A prospective life cycle assessment of drivetrain technologies in offshore wind

Vinit V. Dighe[1], Aaradhya Bansal[2], Kamiel Jansen[2], Joep Breuer[1] and Harald van der Mijle Mijler[1]

[1]Wind Energy Group

[2]Circularity & Sustainability Impact Group

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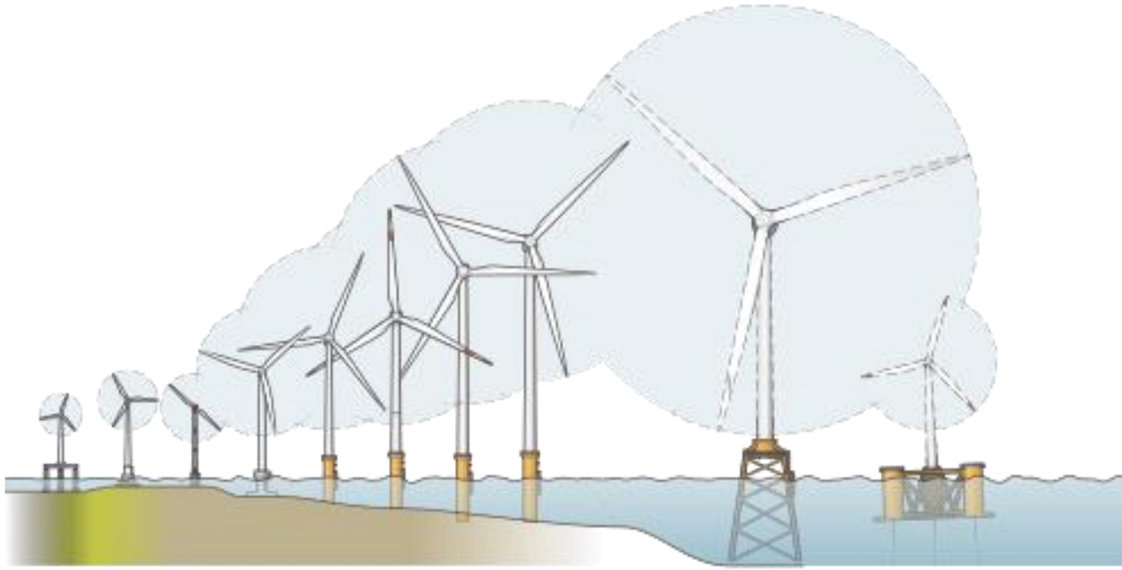
Outline

- Research objective
- Methodology
- Case study
- Results
- Conclusions

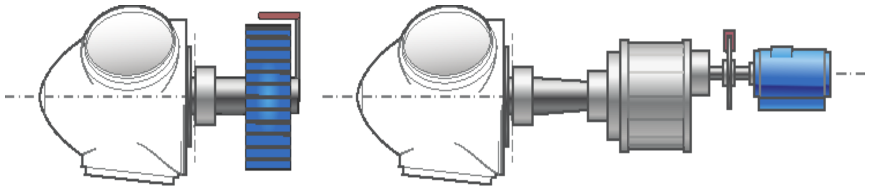
Research objective

Motivation

- **EU climate targets**: 55% GHG emission reduction by 2030 → Offshore wind expansion [1]
- **Drivetrain technology**: Critical for cost, efficiency, and reliability [2]
- **Environmental impacts**: Drivetrains rely on rare earth elements → environmental and social concerns [3]



