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Evaluating cost and environmental impacts of offshore wind drivetrain technologies

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Abstract. This study presents a holistic techno-economic and environmental assessment framework for offshore wind projects at the wind-farm level, integrating capital and operational cost modelling with life-cycle emissions accounting and operational simulation to evaluate how design choices influence project performance. While the framework is generally applicable to offshore wind systems, it is applied here to drivetrain technologies, given their importance for turbine mass, material use, installation, and O&M. A representative case study is conducted for a 2 GW offshore wind farm employing 15 MW turbines based on the IEA reference configuration and site conditions representative of IJmuiden Ver. An early-stage OptiGen drivetrain case is then assessed by modifying generator- and power-converter-related reliability assumptions using uncertainty bands of $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$, and by replacing JUV-based heavy-lift major component replacement campaigns with SOV-based in-situ interventions. The results show that, while CapEx, installation costs, and pre-commissioning emissions remain unchanged, the OptiGen case reduces average annual OpEx from 78.0 to 67.9 k€/MW/year and annual operational emissions from 0.0095 to 0.0074 ktonnes CO₂-eq./MW/year. These findings demonstrate that drivetrain-related design changes can already produce measurable operational and environmental benefits at feasibility stage, while highlighting the value of integrated assessment for guiding future offshore wind technology development.

1. Introduction

The European Union (EU) has established an ambitious climate agenda, aiming to reduce greenhouse gas (GHG) emissions by 55% relative to 1990 levels by 2030 and to achieve full climate neutrality by 2050 [1]. Offshore wind energy is expected to play a central role in this transition, with planned deployment projected to reach 160 GW of installed capacity by 2030 [2]. Achieving this target will require a fivefold increase in annual installation rates compared with historical trends, thereby posing significant financial and environmental challenges for the sector.

Offshore wind projects are highly capital-intensive, with investment requirements estimated at approximately 3 billion € per gigawatt (GW) of installed capacity [3]. Although capital expenditure (CapEx) dominates the development phase, operational expenditure (OpEx) remains a critical cost driver throughout the lifetime of wind farms. As the sector matures, project evaluations increasingly extend beyond purely financial metrics to incorporate environmental considerations. This shift is reflected in recent competitive tenders that include non-price criteria, such as carbon footprint, in order to promote more environmentally sustainable project development [2, 4]. The concurrent emphasis on cost efficiency and





Figure 1. Schematic illustration of the OptiGen drivetrain concept with wheel–rail support system and reduced air-gap dependency on generator diameter.

environmental performance underscores the need to assess lifecycle costs alongside environmental trade-offs when making design choices for offshore wind projects.

Within this context, the wind energy industry has pursued upscaling strategies, developing larger rotor diameters and higher turbine power ratings in order to capture cost efficiencies at the wind farm level. However, beyond a certain threshold, further upscaling yields diminishing returns, as larger turbine sizes no longer necessarily deliver economies of scale. Among the various contributing factors, a key limitation arises from the nonlinear growth of the rotor–nacelle assembly (RNA) with turbine capacity [5]. The disproportionately increasing RNA mass not only raises CapEx and OpEx, but also intensifies environmental impacts through greater demand for critical raw materials, including rare-earth elements and high-grade structural alloys. In addition, the increased RNA weight imposes greater demands on supporting structural components such as the tower, substructure, and foundation, thereby further compounding overall project costs.

A central driver of these challenges is generator design, which constitutes a major share of RNA mass. Consequently, generator selection has become a decisive factor influencing both financial and environmental outcomes [6]. To address this issue, LIGHTWIND, funded under the EU Horizon programme, investigates a novel lightweight drivetrain architecture with modular characteristics, offering scalability to power ratings beyond 15 MW. This concept is intended to achieve a significant reduction in RNA mass while extending lifetime, thereby offering the potential for substantial cost savings and notable environmental benefits.

