Summary Report on Life Cycle Assessment (LCA)

S144-3.x MW Wind Turbine

PREPARED FOR

Suzlon Energy Limited

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ACRONYMS AND ABREVIATIONS

Acronyms	**Description**
Life Cycle Assessment (LCA)	Sum of greenhouse gas emissions and removals in a product system, expressed as CO2 equivalents and based on a life cycle assessment using the single impact category of climate change
ISO	International organization for standardization
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.x). This includes all material and energy inputs as well as emissions to air, land and water.
Functional Unit (FU)	Quantified performance of a product system for use as a reference unit" (ISO 14040:2006, section 3.20)
kWh	kilowatt hour
MW	Megawatt
MWh	Megawatt hour
BOM	Bill of Materials
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)
GWP	Global Warming Potential
Suzlon	Suzlon Group
ERM	ERM India Private Limited
Wind Farm	The wind farm includes the wind turbines, foundations, site cabling (connecting the individual wind turbines to the transformer station) and site equipment (e.g. transformer station) up to the point of the existing grid.
Wind Turbine	The wind turbine refers to the turbine itself and excludes the foundation and other site parts.
S144	S144-3.x MW Wind Turbine
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.

1. INTRODUCTION TO LIFE CYCLE ASSESSMENT (LCA)

A life cycle assessment (LCA) addresses the potential environmental impacts throughout a product's life cycle. Suzlon has initiated a large LCA project to obtain further knowledge about the potential environmental impacts related to its products and be able to identify and evaluate environmental improvement opportunities. Additionally, market requests on the product's environmental impacts are increasing, and the possibility to externally communicate LCA results is therefore also one of the goals of this LCA study.

The LCA study has resulted in two types of reports:

1. A background LCA report which contains a comprehensive description of the LCA project following the guidelines in ISO 14040:2006 (Environmental management — Life cycle assessment — Principles and framework) and ISO 14044:2006 (Environmental management — Life cycle assessment — Requirements and guidelines) and works towards alignment with the requirements in EN 15804:2012+A2:2019 (Sustainability of construction works – Environmental product declarations – Core rules for the product category of WT for onshore wind turbines). The background LCA report has not been reviewed yet but will however be reviewed & form the basis for forthcoming EPD verification. The background LCA report contains proprietary information and is only available for internal use and EPD verification.
2. LCA summary reports (like present document) which is prepared as a public communication document of the related background LCA report (see (1)). This LCA summary report is a summary of methodological aspects and results from the background LCA report. This LCA summary report will first introduce Suzlon and the product of interest. Next it will include a description of goal and scope (including description of product life cycle, system boundary, functional unit, data collection and sources, allocation procedures, limitations and environmental impact categories) and the results.

Moreover, no significant social or environmental concerns and risks arise from production or disposal of Suzlon's products/services as nearly 90-92% of the End of Life (EoL) waste are getting recycled.

2. INTRODUCTION TO SUZLON ENERGY LIMITED

Suzlon Energy Limited is a leading renewable energy company specializing in wind turbine manufacturing and sustainable energy solutions. With a global installed capacity exceeding 20 GW as of FY 2023-24, Suzlon continues to drive the transition toward low-carbon and environmentally prudent energy systems. The company remains committed to environmental responsibility through product stewardship, ensuring minimal environmental impact across the lifecycle of its wind turbines.

Understanding the life cycle impacts of the S144-3.x MW wind turbine allows Suzlon to implement targeted strategies for emissions reduction, optimize production efficiency, and support its customers in achieving their sustainability goals. By continuously improving its design and manufacturing processes, Suzlon strengthens its commitment to delivering cleaner and more energy-efficient wind turbines, contributing to a net-zero future.

3. ABOUT THE PRODUCT

Product Name:	**S144-3.x MW**
Product Manufacturer:	Suzlon Energy Limited
Description of Product:	The S144 is a 3.x MW wind turbine with versatile tower designs (steel tubular, hybrid lattice, hybrid concrete), a 120m rotor diameter with an 11,225m² swept area, and performance of over 98% availability with a 3.0 m/s cut-in wind speed.
Reported Production Quantity of S144 WT (FY 2023-24) (in No):	53
Lifespan of Wind Turbine (in years):	20
Major Components of S144 WT:	Generator, Rotor, Blade, Nacelle Hub & Tower
Tower Hub Height (m):	105m, 120m, and 140m
Rotor Diameter (m):	120m
Swept area (sq. m):	11,225 m²
Number of Rotor Blades:	3

4. GOAL

The goal of this study is to assess the life cycle impacts (LCA) of an S144 which is a 3.x MW Wind Turbine installed on a wind farm following a "cradle to grave" approach as per ISO 14040: 2006 (Environmental management — Life cycle assessment — Principles and framework), ISO 14044:2006 (Environmental management — Life cycle assessment — Requirements and guidelines) and EN 15804:2012+A2:2019 standards.

