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SCIENTIFIC REPORT

Environmental assessment of a novel generator design in a 15 MW wind turbine

ANDERS NORDELÖF

DEPARTMENT OF TECHNOLOGY MANAGEMENT AND ECONOMICS
Division of Environmental Systems Analysis

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Department of Technology Management and Economics
Division of Environmental Systems Analysis
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Summary

The demand for renewable electricity generation is increasing worldwide as fossil energy sources are phased out due to climate change mitigation targets. Wind power plays a key role in this transition. However, wind turbines still impact the natural environment through emissions from various stages in turbine production, including extraction of metal resources from the ground. Hagnesia AB has developed a permanent magnet-based electrical generator design with high electrical and material efficiency, and potential to lower the environmental impacts compared to today's conventional wind turbine generators, not only for the generator as such, but also for the complete turbine.

This study uses life cycle assessment to investigate how the generator design influence climate change and resource use impacts of a 15 MW wind turbine. The reference designs of IEA Wind task 37 (Gaertner et al., 2020) for a 15 MW floating wind turbine for offshore installation, and a 15 MW monopile wind turbine for shallower sea installation, are included int the study as two reference options. These are compared to two alternative turbine options, instead using the generator proposed by Hagnesia. For the floating option with the Hagnesia generator design, the model also captures the effect of lowered tower and foundation masses, which are allowed for by the load reduction that follows from the shift of generator.

Resource use is evaluated using an indicator for long-term mineral and metal scarcity. The study draws its system boundary at the point in the life cycle when the turbines are commissioned at sea and ready to generate, but it excludes the operation. In line with recommendations from previous literature, to provide transparency and replicability, all unit process-level data compiled specifically for the study is reported in Appendix A.

The conclusion is that Hagnesia's generator design is able to reduce the greenhouse gas emissions and resource use of the 15 MW wind turbine significantly in comparison to IEA Wind task 37 reference design. The largest impact reduction potential can be identified for the generator subparts, for which the sum of greenhouse gas emissions is more than one order of magnitude lower compared to the reference design.

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1 Introduction

1.1 Background

The demand for renewable electricity is increasing as the global society is shifting away from fossil energy sources to meet climate change mitigation targets (Carrara et al., 2020). Wind power is one of the key technologies that help meet this demand, with a rapid generation capacity growth over the last decade, which is also expected to continue (Carrara et al., 2020). However, even though wind power plants do not cause greenhouse gas emissions at the moment they generate electricity, as all products, they impact the natural environment in a broader perspective, for example, by demanding extraction of different metal resources from the ground, or through emissions caused during the wind turbine production.

Life cycle assessment (LCA) is a well-proven tool for investigating the environmental impact of goods and services. The framework provides a systematic and systemic approach to analyzing all stages in a product's life cycle – from material extraction, to use and waste management. For each life cycle activity, data is collected for inflows in the form of raw materials and energy, and outflows such as products, emissions or waste. All activities are then interlinked in a model. This model calculates an inventory of inflows of natural resources, and outflows of pollutants (emissions), to and from the natural system that surrounds the technical system under study. Each type of flow is summarized per the so-called functional unit; for wind turbines or other types of power plants that generate electricity, typically in terms of kilowatt-hours (kWh) of electricity delivered at some specific connection point. However, different functional-units can be used to describe the same technical object, depending on the goal and the scope set for the study.

The goal and scope definition phase also entails identifying the reason for carrying out the study, often by specifying questions to which the study is expected to provide answers. The intended use of the results and the intended audience is also stated, along with a description of how the study is delimited in terms of various system boundaries, for example the technical scope. During the subsequent inventory analysis phase, the system model is established, whereafter the output inventory is analyzed to evaluate potential effects for different categories of environmental, for example climate change impacts or resource use, in the life cycle impact assessment phase. These results are subject to interpretation, and the framework is iterative, meaning that previous phases can be revisited, reformulated, remodelled, and recalculated, to make sure that final results and their interpretation, are clear in relation to the stated goal.

A large number of LCA case studies have been conducted on wind turbines and farms of wind power plants, and larger reviews have also been published recurringly (Arvesen & Hertwich, 2012; Mendecka & Lombardi, 2019). In terms of GHGs, values reported per kWh vary considerably, and discrepancy of the results can typically be explained by differences in data and assumptions regarding site-specific wind conditions, but also wind turbine sizes and design (Mendecka & Lombardi, 2019). For example, Raadal et al. (2011) found that emissions for land-based wind power plants vary from 5-55 grams of CO_2-equivalents per kWh, with turbine rating spanning from 3 MW (for the lower end of the emission span) down to 30 kW (at the higher end) as a main explanation. In a later study, Raadal et al. (2014) investigated 5 MW sea-based offshore turbines, including both floating and seabed-standing solutions. The results then varied between 18-31 grams of CO_2-equivalents per kWh, accompanied with the conclusion that the foundation's steel mass is a major driver for the GHG emissions coupled to offshore wind power (Raadal et al., 2014).

In addition to design alterations, Arvesen and Hertwich (2012) point to differences in data collection and modelling approaches as other explanations for variation in results in LCA-studies of wind turbines, where conventional process-oriented LCA studies (differing from those filling gaps by using data from environmentally extended input–output analysis of economic sectors) sometimes suffers from to crude cut-offs, i.e. many details are left out which affect total results in the end. Arvesen and Hertwich (2012) also bring up inconsistent modelling of recycling benefits as a source of error in their reviewed body of literature. The problem occurs when one and the same study include burden-free recycled content as a part of the input of materials to the production phase, while also crediting the system for avoided environmental burdens when "new" secondary materials are recovered at the end of the life cycle, i.e., claiming the benefits of recycling in both ends. This entails a clear risk of underreporting environmental burdens, similar to what also have been found in studies of lithium-ion batteries (Nordelöf, Poulikidou, et al., 2019). To alleviate problems with unclear assumptions and lack of transparency behind variability in results, Arvesen and Hertwich (2012) recommend that LCA studies of wind turbines should report the unit process-level inventory data included in the models as with the largest transparency possible.

Two recent studies have been identified which assess the life cycle of large wind turbines using the International Energy Agency (IEA) 15 MW offshore reference wind turbine (Gaertner et al., 2020), and the linked University of Maine semi-submersible floating reference platform (Allen et al., 2020) as their starting point. Moghadam and Desch (2023) conducts a conceptual design cost-optimization study for different permanent magnet synchronous generator options for offshore wind turbine applications, where different life cycle stages are identified and discussed. However, no environmental accounting is reported in this study, and although the term is not explicitly used, it links to the "life cycle costing" approach rather than environmental LCA. Struthers et al. (2023), on the other hand, an LCA on commercial-scale wind farms for site-specific energy production in Scotland with results for GHG emissions in the range of 17-26 grams of CO_2-equivalents per kWh. They conclude that decarbonizing supply materials, increasing material efficiencies and circularity, and minimizing vessel operations are key for reduced environmental impacts.

1.2 Aim and content of this report

The Swedish company Hagnesia AB has developed a novel permanent magnet-based electrical generator design, defined as a poloidal or tangential flux (PTF) machine, with high electrical and material efficiency. This generator design can be applied in 15 MW wind turbines, with the potential to reduce overall metal requirements for the complete turbine in comparison to current state-of-the-art IEA reference design (Gaertner et al., 2020).

As a part of the VindEl program, which had the goal to support research and innovation in wind power sector, the Swedish Energy Agency funded a project during 2021–2023 named "Prestandaverifiering och modellutveckling av Hagnesias generatorkoncept". An LCA-study was carried out as a part of that project, with the purpose of assessing the environmental impacts a 15 MW wind turbine equipped with an Hagnesia generator design in comparison to the unaltered reference design. This study constituted only a smaller share of the overall project scope, and in order to cut the coat according to the cloth, it was limited in terms of life cycle scope, with the system boundary drawn after the completion of the installation at sea in terms of included life cycle steps, excluding the actual operation of the turbines, decommissioning, and waste treatment. With these limitations, this report provides a first, but relatively detailed, analysis of the installed turbine, as well as a basis for further analysis.

2 Methods, goal and scope

2.1 Goal of the study

This study was carried out with the goal of assessing the environmental impacts of Hagnesia's novel PTF generator design when applied in a 15 MW wind turbine. Specifically, the following research question was addressed:

- How does the generator design influence climate change and resource use impacts of a 15 MW wind turbine, at the point in the life cycle when it is installed and ready for operation?

The study is intended to be used as a performance benchmark for the material efficiency of the PTF design solution. Another aim for its use is that the model and report can serve a foundation for further work, for example, to conduct simplified calculations for how the carbon footprint scale with generator and turbine design modifications, but also further detailed LCA covering the full life cycle. Hagnesia's development team is the first recipient of the report, but the main target group also includes the wind power industry, wind power research community and funding agencies in the wind power research area more broadly.

2.2 Objects of study and functional unit

Two floating offshore wind turbine options are compared in the study:

(1) One 15 MW wind turbine modelled in accordance with the IEA Wind task 37 (Gaertner et al., 2020), also regarding its proposed generator design.

(2) One 15 MW wind turbine equipped with Hagnesia's PTF generator design, with reduced tower and foundation mass, but otherwise identical to option (1).

Two additional turbine options, for shallower sea installation are also included in the study:

(3) One 15 MW wind turbine, with the same generator design as (1), but a monopile foundation and a slimmer tower construction compared to option (1), in accordance with the IEA Wind task 37 (Gaertner et al., 2020).

(4) One 15 MW wind turbine equipped with Hagnesia's PTF generator design, and otherwise identical to option (3), i.e. with no reduction in tower and monopile mass.

The functional unit is one complete 15 MW turbine, commissioned at sea and ready to generate. The study is a cradle-to-gate attributional study, and the basis for the comparison is the stated nominal power generation capacity of the studied turbines.

2.3 System boundaries and life cycle scope

The technical system boundary in terms of life cycle scope is drawn after the completed installation at sea. This includes the extraction and production of materials and sub-components, the manufacture of ready-to-install segments of the turbine, and transportation, both on land and at sea. As previously mentioned, the operating phase is not covered within the study and therefore, it does not capture the fact that the two turbines, and specifically the generators, are subject to different amounts of losses when generating electricity. The turbine's decommissioning and steps for recycling of secondary materials in the end-of-life, or waste treatment processes are not included either. However, recycled materials from other, previous product life cycles are included, depending on the average recycled content rate for different material categories, e.g. steelmaking almost always includes some amount of secondary steel scrap as part of the raw material supply to the manufacturing process, even when it is defined as ore-based.

In general, the manufacturing of components and the assembly of the turbine is modelled in a European average context, while earlier stages in the life cycle, such as the extraction of raw materials and processing into metals or requested industrial metal compounds, are modelled with global market averages. Data for establishing study-specific unit processes, i.e. those constituting the “foreground system” of the model, such as component compositions, typical manufacturing procedures, assembly, transportation, and installation, was gathered from research literature, company reports and environmental product declarations. The aim was to reach an equal level of detail for all parts of the turbine, and include electrical and electronic components, which the literature review had revealed as left out in many studies. However, no mass composition data or production data was found for the type of transistor-based power converter that sometimes are present in power transfer configurations for large wind turbines (ABB, 2023). In the setup selected for this study, it would have been mounted in series in between the generator and the step-up transformer, as a first step to improve the power quality, and increase the voltage while reducing the current, e.g. enabling slimmer cabling, with identical mass and composition for the studied tower options. Due to the lack of data, it is left out of the study for all options.

The time horizon for the study is set to the expected design lifetime of a 15 MW turbine of 30 years, in line with what is reported by Vestas (2023), meaning that at this future point in time, the turbine can be expected to be decommissioned. All background datasets, i.e. those representing the technical system from the cradle to ready-to-use subcomponents and materials, are modelled using the Ecoinvent database version 3.91 (Ecoinvent, 2023; Wernet et al., 2016).

2.4 Selection of impact assessment methods

In response to the focus on two impacts categories – climate change and resource use – as stated in the goal definition of the study, three main indicators at midpoint level were chosen for the analysis:

- Greenhouse gas emissions contributing to climate change over a 20-year-period, quantified as global warming potentials [kg of CO_2 equivalents] (IPCC, 2021).
- Greenhouse gas emissions contributing to climate change over a 100-year-period, quantified as global warming potentials [kg of CO_2 equivalents] (IPCC, 2021).
- The crustal scarcity indicator, capturing mineral resource use contributing to long-term scarcity of metals, quantified as crustal scarcity potentials [kg of Si equivalents] (Arvidsson et al., 2020).

