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A prospective life cycle assessment of drivetrain technologies in offshore wind

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Abstract.
This study employs a prospective life cycle assessment (pLCA) to evaluate the environmental impacts of two drivetrain configurations, direct drive (DD) and medium-speed (MS), at the wind farm level across the entire life cycle. The assessment considers how environmental impacts evolve in the future, reflecting projected changes in macroeconomic indicators and climate targets. The DD configuration shows higher impacts in the material extraction and production phase due to its reliance on critical metals and rare earth elements, which is also offset in the long term through recycling benefits at the end-of-life (EOL) stage. In contrast, the MS configuration has greater emissions during operations, requiring more drivetrain-related maintenance and component replacements, while the DD configuration benefits from lower maintenance demands. The total climate change impact for DD is 6.8 g CO_2-eq/kWh, while for MS, it is slightly higher at 7.1 g CO_2-eq/kWh. A comparison of static LCA and pLCA highlights key differences, particularly in the operational phase, where pLCA indicates lower emissions due to anticipated improvements in supply chains, such as greater use of renewable-powered refineries for vessel fuel. However, pLCA accounts for recycling benefits over time rather than immediately, leading to lower avoided burdens at EOL compared to static LCA. Beyond climate change, metal depletion is a key impact category, with DD showing a 12% higher impact due to its reliance on copper and rare earth elements, while MS exhibits higher emissions from fuel-intensive operations. This study demonstrates the prospective approach for conducting LCA, emphasizing the importance of integrating future technologies and processes in environmental impact assessments for offshore wind.

1 Introduction

The European Union (EU) has set an ambitious target to reduce greenhouse gas emissions by 55% from 1990 levels by 2030 [2]. To achieve this goal, the share of renewable energy in the EU's energy mix must increase from 32% to 40% [3], requiring a substantial expansion in wind power capacity to approximately 450 GW [4]. Offshore wind energy (OWE) will play a critical role in meeting this demand, with turbine sizes continuing to increase. Currently, the largest commercially available wind turbines have a capacity of 16 MW, with prototypes reaching up to 20 MW [5], and future models projected to exceed 25 MW [6].

A significant increase in turbine capacity is facilitated by more robust drivetrains, which play a crucial role in addressing key factors such as cost, weight, size, manufacturing, material selection, efficiency, reliability, operation and maintenance (O&M), and end-of-life considerations. A key component of the

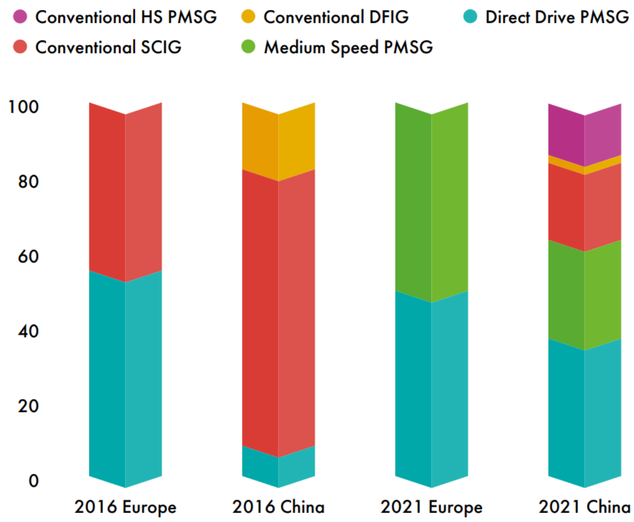

Figure 1: Drivetrain technology market share in Europe and China for 2016 and 2021. Europe shows a shift towards direct drive and medium speed PMSG, while China still relies heavily on conventional geared systems [1].

drivetrain is the wind turbine generator, which can be broadly classified into two types: geared systems and direct drive (DD). Geared systems utilize one or more stages of gearing, commonly configured as high-speed or medium-speed (MS), to convert the rotor's low-speed rotational motion into the higher speeds required by the generator. In contrast, DD systems eliminate the need for gears, employing generators that directly convert mechanical energy into electrical energy, simplifying the drivetrain design.