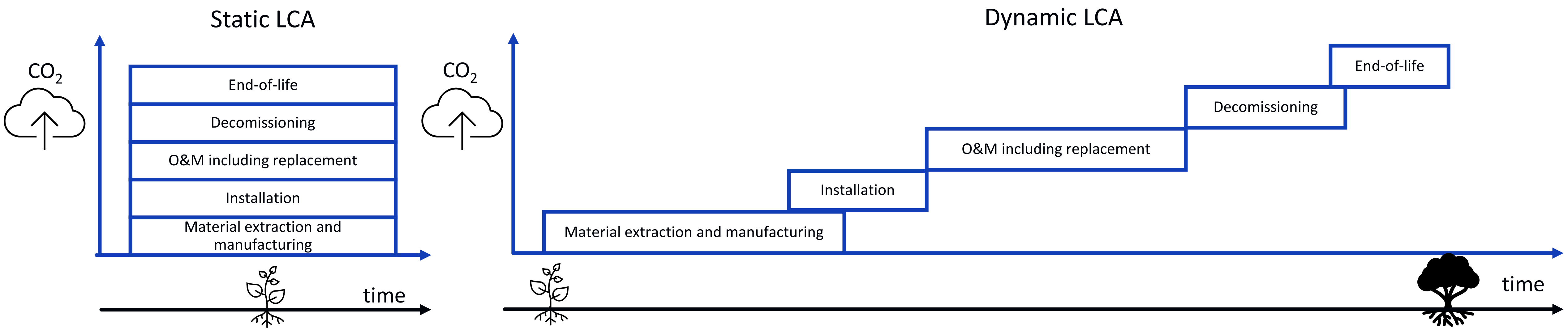
Evolution of offshore wind energy



Direct drive and geared system

Life Cycle Assessment

LCA in offshore wind evaluates environmental impacts from material extraction to end-of-life, identifying key areas to reduce emissions and resource use across the wind farm's lifecycle.



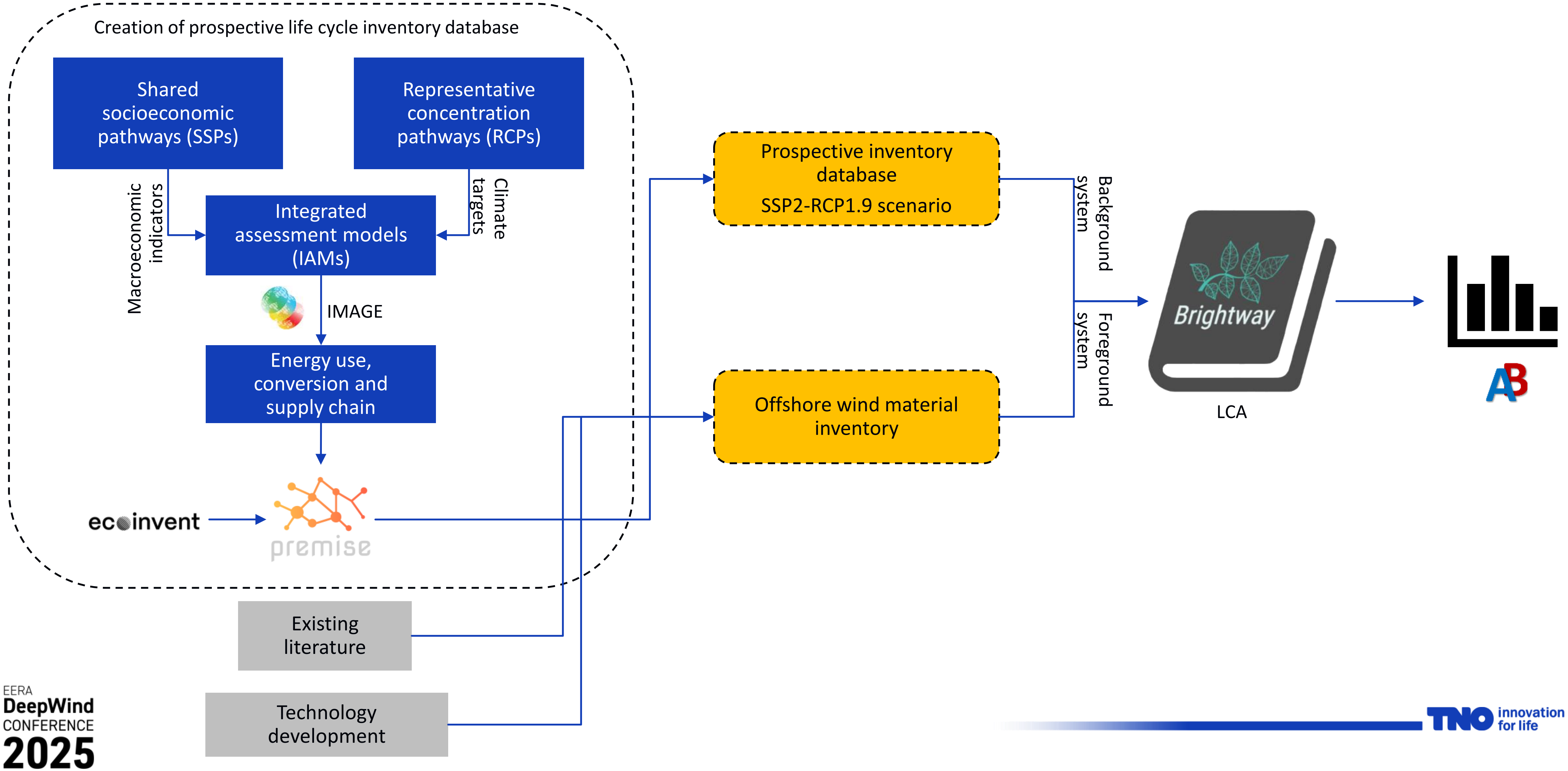
Environmental impacts are aggregated to t_0