In addition to this, for completeness in terms of impact categories, seventeen additional midpoint indicators included in the ReCiPe 2016 package (Huijbregts et al., 2016), i.e. all except for the already reported climate change category, are reported in Appendix B. This compilation represents a broad set of environmental impact categories and compartments, based on the “hierarchist” (H) cultural perspective of the ReCiPe 2016 model package. This perspective is the default setting, offering a consensus between short term technical optimism and long-term precautionary thinking.

3 Inventory modelling

3.1 Turbine design

The design of the 15 MW reference wind turbine investigated in this study is thoroughly described by Gaertner et al. (2020), as an output from the IEA Wind Task 37 on “Systems Engineering in Wind Energy”. The majority of the team contributing to this task were gathered from the National Renewable Energy Laboratory under the United States Department of Energy and the Technical University of Denmark. Members of the IEA Wind Task 37 from the University of Maine focused on the design of a semisubmersible reference platform, enabling floating offshore use of the reference wind turbine (Allen et al., 2020). A monopile design solution for installation of the turbine at sea is also described by Gaertner et al. (2020), but this applies to shallower waters. After the publication of the Gaertner et al. (2020) and Allen et al. (2020) reports, the task work has been continuously updated via documentation on a GitHub repository (IEAWindTask37, 2023). Together, these data sources provided the overarching mass specification of all major components and subcomponents investigated in this study, with the exception of some electrical equipment and the structural changes following from the integration of Hagnesia's generator design into the 15 MW turbine.

The descriptions in Allen et al. (2020); Gaertner et al. (2020) and IEAWindTask37 (2023) provide structural properties, mass data and dimensions of included components and subcomponents, but not their material breakdown data in terms of metals or type of alloys used, or the shares of plastics and paint. Such data was instead gathered from a set of complementary literature sources. Specifically, a more in-depth, but still general description of blade design was found in Thomsen (2009), confirming the representativeness of the composition used for the modelling of the blades, which in turn was acquired from Guilloré et al. (2022). The material compositions of various other components were gathered from Arvesen et al. (2013). This included the hub of the rotor (including its cover), the nacelle housing, and the main shaft. In addition, the composition of several nacelle parts that are reported separately in the IEAWindTask37 (2023) documentation, i.e., the platform, bedplate and nose, were all assumed to have the same material breakdown as the “main frame” reported in Arvesen et al. (2013), with one share of cast iron and another of forged low-alloyed steel. The brakes were also assumed to have identical composition, meaning that the brake pad constituents were not considered specifically, as they otherwise can be organic, sintered or made from composites. The yaw system, bearings and remaining system parts of the hub were all assumed to be made of forged high-alloyed chromium steel in line with Carrara et al. (2020). The material contained in the tower was modelled as 90% rolled low-alloyed steel and 10% forged low-alloyed steel, and the steel contained in floating foundation as rolled low-alloyed steel, based on information provided by BVG Associates (2023). In the monopile versions, it was assumed that the foundation have the same split between rolled and forged steel as the tower structure.

The mass share of paint to cover the surface area of the blades, tower, and foundation was collected from Guilloré et al. (2022). The mass share of dry paint was then estimated also for other components, i.e., 1% for the hub and the bedplate, and 3.5% for the nacelle housing, otherwise made of glass-reinforced plastics. Next, data for the paint itself was compiled assuming a multiple-layer coating system suitable for protecting steel surfaces in corrosive environments, consisting of a protective zinc paint, one intermediate layer of primer (applied as two sublayers to form one joint thicker layer) and a topcoat of polyurethane (Teknos, 2013). The same coating system was then also proxied as a suitable paint for the other external surfaces, i.e., covering cast iron and glass-reinforced plastics. Data for the recommended layer thickness and the mass of both dry and wet paints were established from Teknos (2013): Next, the constituents of the wet paints were gathered from Teknos (2019, 2021b, 2022b) for the protective zinc paint, and from Teknos (2016, 2020, 2022a) for the intermediate primer layer, with the assumption that a non-reported share of the solid paint ingredients consists of "extender" or filler pigment, modelled as precipitated calcium carbonate. The data for the topcoat was also acquired from Teknos (2012, 2015, 2021a). The wet paint constituents, i.e. before drying, are reported in Table 1.

In addition to the direct drive generator, which is at the core of the investigation in this study, the interior of the tower and nacelle contains equipment for safe power conversion, ventilation, and for internal structures such as platforms and staircases. Arvesen et al. (2013) was used to estimate the mass of internal tower structures and electrical cables, in relation to the total tower mass. In line with the description by Gul (2019) it is expected that a large offshore wind turbine generator such as the 15 MW reference turbine will be connected to a power converter in the nacelle, for example the PCS6000 by ABB (2023), and subsequently to a 66 kV/3.3 kV type step-up transformer followed by a 145 kV switchgear substation in the bottom of the tower to provide breaking, switching, measuring and earthing possibilities before further connection on the offshore wind farm level. This setup was also expected to be identical for the turbine modified for Hagnesia's PTF generator design. The IEAWindTask37 (2023) documentation provided mass data for a power converter and a transformer, but not the switchgear. Due to lack of already compiled data, and the large complexity of a big converter unit, it was decided to exclude the power converter from the inventory model, as it would affect the results of all studied options equally. However, although the same reasoning applies for

Table 1: Wet paint layer constituents, including both base and hardener, established from Teknos (2012, 2013, 2015, 2016, 2019, 2020, 2021a, 2021b, 2022a, 2022b).

Protective zinc paint	**Share**
Zinc powder	76%
Xylene	9%
Epoxy resin	8%
4-methyl-2-pentanone	4%
Ethylbenzene	3%
Intermediate epoxy primer	**Share**
Calcium carbonate, precipitated	37%
Epoxy resin	25%
Xylene	12%
Titanium dioxide	10%
Iso-butanol	5%
Ethylbenzene	4%
Naphtha	3%
4-methyl-2-pentanone	2%
Zinc phosphate	2%
Polyurethane topcoat	**Share**
Polyol	50%
Butyl acetate	18%
Xylene	10%
Naphtha	9%
Iso-phorone diisocyanate	6%
Isopropyl acetate	4%
Ethylbenzene	3%

the transformer and the switchgear, both these units were included as detailed data was available, in Schneider Electric (2020a, 2020b) for the transformer and in Pai and Lohrberg (2022) for a matching 3.7 ton gas-insulated high-voltage switchgear substation. Finally, a unit for heating, ventilation, and air conditioning was estimated to be made from low-alloyed steel (Halton, 2018), except for 1% of component mass modelled as paint.

There is a direct drive generator included in the reference turbine specified by Gaertner et al. (2020). It is a permanent-magnet synchronous outer-rotor generator, and a construction with a radial flux topology, surface-mounted permanent magnets, and a maximized winding factor with short end windings (Gaertner et al., 2020). In summary, the reference design specification points to a comparatively large permanent magnet mass and a small copper winding mass. The magnets are specified as sintered neodymium magnets. The exact shares of neodymium, classified as a light rare-earth element (REE), and dysprosium, which is a more scarce REE, classified as "heavy", can vary a bit between different commercial magnets although the fundamental crystal structure of the magnet alloy before milling and sintering is the same (Lucas et al., 2015). A number of factors including the synthesis method decides the specific properties of a selected magnet, but in general, dysprosium is included to improve the magnets' ability to withstand demagnetization at high temperature (Lucas et al., 2015; Nordelöf et al., 2017). Carrara et al. (2020) points to an average composition of neodymium-based magnets for direct drive generators in wind turbines with about 4% dysprosium. Data for such a Nd(Dy)FeB-magnet with that share of dysprosium in the base body, and a nickel surface protection layer was acquired from Nordelöf et al. (2017).

Data for the PTF generator design was acquired directly from the Hagnesia. Compared to the reference design, this much compacter generator gives significant reductions in terms of the subcomponents' masses. The PTF magnets have 94% lower total mass. For the other active parts, the copper windings are reduced in mass by 67% and the electrical steel laminates by 97%, compared to the generator of the reference design. And, as the entire generator becomes much more compact, the cast iron housing mass is also decreased by 95%, while it requires a small addition of structural aluminum. The lighter generator then also enables a slimmer design of the tower and the floating foundation of turbine options (1) and (2).

Wickström (2023) studied this mass reduction potential for the Hagnesia turbine in relation to the IEA reference design for the tower of the floating turbine and estimated a 13% mass decrease. This means that 164 tons out of the 1263 tons originally reported by Gaertner et al. (2020), could be saved. But the reference tower mass was then adjusted to 1483 tons in the later IEAWindTask37 (2023) documentation. However, in order to avoid an overestimation of the mass reduction benefit, the original absolute value of 164 tons was still used in this study for adjusting the mass of the Hagnesia turbine tower compared to the reference option (1). Wickström (2023) also reported a potential 5% mass saving for the total floating platform mass, corresponding to 892 tons. It is conceivable that a major part of this reduction could be achieved mainly through a slimmer steel hull, not affecting the large share of the floating foundation mass that consists of sea water and concrete ballast, but again, to avoid overestimating the benefits of the Hagnesia generator design, a proportional downsizing of the hull and the ballast was assumed and applied. For the hull, this conservative approach implies a 200-ton reduction and for the concrete ballast mass, it leads to a 127-ton reduction. The monopile options were not studied by Wickström (2023) and as the IEAWindTask37 (2023) already reports a lighter tower structure of 854 tons for the reference design, further mass savings for the Hagnesia option (4), was left out in relation to the monopile reference option (4).

Table 2 presents the mass composition for all included components. All study specific datasets, i.e. the foreground unit process datasets used, are reported in Appendix A.

Table 2: Mass composition of studied wind turbine options.

Component	Sub-component	Material	Amount in wind turbine		Unit
			REFERENCE option	HAGNESIA option	
Rotor	Blades	Glass-fiber	107		ton
		Epoxy resin	57		ton
		Sandwich foam	10		ton
		Low-alloy steel, forged	6.2		ton
		Aluminum, wrought	1.2		ton
		PVC	14		ton
		Rubber	2.1		ton
		Paint	7.0		ton
	Hub	Cast iron	13		ton
		Low-alloy steel, forged	8		ton
		Glass-reinforced plastics	0.5		ton
		Paint	0.2		ton
	Hub system parts	Stainless steel, forged	48		ton
Nacelle	Platform	Cast iron	32		ton
		Low-alloy steel, forged	17		ton
	Brakes	Cast iron	17		ton
		Low-alloy steel, forged	9.1		ton
	Bedplate	Cast iron	27		ton
		Low alloyed steel, forged	15		ton
		Paint	0.4		ton
	Nose	Cast iron	4.5		ton
		Low alloyed steel, forged	2.5		ton
	Bearings	Stainless steel, rolled	62		ton
	Yaw system	Stainless steel, forged	28		ton
	Housing	Glass-reinforced plastics	19		ton
		Paint	0.7		ton
	Main shaft	Stainless steel, forged	18		ton
		Low alloyed steel, forged	3.2		ton
	Generator unit	Copper windings	9.1	3.0	ton
		Nd(Dy)FeB magnets	24	1.5	ton
		Electrical steel, laminates	181	6.1	ton
		Low alloyed steel, forged	157	8.5	ton
		Aluminum, wrought	0	2.1	ton
	Power converter unit	*NOT MODELLED*	12		ton
	Transformer unit	*Modelled in more detail*	31		ton
	HVAC unit	Low alloyed steel, rolled	8.9		ton
		Paint	0.1		ton
Tower internals	Internal structures	Aluminum, wrought	11		ton
	Electric cables	*Modelled in more detail*	5.4		ton
	Gas insulated switchgear	*Modelled in more detail*	3.7		ton
Tower with floating foundation	Tower structure	Low alloyed steel, rolled	1308	1163	ton
		Low alloyed steel, forged	145	129	ton
		Paint	30	26	ton
	Floating foundation, hull	Low -alloyed steel, rolled	3934	3738	ton
		Paint	80	76	ton
	Ballast	Concrete normal strength	2540		ton
Tower with monopile foundation	Monopile and tower structure	Low alloyed steel, rolled	1916		ton
		Low alloyed steel, forged	213		ton
		Paint	44		ton

3.2 Production of components

All components of the two wind turbine options, and the subparts of these components, with the exception of internal electrical equipment, but including the direct drive generators, were modelled as arriving semi-processed to the turbine assembly plant. This is where all final manufacturing take place before the turbine is shipped out in readymade pieces for installation at sea. The electrical equipment not going through the assembly plant includes the electrical cables, the transformer and the switchgear, all modelled as delivered directly to the installation site, using existing LCA data in Arvesen et al. (2013), Schneider Electric (2020a, 2020b), and Pai and Lohrberg (2022). In the following, this section describes the production processes accounted for before the turbine assembly plant factory gates, which are not captured by the material composition data reported in previous Section 3.1.