The objective of the study is to identify the main contributors to the product's environmental impact hotspots across its lifecycle. This is a comprehensive cradle to grave analysis of generation of 1 kWh of wind energy at a wind farm with S144 3.x MW wind turbine in India.

The insights gained from this rigorous assessment will have a profound impact on our understanding of the environmental footprint across the life cycle stages of 3.x MW WT. This understanding is essential for effectively communicating the company's commitment to sustainability and environmental responsibility to a broad range of stakeholders, both within the organization and beyond.

5. SCOPE

5.1 FUNCTIONAL UNIT

Wind turbines are critical for renewable energy generation, with their functional unit typically defined by the electricity delivered to the grid. However, the function of the wind farm is the production of electricity including its delivery to the electricity grid.

Therefore, it is important to consider the wind conditions onsite when assessing the potential environmental impacts from a wind plant.

The functional unit (FU) for this LCA study is defined as:

"1 kWh of electricity delivered to the grid by a wind farm comprising of S144-3.x MW Wind Turbine over a lifetime of 20 years"

The functional unit and reference flow have been derived on the design lifetime of the wind farm (of 20 years), along with the total energy produced over the lifetime based on electricity production in special wind conditions. It is also worth noting that the functional unit could have been derived on the 'total electricity production' basis (i.e. total electricity over the lifetime of the plant), but it has been chosen to define the functional unit in this study on a 'unit of electricity delivery' basis (i.e. per one kWh).

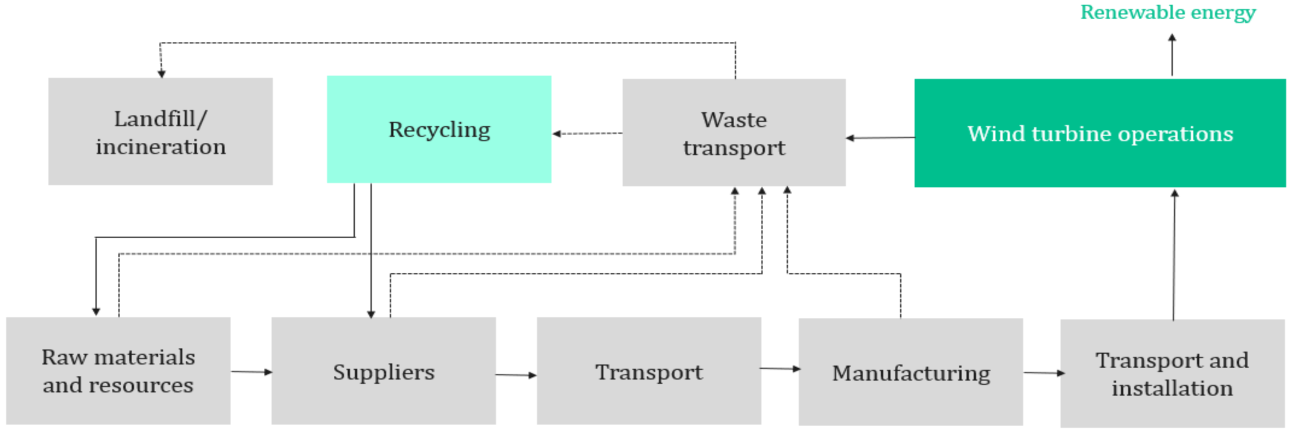
This functional unit serves as the reference for assessing the lifecycle environmental impacts, encompassing raw material production, manufacturing, transportation, operation, and end-of-life stages. Each environmental flow—such as material consumption, energy use, emissions, effluent, and waste—is scaled to this reference unit to ensure accurate cradle-to-grave carbon footprint calculations.