Environmental impacts are distributed over time

Research question: How can future lifecycle impacts be accurately accounted for in offshore wind studies, considering evolving supply chains, technological advancements, and policies?

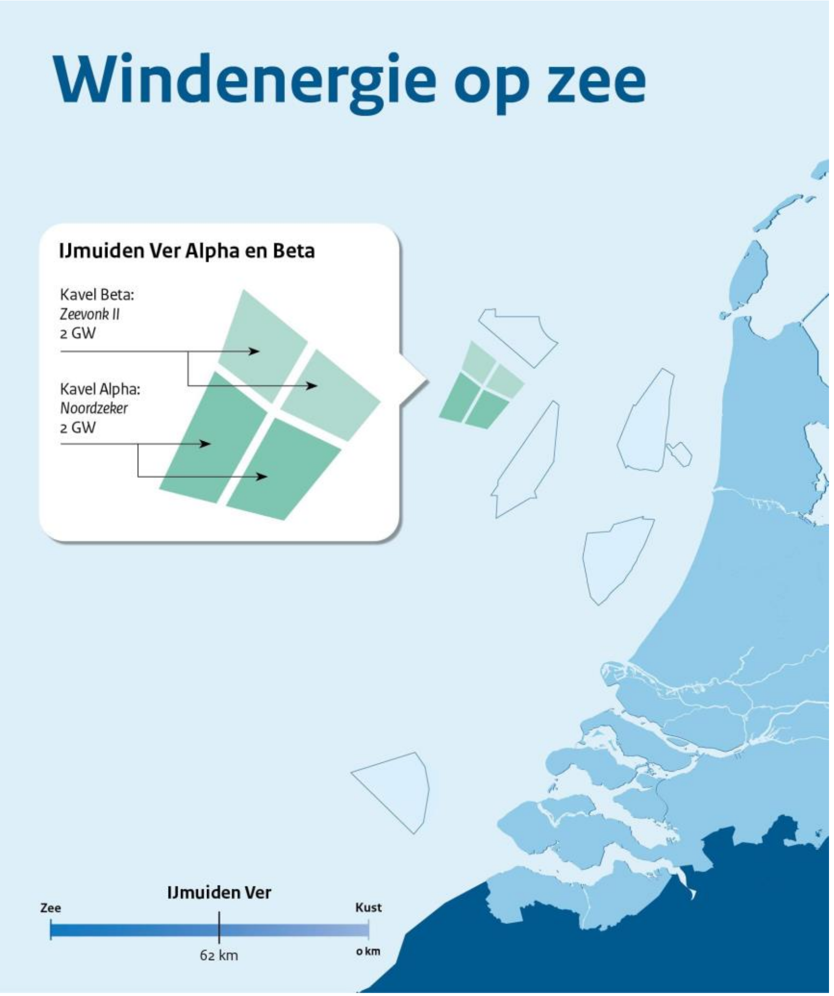
Methodology

Methodology

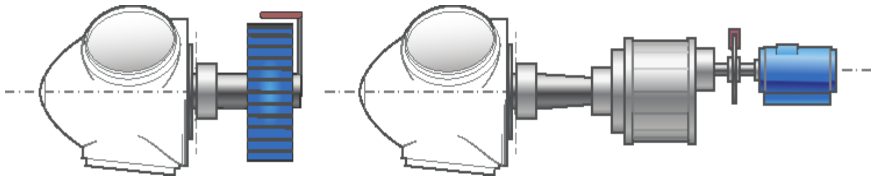


Case study

Reference wind farm



IJmuiden Ver wind farm site [4]

