (for a 20% decrease in lifetime). This shows the lifetime of the windfarm to be an important consideration in the design of the windfarm and that by maximising its operating lifetime, the impact of the full life cycle can be reduced significantly.

5.3.2. Scenario Analysis

Scenario analyses were performed to compare results between different sets of assumptions or modelling choices. The climate change potential for each scenario assessed in this study is presented below in Table 14.

Table 14: Summary of climate change potential for the life cycle of all scenario analysis

Scenario	Value	% Difference
Baseline	6.5	-
1.1 (net AEP of 12.675 MWh/year (p50) and 25 year lifetime)	6.1	-7%
1.2 (net AEP of 10.457 MWh/year (p95) and 20 year lifetime)	9.2	41%
2.1 (foundation with high ground water level)	6.8	3%
3.1 (End-of-life allocation: cut-off approach)	9.2	42%
4.1 (Tolerances for thickness of steel pipes at -1.9%)	6.5	0%
4.2 (Tolerances for thickness of steel pipes at +4.9%)	6.6	-2%
5.1 (100% emissions of sulphur hexafluoride (SF6) gas)	7.4	13%

The scenario analyses are discussed in greater detail in the following sections.

Scenario Analysis 1 – Choice of AEP and windfarm lifetime

The analyses of the annual energy production and windfarm lifetime showed to be significant in comparison to the other scenario analysis. The base case had a net AEP of 11,768 MWh per year and a 25-year lifetime.

Scenario 1.1 showed the largest reduction in the climate change potential of the life cycle at 7% by increasing the net AEP to 12,675 MWh per year (by approximately 8%), maintaining a 25-year life cycle. However, this is less significant than altering the lifetime of the wind turbines to 20 years and reducing the AEP to 10,457 MWh per year (by approximately 11%) as seen in scenario 1.2 whereby the climate change potential of the life cycle is increased by 41%.

This more significant difference in climate change potential is due to the strong dominance of the raw materials and manufacturing stages of the turbine.

The annual energy production (AEP) onsite is highly dependent on the site of the windfarm and the resultant site-specific conditions. The baseline scenario for the study considered an IEC classified light wind site, the other classifications are medium and high wind sites. Wind turbines can be designed dependent on the conditions of the wind site hence, the exact AEP may not be largely impacted by wind site classification.

Scenario Analysis 2 – Choice of ground water level

The baseline scenario for the study assumed a low ground water level as it is often the case for the majority of windfarm sites. This was compared with the scenario of high ground water level which would require an increase in foundation material including steel and concrete.

The scenario analysis showed an increase in the life cycle climate change potential by 3%, increasing it to 6.8g CO_2 eq./kWh for the life cycle impact.

Scenario Analysis 3 – Choice of end-of-life allocation methodology

This analysis compared the results of the life cycle impact using two key approaches used in the case of there being recycled materials or recycling in LCA. The baseline scenario followed the “substitution” approach and this analysis compared it with the “cut-off” approach.

For the baseline scenario, using the substitution approach, the high recycling rate of the materials (particularly steel) at end-of-life is credited, this is based on the net scrap arising after accounting for scrap used in the manufacturing stage.

Scenario 3.1 using the “cut-off” approach, resulted in the highest climate change potential across all scenario analysis. Using the cut-off methodology, no benefits are received for recycling at end-of-life. The cut-off methodology rewards recycled content used in the raw material and manufacturing stage however, very little recycled content is used in the construction of the windfarm. The UO steel pipe dataset from worldsteel that accounts for over 98% of the tower mass, only has an input of approximately 3% recycled content.

As a result, the climate change results using the cut-off approach are 42% higher than for the substitution approach.

Scenario Analysis 4 – Choice of pipe thickness

Altering the thickness of the steel pipes for the towers does not have a significant impact on the climate change potential across the whole life cycle hence, it is not a relevant aspect in terms of design and decision making for the windfarm.

Scenario Analysis 5 – Difference in sulphur hexafluoride emissions

Sulphur hexafluoride gas is used as an insulating and current-breaking medium in the switchgear and other transmission and distribution equipment. It is an extremely potent greenhouse gas and so release of 100% of the SF_6 gas used throughout the life cycle increase the climate change potential by approximately 13%. Hence, the appropriate control and risk management of the utilisation of this gas is essential to avoid leakage as well as being reclaimed and potentially reused at the end-of-life of the windfarm.