Metal parts in the turbine consisting of wrought aluminum were modelled with an average wrought alloy grade as available in the Ecoinvent database (Ecoinvent, 2023; Wernet et al., 2016), plus a sheet rolling activity added to cover for the mechanical treatment. Rolled low-alloyed and stainless steel parts were modelled in a similar way, including both hot rolling and cold sheet rolling. Stainless steel corresponds to 18/8 chromium steel, and in line with the geographical boundaries of the study, average European market conditions were chosen for aluminum and rolled steel parts. Specifically for the HVAC equipment, the rolled low-alloyed steel were also modelled as going through a process of additional metal working, covering for a blend of activities such as bending, forming and to some extent, cutting.

The modelling of forged steel parts, both low-alloyed and stainless steel, was based on data originally collected for large scale forging in an open die press in Canada, but with Canadian specific inputs and outputs in energy and materials switched to average European market data. Cast iron parts were assumed to be casted directly into a rough version of its final shape at the original foundry, and then subsequently drilled to remove excessive material. For each ton of cast iron structure delivered to the assembly plant, it was assumed that 0.23 tons of cast iron has been removed, in line with the average value recommended in the Ecoinvent database (Ecoinvent, 2023; Wernet et al., 2016).

Another part which arrives pre-manufactured to the assembly plant is the sandwich foam used in the turbine blades. It was modelled as styrene-acrylonitrile copolymer which undergoes a polymer foaming process (Ecoinvent, 2023; Wernet et al., 2016).

Additional steps in the paint production, i.e. steps to account for stages subsequent to preparation of individual constituents, such as mixing and heating are accounted for by proxy using values for the production of alkyd paint in the Ecoinvent database (Ecoinvent, 2023; Wernet et al., 2016). This covers the chemical factory and its use of electricity, natural gas and district heating per ton of wet paint produced. For the zinc containing protective paint, air pulverization of zinc into powder was modelled using data from Youcai and Chenglong (2017).

Finally, regarding the direct drive generator components, data for the complete magnet production chain, delivered readymade for generator assembly in the turbine plant, including extraction metals and production of magnets in China, followed by transportation from China to Europe, was acquired from Nordelöf, Grunditz, et al. (2019), which in turn built further from Nordelöf et al. (2017) and established complete datasets for REE-based magnets, including the production of neodymium metal as an input to the initial alloying step. Despite the rapid growth in the production and use of this type of magnet globally, for example in wind turbines and electric vehicles, it was judged that the supply chain operations are still mostly unaltered compared to when these datasets were established. Similarly, the data presented in Nordelöf et al. (2017) for electrical steel sheets, including the alloying process for silicon steel, followed hot rolling and the specific rolling process required at the electrical steel plant, was used for representation of electrical steel coils arriving to the turbine assembly plant for final shaping. Aluminum and steel subcomponents were modelled as described above, leaving only the copper wire for the generator windings. For these, high purity cathode grade copper was modelled to undergo sheet rolling followed by wire drawing.

Both generator designs can be expected to contain smaller amounts of plastics, and isolation and impregnation materials, for example epoxy. As no such materials are reported for the reference generator design (Gaertner et al., 2020), it has been neglected for both options in in the study.

3.3 Turbine assembly, transportation and installation at sea

The data for the turbine assembly plant was gathered and established using the raw sustainability data in the sustainability report for 2021 of Vestas Wind Systems A/S (Vestas, 2022). It contains values for the aggregate capacity delivered during 2021 in combination with data for: fuels bought by the company used in heating processes; electricity; heat supplied to facility; wasted and recycled materials; and water. The compilation of information also states values for material efficiency expressed as ton of waste per MW shipped, excluding internal recycling, and direct emissions of carbon dioxide and volatile organic compounds (VOC) from the facility.[1] Used values are reported in Table 3. Combined, this raw data was used to establish LCA unit process data for a wind turbine assembly plant (reported in Appendix A, along with all other unit processes used in the model) expressed per MW of turbine power capacity, and also to make reasonable cross-check calculations for the emissions. The established unit process data includes a generic compensation for losses across all input materials, process water used, input energy in the form of electricity, heat and fuels, and different categories of material going to recycling, or waste handling in the form of incineration or landfill.

The assembly plant data is expected to cover all processes bringing input materials and semi-finished parts into units ready for installation. This includes the molding of the blades from glass-fiber and resin as described by Mishnaevsky et al. (2017), as well as a part of the hub. It also comprises final shaping of some large turbine parts, e.g. various tower sections, and mounting of smaller components. It also includes applying all layers of wet paint on the outer surfaces and letting these dry to reach the final mass of the paint as reported in Table 2.[2] This means that about 23% of the wet paint mass is released as VOCs in the drying process. If all of these paint emissions were allowed to escape directly into the surrounding external air, they would vastly outnumber the VOCs reported by Vestas (2022) in Table 3, even if their transport-related VOC emissions are taken into account. However, assuming the use of an industrial state of the art VOC scrubber with an efficiency of about 99.7%, which just below what is reported as an industrial best practice efficiency by Dürr (2022), this brings the modelled and reported VOCs into matching figures.

For the transportation fuel use, the energy data reported by Vestas (2022) and extracted to Table 3 was recalculated to mass values by using net calorific heating values for the different fuel types as reported by The Engineering ToolBox (2003). By doing this, it was possible to link the reported transportation fuel use to existing datasets for fuel production and supply in Ecoinvent (Ecoinvent, 2023; Wernet et al., 2016). As a simplification, the energy data reported

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[1] Reported as "Scope 1" emissions, i.e. direct emissions that occur from sources owned or controlled by the reporting organization. This includes emissions generated from on-site combustion of fuels in industrial processes as well as company-owned vehicles or other equipment.

[2] The protective zinc paint and the polyurethane topcoat are applied with wet layer thicknesses in the range of 70-75 µm and dry down to 40 µm. The two layers of primer are applied with a wet layer thickness of about 110 µm each, which dry to 60 µm, respectively.

for liquid petroleum gas was added to and included in the summary for petrol. Next, data was gathered for average emissions during 2021 in Sweden from the combustion of one ton of petrol in light duty trucks, one ton of diesel heavy duty trucks and one ton of marine fuel oil in a fishing vessel deemed suitable to match the kind of ship used for the wind turbine installation at sea, reported in the Swedish Environmental Emissions Data (2023a, 2023b) compilation of inventories for the Emission Factors and Heating Values submission 2023 covering Swedish greenhouse gas emissions during for 1990-2021 as reported to the United Nations Framework Convention on Climate Change, and the Swedish Air Pollutants' emissions for 1990-2021 as reported to the United Nations Economic Commission for Europe’s Convention on Long-range Transboundary Air Pollution. This data was then recalculated to mass instead of energy using the net calorific heating values reported by The Engineering ToolBox (2003). Combined with the data from Vestas (2022), datasets were compiled that accounts for the average fuel use and the linked air emissions, normalized per wind turbine capacity, caused by the land transportation and sea installation services for one wind turbine. Detailed unit process data tables are presented in Appendix A.

Table 3: Values extracted from Vestas’ sustainability report for 2021, for one year of operation.

Raw data used for calculating assembly plant dataset	Value	Unit
Aggregate wind turbine electricity generation capacity delivered, expressed in nominal power	17 845	MW
Oil, used in heating processes	19	GWh
Natural gas, used in heating processes	96	GWh
Electricity, delivered to facility	233	GWh
Heat, delivered to facility	56	GWh
Scrap collected and recycled, all assumed to be non-hazardous	35	kton
Waste sent to incineration, including hazardous	24	kton
Waste sent to landfill	11	kton
Water use	378	kton
Carbon dioxide emissions, from own operations	99	kton
VOC emissions, from own operations	205	ton
Material efficiency, waste per capacity delivered (excluding recycling)	2	ton/MW
Raw data used for calculating fuel use in land transportation and installation at sea	**Value**	**Unit**
Liquefied petroleum gas, used for transportation	1	GWh
Diesel, used for transportation	133	GWh
Petrol, used for transportation	60	GWh
Marine gas oil, used for transportation	139	GWh

4 Impact assessment results

Figure 1 shows the results for the assessment of the floating wind turbine options, with option (1), i.e. the version modelled in full accordance with the IEA reference design to the left in each bar chart, and the turbine equipped with Hagnesia's PTF generator design and reduced tower and foundation mass, but otherwise also modelled based on the IEA reference design, i.e. option (2), to the right.

For contributions to climate change with a 20-year time horizon, the Hagnesia option (2) reduces the impact with 16% in total compared to reference option (1). For the permanent magnet synchronous generator (PMSG) parts, the shift from the conventional design to the PTF generator design leads to a 92% reduction of greenhouse gas emissions for these parts specifically. The reduction of emissions that can be attributed to the lower tower and foundation mass is 6%. The share of contributions from the PMSG parts to the total burden of the turbine is about 12% for the reference option (1) and about 1% for the Hagnesia option (2).

For the resource use indicator, which captures contributions to long-term resource scarcity, the results indicate that the Hagnesia option (2) will decrease the total burden of the turbine with 22% compared to the reference option (1). The contribution of the PMSG parts is 83% lower in the Hagnesia option compared to reference, and the lower tower and foundation mass reduces their contribution with 7%. The share of contributions from the PMSG parts is about 22% for the reference option (1) and about 5% for the Hagnesia option (2).

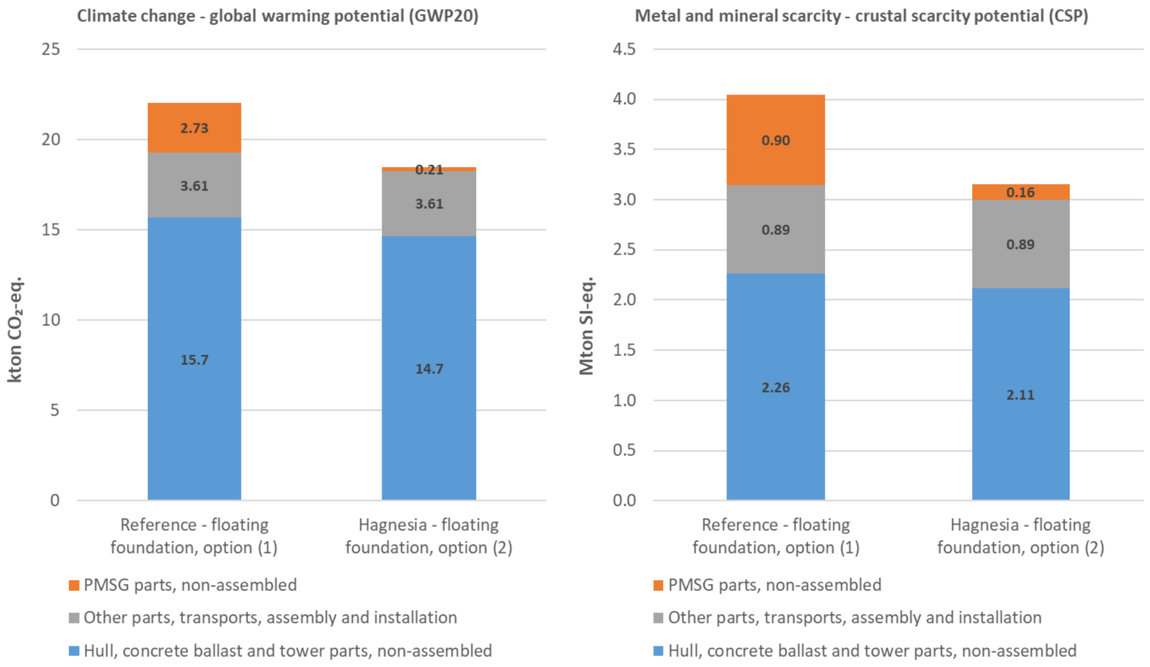

Figure 1: Climate change impacts (global warming potential for a 20-year time horizon, reported in kton of CO_2-equivalents per turbine), left bar chart, and resource use impacts (long-term crustal scarcity potential, reported in Mton of SI-equivalents per turbine), right bar chart, of the two studied 15 MW floating wind turbine options, (1) and (2), after installation, ready for commissioning.