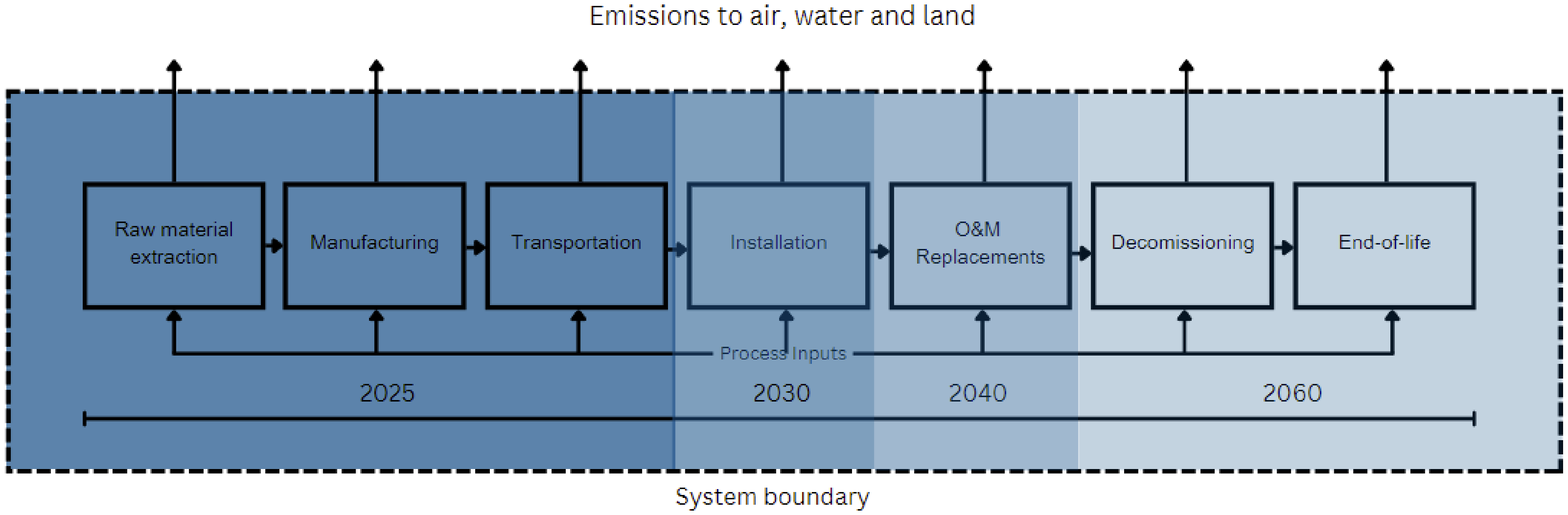


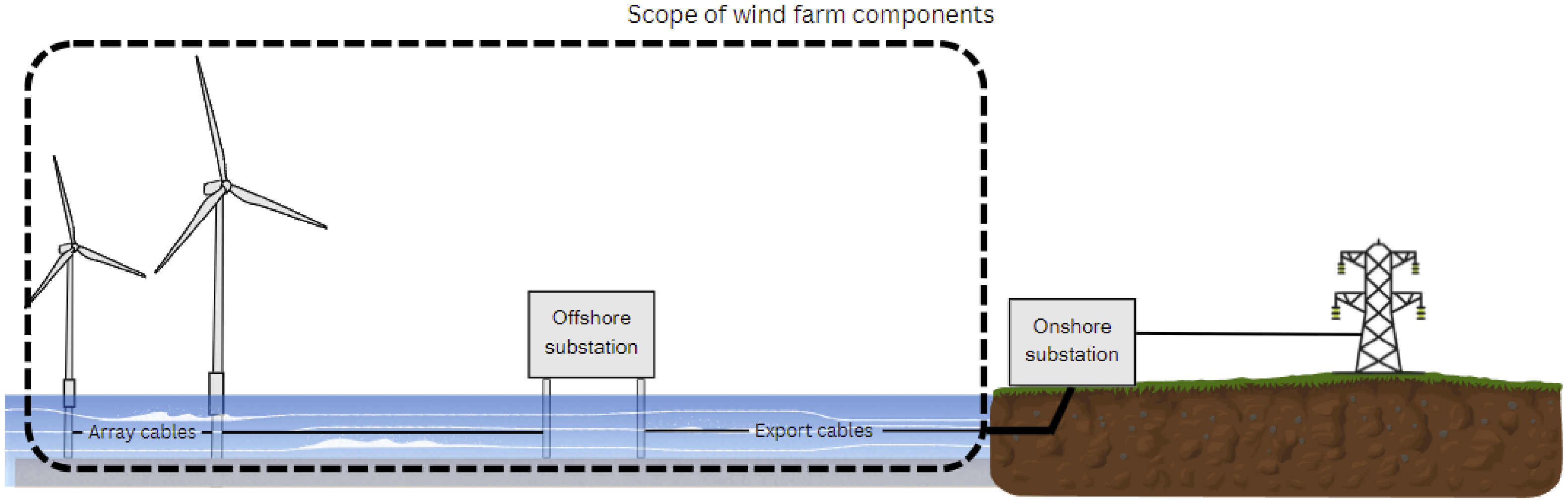
Direct drive and geared system

Parameter	Value	Unit
Number of Turbines	134	p
Lifetime of Wind Farm	35	years
Array Distance	2.40	km
Export Distance	62	km
Manufacturer Distance	600	km
Expected Average Wind Speed	10	m/s

Wind farm characteristics

Scope of the study





- **System boundary**: Covers full wind farm lifecycle: material extraction (cradle-2025) to end-of-life (grave-2060)
- **Scope and functional unit**: Includes turbines, foundations, cables, and substations. Functional unit: g CO_2-eq/kWh, enabling GWP and other impact assessments.
- **Cut off criteria and assumptions**: Excludes flows <0.1% mass or 1% energy unless significant. Assumes > 99% of turbine mass is assessed with scalable layout configurations.