Current research on offshore wind largely overlooks the cost estimation of wind technologies and, in this context, the impact of drivetrain choices. Where such analyses do exist, they seldom integrate both economic and environmental perspectives. The overarching objective of this study is therefore to conduct a holistic comparative evaluation of drivetrain technologies, considering their financial (CapEx and OpEx) and environmental impacts across the entire lifecycle, encompassing both capital investment and operational phases. By combining these perspectives, this work aims to establish a comprehensive framework for evaluating how design choices in wind energy systems influence the long-term financial and environmental viability of offshore wind projects, while also providing a transferable basis for assessing other critical design decisions.

The remainder of this paper is organised as follows. Section 2 introduces the drivetrain technologies considered in this study. Section 3 describes the integrated techno-economic and environmental assessment framework. Section 4 presents the case study setup, including wind farm characteristics, metocean conditions, failure rates, and resource assumptions. Section 5 discusses the results for the baseline configuration, focusing on cost and environmental performance. Finally, Section 6 concludes the paper and outlines directions for future work.

2. Drivetrain technology

One of the key challenges in scaling up direct-drive wind turbine generators is maintaining the air-gap length, defined as the radial distance between the active parts of the rotor and stator, i.e. between the permanent magnets and the stator core and windings. In current 12–15 MW layouts, such as the IEA 15 MW reference turbine adopted here as the baseline [6], the bearing assembly typically consists of two main bearings with diameters of 3–4 m, while the generator air-gap diameter approaches 10 m. This creates a substantial structural challenge: large aerodynamic loads transmitted through the blades must be accommodated while maintaining a stable and narrow clearance between rotor and stator at a significant distance from the supporting elements. In addition, magnetic attraction forces across the air-gap increase nonlinearly as the clearance decreases, thereby further intensifying structural design requirements.

To mitigate the risk of air-gap collapse, conventional design approaches rely either on increasing the structural stiffness of the rotor and stator assemblies or on enlarging the air-gap length. While structural reinforcement increases rotor–nacelle mass and the associated installation and maintenance costs, enlarging the air-gap reduces electromagnetic efficiency and typically requires stronger magnetic fields and greater use of permanent magnet material, including rare-earth elements. Conversely, a design that enables stable control of a smaller air-gap can reduce both structural material demand and the amount of magnetic material required, thereby affecting not only mass and cost, but also embedded environmental impacts.

The OptiGen drivetrain concept developed within the LIGHTWIND project proposes an alternative configuration to address these challenges. Instead of a conventional main-bearing arrangement, the rotor is supported by a wheel–rail system in which stator-mounted bogies run on parallel circular rails located close to the generator air-gap diameter. This significantly reduces the structural span between the supporting elements and the air-gap from several metres to only a few centimetres. Pre-compressed elastomeric elements integrated into the bogies ensure continuous wheel–rail contact, enable load sharing, and decouple local structural deformations from the generator air-gap, thereby relaxing manufacturing and assembly tolerances. This configuration also makes the air-gap less sensitive to generator diameter, with direct implications for design optimisation and material use.

In addition to its structural benefits, the modular nature of the wheel–rail concept allows large drivetrain components to be manufactured as smaller subassemblies, thereby facilitating transport, installation, and in-situ offshore repair or replacement of wear-prone elements such as wheels, rails, bearings, and elastomeric supports. Compared with conventional designs, this can reduce the need for major component exchanges, lower vessel and crane requirements, shorten offshore intervention times, and thereby affect both operational costs and emissions.

In this study, these distinctive design and operational characteristics of the OptiGen drivetrain are explicitly translated into techno-economic model parameters in order to quantify their impact on CapEx, OpEx, and greenhouse gas emissions associated with offshore installation and maintenance activities. This provides a structured basis for assessing the financial and environmental performance of the OptiGen drivetrain relative to the IEA 15 MW baseline configuration.

3. Integrated cost–environmental assessment model

The integrated modelling framework employed in this study follows an input–model–output architecture, as illustrated in Figure 2. The framework links offshore wind project characteristics to economic and environmental performance indicators by combining a cost model with a life cycle assessment (LCA) model. The two modules are loosely coupled: they share a common set of inputs and exchange selected activity data, thereby ensuring that the environmental implications of cost-driving operational events are captured consistently.