The Global Wind Energy Council (GWEC) has identified trends in the offshore wind drivetrain market, as illustrated in Figure 1, highlighting differences between Europe and China up to 2021 [1]. In Europe, there has been a clear transition toward DD and MS designs, with the use of Squirrel Cage Induction Generators (SCIG) ceasing entirely after 2016. Conversely, in China, the adoption of DD systems has gradually increased, although the majority of turbines still rely on geared systems. This indicates that DD and MS are the dominant drivetrain technologies in both regions.

A compact and lightweight drivetrain offers the most cost-effective solution for large offshore wind turbines by reducing nacelle mass. This, in turn, lowers the mass and cost associated with the tower, foundation, or floating platform by minimizing structural loads. While cost has traditionally been the primary focus of OWE projects, there is an increasing emphasis on non-price considerations, particularly environmental impacts. This shift is driven by evolving policies, as European governments are increasingly incorporating environmental criteria into upcoming wind farm tenders, where such considerations can account for up to 30% of evaluation scores [7]. Wind turbine generators, in particular, often rely on critical raw materials such as rare earth elements (REEs), which have significant environmental implications related to their extraction, processing, operation, and end-of-life management [8]. As a result, a structured assessment of drivetrain technology selection in OWE based on environmental impact has become standard practice.

Life Cycle Assessment (LCA) is a widely adopted methodology for evaluating the environmental impacts of OWE projects across their entire lifecycle, from raw material extraction to end-of-life. Existing LCA studies have compared the environmental impacts of different wind turbine drivetrain designs [9, 10, 11]. For instance, Schreiber et al. [9] analyzed onshore wind turbines with a 3 MW rating, considering three drivetrain configurations: a geared converter with a doubly-fed induction generator (DFIG), a direct-driven synchronous generator electrically excited, and a direct-drive permanent magnet synchronous generator. The study found that environmental impacts were primarily concentrated in the manufacturing phase of the nacelle, driven by materials such as copper, steel, and, in the case of DD systems, REEs. It also highlighted that DD configurations exhibited higher environmental impacts than geared systems across multiple categories. Additionally, Schreiber et al. noted that incorporating future recycling options could alter these results. A key limitation of this and similar studies is their reliance on static life cycle inventories, which are based on past and present technologies and processes.

These inventories typically reflect industrial practices from the last 5–15 years, depending on database updates, and often fail to account for technological advancements, shifts in energy production methods, or evolving environmental policies. Given that OWE projects now frequently exceed a lifespan of 35 years, integrating future developments in supply chains and technology is essential for a more prospective and forward-looking assessment of environmental impacts.

To better capture the dynamic nature of environmental impacts over time, this research employs a prospective Life Cycle Assessment (pLCA) approach. This method incorporates prospective inventories that reflect anticipated changes in the supply chain, such as advancements in transportation efficiency and a growing share of renewable energy in the electricity mix. These changes are modeled using macroeconomic indicators such as population growth, economic development, and technological progress—outlined in the Shared Socioeconomic Pathways (SSPs) and linked to future greenhouse gas concentration scenarios described by the Representative Concentration Pathways (RCPs). The study leverages Premise, a tool that integrates Ecoinvent life cycle inventories with evolving supply chain data, to create a dynamic background database for pLCA. By combining traditional LCA with pLCA approaches, the environmental impacts of DD and MS drivetrain technologies, commonly used in 15 MW offshore wind turbines, are assessed at the wind farm level over their entire operational lifetime.

The paper is organized as follows. Section 2 describes the methodology employed in this study. Section 3 defines the goal and scope of the assessment, specifying the system boundaries, functional unit, and key assumptions for comparing DD and MS drivetrain technologies. Section 4 presents the life cycle impact assessment (LCIA) results and evaluates the findings within the context of the pLCA framework. Finally, Section 5 summarizes the main conclusions and provides recommendations for future research.