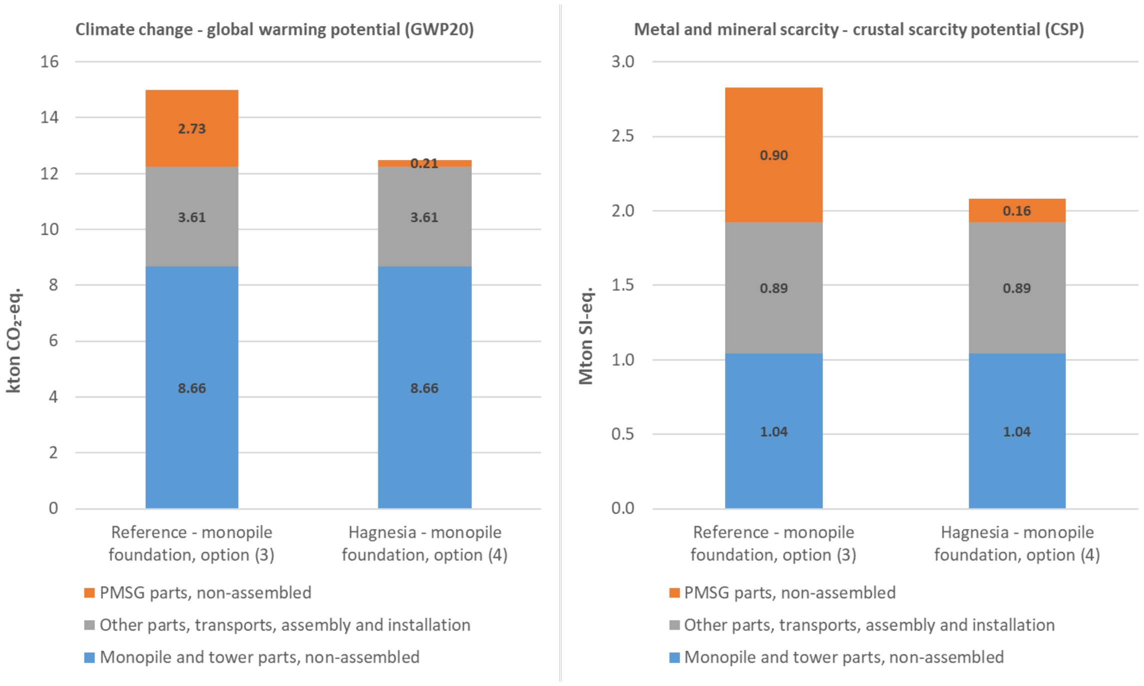

Figure 2: Climate change impacts (global warming potential for a 20-year time horizon, reported in kton of CO_2-equivalents per turbine), left bar chart, and resource use impacts (long-term crustal scarcity potential, reported in Mton of SI-equivalents per turbine), right bar chart, of the two studied 15 MW monopile wind turbine options, (3) and (4), after installation, ready for commissioning.

Figure 2 shows the results for the assessment of the monopile wind turbine options, again with the version modelled in full accordance with the IEA reference design to the left in each bar chart, option (3), and the turbine equipped with Hagnesia's PTF generator design to the right, option (4). For the monopile versions, the tower and monopile have the same design and mass in both options (3) and (4).

In this case, the Hagnesia option (4) gives 17% lower contributions to climate change with a 20-year time horizon compared to reference option (3), for the complete turbine. As for the floating option, the PTF generator design shifts the contribution of the PMSG parts downwards with a 92% reduction compared to the PMSG parts in the reference option (3). The share of contributions from the PMSG parts to the total turbine burden is about 18% for the reference option (1), and about 2% for the Hagnesia option (2).

For the crustal scarcity of the resources used, the results indicate that the Hagnesia option (2) will decrease the total burden of turbine with 26% compared to the reference option (1). Again, the same reduction occurs for the PMSG parts as is in the floating turbine version (83%), whereas there is no difference between reference option (3) and the Hagnesia option (4) for the tower structure and monopile. The share of contributions from the PMSG parts is about 32% for the reference option (3) and about 8% for the Hagnesia option (4).

Figure 3 shows the results for all four options (1-4) for contributions to climate change with a 100-year time horizon. Similar to the results for climate change in figures 1 and 2, the reduction of contribution from the PMSG parts in the reference options (1 and 3) to the PMSG parts in the Hagnesia options (2 and 4), is 92%, meaning that the relationship between the different time perspectives of the climate change indicator is largely linear. Another observation that can be made in Figure 3 is the lower overall greenhouse gas emission burden of the monopile options when compared to the floating turbines.

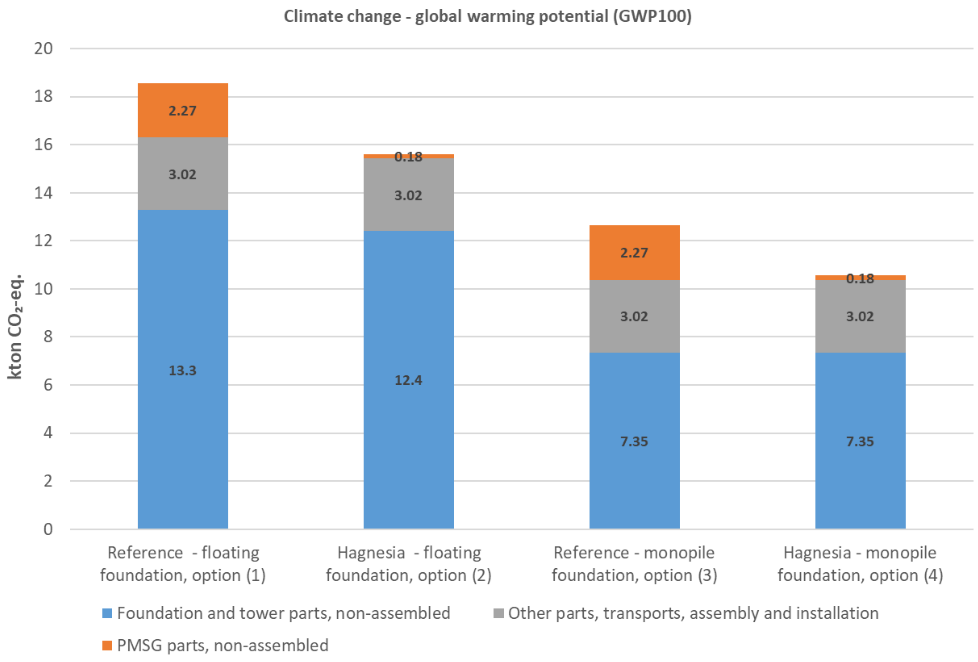

Figure 3: Climate change impacts (global warming potential for a 100-year time horizon, reported in kton of CO_2-equivalents per turbine), of all studied 15 MW wind turbine, i.e. floating options(1) and (2), and monopile options (3) and (4), after installation, ready for commissioning.

Table 4 reports the contributions to climate change in greater detail, i.e., for the two generators design and their different subparts, for both the 20-year and 100-year time horizons. The permanent magnets are causing about half of the greenhouse gas emissions for the reference generator and about 40% for the Hagnesia generator. In absolute numbers, the magnets are responsible for close to half of the greenhouse gas emission reduction of Hagnesia's PTF design compared to the reference PMSG, for both time perspectives. However, for other subparts, the relationship between the designs is different. The copper wire in the windings are responsible for a much smaller share of the burden of the reference PMSG (4%) compared to the PTF design (18%). Oppositely, the share of the electrical steel laminates is higher in the reference design (22-23%) than in the PTF design (10%). Expressed differently,

Table 4: Climate change impacts (global warming potential for a 20-year and a 100-year time horizon), for the subparts of the two generator designs included in the study.

Subparts of the Reference PMSG	**GWP20**			**GWP100**		
Copper wire in windings	115	ton CO_2-eq.	4%	98	ton CO_2-eq.	4%
Electrical steel laminates	614	ton CO_2-eq.	22%	516	ton CO_2-eq.	23%
Forged low-alloyed steel parts	643	ton CO_2-eq.	24%	546	ton CO_2-eq.	24%
Nd(Dy)FeB-magnets	1361	ton CO_2-eq.	50%	1110	ton CO_2-eq.	49%
Sum	2733	ton CO_2-eq.		2270	ton CO_2-eq.	
Subparts of the PTF PMSG	**GWP20**			**GWP100**		
Aluminum parts	36	ton CO_2-eq.	17%	31	ton CO_2-eq.	17%
Copper wire in windings	38	ton CO_2-eq.	18%	32	ton CO_2-eq.	18%
Electrical steel laminates	21	ton CO_2-eq.	10%	17	ton CO_2-eq.	10%
Forged low-alloyed steel parts	35	ton CO_2-eq.	16%	30	ton CO_2-eq.	17%
Nd(Dy)FeB-magnets	84	ton CO_2-eq.	39%	69	ton CO_2-eq.	39%
Sum	214	ton CO_2-eq.		179	ton CO_2-eq.	

in absolute numbers, the greenhouse gas emissions from the copper windings of the reference PMSG are about three times larger than the corresponding emissions for the PTF design, whereas it is almost 30 times larger for electrical steel laminates. The reference design does not contain any aluminum parts. In the Hagnesia generator, they contribute on par with the forged low-alloyed steel parts.

Furthermore, regarding the greenhouse gas emissions caused by specific subparts and constituent materials for the complete turbines, it can be noted that the permanent magnets in the generators are still by far the most emission intensive parts when accounted for per unit of mass. Each ton of permanent magnet causes about four and sixteen times more greenhouse gas emissions than each ton of copper wire and electrical steel laminates, respectively, irrespective of the 20- or 100-year perspective for the climate change impacts. The aluminum is the second most emission intensive material. An important explanation is that smelting of primary aluminum is an electrolysis-based process, which is largely fed from fossil electricity generation when accounting for the global average. This burden can be reduced by acquiring aluminum where this electricity instead is supplied from renewable sources. In the lower end in terms of emission intensity, it can be noted that the concrete in foundations has a relatively small contribution per unit of mass. Concrete contains cement, which is relatively more greenhouse gas emission intensive, but it is only a smaller share. Results for the different subparts and materials per unit of mass can be found in Appendix B.

Given the results presented in figures 1-3 and Table 4, and the point made regarding the greenhouse gas emissions per unit of mass for the permanent magnets, it can be argued that the emission profile of the PMSG parts supply chain and the data selected for the modelling of turbine life cycle is specifically important for how much Hagnesia's PTF generator design saves, both in terms of the absolute numbers reported, and the relative relationship to the rest of the turbine. For this reason, another available dataset for the permanent magnets was tested, available in the Ecoinvent database version 3.91 (Ecoinvent, 2023; Wernet et al., 2016). This dataset is less detailed in terms of the coverage of specific processes in the magnet production and material supply chain, and foremost, it represents magnets without the heavy REE dysprosium, compared to the original dataset used in this study. Using the alternative dataset, the emissions causing climate change over a 100-year time horizon decreased from the PMSM parts with 13% and 10% respectively for the reference and Hagnesia options. Even so, overall, this data sensitivity test show little effect on total results, and for the floating turbines, the shift down, from the reference to the Hagnesia option, goes from 16% to 15%.

A complementary set of impact categories included in the ReCiPe 2016 package (Huijbregts et al., 2016), are reported in Appendix B for completeness, but not discussed further here as they are not in focus in this analysis.

5 Conclusions

This study shows that Hagnesia's novel PTF generator design has the potential to notably reduce the environmental effects of a 15 MW wind turbine when the reference design of the IEA Wind task 37 (Gaertner et al., 2020) is used as the benchmark, even as the study only covers the life cycle stages from raw material extraction and to the point when the turbines are installed at sea and ready to generate. More specifically, this refers to clear reductions in terms of greenhouse gas emissions and resource use when evaluated for long-term mineral and metal scarcity. This is shown both for wind turbines with floating foundations for deep-sea installations, and for monopile options, aimed for shallower sea installations.

The largest greenhouse gas savings potential can be identified among the generator subparts. The fact that the novel Hagnesia generator design can achieve the same electromechanical work as the reference generator design, at the same time as it enables a substantial mass reduction for the electrical steel laminates, the low-alloyed structural steel and most importantly, the amounts of permanent magnets needed, is the key driver for lowered emissions and resource use. It can also be noted that there is a large potential to lower the emissions caused by the aluminum parts, by sourcing this material from supply route using renewable energy in the smelting step for the primary input, further reducing the burdens of the generator. The total greenhouse gas emission reduction linked directly to the generator subparts is larger than one order of magnitude, indicating that these conclusions are very robust.

It should be noted that since the operation stage is not included, this study does not account for differences in conversion efficiencies between the turbines, i.e., differences in the amount of electricity generated for the same amount of input wind energy passing through the rotor area.