5.2 DATA SOURCES AND COLLECTION

- Data, such as bill of materials, energy consumption for each stage of the lifecycle and transport were collated and gaps were filled with assumptions. Primary data on manufacturing processes was preferred. A tailored data collection questionnaire was developed and distributed to Suzlon SPOCs throughout relevant functions to monitor and support data collection.
- Engagement with the data owners and providers to fill any data gaps was facilitated. Where primary data was not readily available, the gaps were filled using literature, assumptions, estimates or selected secondary data sources. The collated data was used to develop a life cycle inventory (LCI) for S144 WT, which was used to develop the LCA model.
- The data collection is related to one year of operation and the data was derived for the period FY 2023-24 i.e. 1st April 2023-31st March 2024 according to the S144-3.x MW Wind turbines.
- The time period for service/maintenance represents the typical 20-year design life.
- This study assesses the production of Suzlon's S144-3.x Wind turbines, erection of wind turbines/wind plant set up, site operations/maintenance, as well as dismantling and scrapping of the wind farm components at end-of-life. These processes have been modelled based on state-of-the-art technologies used by Suzlon.
- For the purpose of this study a typical "virtual" wind farm site has been assessed within Indian geography. The aim is to give an overall picture of wind power production rather than to assess any location.
- The following cut-off criteria were used to ensure that all relevant potential environmental impacts were appropriately represented:
- Mass – if a flow is less than 1% of the mass at a product-level, then it may be excluded, provided its environmental relevance is not of concern.
- Energy – if a flow is less than 1% of the energy at a product-level, then it may be excluded, provided its environmental relevance is not a concern.
- Scaling of the turbine up to 100% of total mass has not been conducted. Additionally, all site parts, foundations and cables are also included in their entirety for the complete wind farm.

5.3 SYSTEM BOUNDARY

The life cycle boundary of a wind turbine under the "cradle to grave" approach encompasses all stages from raw material extraction to the end-of-life disposal. Here are the key phases included in this boundary:



- **Raw Material Extraction**: This phase involves the extraction of raw materials needed for the wind turbine components, such as steel, concrete, copper, and rare earth metals.
- **Manufacturing**: This stage includes the production of various components of the wind turbine, such as the tower, rotor blades, nacelle, and electrical systems. It covers all processes involved in transforming raw materials into finished products.
- **Transportation**: This phase accounts for the transportation of the manufactured components to the installation site. It includes the logistics of moving large and heavy parts, which may require specialized vehicles.
- **Installation**: This stage involves the assembly and installation of the wind turbine at the designated site, including the construction of foundations and any necessary infrastructure.
- **Operation and Maintenance**: This phase covers the operational life of the wind turbine, including energy production, routine maintenance, and any repairs needed to ensure optimal performance.
- **Decommissioning**: This stage includes the process of safely dismantling the wind turbine at the end of its operational life, which may involve removing components and restoring the site.
- **End-of-Life Disposal**: This final phase addresses the disposal or recycling of the turbine components, including the management of materials such as blades, which can be challenging to recycle.

6. ALLOCATION

Allocation procedures follow the hierarchy in ISO 14040:2006 and ISO 14044:2006, and with reference to the guidelines in EN15804:2012+A2:2019.

For the upstream processes and other processes where generic background data from databases is used, the default allocation already included in the process is followed.

For the core processes, allocation is applied at the production sites which produce multiple products. Allocation is conducted based on a physical relationship (mass) and other technical and product specifications based on expert inputs.

For allocation concerning reuse, use of secondary materials and recovery, the cut-off approach is applied through use of the system model ‘allocation, cut-off by classification’ in the Eco invent database version 3.10. To exemplify, this means that the use of recycled materials is modelled burden free of its original product life cycle. However, any processes and impacts related to other end of life treatment processes is included in the modelling and represented in the results.

7. ASSUMPTIONS & LIMITATIONS

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

Wind Plant Lifetime: The plant lifetime is a dominant factor when determining the impacts of the electricity production per kWh. This LCA assumes a turbine lifetime of 20 years which matches the standard design.

Electricity Production: the electricity production per kWh is substantially affected by the wind plant siting and site-specific wind conditions that the turbine operates under (i.e. low, medium or high wind classes defined by the IEC). Suzlon wind turbines are designed to match these different wind classes and wind speeds, so it is not always the size of the rotor or the generator rating (in MW) that determines the electricity production of the turbine; but wind class is a dominant factor.