2 Methodology

The pLCA study complies with ISO 14040:2006 and ISO 14044:2006 standards [12], ensuring a comprehensive evaluation of environmental impacts while accounting for changes in the future depending on the scenario. It incorporates forecasted trends of macroeconomic indicators and climate targets [13]. The assessment evaluates the environmental impacts of two generator types throughout their lifecycle, from cradle to grave, including recycling, using a reference wind farm as a case study, which is detailed in the following section. In this pLCA study, the foreground data, representing direct processes related to wind turbine components and operations, remain consistent with those used in the current time LCA. However, the background data, which account for upstream and external processes such as energy production and material supply, vary according to the time of the life cycle phase being considered.

The analysis was conducted using Brightway 2.0, supported by the Ecoinvent v3.9.1 database as the primary dataset. To explore environmental impacts under various climate mitigation scenarios, this study incorporates external development pathways based on the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs), derived from Integrated Assessment Models (IAMs) [12]. The open-source Python library Premise was utilized to integrate built-in IAM estimates, incorporating sectoral changes in energy and transportation into the Ecoinvent database [14].

The IAM model IMAGE was selected under the SSP2-RCP1.9 scenario, representing a stringent mitigation pathway that stabilizes radiative forcing at 1.9 W/m^2 by 2100, aligning with the goal of limiting global warming to below 1.5°C [15]. SSP2, often referred to as the 'middle of the road' scenario, reflects a world where global development proceeds at a moderate pace, balancing economic growth, population dynamics, and technological advancements without extreme shifts toward sustainability or regional fragmentation. This scenario envisions gradual progress in climate mitigation and adaptation, in contrast to more aggressive sustainability efforts (SSP1) or heightened inequality (SSP3). IMAGE models these transitions by focusing on shifts in the global energy mix, reduced dependence on fossil fuels, and increased material efficiency. By incorporating socio-economic factors such as urbanization and technological innovation, the study captures a future where global cooperation and moderate technological progress drive emissions reductions while maintaining economic stability. Brightway's integrated visualization tool, the Activity Browser, was used to analyze and interpret the results effectively [16].

3 Goal and scope definition

The goal of this study is to assess the environmental impacts of two widely used drivetrain configurations for offshore wind turbines throughout their life cycle: DD and MS. The analysis is based on the IJmuiden Ver wind farm site [17], located in the North Sea, which serves as the reference location. This wind farm is planned to consist of 134 bottom-fixed wind turbines with a total installed capacity of 2 GW. The design and layout of the wind farm are based on publicly available site boundary data, though future developments may influence the final layout configuration. In the absence of specific turbine coordinates,

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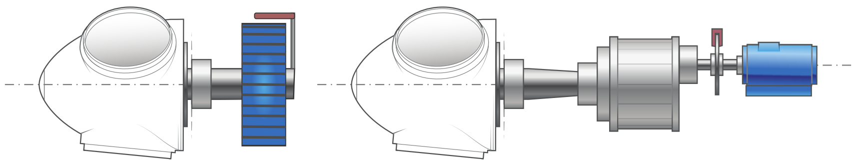
Table 1: Graphical representation of Direct Drive (DD) and Medium-Speed (MS) gearbox wind turbine generators (top) and key parameters for the reference wind farm (bottom). The table outlines the parameters used for comparing two generator types, including the number of turbines, wind farm lifetime, expected average wind speed, and annual production per turbine.



Parameter	**Value**	**Unit**
Number of turbines	134	-
Lifetime of wind farm	35	years
Array cables distance	2.40	km
Export cables distance	62	km
Manufacturer distance	600	km
Expected average wind speed	10	m/s
Annual production (DD)	77.5	GWh/year
Annual production (MS)	75	GWh/year

a uniform distribution of turbines within the wind farm area is assumed. For this study, turbines are rated at 15 MW each.