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Appendix A:Foreground unit process datasets

Final transportation and installation at sea − floating and monopile options

15 MW HAGNESIA/REFERENCE wind turbine, installation at sea, average operation services - RER

Input Flow	Amount	Unit	Providing process
15 MW HAGNESIA/REFERENCE wind turbine, main components, for installation	1	Item(s)	15 MW HAGNESIA/REFERENCE wind turbine, average land transportation services - RER
Electrical cables	5.4	t	Production of electrical cables - RER
Gas-insulated switchgear, 1 bay, 3.3 tons, 145 kV	1	Item(s)	Switchgear, average transportation from supplier - RER
Marine gas oil combusted during ship operation	9.83	t	Combustion of marine gas oil in ship, for sea operation services - SE
Oil immersed Medium Power Transformer, 31 tons	1	Item(s)	Transformer, average transportation from supplier - RER
Output Flow	**Amount**	**Unit**	**Providing process**
15 MW HAGNESIA/REFERENCE wind turbine, installed	1	Item(s)	*System reference flow*

Source(s): Gaertner et al. (2020), Gul (2019), IEAWindTask37 (2023), Vestas (2022), Pai and Lohrberg (2022)

15 MW HAGNESIA/REFERENCE wind turbine, average land transportation services - RER

Input Flow	Amount	Unit	Providing process
15 MW HAGNESIA/REFERENCE wind turbine, main components, for installation	1	Item(s)	15 MW HAGNESIA/REFERENCE wind turbine, main components manufacturing - RER
Diesel combusted in heavy duty vehicle	9.45	t	Combustion of diesel in heavy duty vehicle - SE
Petrol combusted in light duty vehicle	4.25	t	Combustion of petrol in light duty vehicle - SE
Output Flow	**Amount**	**Unit**	**Providing process**
15 MW HAGNESIA/REFERENCE wind turbine, main components, for installation	1	Item(s)	*Unit process reference flow*

Source(s): Vestas (2022)

Turbine components and assembly − floating options only

15 MW HAGNESIA/REFERENCE wind turbine, main components manufacturing - RER

Input Flow	Amount	Unit	Providing process
electricity, medium voltage	196000	kWh	**Ecoinvent:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RER
heat, district or industrial, natural gas	291000	MJ	**Ecoinvent:** heat and power co-generation, natural gas, 1MW electrical, lean burn | Cutoff, U - Europe without Switzerland
heat, district or industrial, other than natural gas	169000	MJ	**Ecoinvent:** market group for heat, district or industrial, other than natural gas | Cutoff, U - RER
heavy fuel oil, burned in refinery furnace	57500	MJ	**Ecoinvent:** market for heavy fuel oil, burned in refinery furnace | Cutoff, U - GLO
Hull and tower interface parts	1.009	Item(s)	Hull and tower interface parts, delivery for HAGNESIA/REFERENCE turbine manufacturing - RER
Internal tower components, aluminium parts	1.009	Item(s)	Internal tower components, aluminium parts, delivery for turbine manufacturing - RER
Nacelle parts	1.009	Item(s)	Nacelle parts, delivery for wind turbine manufacturing - RER
PMSG - direct drive generator, not mounted	1.009	Item(s)	PMSG - HAGNESIA/REFERENCE direct drive generator, not mounted, delivery to turbine manufacturing - RER
Rotor parts	1.009	Item(s)	Rotor parts, delivery for turbine manufacturing - RER
tap water	318	t	**Ecoinvent:** market for tap water | Cutoff, U - Europe without Switzerland
Tower structure parts	1.009	Item(s)	Tower structure parts, delivery for HAGNESIA/REFERENCE turbine manufacturing - RER
Output Flow	**Amount**	**Unit**	**Providing process**
15 MW HAGNESIA/REFERENCE wind turbine, main components, for installation	1	Item(s)	*Unit process reference flow*
hazardous waste, for incineration	5	t	**Ecoinvent:** market for hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
Non-hazardous waste, for treatment	15	t	Treatment of non-hazardous waste, inert landfill - RoW
Non-hazardous waste, for treatment	9	t	Treatment of non-hazardous waste, municipal waste incineration - RER
Recyclable materials	30	t	*Cut-off flow, exits from life cycle*
VOC, volatile organic compounds	121	kg	*Elementary flow - emission to air*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023), Vestas (2022)

Hull and tower interface parts, delivery for HAGNESIA turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
concrete block	2540	t	**Ecoinvent:** market for concrete block | Cutoff, U - RoW
Paint for spray painting, four layers, expressed in dry mass	76.3	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
steel, low-alloyed, hot rolled	3738	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Hull and tower interface parts	1	Item(s)	*Unit process reference flow*

Source(s): Allen et al. (2020), Gaertner et al. (2020), IEAWindTask37 (2023), Wickström (2023)

Hull and tower interface parts, delivery for REFERENCE turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
concrete block	2540	t	**Ecoinvent:** market for concrete block | Cutoff, U - RoW
Paint for spray painting, four layers, expressed in dry mass	80.3	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
steel, low-alloyed, hot rolled	3934	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Hull and tower interface parts	1	Item(s)	*Unit process reference flow*

Source(s): Allen et al. (2020), Gaertner et al. (2020), IEAWindTask37 (2023)

Tower structure parts, delivery for HAGNESIA turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Low-alloyed steel, forged	129	t	Forging, low-alloyed steel, large open die - RER
Paint for spray painting, four layers, expressed in dry mass	26.4	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
steel, low-alloyed, hot rolled	1163	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Tower structure parts	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023), Wickström (2023)

Tower structure parts, delivery for REFERENCE turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Low-alloyed steel, forged	145	t	Forging, low-alloyed steel, large open die - RER
Paint for spray painting, four layers, expressed in dry mass	29.7	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
steel, low-alloyed, hot rolled	1308	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Tower structure parts	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023)

Turbine components and assembly – monopile options only

15 MW HAGNESIA/REFERENCE wind turbine, main components manufacturing - RER

Input Flow	Amount	Unit	Providing process
electricity, medium voltage	196000	kWh	**Ecoinvent:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RER
heat, district or industrial, natural gas	291000	MJ	**Ecoinvent:** heat and power co-generation, natural gas, 1MW electrical, lean burn | Cutoff, U - Europe without Switzerland
heat, district or industrial, other than natural gas	169000	MJ	**Ecoinvent:** market group for heat, district or industrial, other than natural gas | Cutoff, U - RER
heavy fuel oil, burned in refinery furnace	57500	MJ	**Ecoinvent:** market for heavy fuel oil, burned in refinery furnace | Cutoff, U - GLO
Internal tower components, aluminium parts	1.009	Item(s)	Internal tower components, aluminium parts, delivery for turbine manufacturing - RER
Monopile, interface and tower structure	1.009	Item(s)	Monopile, interface and tower structure parts, delivery for turbine manufacturing - RER
Nacelle parts	1.009	Item(s)	Nacelle parts, delivery for wind turbine manufacturing - RER
PMSG - direct drive generator, not mounted	1.009	Item(s)	PMSG - HAGNESIA/REFERENCE direct drive generator, not mounted, delivery to turbine manufacturing - RER
Rotor parts	1.009	Item(s)	Rotor parts, delivery for turbine manufacturing - RER
tap water	318	t	**Ecoinvent:** market for tap water | Cutoff, U - Europe without Switzerland
Output Flow	**Amount**	**Unit**	**Providing process**
15 MW HAGNESIA/REFERENCE wind turbine, main components, for installation	1	Item(s)	*Unit process reference flow*
hazardous waste, for incineration	5	t	**Ecoinvent:** market for hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
Non-hazardous waste, for treatment	15	t	Treatment of non-hazardous waste, inert landfill - RoW
Non-hazardous waste, for treatment	9	t	Treatment of non-hazardous waste, municipal waste incineration - RER
Recyclable materials	30	t	*Cut-off flow, exits from life cycle*
VOC, volatile organic compounds	121	kg	*Elementary flow - emission to air*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023), Vestas (2022)

Monopile, interface and tower structure parts, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Low-alloyed steel, forged	1916.3	t	Forging, low-alloyed steel, large open die - RER
Paint for spray painting, four layers, expressed in dry mass	43.5	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
steel, low-alloyed, hot rolled	212.9	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Monopile, interface and tower structure	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023)

PMSG parts – floating and monopile options

PMSG - HAGNESIA direct drive generator, not mounted, delivery to turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Aluminium coil	2.1	t	Production of aluminium coil - GLO
copper, cathode	3.0	t	**Ecoinvent:** market for copper, cathode| Cutoff, U - GLO
Electrical steel sheet	6.1	t	Production of electrical steel sheets - RER
Low-alloyed steel, forged	8.5	t	Forging, low-alloyed steel, large open die - RER
metal working, average for copper product manufacturing	3.0	t	**Ecoinvent:** market for metal working, average for copper product manufacturing | Cutoff, U - GLO
Nd(Dy)FeB magnets	1.5	t	Transportation of Nd(Dy)FeB magnets, intercontinental - GLO
wire drawing, copper	3.0	t	**Ecoinvent:** market for wire drawing, copper | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
PMSG - direct drive generator, not mounted	1	Item(s)	*Unit process reference flow*

Source(s): *Direct dialogue with Hagnesia AB*

PMSG - REFERENCE direct drive generator, not mounted, delivery to turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
copper, cathode	9.1	t	**Ecoinvent:** market for copper, cathode | Cutoff, U - GLO
Electrical steel sheet	181	t	Production of electrical steel sheets - RER
Low-alloyed steel, forged	157.3	t	Forging, low-alloyed steel, large open die - RER
metal working, average for copper product manufacturing	9.1	t	**Ecoinvent:** market for metal working, average for copper product manufacturing | Cutoff, U - GLO
Nd(Dy)FeB magnets	24.2	t	Transportation of Nd(Dy)FeB magnets, intercontinental - GLO
wire drawing, copper	9.1	t	**Ecoinvent:** market for wire drawing, copper | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
PMSG - direct drive generator, not mounted	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023)

Other processes, alphabetical order – all options

Air pulverization, zinc powder production - GLO

Input Flow	Amount	Unit	Providing process
electricity, medium voltage	2	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - GLO
zinc	1	kg	**Ecoinvent:** market for zinc | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Zinc powder	1	kg	*Unit process reference flow*

Source(s): Youcai and Chenglong (2017)

Combustion of diesel in heavy duty vehicle - SE

Input Flow	Amount	Unit	Providing process
diesel, low-sulfur	1.0	t	**Ecoinvent:** market group for diesel, low-sulfur | Cutoff, U - RER

Output Flow	Amount	Unit	Providing process
Diesel combusted in heavy duty vehicle	1.0	t	*Unit process reference flow*
Ammonia	5.0E-05	t	*Elementary flow - emission to air*
Carbon dioxide, fossil	2.20	t	*Elementary flow - emission to air*
Carbon monoxide, fossil	3.7E-03	t	*Elementary flow - emission to air*
Dinitrogen monoxide	1.6E-04	t	*Elementary flow - emission to air*
Hydrocarbons, unspecified	1.3E-04	t	*Elementary flow - emission to air*
Methane	3.2E-06	t	*Elementary flow - emission to air*
Nitrogen oxides	5.8E-03	t	*Elementary flow - emission to air*
NMVOC, non-methane volatile organic compounds	1.3E-04	t	*Elementary flow - emission to air*
Particulate Matter, < 2.5 um	4.7E-05	t	*Elementary flow - emission to air*
Particulate Matter, > 2.5 um and < 10um	9.1E-05	t	*Elementary flow - emission to air*
Sulfur dioxide	4.8E-06	t	*Elementary flow - emission to air*

Source(s): Swedish Environmental Emissions Data (2023a, 2023b)

Combustion of marine gas oil in ship, for sea operation services - SE

Input Flow	Amount	Unit	Providing process
heavy fuel oil	1.0	t	**Ecoinvent:** market group for heavy fuel oil | heavy fuel oil | Cutoff, U - RER

Output Flow	Amount	Unit	Providing process
Marine gas oil combusted during ship operation	1.0	t	*Unit process reference flow*
Carbon monoxide, fossil	4.1E-03	t	*Elementary flow - emission to air*
Chromium compounds	7.6E-08	t	*Elementary flow - emission to air*
Copper compounds	2.0E-06	t	*Elementary flow - emission to air*
Dinitrogen monoxide	1.5E-04	t	*Elementary flow - emission to air*
Dioxins, measured as 2,3,7,8-tetrachlorodibenzo-p-dioxin	1.4E-13	t	*Elementary flow - emission to air*
Indeno(1,2,3-cd)pyrene	8.8E-09	t	*Elementary flow - emission to air*
Lead compounds	1.5E-07	t	*Elementary flow - emission to air*
Mercury compounds	5.0E-11	t	*Elementary flow - emission to air*
Methane	2.0E-05	t	*Elementary flow - emission to air*
Nickel compounds	5.8E-07	t	*Elementary flow - emission to air*
Nitrogen oxides	3.4E-02	t	*Elementary flow - emission to air*
NMVOC, non-methane volatile organic compounds	8.1E-04	t	*Elementary flow - emission to air*
PAH, polycyclic aromatic hydrocarbons	2.2E-05	t	*Elementary flow - emission to air*
Particulate Matter, < 2.5 um	1.1E-04	t	*Elementary flow - emission to air*
Particulate Matter, > 10 um	1.2E-03	t	*Elementary flow - emission to air*
Particulate Matter, > 2.5 um and < 10um	1.2E-03	t	*Elementary flow - emission to air*
Polychlorinated biphenyls	4.3E-10	t	*Elementary flow - emission to air*
Selenium compounds	5.0E-11	t	*Elementary flow - emission to air*
Sulfur dioxide	1.1E-03	t	*Elementary flow - emission to air*
TSP	1.2E-03	t	*Elementary flow - emission to air*
Zinc compounds	8.8E-07	t	*Elementary flow - emission to air*