5.4. 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 GaBi 2019 database were used. The LCI datasets from the GaBi 2019 database are widely distributed and used with the GaBi 9 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.

5.4.1. 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 GaBi 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 GaBi databases with the documented completeness.

5.4.2. 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 GaBi 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.

5.4.3. Representativeness

- ✓ **Temporal:** All primary data were collected for the year 2019. Most secondary data come from the GaBi 2019 databases and are representative of the years 2012-2019 (although one dataset has a reference year of 2005). As the study intended to compare the product systems for the reference year 2019, 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 high.
- ✓ **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.

5.5. Model Completeness and Consistency

5.5.1. 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.

5.5.2. 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 GaBi 2019 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.

5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

This study has evaluated the environmental performance of the Nordex Delta4000 pilot windfarm situated in Sweden, in a light wind site with an IEC wind class III, which is defined as less than

7.5°m/s average wind speed at hub height. The actual applied average wind speed at hub height: in this study is 6.8 m/s.

For the baseline scenario, which assumes a 25-year windfarm lifetime and net annual energy production (AEP) of 11,768 MWh per annum (P75), the climate change impact of the electricity generated was found to be 6.5 g CO_2 eq./kWh. For comparison, the average climate change burden of electricity from the Swedish and German electricity grids is 37 g CO_2 eq./kWh and 570 g CO_2 eq./kWh, respectively. Large reductions were also seen for other impact categories assessed in this study (as reported in the normalised results). This demonstrates the great improvements in environmental performance that can be achieved through increasing the proportion of electricity generated using wind power.

The impacts associated with the windfarm are dominated by the manufacturing of the turbines – this typically accounts for 80-90% of the total cradle-to-use burden across all impact categories. Other life cycle stages, such as installation, logistics, other windfarm infrastructure, etc. have a minor contribution in comparison. However, the decommissioning stage of the life cycle shows a significant beneficial contribution due to the credits received from recycling at end-of-life.

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

The sensitivity and scenario analyses helped to identify the aspects of the windfarm life cycle that had the most influence on the results of the study.

- The lifetime of the windfarm was seen to be an important factor. As noted above, the manufacturing stage of the life cycle has the largest contribution to the burdens of the windfarm. Therefore, as the lifetime of the windfarm increases, these manufacturing burdens are spread across the generation of a greater quantity of electricity, reducing overall impacts per kWh. Equivalently, reducing the windfarm lifetime will result in an increase in overall burden.
- Assumptions around the net annual energy production (AEP) are also important for much the same reason. The more energy that is generated by the windfarm, the more the burdens of manufacturing are shared and diluted, reducing the impacts per kWh electricity.
- The choice of methodology for accounting for recycling and recycled content is another important factor on the overall results. Changing from the substitution approach to the cut-off approach results in a 42% increase in burdens. This is because very little recycled content is used in the raw material inputs, but quite large amounts are recycled at end-of-life. We believe that the substitution approach is preferred for this LCA given the characteristics of the materials used to manufacture the wind turbine – this is the approach recommended by the worldsteel association (and the metals industry in general).
- Management of sulphur hexafluoride used in switchgears is important for climate change impacts. This is an extremely potent greenhouse gas so the emission of even small quantities can have a very large impact. It should be a priority to ensure that this is captured and recycled during maintenance and decommissioning of the windfarm.
- Other aspects that were assessed, such as the quantity of cabling required, the tolerances of the steel pipe used and the effect of water level on the amount of foundations required, had minimal influence on the study results.

5.6.2. Limitations

This study reflects a windfarm comprising Delta4000 wind turbines, which is operated in Sweden under specific wind conditions. It may not be valid to extrapolate these results to windfarms in other regions or operating under different conditions.

The comparisons that have been made for generating 1 kWh of energy via the windfarm in comparison to the grid mix for both Germany and Sweden have utilised the 2016 grid mix assumptions for both countries. It is likely that both grid mixes have increased their proportion of renewable energy sources contributing to the grid mix since then. However, it is very likely, considering the scale of the difference seen in Table 13 that the windfarm will still be considerably less damaging for the majority of impact categories.