The difference in annual production between the two drivetrain configurations is determined based on their respective capacity factors, assumed to be 59% for DD and 57% for MS [18, 19]. These values are conservative estimates derived from discussions and verifications with OEMs. While subject to potential revision as turbine configurations evolve, these capacity factors provide a representative basis for the analysis. The key parameters used in the study are outlined in Table 1. These estimates form the foundation of the analysis, which may vary depending on factors such as wind farm design, drivetrain configuration, and supply chain developments.

3.1 System boundaries
The system boundaries for the pLCA of the wind farm, as shown in Figure 2, encompass the entire life cycle of the wind farm. The pLCA considers emissions to air, water, and land, including all significant stages, starting with material extraction and manufacturing (2025) and concluding with decommissioning and end-of-life treatment (post-2060).

3.2 Scope and functional unit
The scope of this study includes wind turbines, foundations, array cables, offshore substations, and export cables leading to the onshore substation, as illustrated in Figure 2. Elements beyond the export cables are excluded from the system boundary. The functional unit for this study is 1 kilowatt-hour (kWh) of electricity generated by the wind farm.

3.3 Cut-off Criteria and limitations
This study applies specific cut-off criteria to ensure that all relevant environmental impacts are considered. Material flows contributing less than 0.1% of the total mass or energy flows accounting for less than 1% of the total energy at the product level are excluded unless they are determined to be environmentally significant. The cumulative impact of excluded material flows does not exceed 5% of the total mass, energy, or environmental significance. The analysis accounts for over 99% of the total mass of materials used in the wind turbines, including all major components. Additionally, a limitation of this study is the availability of inventory data for turbine components. When specific data were unavailable, values were estimated using scaling laws.

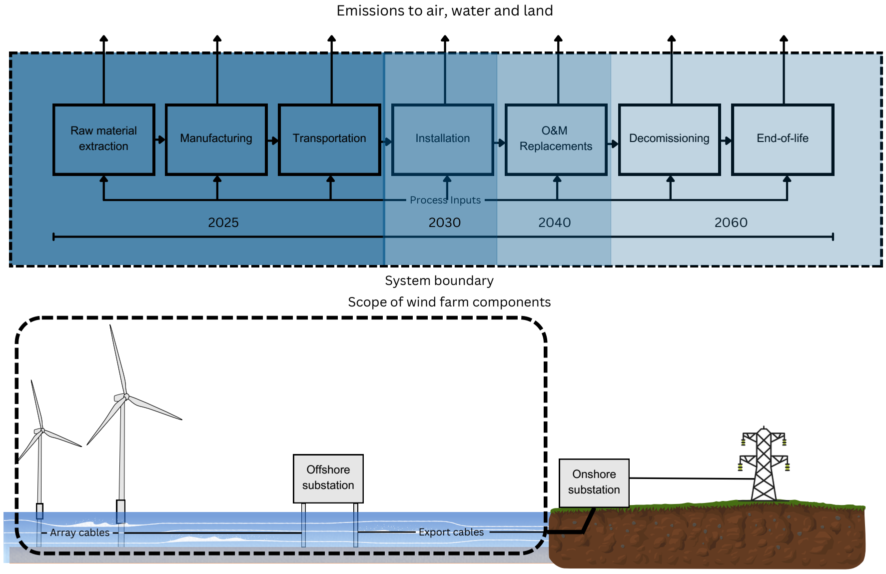


Figure 2: System boundary diagram for the life cycle assessment of the wind farm, illustrating the phases considered: material extraction and production, manufacturing, transportation, installation, operations and maintenance (O&M) including replacements, decommissioning, and end-of-life treatment. The scope includes components of the wind farm such as turbines, offshore and onshore substations, array cables, and export cables. Emissions to air, water, and land are also represented throughout the different stages of the wind farm's lifecycle, spanning from 2025 to 2060.

3.4 Inventory analysis

The life cycle inventory for modeling different phases is based on publicly available literature, with a detailed breakdown provided in the Supplementary Material. Material compositions of turbine components are often proprietary and subject to restrictions imposed by OEMs. To address this, a detailed material inventory for the DTU reference 15 MW turbine, obtained from [20], is used.