Source(s): Swedish Environmental Emissions Data (2023a, 2023b)

Combustion of petrol in light duty vehicle - SE

Input Flow	Amount	Unit	Providing process
petrol, unleaded	1.0	t	**Ecoinvent:** market for petrol, unleaded | Cutoff, U - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Petrol combusted in light duty vehicle	1.0	t	*Unit process reference flow*
Ammonia	6.1E-04	t	*Elementary flow - emission to air*
Carbon dioxide, fossil	2.95	t	*Elementary flow - emission to air*
Carbon monoxide, fossil	1.1E-01	t	*Elementary flow - emission to air*
Dinitrogen monoxide	6.3E-05	t	*Elementary flow - emission to air*
Hydrocarbons, unspecified	1.3E-04	t	*Elementary flow - emission to air*
Methane	4.1E-04	t	*Elementary flow - emission to air*
Nitrogen oxides	7.0E-03	t	*Elementary flow - emission to air*
NMVOC, non-methane volatile organic compounds	6.3E-03	t	*Elementary flow - emission to air*
Particulate Matter, < 2.5 um	2.0E-05	t	*Elementary flow - emission to air*
Particulate Matter, > 2.5 um and < 10um	1.1E-04	t	*Elementary flow - emission to air*
Sulfur dioxide	8.5E-06	t	*Elementary flow - emission to air*

Source(s): Swedish Environmental Emissions Data (2023a, 2023b)

Bedplate semifinised parts, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Cast iron structure	27	t	Production of cast iron structure - GLO
Low-alloyed steel, forged	14.6	t	Forging, low-alloyed steel, large open die - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Bedplate, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Blade semifinished parts, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Aluminium coil	0.4	t	Production of aluminium coil - GLO
epoxy resin, liquid	19.2	t	**Ecoinvent:** market for epoxy resin, liquid | Cutoff, U - RER
glass fibre	35.6	t	**Ecoinvent:** market for glass fibre |Cutoff, U - GLO
Low-alloyed steel, forged	2.1	t	Forging, low-alloyed steel, large open die - RER
Paint for spray painting, four layers, expressed in dry mass	2.3	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
polyvinylchloride, bulk polymerised	4.8	t	**Ecoinvent:** market for polyvinylchloride, bulk polymerised | Cutoff, U - GLO
Sandwich foam	3.4	t	Sandwich foam production - GLO
synthetic rubber	0.7	t	**Ecoinvent:** market for synthetic rubber | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Blade semifinished parts, 1 blade	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), Guilloré et al. (2022), IEAWindTask37 (2023)

Brakes, delivery for wind turbine manufactuing - RER

Input Flow	Amount	Unit	Providing process
Cast iron structure	16.9	t	Production of cast iron structure - GLO
Low-alloyed steel, forged	9.1	t	Forging, low-alloyed steel, large open die - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Brakes, not mounted	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Die casting of aluminum - RER

Input Flow	Amount	Unit	Providing process
aluminium, cast alloy	1.06	kg	**Ecoinvent:** market for aluminium, cast alloy | Cutoff, U - GLO
electricity, medium voltage	2.6	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
heat, district or industrial, natural gas	10.8	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - RER
lubricating oil	20	g	**Ecoinvent:** market for lubricating oil | Cutoff, U - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Die cast aluminium parts	1.0	kg	*Unit process reference flow*
Aluminium III	0.4	g	*Elementary flow - emission to air*
NMVOC, non-methane volatile organic compounds	1.0	g	Treatment of non-hazardous waste, inert landfill - RoW
waste aluminium	0.06	kg	**Ecoinvent:** market for waste aluminium | Cutoff, U - GLO

Source(s): Nordelöf et al. (2017)

Forging, low-alloyed steel, large open die

Modification of Ecoinvent process originally collected for Quebec, Canada. Steel input modified to include both the metal contained in the product and losses, not only the compensation for losses, as in the original unit process. Electricity input shifted to RER.

Forging, stainless steel, large open die

Modification of Ecoinvent process originally collected for Quebec, Canada. Steel input modified to include both the metal contained in the product and losses, not only the compensation for losses, as in the original unit process. Electricity input shifted to RER.

Hub system, semifinished parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Stainless steel, forged	47.6	t	Forging, stainless steel, large open die - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Hub system, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Carrara et al. (2020), Gaertner et al. (2020), IEAWindTask37 (2023)

Hub with cone/cover, semifinished parts, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Cast iron structure	12.9	t	Production of cast iron structure - GLO
glass fibre reinforced plastic, polyamide, injection moulded	0.5	t	**Ecoinvent:** market for glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
Low-alloyed steel, forged	7.8	t	Forging, low-alloyed steel, large open die - RER
Paint for spray painting, four layers, expressed in dry mass	0.2	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Hub with cone/cover, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), Guilloré et al. (2022), IEAWindTask37 (2023)

Insulation gas mixture - RER

Input Flow	Amount	Unit	Providing process
carbon dioxide, liquid	0.865	kg	**Ecoinvent:** market for carbon dioxide, liquid | Cutoff, U - RER
chemical, organic	0.035	kg	**Ecoinvent:** market for chemical, organic | Cutoff, U - GLO
oxygen, liquid	0.100	kg	**Ecoinvent:** market for oxygen, liquid | Cutoff, U - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Insulation gas	1	kg	*Unit process reference flow*

Source(s): Pai and Lohrberg (2022)

Internal tower components, aluminium parts, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Aluminium coil	11	t	Production of aluminium coil - GLO
metal working, average for aluminium product manufacturing	11	t	**Ecoinvent:** market for metal working, average for aluminium product manufacturing | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Internal tower components, aluminium parts	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013)

Magnet production, Nd(Dy)FeB - CN

Input Flow	Amount	Unit	Providing process
boron carbide	15	g	**Ecoinvent:** market for boron carbide | Cutoff, U - GLO
dysprosium oxide	46	g	**Ecoinvent:** market for dysprosium oxide | Cutoff, U - GLO
electricity, medium voltage	14.0	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - CN
Electrolytic iron	0.830	kg	Production of electrolytic iron - CN
hydrogen, liquid	0.600	kg	**Ecoinvent:** market for hydrogen, liquid | Cutoff, U - RoW
Neodymium metal	0.310	kg	Production of neodymium metal through fused-salt electrolysis - CN
nickel, class 1	13	g	**Ecoinvent:** market for nickel, class 1 | Cutoff, U - GLO
sodium hydroxide, without water, in 50% solution state	1.0	g	**Ecoinvent:** market for sodium hydroxide, without water, in 50% solution state | Cutoff, U - GLO
sulfuric acid	1.4	g	**Ecoinvent:** market for sulfuric acid | Cutoff, U - RoW
tap water	6.0	kg	**Ecoinvent:** market group for tap water | Cutoff, U - GLO

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Output Flow	Amount	Unit	Providing process
Nd(Dy)FeB magnets	1.0	kg	*Unit process reference flow*
hazardous waste, for underground deposit	2.1	g	**Ecoinvent:** market for hazardous waste, for underground deposit | Cutoff, U - RoW
Nickel II	4.2	mg	*Elementary flow - emission to air*
Nickel II	5.1	mg	*Elementary flow - emission to water*
Recyclable materials	0.2	kg	*Cut-off flow, exits from life cycle*

Source(s): Nordelöf et al. (2017)

Main shaft, semifinished, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Low-alloyed steel, forged	3.2	t	Forging, low-alloyed steel, large open die - RER
Stainless steel, forged	18.3	t	Forging, stainless steel, large open die - RER

Output Flow	Amount	Unit	Providing process
Main shaft, semifinished	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Manufacturing of Oil immersed Medium Power Transformer, 31 tons - RER

Input Flow	Amount	Unit	Providing process
aluminium, wrought alloy	0.1	t	**Ecoinvent:** market for aluminium, wrought alloy | Cutoff, U - GLO
Cast iron structure	0.2	t	Production of cast iron structure - GLO
copper, cathode	2.4	t	**Ecoinvent:** market for copper, cathode | Cutoff, U - GLO
corrugated board box	0.2	t	**Ecoinvent:** market for corrugated board box | Cutoff, U - RER
Electrical steel sheet	9.5	t	Production of electrical steel sheets - RER
electricity, medium voltage	7.0	MWh	**Ecoinvent:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RER
heat, district or industrial, natural gas	110.0	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - RER
Low-alloyed steel parts in ready-made components	11.2	t	Production of low-alloyed steel parts in ready-made subcomponents - GLO
metal working, average for aluminium product manufacturing	0.1	t	**Ecoinvent:** market for metal working, average for aluminium product manufacturing | Cutoff, U - GLO
naphtha	1.4	t	**Ecoinvent:** market for naphtha | Cutoff, U - RER
paraffin	5.4	t	**Ecoinvent:** market for paraffin | Cutoff, U - GLO
sheet rolling, aluminium	0.1	t	**Ecoinvent:** market for sheet rolling, aluminium | Cutoff, U - GLO
sheet rolling, copper	2.4	t	**Ecoinvent:** market for sheet rolling, copper | Cutoff, U - GLO
Stainless steel parts in ready-made subcomponents	0.2	t	Production of stainless steel parts in ready-made subcomponents - GLO
wire drawing, copper	2.4	t	**Ecoinvent:** market for wire drawing, copper | Cutoff, U - GLO

Output Flow	Amount	Unit	Providing process
Oil immersed Medium Power Transformer, 31 tons	1	Item(s)	*Unit process reference flow*

Source(s): Schneider Electric (2020a, 2020b)

Nacelle housing, semifinished parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
glass fibre reinforced plastic, polyamide, injection moulded	19.3	t	**Ecoinvent:** market for glass fibre reinforced plastic, polyamide, injection moulded | Cutoff, U - GLO
Paint for spray painting, four layers, expressed in dry mass	0.7	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Nacelle housing, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Nacelle parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Bedplate, semifinished parts	1.0	Item(s)	Bedplate semifinised parts, delivery for turbine manufacturing - RER
HVAC, semifinished parts	1.0	Item(s)	Production of HVAC, semifinished parts, delivery for wind turbine manufacturing
Main shaft, semifinished	1.0	Item(s)	Main shaft, semifinished, delivery for wind turbine manufacturing - RER
Nacelle housing, semifinished parts	1.0	Item(s)	Nacelle housing, semifinished parts, delivery for wind turbine manufacturing - RER
Nose, semifinished parts	1.0	Item(s)	Nose, semifinished parts, delivery for wind turbine manufacturing - RER
Platform, not mounted	1.0	Item(s)	Platform parts, not mounted, delivery for turbine manufacturing - RER
Shaft bearings, not mounted	1.0	Item(s)	Production of shaft bearings - GLO
Yaw system, semifinished parts	1.0	Item(s)	Yaw system, semifinished parts, delivery for wind turbine manufacturing - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Nacelle parts	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023)

Nose, semifinished parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Cast iron structure	4.5	t	Production of cast iron structure - GLO
Low-alloyed steel, forged	2.5	t	Forging, low-alloyed steel, large open die - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Nose, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Paint for spray painting, matching four layers, for wind turbine, including transportation - RER

Input Flow	Amount	Unit	Providing process
Epoxy primer, second and third coat layer, for wind turbine	0.680	kg	Production of epoxy primer, intermediate coat layers, for wind turbine - RER
Polyurethane paint, top coat layer, for wind turbine	0.200	kg	Production of polyurethane paint, top coat layer, for wind turbine - RER
transport, freight train	0.057	t*km	**Ecoinvent:** market group for transport, freight train | Cutoff, U - RER
transport, freight, inland waterways, barge	0.028	t*km	**Ecoinvent:** market for transport, freight, inland waterways, barge | Cutoff, U - RER
transport, freight, lorry, unspecified	0.223	t*km	**Ecoinvent:** market for transport, freight, lorry, unspecified | Cutoff, U - RER
Zinc-rich epoxy paint, first layer corrosion primer, for wind turbine	0.420	kg	Production of zinc-rich epoxy paint, first layer corrosion primer, for wind turbine - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Paint for spray painting, four layers, expressed in dry mass	1.0	kg	*Unit process reference flow*

Source(s): Ecoinvent (2023), Teknos (2013)