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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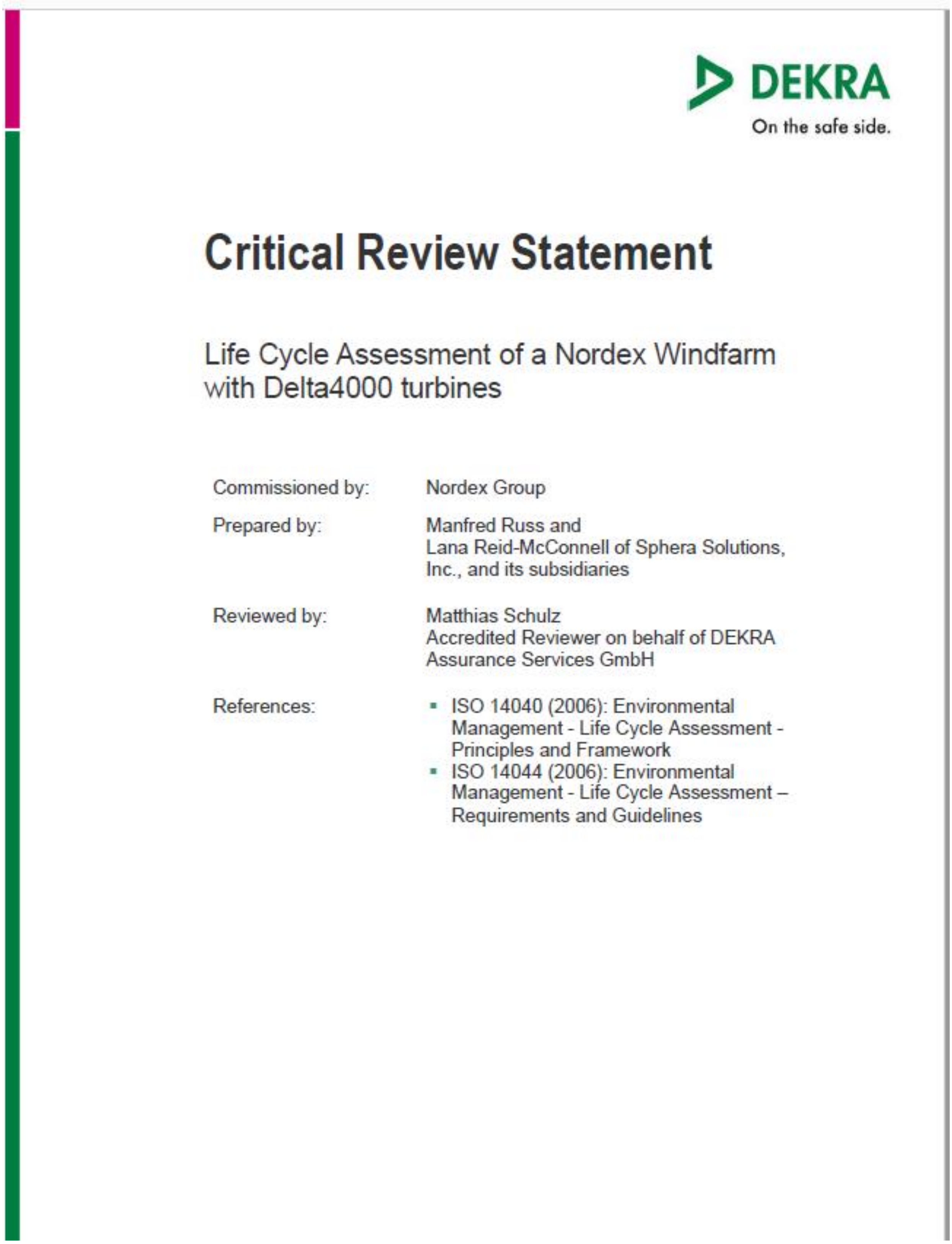
Annex A: Critical Review Statement