Mathematically, the relationship between the input space $\mathcal{X}$, the coupled models $\mathcal{M} =$

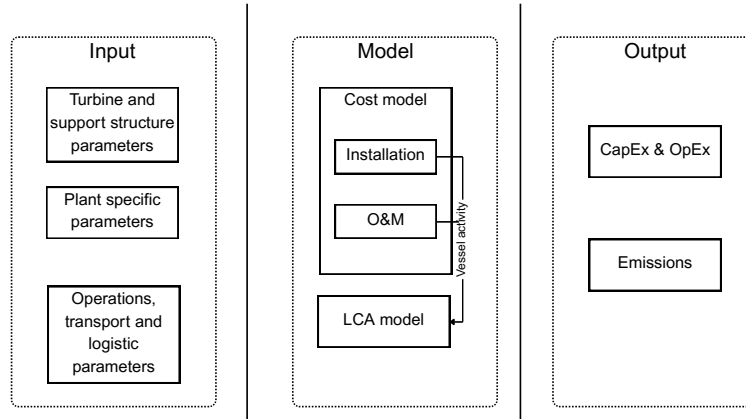


Figure 2. Integrated cost–environmental modelling framework with an input–model–output architecture, linking technical and operational inputs to a cost model (CapEx, OpEx) and an LCA model, and producing LCOE and emissions as outputs.

$(\mathcal{M}_{\text{cost}}, \mathcal{M}_{\text{LCA}})$, and the outputs $\mathcal{Y}$ can be expressed as

$$\mathcal{Y} = \mathcal{M}(\mathcal{X}) = \{Y_{\text{CapEx}}, Y_{\text{OpEx}}, Y_{\text{emissions}}\},$$

where Y_{CapEx} denotes the capital expenditure, Y_{OpEx} the operational expenditure, and $Y_{\text{emissions}}$ the lifecycle CO_2 -equivalent emissions.

The input space $\mathcal{X}$ comprises the technical and operational information required to run the coupled framework. In practice, $\mathcal{X}$ includes wind farm descriptors, such as turbine model specifications, wind farm layout and spacing, and port selection; metocean data, including hourly time series of wind and wave conditions at the site and along the transit route; failure-related inputs, such as component-level failure rates used to generate time-to-failure behaviour; and resource and maintenance definitions, including vessel and technician characteristics, availability and costs, as well as repair durations and operational constraints. Collectively, these inputs define the boundary conditions under which operational activities can be planned and executed, and thereby determine both the resulting cost and emissions profiles.

The modelling framework consists of two modules. The cost module $\mathcal{M}_{\text{cost}}$ estimates economic performance through a breakdown of CapEx and OpEx. CapEx comprises investments in major subsystems, including the rotor, nacelle, tower, substructure, and balance-of-plant infrastructure, together with their associated installation activities. By contrast, OpEx represents the recurring expenditures incurred over the project lifetime, including preventive and corrective maintenance, spare parts, logistics, and the deployment of vessels and technicians.

The environmental module $\mathcal{M}_{\text{LCA}}$ quantifies lifecycle environmental impacts, with particular emphasis on CO_2 -equivalent emissions, and is implemented in the commercial LCA software SimaPro. To represent both installation and operational behaviour, and to generate the activity data required by the LCA, the project phases are simulated using UWiSE, a discrete-event simulation environment developed by TNO [7]. For the installation phase, UWiSE models offshore transport, resource dispatch, and the execution of installation activities using the same metocean, vessel, technician, and operational-constraint inputs as in the operational phase, but without failure-related inputs. These installation activities are subsequently translated into CapEx. For the operational phase, UWiSE governs failure generation, resource dispatch, and repair execution over the asset lifetime. Component failures are triggered based on mean time-to-failure values sampled from user-defined statistical distributions. When a repair or replacement

Table 1. Overview of the wind farm characteristics used in the simulation.