Offshore operations, including installation, operation and maintenance (O&M), component replacements, and decommissioning, require offshore activities that lead to fuel consumption. These operations are modeled using TNO UWiSE, an in-house operations modeling software that utilizes component reliability data and operational procedures to estimate the duration of offshore activities throughout the wind farm's lifetime. These durations are then used to calculate fuel consumption based on different vessel activities. For this study, Marine Gas Oil (MGO) fuel is considered for the various vessels, including scope 3 emissions associated with fuel production and supply.

For end-of-life treatment, avoided burdens for materials such as steel, aluminum, and copper are calculated using data from the Nationale Milieu Database (NMD). Non-metallic materials such as epoxy, polyurethane, and glass fiber are modeled for incineration. Magnet recycling is assessed using a hydrogen decrepitation-based method.

Changes in the background system of the inventory account for material use in 2025, installation in 2030, O&M and replacement activities between 2030 and 2060, and decommissioning and end-of-life processes beginning in 2060. Differences in life cycle phases due to drivetrain design variations are particularly observed in material use, offshore operations, and end-of-life processes. These variations form the basis for the subsequent impact assessment.

- Material composition: The material composition differences between DD and MS configurations are based on the study by Khazaeli Moghadam and Desch [21] and summarized in Table 2.

  The DD generator weighs 185.3 tons, significantly more than the 57.6 tons of MS, due to its larger structural requirements and higher demand for active materials such as copper, permanent magnets, and steel. DD generators require 10.9 tons of permanent magnets, which is 91% more than MS, and 20.5 tons of copper, representing a 71% increase. In contrast, MS incorporates a two-stage gearbox that reduces generator size and weight while redistributing mechanical stresses.

Table 2: Generator specifications: weight comparison for DD and MS systems [21].

Specification	**DD (ton)**	**MS (ton)**
Armature copper weight	20.466	5.842
Permanent magnet weight	10.904	0.961
Stator core weight	38.785	10.642
Rotor core weight	14.497	7.860
Total active material weight	84.653	25.306
Approximated structure weight	100.630	32.250
Total weight	185.283	57.556

Table 3: Failure rates of DD and MS drivetrain components assumed for modeling offshore logistics [22].

Component	**Failure mode**	**DD (λ)**	**MS (λ)**
Gearbox	Replacement	n/a	0.022
	Planet wheel repair	n/a	0.05
	Other minor repair	n/a	0.32
Generator	Replacement	0.021	0.01
	Bearing replacement	0	0
	Bearing repair	0.196	0
	Other minor repair	0.22	0.22
Main bearing	Replacement	0.015	0.009
	Repair	0.062	0.006

Beyond the generator, drivetrain-related material differences may influence other turbine components. DD requires a larger nacelle, potentially increasing composite material use, while MS relies more on cast iron and high-strength steel for the gearbox. Differences in weight distribution and load dynamics may also impact foundation designs. However, this study focuses on differences in drive-train's material composition, with broader structural variations beyond its scope.

- Offshore operations: O&M, including component replacements, varies between DD and MS due to drivetrain-related failure rates, while non-drivetrain components are assumed to have equivalent failure rates. Table 3, adopted from [22], summarizes these differences, expressed as λ (failures/turbine·year), and is used to estimate fuel consumption during logistic operations. DD turbines have a higher generator failure rate ($\lambda = 0.021$) than MS ($\lambda = 0.01$), leading to fewer generator replacements over 35 years. However, DD has a higher main bearing failure rate ($\lambda = 0.015$ vs. $\lambda = 0.009$ for MS), as the absence of a gearbox increases mechanical loads on the bearing.

  MS turbines require more frequent gearbox-related maintenance, with a gearbox replacement rate of $\lambda = 0.022$, a planet wheel repair rate of $\lambda = 0.05$, and minor gearbox repairs at $\lambda = 0.32$ [23]. The complexity and downtime associated with these failures result in higher maintenance demands. Advancements in turbine design and monitoring have improved reliability. DD benefits from modular generator designs that allow partial replacements, while MS reliability has improved with fewer gearbox stages. Condition-based monitoring further reduces failure risks by enabling early fault detection [22].