Critical Review Statement

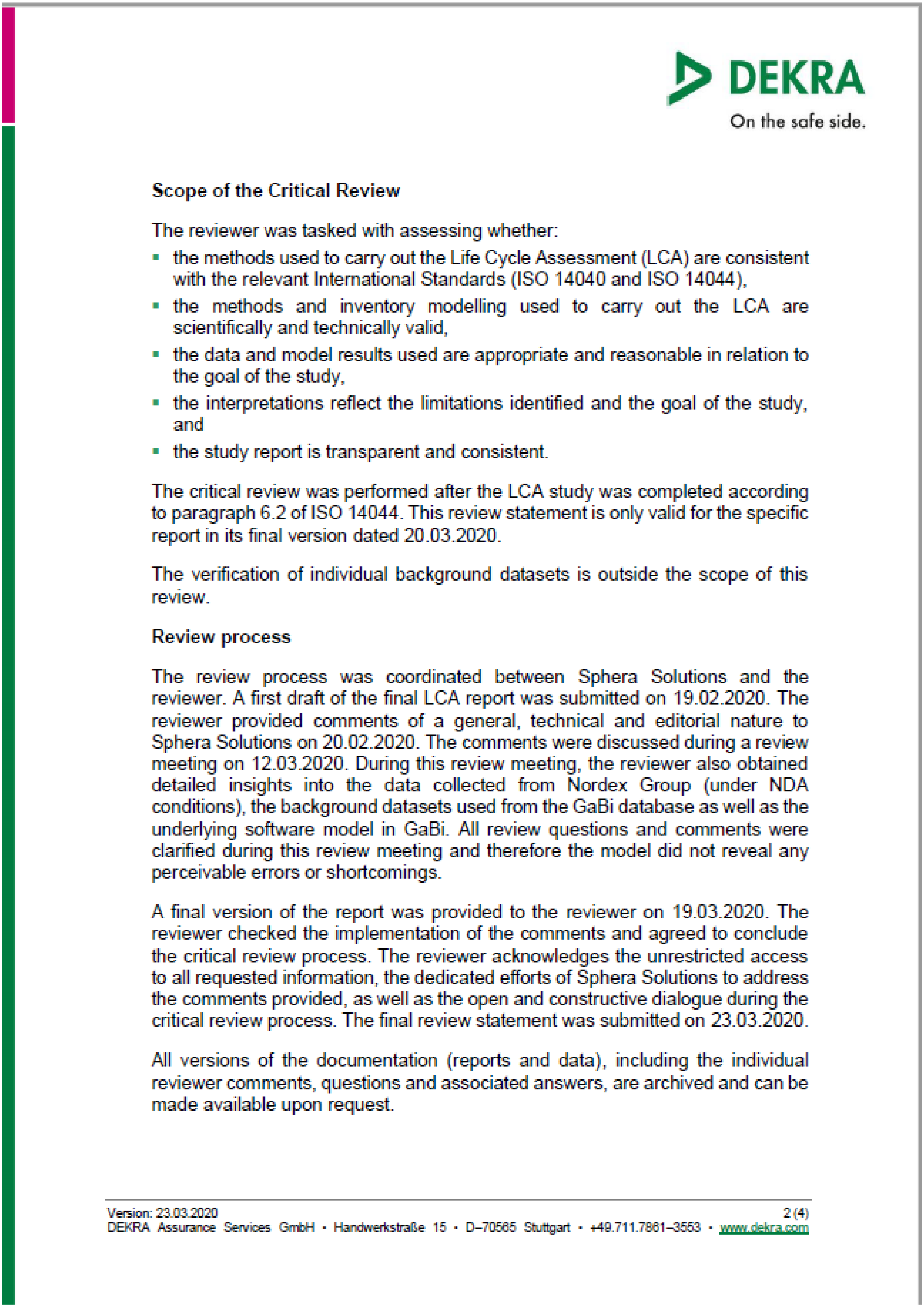
Life Cycle Assessment of a Nordex Windfarm with Delta4000 turbines

Commissioned by: Nordex Group

Prepared by: Manfred Russ and
Lana Reid-McConnell of Sphera Solutions, Inc., and its subsidiaries

Reviewed by: Matthias Schulz
Accredited Reviewer on behalf of DEKRA Assurance Services GmbH

References:
- ISO 14040 (2006): Environmental Management - Life Cycle Assessment - Principles and Framework
- ISO 14044 (2006): Environmental Management - Life Cycle Assessment – Requirements and Guidelines



Scope of the Critical Review

The reviewer was tasked with assessing whether:

- the methods used to carry out the Life Cycle Assessment (LCA) are consistent with the relevant International Standards (ISO 14040 and ISO 14044),
- the methods and inventory modelling used to carry out the LCA are scientifically and technically valid,
- the data and model results 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 critical review was performed after the LCA study was completed according to paragraph 6.2 of ISO 14044. This review statement is only valid for the specific report in its final version dated 20.03.2020.