Parameter	Value
Wind farm layout	133×15 MW
Turbine model	15 MW IEA reference turbine
Turbine spacing	$5.5 \times D$
Mean wind speed at hub height	10.5 m/s
Water depth	16.8–46.9 m LAT
Operational port	IJmuiden
Distance to port	~62 km
Operational lifetime	25 years

is required, the model identifies the relevant maintenance action and evaluates whether execution is feasible under the prevailing environmental and logistical constraints. In particular, a task is initiated only if the wind speed (U_{10}) and significant wave height (H_s) remain within the operational limits of the assigned vessels and technicians, and if the required resources are available. To represent stochastic variability, the model applies Monte Carlo sampling from the specified failure-time distributions and from historical weather years.

Following each simulated installation or maintenance event, UWise records vessel-related activity data, including operating hours by vessel type. These data are transferred to SimaPro, where vessel-specific emission factors are applied together with background inventory data (e.g., Ecoinvent) to estimate lifecycle impacts in accordance with ISO 14040 [8] and ISO 14044 [9]. Climate impacts are evaluated using the GWP100 methodology [10]. This integrated structure enables a consistent assessment of how installation and operational decisions, together with uncertainty in failure behaviour, propagate to economic outcomes through Y_{CapEx} and Y_{OpEx} , and to environmental outcomes through $Y_{\text{emissions}}$.

4. Case study

This case study quantifies the economic and environmental impacts associated with investing in, constructing, and operating a representative offshore wind farm. The analysis focuses on capital expenditure (CAPEX), operational expenditure (OPEX), and lifecycle environmental impacts, while comparing alternative drivetrain technologies. This section summarises the input parameters used for modelling and the key assumptions defining the input space.

4.1. Wind farm data

A representative offshore site is defined based on the IJmuiden Ver Wind Farm Zone 3 in the Dutch North Sea [11]. The site is located approximately 62 km offshore and is supported by the Port of IJmuiden, which serves as the logistics and maintenance base. The wind farm comprises 133 turbines rated at 15 MW, modelled using the IEA 15 MW reference turbine [6]. Turbine spacing of 5.5 rotor diameters is assumed, and the operational lifetime is 25 years. Key site and project characteristics are summarised in Table 1.

4.2. Metocean data

Metocean inputs are obtained from the ERA5 reanalysis hindcast product [12]. The dataset provides hourly time series from 1 January 1980 to 1 October 2023 for the IJmuiden Ver location. The primary variables used are the 10-m mean wind speed (U_{10} , m/s) and significant wave height (H_s , m). Figure 3 shows the raw hourly series and a centred moving-average trend (bin size = 500).

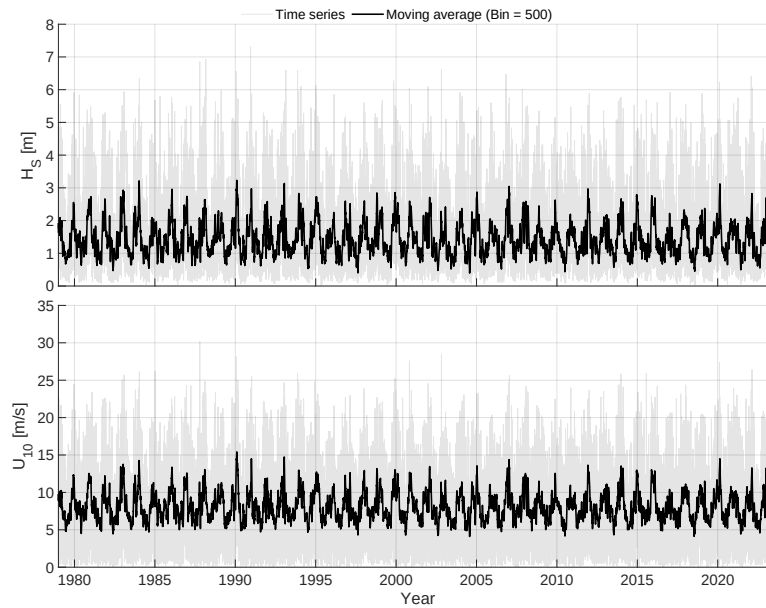


Figure 3. Time series and moving averages (bin size = 500) of significant wave height (H_S) and 10-m wind speed (U_{10}). Transparent lines show hourly data; solid lines show the centred moving average.