Platform parts, not mounted, delivery for turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Cast iron structure	31.8	t	Production of cast iron structure - GLO
Low-alloyed steel, forged	17.2	t	Forging, low-alloyed steel, large open die - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Platform, not mounted	1	Item(s)	*Unit process reference flow*

Source(s): Arvesen et al. (2013), Gaertner et al. (2020), IEAWindTask37 (2023)

Production of aluminium coil - GLO

Input Flow	Amount	Unit	Providing process
aluminium, wrought alloy	1	t	**Ecoinvent:** market for aluminium, wrought alloy | Cutoff, U - GLO
sheet rolling, aluminium	1	t	**Ecoinvent:** market for sheet rolling, aluminium | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Aluminium coil	1	t	*Unit process reference flow*

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Production of cast iron structure - GLO

Input Flow	Amount	Unit	Providing process
cast iron	1.000	kg	**Ecoinvent:** market for cast iron | Cutoff, U - GLO
cast iron removed by milling, large parts	0.230	kg	**Ecoinvent:** market for cast iron removed by milling, large parts | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Cast iron structure	1.0	kg	*Unit process reference flow*

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Production of electrical cables - RER

Input Flow	Amount	Unit	Providing process
copper, cathode	222	kg	**Ecoinvent:** market for copper, cathode | Cutoff, U - GLO
electricity, medium voltage	1120	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
heat, district or industrial, natural gas	7650	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - RER
lead	264	kg	**Ecoinvent:** market for lead | Cutoff, U - GLO
polyethylene, high density, granulate	63	kg	**Ecoinvent:** market for polyethylene, high density, granulate | Cutoff, U - GLO
polypropylene, granulate	42	kg	**Ecoinvent:** market for polypropylene, granulate | Cutoff, U - GLO
steel, low-alloyed, hot rolled	394	kg	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
zinc coat, pieces	15	m2	**Ecoinvent:** market for zinc coat, pieces | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Electrical cables	1	t	*Unit process reference flow*

Source(s): Arvesen et al. (2013)

Production of electrical steel sheets - RER

Input Flow	Amount	Unit	Providing process
electricity, medium voltage	0.63	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
liquefied petroleum gas	12	g	**Ecoinvent:** market group for liquefied petroleum gas | Cutoff, U - GLO
lubricating oil	0.4	g	**Ecoinvent:** market for lubricating oil | Cutoff, U - RER
phenolic resin	1.0	g	**Ecoinvent:** market for phenolic resin | Cutoff, U - RER
quicklime, milled, packed	0.8	g	**Ecoinvent:** market for quicklime, milled, packed | Cutoff, U - RER
Silicon steel, hot rolled coil	1.140	kg	Production of silicon steel coil
sulfuric acid	19	g	**Ecoinvent:** market for sulfuric acid | Cutoff, U - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Electrical steel sheet	1.0	kg	*Unit process reference flow*
hazardous waste, for incineration	3.3	g	**Ecoinvent:** market for hazardous waste, for incineration | Cutoff, U - Europe without Switzerland
Carbon dioxide, fossil	36	g	*Elementary flow - emission to air*
Nitrogen oxides	0.1	g	*Elementary flow - emission to air*
Recyclable materials	0.114	kg	*Cut-off flow, exits from life cycle*
Sulfur dioxide	60	mg	*Elementary flow - emission to air*

Source(s): Nordelöf et al. (2017)

Production of electrolytic iron - CN

Input Flow	Amount	Unit	Providing process
electricity, medium voltage	2.0	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - CN
steel, unalloyed	1.1	kg	market for steel, unalloyed | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Electrolytic iron	1.0	kg	*Unit process reference flow*
hazardous waste, for incineration	0.25	kg	**Ecoinvent:** market for hazardous waste, for incineration | Cutoff, U - RoW

Source(s): Nordelöf et al. (2017)

Production of epoxy primer, intermediate coat layers, for wind turbine - RER

Input Flow	Amount	Unit	Providing process
4-methyl-2-pentanone	0.020	kg	**Ecoinvent:** market for 4-methyl-2-pentanone | Cutoff, U - GLO
calcium carbonate, precipitated	0.370	kg	**Ecoinvent:** market for calcium carbonate, precipitated |Cutoff, U - RER
chemical factory, organics	4.0E-10	Item(s)	**Ecoinvent:** market for chemical factory, organics | Cutoff, U - GLO
electricity, medium voltage	0.167	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
epoxy resin, liquid	0.250	kg	**Ecoinvent:** market for epoxy resin, liquid | Cutoff, U - RER
ethyl benzene	0.040	kg	**Ecoinvent:** market for ethyl benzene | Cutoff, U - RER
heat, district or industrial, natural gas	5.624	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - GLO
heat, district or industrial, other than natural gas	3.139	MJ	**Ecoinvent:** market group for heat, district or industrial, other than natural gas | Cutoff, U - GLO
isobutanol	0.045	kg	**Ecoinvent:** market for isobutanol | Cutoff, U - RER
naphtha	0.033	kg	**Ecoinvent:** market for naphtha | Cutoff, U - RER
titanium dioxide	0.100	kg	**Ecoinvent:** market for titanium dioxide | Cutoff, U - RER
trisodium phosphate	0.020	kg	**Ecoinvent:** market for trisodium phosphate | Cutoff, U - GLO
xylene	0.120	kg	**Ecoinvent:** market for xylene | Cutoff, U - RER

Output Flow	Amount	Unit	Providing process
Paint for spray painting, four layers, expressed in dry mass	1.0	kg	*Unit process reference flow*

Source(s): Ecoinvent (2023), Teknos (2013, 2016, 2020, 2022a)

Production of gas-insulated switchgear - RER

Input Flow	Amount	Unit	Providing process
aluminium, wrought alloy	1300	kg	**Ecoinvent:** market for aluminium, wrought alloy | Cutoff, U - GLO
copper, cathode	408	kg	**Ecoinvent:** market for copper, cathode | Cutoff, U - GLO
Die cast aluminium parts	650	kg	Die casting of aluminum
electricity, medium voltage	140	kWh	**Ecoinvent:** market group for electricity, medium voltage | electricity, medium voltage | Cutoff, U - RER
epoxy resin, liquid	220	kg	**Ecoinvent:** market for epoxy resin, liquid | Cutoff, U - RER
heat, district or industrial, natural gas	289	kWh	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - RER
Insulation gas	35	kg	Insulation gas mixture - RER
Low-alloyed steel parts in ready-made components	774	kg	Production of low-alloyed steel parts in ready-made subcomponents - GLO
polyvinylchloride, bulk polymerised	58	kg	**Ecoinvent:** market for polyvinylchloride, bulk polymerised | Cutoff, U - GLO
section bar extrusion, aluminium	650	kg	**Ecoinvent:** market for section bar extrusion, aluminium | Cutoff, U - GLO
sheet rolling, aluminium	650	kg	**Ecoinvent:** market for sheet rolling, aluminium | Cutoff, U - GLO
silver	0.7	kg	**Ecoinvent:** market for silver | Cutoff, U - GLO
Stainless steel parts in ready-made subcomponents	90.5	kg	Production of stainless steel parts in ready-made subcomponents - GLO
synthetic rubber	6.0	kg	**Ecoinvent:** market for synthetic rubber | Cutoff, U - GLO
tap water	0.40	t	**Ecoinvent:** market group for tap water | Cutoff, U - RER
wire drawing, copper	408	kg	**Ecoinvent:** market for wire drawing, copper | Cutoff, U - GLO
zinc coat, coils	49.6	m2	**Ecoinvent:** market for zinc coat, coils | Cutoff, U - GLO

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Output Flow	Amount	Unit	Providing process
Gas-insulated switchgear, 1 bay, 3.3 tons, 145 kV	1	Item(s)	*Unit process reference flow*

Source(s): Pai and Lohrberg (2022)

Production of HVAC, semifinished parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Low-alloyed steel parts in ready-made components	8.9	t	Production of low-alloyed steel parts in ready-made subcomponents - GLO
metal working, average for steel product manufacturing	8.9	t	**Ecoinvent:** market for metal working, average for steel product manufacturing | Cutoff, U - GLO
Paint for spray painting, four layers, expressed in dry mass	0.2	t	Paint for spray painting, matching four layers, for wind turbine, including transportation - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Hub with cone/cover, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Halton (2018)

Production of low-alloyed steel parts in ready-made subcomponents - GLO

Input Flow	Amount	Unit	Providing process
sheet rolling, steel	1	t	**Ecoinvent:** market for sheet rolling, steel | Cutoff, U - GLO
steel, low-alloyed, hot rolled	1	t	**Ecoinvent:** market for steel, low-alloyed, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Low-alloyed steel parts in ready-made components	1	t	*Unit process reference flow*

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Production of neodymium metal through fused-salt electrolysis - CN

Input Flow	Amount	Unit	Providing process
anode, graphite, for Li-ion battery	0.3	kg	**Ecoinvent:** market for anode, graphite, for Li-ion battery | Cutoff, U - CN
electricity, medium voltage	10.6	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - CN
lithium fluoride	10	g	**Ecoinvent:** market for lithium fluoride | Cutoff, U - GLO
neodymium oxide	1.3	kg	**Ecoinvent:** market for neodymium oxide | Cutoff, U - GLO
quicklime, milled, packed	45	g	**Ecoinvent:** market for quicklime, milled, packed | Cutoff, U - RoW
Output Flow	**Amount**	**Unit**	**Providing process**
Neodymium metal	1.0	kg	*Unit process reference flow*
Carbon dioxide, fossil	1.1	kg	*Elementary flow - emission to air*
Hydrogen fluoride	7	g	*Elementary flow - emission to air*
Particulate Matter, > 2.5 um and < 10um	5	g	*Elementary flow - emission to air*
sludge, NaCl electrolysis	96	g	**Ecoinvent:** market for sludge, NaCl electrolysis | Cutoff, U - GLO

Source(s): Nordelöf et al. (2017)

Production of polyurethane paint, top coat layer, for wind turbine - RER

Input Flow	Amount	Unit	Providing process
butyl acrylate	0.180	kg	**Ecoinvent:** market for butyl acrylate | Cutoff, U - RER
chemical factory, organics	4.0E-10	Item(s)	**Ecoinvent:** market for chemical factory, organics | Cutoff, U - GLO
electricity, medium voltage	0.167	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
ethyl benzene	0.030	kg	**Ecoinvent:** market for ethyl benzene | Cutoff, U - RER
heat, district or industrial, natural gas	5.624	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - GLO
heat, district or industrial, other than natural gas	3.139	MJ	**Ecoinvent:** market group for heat, district or industrial, other than natural gas | Cutoff, U - GLO
isophorondiisocyante	0.060	kg	**Ecoinvent:** market for isophorondiisocyante | Cutoff, U - RER
isopropyl acetate	0.040	kg	**Ecoinvent:** market for isopropyl acetate | Cutoff, U - RER
naphtha	0.090	kg	**Ecoinvent:** market for naphtha | Cutoff, U - RER
polyol	0.500	kg	**Ecoinvent:** market for polyol | pCutoff, U - RER
xylene	0.100	kg	**Ecoinvent:** market for xylene | Cutoff, U - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Polyurethane paint, top coat layer, for wind turbine	1.0	kg	*Unit process reference flow*

Source(s): Ecoinvent (2023), Teknos (2012, 2013, 2015, 2021a)

Production of shaft bearings - GLO

Input Flow	Amount	Unit	Providing process
metal working, average for chromium steel product manufacturing	61.5	t	**Ecoinvent:** market for metal working, average for chromium steel product manufacturing | Cutoff, U - GLO
section bar rolling, steel	61.5	t	**Ecoinvent:** market for section bar rolling, steel | Cutoff, U - GLO
steel, chromium steel 18/8, hot rolled	61.5	t	**Ecoinvent:** market for steel, chromium steel 18/8, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Shaft bearings, not mounted	1	Item(s)	*Unit process reference flow*

Source(s): Carrara et al. (2020), *and a combination of existing datasets in* Ecoinvent (2023)

Production of silicon steel coil - GLO

Input Flow	Amount	Unit	Providing process
aluminium, cast alloy	4.0	g	**Ecoinvent:** market for aluminium, cast alloy | Cutoff, U - GLO
ferrosilicon	21	g	**Ecoinvent:** market for ferrosilicon | Cutoff, U - GLO
hot rolling, steel	1.00	kg	**Ecoinvent:** market for hot rolling, steel | Cutoff, U - GLO
steel, unalloyed	0.98	kg	**Ecoinvent:** market for steel, unalloyed | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Silicon steel, hot rolled coil	1.00	kg	*Unit process reference flow*

Source(s): Nordelöf et al. (2017)