- End-of-life: The EOL process for wind turbine components involves a combination of recycling, incineration, or disposal, as outlined in the Supplementary Material. This study focuses on drivetrain components, specifically considering the hydrogen decrepitation process for magnet recycling [24]. Hydrogen decrepitation is expected to achieve a 60% reduction in virgin material use, with 60% of the final magnet consisting of recycled powder and 40% composed of newly added neodymium, dysprosium, and other alloys. The total availability of NdFeB magnets for recycling depends on drivetrain configurations, as outlined in the material composition phase. Further details on the process and energy usage can be found in the Supplementary Material.

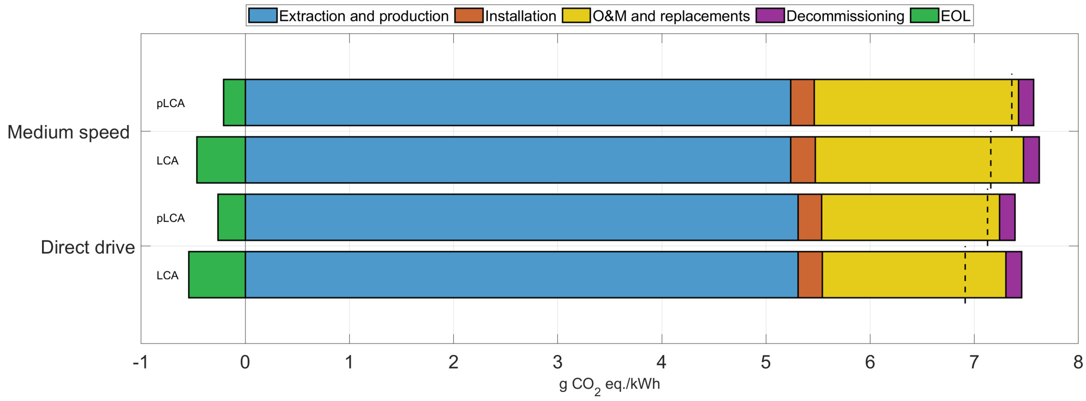


Figure 3: Comparison of global warming potential (GWP100) for DD and MS systems in g CO_2 eq./kWh, using pLCA and LCA. Bars show contributions from different life cycle phases. The dashed line indicates the total aggregated GWP100.

4 Results and interpretation

Based on the inventory described in the previous section, the environmental impacts of the wind farm over its life cycle are assessed for both drivetrain configurations. First, the impact on climate change is evaluated, with results from both static and pLCA approaches presented and discussed. Subsequently, other impact indicators from the pLCA are compared and analyzed.

4.1 Impact on climate change

The impact on climate change is expressed in g CO_2-eq/kWh, accounting for the contributions of various greenhouse gases using the global warming potential (GWP) indicator. As shown in Figure 3, the total impact in the static LCA is 6.9 g CO_2-eq/kWh for DD and 7.2 g CO_2-eq/kWh for MS, representing a difference of approximately 3.4%.

The largest contributor to climate impact in both configurations is the extraction and production phase, which includes raw material extraction and the production of key components such as steel. For DD, extraction and production accounts for 5.3 g CO_2-eq/kWh , while for MS, it contributes 5.2 g CO_2-eq/kWh. Additionally, materials such as copper, fiberglass, and rare earth elements further add to the extraction and production impact.

The O&M phase also plays a significant role, emphasizing the differences between the two configurations. In the static LCA, O&M emissions are 1.8 g CO_2-eq/kWh for DD and 2.0 g CO_2-eq/kWh for MS. The higher impact in MS is primarily due to increased drivetrain-related maintenance, leading to greater fuel consumption during offshore operations.