4.3. Failure rate data

Publicly available operational reliability data for next-generation offshore wind turbines 15 MW remain limited. Therefore, this study adopts component-level failure rate characteristics from established literature sources, using the baseline estimates reported in [7]. These values represent typical reliability behaviour for large offshore turbines and form the reference dataset for the techno-economic and environmental modelling framework. The baseline failure rate inputs applied in the model are summarised in Table 2.

Since the OptiGen drivetrain represents a novel generator concept that has not yet accumulated long-term field reliability data, a feasibility-oriented uncertainty approach is applied. Specifically, three levels of multiplicative uncertainty ($\pm 5\%$, $\pm 10\%$, and $\pm 15\%$) are introduced for selected components directly affected by generator design changes, namely the direct-drive generator and the associated power-converter subsystem. These uncertainty bands reflect the expected variation in reliability performance prior to detailed physics-based reliability modelling and laboratory validation, which are planned in subsequent development stages.

All remaining turbine subsystems are assumed to retain the same baseline failure characteristics across drivetrain configurations. This assumption is supported by expert discussions with original equipment manufacturers (OEMs), indicating that the structural and operational modifications introduced by the OptiGen concept are expected to primarily influence generator-related components rather than the wider turbine system.

This treatment provides a structured basis for comparing drivetrain concepts at an early feasibility stage, while recognising that future work will refine the failure-rate assumptions through load-driven reliability modelling, component-level testing, and, where available, operational field data.

Table 2. Overview of the O&M failure characteristics used in the feasibility analysis (failure rate per turbine per year). “Rest of turbine” aggregates Main Shaft, Power Electrical System, Yaw System, Pitch System, Blades, Inter Array Cable, and Export Cable (summed by maintenance class). “Preventive maintenance” aggregates the annual campaigns for WTG, Other structures, and IAC. Entries marked with [†] are perturbed in the generator-design uncertainty study. Abbreviations: MCR = Major Component Replacement, MR = Major Repair, mR = Minor Repair, AC = Annual Campaign.

Component	Maint.	Failure rate (turb ⁻¹ yr ⁻¹)
Corrective maintenance		
DD Generator [†]	mR	0.546
	MR	0.030
	MCR	0.009
Power Converter [†]	mR	0.538
	MR	0.338
	MCR	0.077
Rest of turbine	mR	2.031
	MR	0.282
	MCR	0.030
Preventive maintenance		
Preventive maintenance	AC	3.000

[†]Uncertainty study: multiplicative perturbations are applied only to the marked failure rates, using uncertainty bands of $\pm 5\%$, $\pm 10\%$, and $\pm 15\%$, while all other component failure rates remain fixed at their baseline values.

4.4. Resources data

Offshore operations are represented using three primary vessel types: service operation vessels (SOVs), jack-up vessels (JUVs), and cable-laying vessels (CLVs), with each primary vessel supported, where required for site-specific operations, by either a daughter craft or a remotely operated vehicle (ROV) vessel. Under the baseline logistics assumptions, major turbine replacement activities are performed using a JUV, cable-related interventions are assigned to a CLV, and all other activities default to an SOV unless otherwise specified. For the OptiGen drivetrain concept, the installation-phase assumptions remain identical to those of the baseline configuration; however, in the O&M phase, selected interventions associated with major corrective replacements (MCR) involving generator-related components are modelled using lighter in-situ replacement strategies based on SOV operations equipped with an onboard crane. This reflects the modular and more accessible drivetrain architecture, which, in principle, enables local offshore intervention and partial replacement without requiring the large heavy-lift (JUV) campaigns assumed in the baseline case.