Production of stainless steel parts in ready-made subcomponents - GLO

Input Flow	Amount	Unit	Providing process
sheet rolling, chromium steel	1	t	**Ecoinvent:** market for sheet rolling, chromium steel | Cutoff, U - GLO
steel, chromium steel 18/8, hot rolled	1	t	**Ecoinvent:** market for steel, chromium steel 18/8, hot rolled | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Low-alloyed steel parts in ready-made components	1	t	*Unit process reference flow*

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Production of zinc-rich epoxy paint, first layer corrosion primer, for wind turbine - RER

Input Flow	Amount	Unit	Providing process
4-methyl-2-pentanone	0.040	kg	**Ecoinvent:** market for 4-methyl-2-pentanone | Cutoff, U - GLO
chemical factory, organics	4.0E-10	Item(s)	**Ecoinvent:** market for chemical factory, organics | Cutoff, U - GLO
electricity, medium voltage	0.167	kWh	**Ecoinvent:** market group for electricity, medium voltage | Cutoff, U - RER
epoxy resin, liquid	0.080	kg	**Ecoinvent:** market for epoxy resin, liquid |Cutoff, U - RER
ethyl benzene	0.030	kg	**Ecoinvent:** market for ethyl benzene | Cutoff, U - RER
heat, district or industrial, natural gas	5.624	MJ	**Ecoinvent:** market group for heat, district or industrial, natural gas | Cutoff, U - GLO
heat, district or industrial, other than natural gas	3.139	MJ	**Ecoinvent:** market group for heat, district or industrial, other than natural gas | Cutoff, U - GLO
xylene	0.090	kg	**Ecoinvent:** market for xylene | Cutoff, U - RER
Zinc powder	0.760	kg	Air pulverization, zinc powder production - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Zinc-rich epoxy paint, first layer corrosion primer, for wind turbine	1.0	kg	*Unit process reference flow*

Source(s): Ecoinvent (2023), Teknos (2013, 2019, 2021b, 2022b)

Rotor parts, delivery for turbine manufacturing - GLO

Input Flow	Amount	Unit	Providing process
Blade semifinished parts, 1 blade	3	Item(s)	Blade semifinished parts, delivery for turbine manufacturing - RER
Hub system, semifinished parts	1	Item(s)	Hub system, semifinished parts, delivery for wind turbine manufacturing - RER
Hub with cone/cover, semifinished parts	1	Item(s)	Hub with cone/cover, semifinished parts, delivery for turbine manufacturing - RER
Output Flow	**Amount**	**Unit**	**Providing process**
Rotor parts	1	Item(s)	*Unit process reference flow*

Source(s): Gaertner et al. (2020), IEAWindTask37 (2023)

Sandwich foam production - GLO

Input Flow	Amount	Unit	Providing process
polymer foaming	1	t	**Ecoinvent:** market for polymer foaming | Cutoff, U - GLO
styrene-acrylonitrile copolymer	1	t	**Ecoinvent:** market for styrene-acrylonitrile copolymer | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Sandwich foam	1	t	*Unit process reference flow*

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Switchgear, average transportation from supplier - GLO

Input Flow	Amount	Unit	Providing process
Gas-insulated switchgear, 1 bay, 3.3 tons, 145 kV	1	Item(s)	Production of gas-insulated switchgear - RER
transport, freight, lorry 16-32 metric ton, EURO6	5513	t*km	**Ecoinvent:** market for transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER
transport, freight, sea, container ship	13655	t*km	**Ecoinvent:** market for transport, freight, sea, container ship | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Switchgear, average transportation from supplier	1	Item(s)	*Unit process reference flow*

Source(s): Pai and Lohrberg (2022)

Transformer, average transportation from supplier - GLO

Input Flow	Amount	Unit	Providing process
Oil immersed Medium Power Transformer, 31 tons	1	Item(s)	Manufacturing of Oil immersed Medium Power Transformer, 31 tons - RER
transport, freight, lorry 16-32 metric ton, EURO6	51121	t*km	**Ecoinvent:** market for transport, freight, lorry 16-32 metric ton, EURO6 | Cutoff, U - RER
transport, freight, sea, container ship	126619	t*km	**Ecoinvent:** market for transport, freight, sea, container ship | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Oil immersed Medium Power Transformer, 31 tons	1	Item(s)	*Unit process reference flow*

Source(s): *Proxied from* Pai and Lohrberg (2022)*, switchgear transportation data scaled by mass*

Transportation of Nd(Dy)FeB magnets, intercontinental - GLO

Input Flow	Amount	Unit	Providing process
Nd(Dy)FeB magnets	1	t	Magnet production, Nd(Dy)FeB - CN
transport, freight train	1000	t*km	**Ecoinvent:** market for transport, freight train | Cutoff, U - CN
transport, freight, sea, container ship	21000	t*km	**Ecoinvent:** market for transport, freight, sea, container ship | Cutoff, U - GLO
Output Flow	**Amount**	**Unit**	**Providing process**
Nd(Dy)FeB magnets	1	t	*Unit process reference flow*

Source(s): Nordelöf, Grunditz, et al. (2019)

Treatment of non-hazardous waste, inert landfill - RoW (waste treatment process)

Input Flow	Amount	Unit	Providing process
Non-hazardous waste, for treatment	1	t	*Unit process reference flow*
process-specific burdens, inert material landfill	1	t	**Ecoinvent:** market for process-specific burdens, inert material landfill | Cutoff, U - RoW

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Treatment of non-hazardous waste, municipal waste incineration - RER (waste treatment process)

Input Flow	Amount	Unit	Providing process
Non-hazardous waste, for treatment	1	t	*Unit process reference flow*
process-specific burdens, municipal waste incineration	1	t	**Ecoinvent:** market for process-specific burdens, municipal waste incineration | Cutoff, U - Europe without Switzerland

Source(s): *Combination of existing datasets,* Ecoinvent (2023)

Yaw system, semifinished parts, delivery for wind turbine manufacturing - RER

Input Flow	Amount	Unit	Providing process
Stainless steel, forged	28	t	Forging, stainless steel, large open die - RER

Output Flow	Amount	Unit	Providing process
Yaw system, semifinished parts	1	Item(s)	*Unit process reference flow*

Source(s): Carrara et al. (2020), Gaertner et al. (2020), IEAWindTask37 (2023)

Appendix B: Result tables

Greenhouse gas emission factors per unit of mass in selected subparts, covering all life cycle steps from raw material extraction to installation of the wind turbine at sea.

Global warming potential for a 20-year time horizon	**Value**	**Unit**
Aluminum parts in PMSG	17252	kg CO$_2$-eq./ton
Concrete in hull	175	kg CO$_2$-eq./ton
Copper wire in generator windings	12631	kg CO$_2$-eq./ton
Electrical steel laminates	3394	kg CO$_2$-eq./ton
Low-alloyed steel, forged, in PMSG and 10% of monopile and tower structure	4087	kg CO$_2$-eq./ton
Low-alloyed steel, rolled, in foundation and 90% of monopile and tower structure	2666	kg CO$_2$-eq./ton
Nd(Dy)FeB-magnets	56224	kg CO$_2$-eq./ton
Paint on tower and hull (2% of mass)	6049	kg CO$_2$-eq./ton
Remaining parts[1] of 15 MW turbine, including assembly and installation at sea	3605	ton CO$_2$-eq.
Global warming potential for a 100-year time horizon	**Value**	**Unit**
Aluminum parts in PMSG	14609	kg CO$_2$-eq./ton
Concrete in hull	158	kg CO$_2$-eq./ton
Copper wire in generator windings	10754	kg CO$_2$-eq./ton
Electrical steel laminates	2851	kg CO$_2$-eq./ton
Low-alloyed steel, forged, in PMSG and 10% of monopile and tower structure	3474	kg CO$_2$-eq./ton
Low-alloyed steel, rolled, in foundation and 90% of monopile and tower structure	2255	kg CO$_2$-eq./ton
Nd(Dy)FeB-magnets	45869	kg CO$_2$-eq./ton
Paint on tower and hull (2% of mass)	4990	kg CO$_2$-eq./ton
Remaining parts[1] of 15 MW turbine, including assembly and installation at sea	3023	ton CO$_2$-eq.

1. "Remaining parts" refer to all parts of the nacelle and the rotor, including blades, except for the generator.

Complementary midpoint indicators – 15 MW wind turbines with floating foundation

ReCiPe 2016 v1.03, midpoint (H)	**Reference - floating foundation, option (1)**	**Hagnesia – floating foundation, option (2)**	**Unit**
Acidification: terrestrial - terrestrial acidification potential (TAP)	6.42E+04	5.08E+04	kg SO$_2$-eq.
Ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	2.10E+06	1.59E+06	kg 1,4-DCB-eq.
Ecotoxicity: marine - marine ecotoxicity potential (METP)	2.86E+06	2.18E+06	kg 1,4-DCB-eq.
Ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	1.89E+08	1.44E+08	kg 1,4-DCB-eq.
Energy resources: non-renewable, fossil - fossil fuel potential (FFP)	4.66E+06	3.93E+06	kg oil-eq.
Eutrophication: freshwater - freshwater eutrophication potential (FEP)	8.59E+03	7.08E+03	kg P-eq.
Eutrophication: marine - marine eutrophication potential (MEP)	8.54E+03	1.49E+03	kg N-eq.
Human toxicity: carcinogenic - human toxicity potential (HTPc)	2.00E+07	1.80E+07	kg 1,4-DCB-eq.
Human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	3.29E+07	2.43E+07	kg 1,4-DCB-eq.
Ionising radiation - ionising radiation potential (IRP)	8.28E+05	6.38E+05	kBq Co-60-eq.
Land use - agricultural land occupation (LOP)	5.50E+05	3.45E+05	m^2*a crop-eq.
Material resources: metals/minerals - surplus ore potential (SOP)	5.81E+07	6.89E+06	kg Cu-eq.
Ozone depletion - ozone depletion potential (ODPinfinite)	4.41E+00	3.51E+00	kg CFC-11-eq.
Particulate matter formation - particulate matter formation potential (PMFP)	3.72E+04	3.08E+04	kg PM2.5-eq.
Photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	4.94E+04	4.12E+04	kg NOx-eq.
Photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	5.26E+04	4.40E+04	kg NOx-eq.
Water use - water consumption potential (WCP)	1.87E+05	1.58E+05	m^3

Complementary midpoint indicators – 15 MW wind turbines with monopile foundation

ReCiPe 2016 v1.03, midpoint (H)	Reference - monopile foundation, option (3)	Hagnesia – monopile foundation, option (4)	Unit
Acidification: terrestrial - terrestrial acidification potential (TAP)	4.12E+04	3.27E+04	kg SO_2-eq.
Ecotoxicity: freshwater - freshwater ecotoxicity potential (FETP)	1.33E+06	1.06E+06	kg 1,4-DCB-eq.
Ecotoxicity: marine - marine ecotoxicity potential (METP)	1.80E+06	1.44E+06	kg 1,4-DCB-eq.
Ecotoxicity: terrestrial - terrestrial ecotoxicity potential (TETP)	1.31E+08	1.06E+08	kg 1,4-DCB-eq.
Energy resources: non-renewable, fossil - fossil fuel potential (FFP)	3.31E+06	2.85E+06	kg oil-eq.
Eutrophication: freshwater - freshwater eutrophication potential (FEP)	5.18E+03	4.30E+03	kg P-eq.
Eutrophication: marine - marine eutrophication potential (MEP)	8.05E+03	1.07E+03	kg N-eq.
Human toxicity: carcinogenic - human toxicity potential (HTPc)	1.10E+07	1.02E+07	kg 1,4-DCB-eq.
Human toxicity: non-carcinogenic - human toxicity potential (HTPnc)	2.12E+07	1.62E+07	kg 1,4-DCB-eq.
Ionising radiation - ionising radiation potential (IRP)	6.93E+05	5.44E+05	kBq Co-60-eq.
Land use - agricultural land occupation (LOP)	3.93E+05	2.13E+05	m^2*a crop-eq.
Material resources: metals/minerals - surplus ore potential (SOP)	5.62E+07	5.23E+06	kg Cu-eq.
Ozone depletion - ozone depletion potential (ODPinfinite)	3.18E+00	2.51E+00	kg CFC-11-eq.
Particulate matter formation - particulate matter formation potential (PMFP)	2.31E+04	1.92E+04	kg PM2.5-eq.
Photochemical oxidant formation: human health - photochemical oxidant formation potential: humans (HOFP)	3.01E+04	2.51E+04	kg NOx-eq.
Photochemical oxidant formation: terrestrial ecosystems - photochemical oxidant formation potential: ecosystems (EOFP)	3.20E+04	2.68E+04	kg NOx-eq.
Water use - water consumption potential (WCP)	9.72E+04	7.90E+04	m^3

DEPARTMENT OF TECHNOLOGY
MANAGEMENT AND ECONOMICS
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden
www.chalmers.se

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