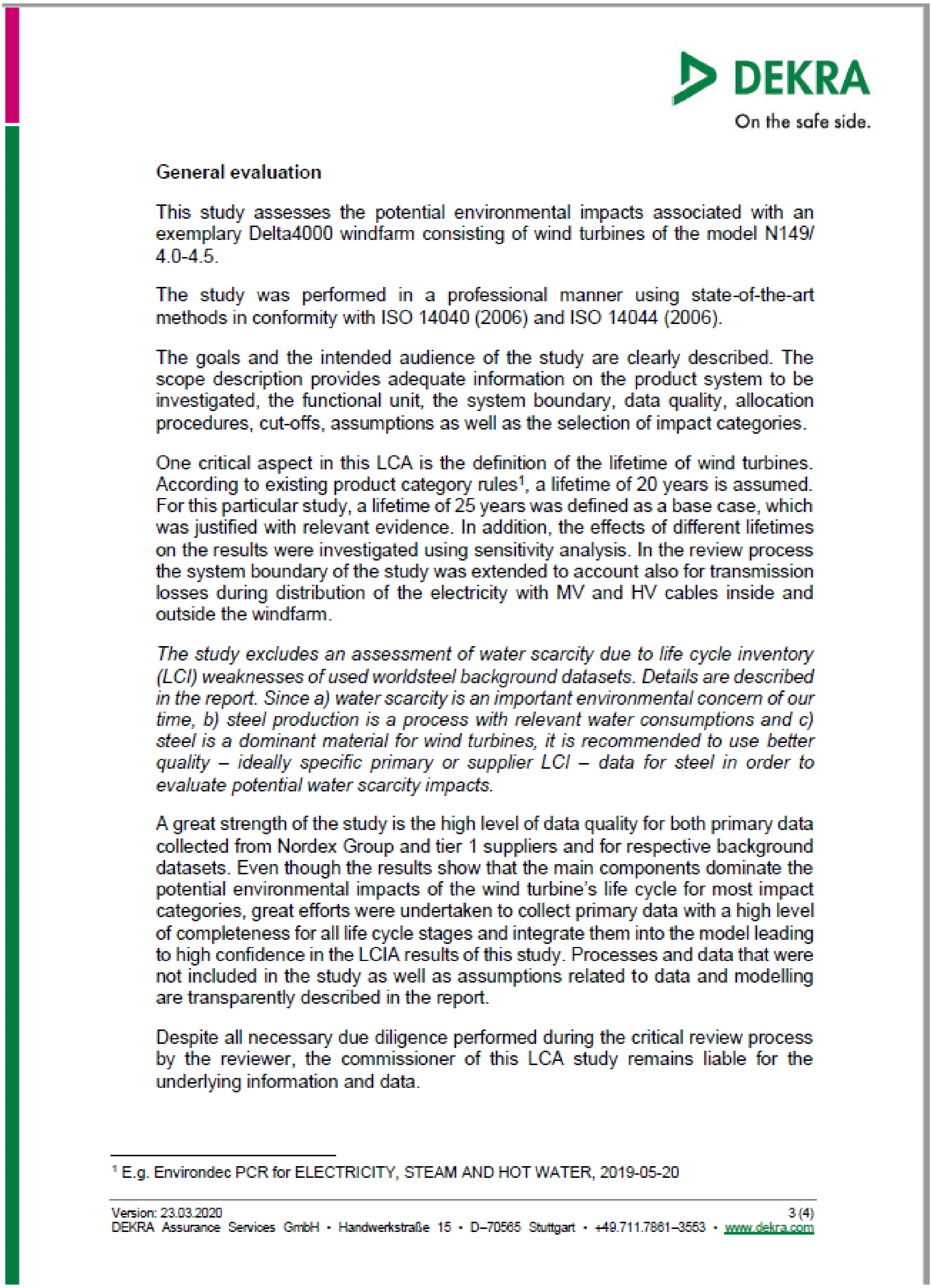
The verification of individual background datasets is outside the scope of this review.

Review process

The review process was coordinated between Sphera Solutions and the reviewer. A first draft of the final LCA report was submitted on 19.02.2020. The reviewer provided comments of a general, technical and editorial nature to Sphera Solutions on 20.02.2020. The comments were discussed during a review meeting on 12.03.2020. During this review meeting, the reviewer also obtained detailed insights into the data collected from Nordex Group (under NDA conditions), the background datasets used from the GaBi database as well as the underlying software model in GaBi. All review questions and comments were clarified during this review meeting and therefore the model did not reveal any perceivable errors or shortcomings.