Transportation: Secondary data for average road freight distance has been used in place of the raw upstream logistics data. This decision was made because the available transport data does not clearly distinguish between domestic and import road transport distances, however, all road import data is within India from relevant port to relevant Suzlon site. Additionally, the provided distances include inter-karting and internal movements, which may not fall within the defined upstream boundary for Suzlon’s supply chain. Using these values as-is would risk inflating the transport-related emissions without sufficient justification. Therefore, a standardized average value for freight road distance has been applied to ensure consistency and conservativeness in the modeling.

Impacts of Material Production & Recycling: the turbine is constructed of around 89% metal (primarily iron and steel, and to a lesser extent Aluminium and Copper), and it is the production-phase and end-of-life phase that dominates the studied environmental impacts. Datasets for metal production are based on established and credible industry association sources (such as those from world steel and the European Aluminium Association). End-of life recycling of metals in the power plant also provides environmental credits. This LCA uses an ‘avoided impacts’ approach accounting also for burdens of input scrap of raw materials; methodologically speaking, this is a consistent approach to environmental crediting for recycling. Additionally, specific parts of the turbine and power plant are applied different recycling rates depending on their ease to disassemble and recycle.

8. IMPACT CATEGORIES AND INDICATORS

Impact Category	Description	Unit
Global warming	Measures the potential contribution of greenhouse gas emissions to climate change. It aggregates emissions like CO_2, methane, and nitrous oxide into a common unit based on their global warming potential over a specified time horizon (usually 100 years). The unit is grams of CO_2-equivalents (g CO_2 eq), reflecting the total greenhouse gas effect of the emissions.	g CO_2 eq
Stratospheric ozone depletion	Reflects the potential of substances to destroy the ozone in the stratosphere, which protects Earth from harmful ultraviolet radiation. It accounts for emissions of ozone-depleting substances like CFCs and halons, using equivalency factors related to CFC-11. The unit is grams of CFC-11 equivalents (g CFC11 eq).	g CFC11 eq
Ionizing radiation	Assesses the potential radiological impact of radionuclide emissions on human health and the environment. It considers the transport and dispersion of radionuclides and their exposure risks. Characterization factors convert emissions into an equivalent dose, expressed in becquerel cobalt-60 equivalents (Bq Co-60 eq), a standard for ionizing radiation impact in LCA.	Bq Co-60 eq
Ozone formation, Human health	Quantifies the formation of ground-level ozone (smog) that affects human respiratory health. It is usually expressed in grams of NO_x equivalents (g NO_x eq), as nitrogen oxides are key precursors to ozone formation impacting human health.	g NO_x eq
Fine particulate matter formation	Measures the formation of fine particulate matter ($PM_{2.5}$) in the atmosphere, which affects air quality and human health. The unit is grams of $PM_{2.5}$ equivalents (g $PM_{2.5}$ eq), representing the potential to form harmful airborne particles.	g $PM_{2.5}$ eq
Ozone formation, Terrestrial ecosystems	Reflects the potential for ground-level ozone to damage terrestrial ecosystems (plants and soil). Like human health ozone formation, it is expressed in grams of NO_x equivalents (g NO_x eq).	g NO_x eq
Terrestrial acidification	Measures the potential of emissions (mainly sulfur dioxide, nitrogen oxides, and ammonia) to acidify soils and water bodies, harming terrestrial ecosystems. It is expressed in grams of sulfur dioxide equivalents (g SO_2 eq).	g SO_2 eq
Freshwater eutrophication	Assesses the potential for nutrient enrichment (mainly phosphorus compounds) in freshwater systems, leading to algal blooms and oxygen depletion. Expressed in grams of phosphorus equivalents (g P eq).	g P eq
Marine eutrophication	Like freshwater eutrophication but focused on nutrient enrichment (mainly nitrogen compounds) in marine environments, causing harmful algal blooms and	g N eq