A comparison of pLCA and static LCA highlights key differences. Unlike the static approach, which evaluates all phases under current conditions, pLCA accounts for prospective changes in the background system starting from the installation phase while keeping the foreground system unchanged. The prospective approach leads to slight improvements in the operations phase, particularly in O&M, with DD decreasing to 1.7 g CO_2-eq/kWh and MS reducing to 1.95 g CO_2-eq/kWh. These reductions result from prospective improvements in the supply chain, such as increased reliance on renewable-powered refineries for vessel fuel production. Consequently, emissions associated with operational phases in the OWE lifecycle are lower in pLCA.

The EOL phase has a positive environmental impact, represented on the negative axis in Figure 3, due to material recovery and recycling. However, avoided burdens in pLCA are less favorable than in static LCA. In static LCA, avoided burdens are calculated in the same year for both manufacturing and EOL, leading to greater recycling benefits. In contrast, in pLCA, where the EOL phase occurs around 2060, the benefits of recycling are not directly attributed to the extraction phase due to assumptions about future material recovery efficiencies and projections based on prospective inventories. As a result, avoided burdens are lower, with DD at -0.3 g CO_2-eq/kWh and MS at -0.2 g CO_2-eq/kWh.

Table 4: Comparison of different midpoint indicator values for DD and MS systems.

Impact Category	**Unit**	**DD**	**MS**	**MS/DD**
Acidification	mol H^+-eq.	5.4×10^{-5}	5.4×10^{-5}	1.01
Climate Change	kg CO_2-eq.	6.8×10^{-3}	7.1×10^{-3}	1.03
Ecotoxicity	CTUe	5.5×10^{-2}	5.5×10^{-2}	0.99
Non-Renewable Energy	MJ net cal. val.	9.1×10^{-2}	9.3×10^{-2}	1.03
Eutrophication Freshwater	kg P-eq.	2.1×10^{-6}	2.1×10^{-6}	1.00
Eutrophication Marine	kg N-eq.	1.9×10^{-5}	1.9×10^{-5}	1.03
Eutrophication Terrestrial	mol N-eq.	1.8×10^{-4}	1.9×10^{-4}	1.06
Toxicity Carcinogenic	CTUh	3.7×10^{-11}	3.8×10^{-11}	1.04
Toxicity Non-Carcinogenic	CTUh	2.9×10^{-10}	2.8×10^{-10}	0.99
Ionising Radiation	kBq U_{235}-eq.	6.2×10^{-4}	6.1×10^{-4}	0.99
Land Use	m^2a	2.6×10^{-2}	2.5×10^{-2}	0.98
Abiotic Depletion Metals	kg Sb-eq.	1.9×10^{-7}	1.6×10^{-7}	0.88
Ozone Depletion	kg CFC_{11}-eq.	4.0×10^{-10}	4.0×10^{-10}	1.01
Particulate Matter	Health incidences	4.3×10^{-10}	4.4×10^{-10}	1.03
Photochemical Oxidants	kg NMVOC-eq.	5.4×10^{-5}	5.7×10^{-5}	1.05
Water Use	m^3 world eq. deprived	2.9×10^{-3}	2.8×10^{-3}	0.96

4.2 Other environmental impacts

Comparing the pLCA results for different environmental impact indicators between the DD and MS configurations reveals distinct differences. Table 4 presents the midpoint indicator values for both drivetrain configurations, providing insights into their relative environmental performance. The MS/DD ratio column offers a direct comparison, highlighting areas where one configuration imposes a greater environmental burden than the other.

The most significant difference is observed in the metal depletion indicator, where the MS/DD ratio is 0.88, indicating that the DD configuration has a notably higher impact due to its greater reliance on critical raw materials, such as copper and rare earth elements. This increased impact stems from the higher consumption of these materials in DD compared to MS, driven by the absence of a gearbox, which necessitates the use of a larger generator with higher amounts of permanent magnets. Additionally, this impact considers the depletion of these materials in the future under the prospective EoL approach, where material recovery rates and recycling efficiencies may evolve, influencing resource availability.