A final version of the report was provided to the reviewer on 19.03.2020. The reviewer checked the implementation of the comments and agreed to conclude the critical review process. The reviewer acknowledges the unrestricted access to all requested information, the dedicated efforts of Sphera Solutions to address the comments provided, as well as the open and constructive dialogue during the critical review process. The final review statement was submitted on 23.03.2020.

All versions of the documentation (reports and data), including the individual reviewer comments, questions and associated answers, are archived and can be made available upon request.



General evaluation

This study assesses the potential environmental impacts associated with an exemplary Delta4000 windfarm consisting of wind turbines of the model N149/ 4.0-4.5.

The study was performed in a professional manner using state-of-the-art methods in conformity with ISO 14040 (2006) and ISO 14044 (2006).

The goals and the intended audience of the study are clearly described. The scope description provides adequate information on the product system to be investigated, the functional unit, the system boundary, data quality, allocation procedures, cut-offs, assumptions as well as the selection of impact categories.

One critical aspect in this LCA is the definition of the lifetime of wind turbines. According to existing product category rules[1], a lifetime of 20 years is assumed. For this particular study, a lifetime of 25 years was defined as a base case, which was justified with relevant evidence. In addition, the effects of different lifetimes on the results were investigated using sensitivity analysis. In the review process the system boundary of the study was extended to account also for transmission losses during distribution of the electricity with MV and HV cables inside and outside the windfarm.

The study excludes an assessment of water scarcity due to life cycle inventory (LCI) weaknesses of used worldsteel background datasets. Details are described in the report. Since a) water scarcity is an important environmental concern of our time, b) steel production is a process with relevant water consumptions and c) steel is a dominant material for wind turbines, it is recommended to use better quality – ideally specific primary or supplier LCI – data for steel in order to evaluate potential water scarcity impacts.

A great strength of the study is the high level of data quality for both primary data collected from Nordex Group and tier 1 suppliers and for respective background datasets. Even though the results show that the main components dominate the potential environmental impacts of the wind turbine's life cycle for most impact categories, great efforts were undertaken to collect primary data with a high level of completeness for all life cycle stages and integrate them into the model leading to high confidence in the LCIA results of this study. Processes and data that were not included in the study as well as assumptions related to data and modelling are transparently described in the report.

Despite all necessary due diligence performed during the critical review process by the reviewer, the commissioner of this LCA study remains liable for the underlying information and data.