The vessel cost structure includes daily operating (day/wait) rates and mobilisation/demobilisation (M/D) costs incurred as lump sums per campaign. Table 3 summarises the vessel characteristics adopted in the simulation. These values are based on publicly available sources and stakeholder consultations [7]. Fuel consumption is modelled separately for transit and for working/waiting periods, denoted as F_{con}^T and F_{con}^W , respectively, and is used for emissions accounting. While real-world fuel use varies with speed, weather, and operational state, a standardised representation is applied consistently across scenarios, aligned with common practice in offshore O&M studies [13]. For the OptiGen case, differences therefore arise only through the selection and utilisation of resources during maintenance activities, rather than through modified vessel characteristics themselves.

In addition to vessel resources, two technician groups are defined to reflect different

Table 3. Vessel characteristics used in the study. D/W = Day/Wait rate, M/D = Mobilisation/Demobilisation rate, V_s = vessel speed, F_{con}^T = fuel consumption during transit, F_{con}^W = fuel consumption during working/waiting.

Vessel	D/W Rate (€)	M/D Rate (€)	V_s (kts)	F_{con}^T (t/h)	F_{con}^W (t/h)
SOV	75,000	225,000	11.2	2.1	1.4
JUV	290,000	325,000	8.0	3.8	2.5
CLV	80,000	160,000	12.0	3.0	1.7

deployment and work schedules. Technician Group A operates in 12-hour shifts with a day/wait rate of €1200 and is assigned to routine and planned maintenance. Technician Group B operates on a 24-hour schedule with a day/wait rate of €2400 and is used for critical repairs directly influencing turbine downtime. This separation supports a more realistic representation of labour costs and operational constraints within the O&M simulations, while also allowing the OptiGen concept to capture potential reductions in heavy-lift dependence during generator-related offshore interventions.

5. Results and discussion

Table 4 summarises the baseline and OptiGen results on a per-megawatt basis. As the current OptiGen feasibility case does not include revised component manufacturing costs or alternative installation procedures, CapEx, installation costs, and pre-commissioning emissions remain unchanged. The design change considered here affects only the operational phase: for DD-generator and power-converter MCR events, the baseline JUV-based heavy-lift campaigns are replaced by SOV-based in-situ interventions using an onboard crane. The resulting differences therefore appear in offshore O&M costs and vessel-related operational emissions.

The baseline project is dominated by turbine and balance-of-plant investment costs, with wind turbine CapEx amounting to approximately 1.41 M€/MW and total CapEx reaching 2.673 M€/MW. Installation costs are likewise unchanged, since the same installation procedures are assumed irrespective of the drivetrain design changes considered here. Accordingly, pre-commissioning emissions remain constant at 0.716 ktonnes CO₂-eq./MW.

The main effect of the OptiGen assumptions is observed in OpEx. In the baseline case, DD-generator and power-converter MCR campaigns contribute approximately 17.85 k€/MW/year in vessel-related OpEx under JUV-based execution. Reassigning these interventions to SOV-based campaigns with an onboard crane reduces this contribution to 7.74 k€/MW/year in the mean OptiGen case, corresponding to a reduction of about 56.6% for the affected interventions. This decrease is driven primarily by the lower mobilisation/demobilisation and day rates of SOVs relative to JUVs. At total project level, the annual average OpEx decreases from 78.0 to 67.9 k€/MW/year, corresponding to an overall reduction of approximately 13.0%. Under the applied uncertainty bands on DD-generator and power-converter failure rates, the OptiGen annual OpEx ranges from 67.5–68.3 k€/MW/year for the $\pm 5\%$ case, 67.1–68.7 k€/MW/year for the $\pm 10\%$ case, and 66.7–69.1 k€/MW/year for the $\pm 15\%$ case. These ranges represent a conservative sensitivity estimate; if the actual failure rates deviate more substantially from the baseline assumptions, the resulting benefits may be less pronounced.