	oxygen depletion. Expressed in grams of nitrogen equivalents (g N eq).	
Terrestrial ecotoxicity	Represents the potential toxic effects of chemical emissions on terrestrial organisms. It uses characterization factors based on a reference substance, often 1,4-dichlorobenzene (g 1,4-DCB), to express toxicity potential.	g 1,4-DCB
Freshwater ecotoxicity	Like terrestrial ecotoxicity but focused on freshwater species. It quantifies the potential harm of toxic substances to aquatic life, expressed in grams of 1,4-dichlorobenzene equivalents.	g 1,4-DCB
Marine ecotoxicity	Assesses toxic impacts on marine organisms from chemical emissions, expressed in grams of 1,4-dichlorobenzene equivalents.	g 1,4-DCB
Human carcinogenic toxicity	Measures the potential cancer-causing effects of chemical emissions on humans. Characterization is based on toxicological data and expressed in grams of 1,4-dichlorobenzene equivalents.	g 1,4-DCB
Human non-carcinogenic toxicity	Quantifies other (non-cancer) toxic effects on human health from chemical emissions, also expressed in grams of 1,4-dichlorobenzene equivalents.	g 1,4-DCB
Land use	Evaluates the impacts of land occupation and transformation on ecosystem quality and biodiversity. It is often expressed in terms of area and time, such as square millimeters per year of crop-equivalent land use (mm2a crop eq), reflecting the extent and duration of land use changes.	mm2a crop eq
Mineral resource scarcity	Measures the depletion of mineral resources based on their availability and extraction difficulty. It uses characterization factors to express scarcity in grams of copper equivalents (g Cu eq), linking different minerals to a common reference.	g Cu eq
Fossil resource scarcity	Assesses the depletion of fossil fuels (oil, coal, natural gas) based on availability and extraction effort. Expressed in grams of oil equivalents (g oil eq) to standardize various fossil resources.	g oil eq
Water consumption	Quantifies the volume of water used (consumed) during the life cycle of a product, often expressed in cubic millimeters (mmÂ^{3}). This includes water withdrawn and not returned to the original source, affecting water availability.	mmÂ^{3}

9. KEY RESULTS & FINDINGS

Impact category	Unit per kWh	Total	S144 Assembly	Construction & Installation S144	Decommissioning S144	Energy Input into manufacturing S144	Maintenance and Repair S144	Material transport to site	Transport to Waste treatment facility S144	S144 EoL
Global warming	g CO2 eq	6.170	4.075	0.124	0.124	0.485	0.084	0.951	0.010	0.317
Stratospheric ozone depletion	g CFC11 eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ionizing radiation	Bq Co-60 eq	0.247	0.214	0.003	0.003	0.011	0.002	0.010	0.000	0.005
Ozone formation, Human health	g NOx eq	0.017	0.012	0.000	0.000	0.001	0.000	0.002	0.000	0.001
Fine particulate matter formation	g PM2.5 eq	0.011	0.008	0.000	0.000	0.001	0.000	0.001	0.000	0.000
Ozone formation, Terrestrial ecosystems	g NOx eq	0.019	0.013	0.000	0.000	0.001	0.000	0.002	0.000	0.001
Terrestrial acidification	g SO2 eq	0.023	0.018	0.000	0.000	0.001	0.000	0.002	0.000	0.001
Freshwater eutrophication	g P eq	0.004	0.003	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Marine eutrophication	g N eq	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Terrestrial ecotoxicity	g 1,4-DCB	46.594	27.428	0.093	0.093	0.346	0.234	16.646	0.181	1.574
Freshwater ecotoxicity	g 1,4-DCB	2.745	1.099	0.004	0.004	0.016	0.004	0.026	0.000	1.592
Marine ecotoxicity	g 1,4-DCB	3.426	1.444	0.005	0.005	0.022	0.006	0.043	0.000	1.902
Human carcinogenic toxicity	g 1,4-DCB	7.691	7.058	0.015	0.015	0.067	0.017	0.169	0.002	0.347
Human non-carcinogenic toxicity	g 1,4-DCB	24.075	21.763	0.152	0.152	0.667	0.087	0.883	0.009	0.361
Land use	mm2a crop eq	0.327	0.200	0.002	0.002	0.009	0.002	0.067	0.001	0.044
Mineral resource scarcity	g Cu eq	0.119	0.109	0.000	0.000	0.000	0.000	0.002	0.000	0.007
Fossil resource scarcity	g oil eq	1.904	1.225	0.043	0.043	0.126	0.057	0.315	0.003	0.092
Water consumption	mm3	0.040	0.033	0.001	0.001	0.002	0.000	0.002	0.000	0.002

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