Case study

The inventory of 15 MW offshore wind turbines highlights significant variations across three key phases:

Specification	DD (ton)	MS (ton)
Armature copper weight	20.5	5.9
Permanent magnet weight	10.9	0.9
Stator core weight	38.7	10.6
Rotor core weight	14.4	7.8
Total active material weight	84.6	25.3
Approximated structure weight	100.6	32.2
Total weight	185.2	57.5

Weight distribution comparison [5]

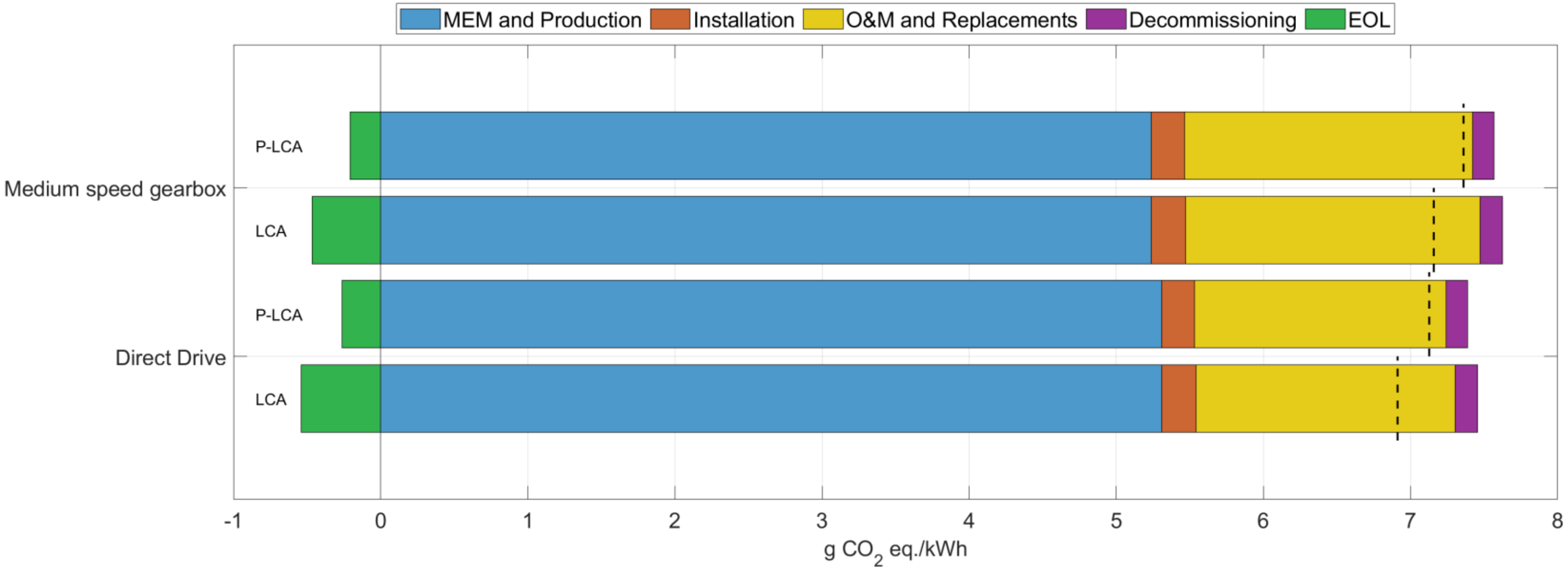
Component	Failure mode	DD	MS
Gearbox	Replacement	n/a	0.022
	Planet wheel repair	n/a	0.05
	Other minor repair	n/a	0.32
Generator	Replacement	0.021	0.01
	Bearing replacement	0	0
	Bearing repair	0.196	0
	Other minor repair	0.22	0.22
Main bearing	Replacement	0.015	0.009
	Repair	0.062	0.006