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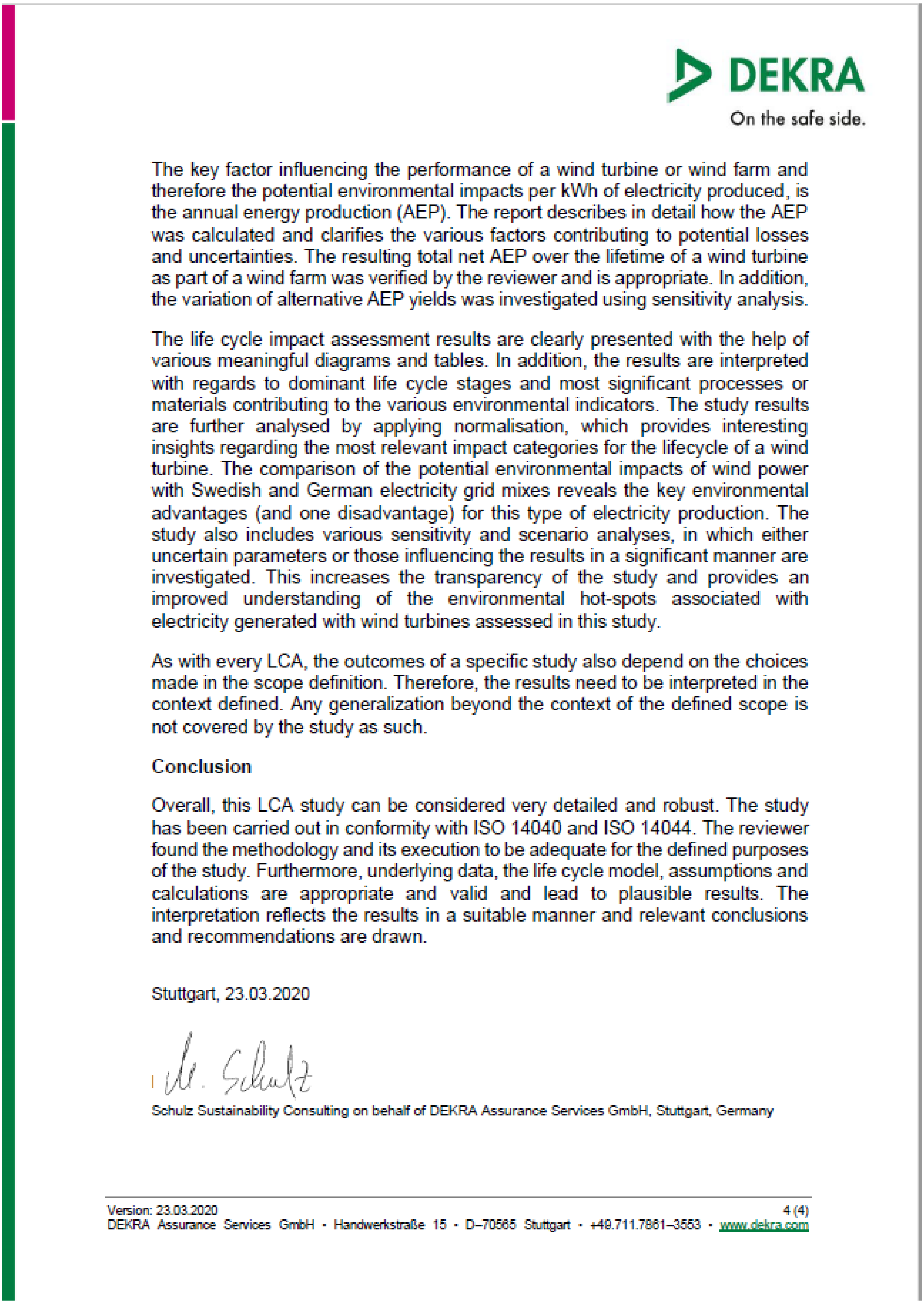
[1] E.g. Environdec PCR for ELECTRICITY, STEAM AND HOT WATER, 2019-05-20



On the safe side.

The key factor influencing the performance of a wind turbine or wind farm and therefore the potential environmental impacts per kWh of electricity produced, is the annual energy production (AEP). The report describes in detail how the AEP was calculated and clarifies the various factors contributing to potential losses and uncertainties. The resulting total net AEP over the lifetime of a wind turbine as part of a wind farm was verified by the reviewer and is appropriate. In addition, the variation of alternative AEP yields was investigated using sensitivity analysis.

The life cycle impact assessment results are clearly presented with the help of various meaningful diagrams and tables. In addition, the results are interpreted with regards to dominant life cycle stages and most significant processes or materials contributing to the various environmental indicators. The study results are further analysed by applying normalisation, which provides interesting insights regarding the most relevant impact categories for the lifecycle of a wind turbine. The comparison of the potential environmental impacts of wind power with Swedish and German electricity grid mixes reveals the key environmental advantages (and one disadvantage) for this type of electricity production. The study also includes various sensitivity and scenario analyses, in which either uncertain parameters or those influencing the results in a significant manner are investigated. This increases the transparency of the study and provides an improved understanding of the environmental hot-spots associated with electricity generated with wind turbines assessed in this study.

As with every LCA, the outcomes of a specific study also depend on the choices made in the scope definition. Therefore, the results need to be interpreted in the context defined. Any generalization beyond the context of the defined scope is not covered by the study as such.

Conclusion

Overall, this LCA study can be considered very detailed and robust. The study has been carried out in conformity with ISO 14040 and ISO 14044. The reviewer found the methodology and its execution to be adequate for the defined purposes of the study. Furthermore, underlying data, the life cycle model, assumptions and calculations are appropriate and valid and lead to plausible results. The interpretation reflects the results in a suitable manner and relevant conclusions and recommendations are drawn.

Stuttgart, 23.03.2020

M. Schulz

Schulz Sustainability Consulting on behalf of DEKRA Assurance Services GmbH, Stuttgart, Germany