A similar pattern is observed for the operational environmental indicator. In the baseline case, DD-generator and power-converter MCR vessel campaigns account for approximately 9.57 tCO₂-eq./MW/year. Replacing JUV operations with SOV-based in-situ replacements lowers this contribution to 7.49 tCO₂-eq./MW/year in the mean OptiGen case, corresponding to a reduction of about 21.7% for the affected interventions. At total project level, annual operational emissions

Table 4. Comparison of baseline and OptiGen financial and environmental results for the 15 MW offshore wind farm. For CapEx and installation, baseline and OptiGen values are identical and are therefore reported only once. OptiGen values in the operational phase reflect SOV-based in-situ replacement for DD-generator and power-converter MCR events only; CapEx and installation assumptions remain unchanged. Uncertainty ranges correspond to the $\pm 15\%$ failure-rate case, while the text reports the narrower $\pm 5\%$ and $\pm 10\%$ bands.

Category	Value (Baseline = OptiGen)		
Capital Expenditure (CapEx)			
Wind turbine (nacelle, rotor, tower) [k€/MW]		1410	
Balance of plant [k€/MW]		1263	
Total CapEx [k€/MW]		2673	
Foundation installation [k€/MW]		190.4	
Turbine installation [k€/MW]		152.0	
Other installation activities [k€/MW]		820.3	
Total installation cost [k€/MW]		1162.7	
Operational and environmental indicators			
	Baseline	OptiGen mean	OptiGen range
Annual average OpEx (k€/MW/year)	78.0	67.9	66.7–69.1
Pre-commissioning emissions (k tonnes CO ₂ -eq./MW)	0.716	0.716	–
Annual operational emissions (k tonnes CO ₂ -eq./MW/year)	0.0095	0.0074	0.0063–0.0085

decrease from approximately 0.0095 to 0.0074 ktonnes CO₂-eq./MW/year. The corresponding OptiGen uncertainty ranges are 0.0070–0.0078 ktonnes CO₂-eq./MW/year for the $\pm 5\%$ case, 0.0067–0.0082 ktonnes CO₂-eq./MW/year for the $\pm 10\%$ case, and 0.0063–0.0085 ktonnes CO₂-eq./MW/year for the $\pm 15\%$ case.

Overall, the OptiGen concept shows clear potential to reduce OpEx and operational emissions; given that O&M typically accounts for around 30% of LCOE, such reductions can also be expected to have a noticeable effect on overall project economics.

6. Conclusion

This study highlights the growing need for holistic assessment frameworks in offshore wind feasibility studies, where design choices are increasingly evaluated not only in terms of cost, but also in terms of their broader environmental implications. In this context, drivetrain technology is a particularly relevant design variable, given its influence on turbine mass, material demand, installation requirements, and O&M strategy.

The OptiGen generator concept, which is currently at an early stage of development, proposes a lightweight and modular drivetrain architecture with the potential to reduce dependence on heavy offshore replacement campaigns. To investigate this potential, a case study was developed for a realistic upcoming offshore wind farm based on IJmuiden Ver conditions, using the IEA 15 MW reference turbine as the baseline configuration. As reliability data for the OptiGen concept are not yet available, uncertainty bands were applied only to the generator and power-converter components most directly affected by the design change, while the revised MCR strategy was adapted in consultation with the OEM.

The results show that, even without any assumed CapEx or installation benefit, the OptiGen concept can deliver a clear operational advantage. Replacing JUV-based heavy-lift MCR campaigns with SOV-based in-situ interventions reduces annual OpEx by about 13% and annual operational emissions by about 22%, while the uncertainty analysis indicates that these benefits

remain visible across the assumed feasibility range. Given the importance of O&M within overall project economics, these reductions are also expected to contribute positively to LCOE.

Future work will extend the present assessment by incorporating more detailed installation and O&M procedures, together with improved reliability modelling and component-level validation. This will provide greater granularity in the representation of offshore interventions and help quantify more accurately how drivetrain design choices propagate to long-term economic and environmental performance.

Acknowledgments

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