Failure rate comparison [6]

- **Material composition**: DD systems need more active materials (copper, magnets) and structural support vs. MS systems.
- **O&M and replacements**: MS systems face higher gearbox-related failures; DD systems have increased main bearing replacements.
- **End-of-life**: NdFeB magnet recycling (hydrogen decrepitation) cuts virgin material use by 60%.

Results

Impact on climate change



- **GWP comparison**: MS systems show higher GWP100 (LCA: 7.16, pLCA: 7.32 g CO_2-eq/kWh) vs. DD systems (LCA: 6.91, pLCA: 7.23 g CO_2-eq/kWh).
- **Major impact**: MEM contributes >70% of GWP100 in both LCA and pLCA due to energy-intensive.
- **LCA vs. pLCA**: pLCA reflects reduced O&M impacts due to cleaner energy and improved supply chains, but lower recycling benefits as recovered materials apply to future processes, unlike LCA's immediate crediting to current extraction.

Other environmental impacts

- **Resource-related impacts higher for DD**: Higher due to reliance on rare earth materials and copper, increasing resource depletion, land use, and water use impacts.
- **Operational and fuel-related impacts higher for MS**: Frequent maintenance and gearbox failures lead to increased fuel consumption, affecting acidification, GWP100, eutrophication, and ozone formation.
- **End-of-life recycling advantage for DD**: Larger recyclable material volumes, like rare earth magnets, offset extraction and manufacturing impacts, reducing lifecycle burdens.

Impact Category	Unit	Value (DD)	Value (MS)	Difference (%)
Acidification	mol H+-eq.	5.36E-05	**5.44E-05**	+1.49%
Climate Change	kg CO2-eq.	6.84E-03	**7.05E-03**	+3.07%
Ecotoxicity	CTUe	**5.52E-02**	5.45E-02	-1.27%
Non-Renewable Energy	MJ net cal. val.	9.05E-02	**9.30E-02**	+2.76%
Eutrophication Freshwater	kg P-eq.	2.07E-06	2.07E-06	0.00%
Eutrophication Marine	kg N-eq.	1.87E-05	**1.92E-05**	+2.67%
Eutrophication Terrestrial	mol N-eq.	1.80E-04	**1.90E-04**	+5.56%
Toxicity Carcinogenic	CTUh	3.65E-11	**3.81E-11**	+4.38%
Toxicity Non-Carcinogenic	CTUh	**2.86E-10**	2.83E-10	-1.05%
Ionising Radiation	kBq U235-eq.	**6.16E-04**	6.08E-04	-1.30%
Land Use	Dimensionless	**2.57E-02**	2.53E-02	-1.56%
Abiotic Depletion Metals	kg Sb-eq.	**1.86E-07**	1.63E-07	-12.37%
Ozone Depletion	kg CFC11-eq.	3.96E-10	**3.98E-10**	+0.51%
Particulate Matter	Health problems - incidence	4.25E-10	**4.38E-10**	+3.06%
Photochemical Oxidants	kg NMVOC-eq.	5.41E-05	**5.68E-05**	+4.99%
Water Use	m3 world eq. deprived	**2.94E-03**	2.83E-03	-3.74%

Conclusions

Conclusions

- **pLCA methodology:** Incorporates future supply chain dynamics using macroeconomic and climate models, addressing static inventory limitations of conventional LCA.
- **Drivetrain comparison:** MS systems show higher overall GWP impacts due to gearbox-related failures; DD systems have higher resource-related impacts but benefit from significant recycling gains.
- **LCA vs. pLCA variations**: Future recycling processes and evolving supply chains reshape how avoided burdens are accounted for.
- **Future scope:** Expand pLCA to include foreground systems (e.g., turbine designs, operational strategies) and address data gaps for advanced scenario modeling.

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Thank you

email: vinit.dighe@tno.nl