The higher impacts of the DD configuration in resource-intensive categories are also evident, particularly in those linked to the extraction and processing of critical materials. For instance, in land use, the MS/DD ratio is 0.98, reflecting a slightly greater impact for DD due to mining activities associated with raw material extraction. Similarly, in water use, the MS/DD ratio of 0.96 indicates a somewhat higher demand for DD, reinforcing its greater resource intensity.

However, in several categories, the environmental impacts of both configurations are nearly identical. This is observed in acidification, ecotoxicity, non-carcinogenic human toxicity, ionizing radiation, and ozone depletion. The similarity in these impacts suggests that drivetrain configuration variations do not significantly alter the environmental burden in these categories.

Conversely, the MS configuration exhibits higher impacts in categories associated with fuel consumption and operational emissions, primarily due to its increased maintenance requirements and the resulting energy and fuel demands for vessel operations. The most pronounced differences appear in terrestrial eutrophication, where the MS/DD ratio is 1.06, reflecting higher emissions from more frequent maintenance activities and vessel fuel combustion. A similar trend is observed in photochemical ozone formation, with an MS/DD ratio of 1.05, highlighting the contribution of operational emissions to atmospheric reactions that lead to ground-level ozone formation. Particulate matter formation follows this pattern, with a ratio of 1.03, further reinforcing the increased emissions associated with the MS configuration's operation. These impacts stem from the greater frequency of vessel trips for maintenance, which leads to higher exhaust emissions, particularly from diesel-powered support vessels operating offshore.

5 Conclusions

This study presented a pLCA approach to evaluate the environmental impacts of two drivetrain configurations, DD and MS, at the wind farm level. By incorporating a temporal scale, the assessment considered how environmental impacts evolve in the future, reflecting changes in macroeconomic indicators and climate targets.

The comparative assessment of climate change impacts revealed notable differences between the two drivetrain configurations. The DD configuration exhibited a total impact of 6.8 g CO_2-eq/kWh, while the MS configuration had a slightly higher value of 7.1 g CO_2-eq/kWh. The DD configuration showed a higher impact in the material extraction and production phase due to its greater reliance on critical metals and rare earth elements. However, this initial impact could potentially be offset in the long term through recycling benefits at the end-of-life (EOL) stage, contributing to environmental gains. In contrast, difference between the configurations was observed in the operational phase. The MS configuration requires more drivetrain-related maintenance and component replacements, leading to increased emissions from operational activities, whereas the DD configuration benefits from lower maintenance requirements, reducing its overall O&M-related impact.

A comparison between static LCA and pLCA results further highlighted key differences. In the operational phase, the pLCA approach indicated a reduction in emissions, largely driven by anticipated improvements in the supply chain, such as a greater reliance on renewable-powered refineries for vessel fuel production in offshore operations. However, the environmental benefits at EOL were lower in pLCA compared to static LCA. This difference stems from how avoided burdens from recycling are accounted for, with pLCA distributing these benefits over time rather than applying them immediately, as done in static LCA.

Beyond climate change impacts, the evaluation of other environmental indicators identified metal depletion as the most significant category of difference between the drivetrain configurations. The DD configuration exhibited a 12% higher impact in this category due to its larger material requirements for active materials such as copper and rare earth elements used in permanent magnets. This greater reliance on critical raw materials significantly contributes to resource depletion. Conversely, the MS configuration showed higher impacts in categories linked to fuel consumption and operational emissions, primarily due to its greater maintenance demands throughout its operational lifetime.

This study evaluated a single prospective scenario for drivetrain configurations in offshore wind energy, providing a structured framework for future LCA studies in the sector. A more comprehensive assessment would incorporate multiple prospective scenarios, allowing stakeholders to better understand and anticipate the evolving environmental impacts of their technologies and projects. Integrating such scenario-based approaches into decision-making processes could enhance sustainability assessments and support more informed choices in offshore wind energy development.

Supplementary Material

The Supplementary Material includes the detailed inventory data for the different life cycle phases used in this assessment. It can be obtained by contacting the corresponding author.

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