CARBON TRUST

SUSTAINABILITY JOINT INDUSTRY PROGRAMME

Offshore wind decarbonisation pathway

Where we are now, how we can decarbonise, and who has a role to play in the Net Zero transition of the offshore wind sector

December 2024

ScottishPower Renewables · EnBW · equinor · RWE · SSE Renewables · Parkwind · bp · TotalEnergies · Vattenfall · Ørsted · Fred. Olsen Seawind · Shell

About the Sustainability JIP

The Sustainability Joint Industry Programme (SUS JIP) is a developer-funded and developer-led collaborative initiative. The programme aims to accelerate decarbonisation action across future fixed and floating offshore wind farm projects for a Net Zero future.

This report summarises the key findings from the research related to decarbonisation action within the offshore wind (OSW) industry:

- A decarbonisation pathway for offshore wind developers based on Net Zero pathway projections;
- Industry actions required to help achieve the decarbonisation pathway and the responsible parties.

The Sustainability JIP partners commissioned the Offshore Wind Industry Product Carbon Footprinting (PCF) Guidance, hereafter referred to as "the methodology", which was published in September 2024. The methodology provides a standardised approach for calculating the life cycle carbon footprint of OSW development and is encouraged to be used with the outputs of this Offshore Wind Decarbonisation Pathway to accurately report on the carbon emissions of an OSW development.

The Sustainability JIP Phase 1 (2023-2024) is a collaboration between the Carbon Trust and 12 OSW developers: bp, EnBW, Equinor, Fred Olsen Seawind, Ørsted, Parkwind, RWE Offshore Wind GmbH, ScottishPower Renewables, Shell, SSE Renewables, TotalEnergies and Vattenfall.

Acknowledgements

The Carbon Trust collaborated closely with the Sustainability JIP Phase 1 project partners throughout the development of this project. Additionally, the Carbon Trust engaged with numerous stakeholders from the OSW supply chain and wider industry experts. While we will not list all contributing stakeholders for confidentiality purposes, we would like to thank all of those who provided input.

Who we are

The Carbon Trust's mission is to accelerate the move to a decarbonised future. We have been climate pioneers for more than 20 years, partnering with leading businesses, governments and financial institutions globally. From strategic planning and target setting to activation and communication - we are your expert guide to turn your climate ambition into impact.

We are one global network of 400 experts with offices in the UK, the Netherlands, Germany, South Africa, Singapore and Mexico. To date, we have helped set 200+ science-based targets and guided 3,000+ organisations in 70 countries on their route to Net Zero.

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1. Executive summary

OSW power is a clean source of electricity generation, emitting much lower carbon emissions than fossil fuels. However, there are opportunities to further reduce emissions throughout the wind farm's life cycle, aiding the transition to Net Zero. Reducing emissions will involve challenging the conventional manufacturing, construction, and operational processes through environmentally conscious designs, circularity processes, and innovative approaches. Given the reliance on complex supply chains across multiple sectors, achieving a substantial industry transformation at scale will require significant cross sectoral collaborative efforts to decarbonise the materials and inputs.

The Sustainability JIP partners share key insights into an overarching OSW decarbonisation pathway, emphasising a holistic assessment of the emissions profile. This approach considers the emission reduction potential not only at the component level but across the entire industry, considering all aspects of individual wind farms. With greener materials and inputs expected to become more widely available in the coming years, integrating individual OSW farm carbon footprint data with a broader decarbonisation pathway will enhance confidence and transparency around the necessary interventions. This report shows that a carbon emissions reduction of 90% is achievable by 2050 should the relevant decarbonisation pathways across materials and activities take shape.

Analysis of existing emission sources from an average OSW farm (this study's baseline) reveals that material inputs from the supply chain contribute 60-80% of total emissions. Specifically, steel accounts for over 50% of life cycle carbon emissions in an average development, with other materials contributing 24%. Emissions from construction, installation, and operational activities, primarily driven by vessel fuel type, typically form 15-20%. Achieving industry decarbonisation will require strengthened communication and strategic action between all interfacing sectors that contribute these inputs.

A key message of this report is the critical short-term actions needed to accelerate decarbonisation within the wind industry. This report identifies the stakeholders necessary to drive these changes. Achieving meaningful progress will require collaborative action across sectors by a wide range of international stakeholders – such as the supply chain, OSW developers, governments, and financial institutions. Each stakeholder must take responsibility for exploring pathways to Net Zero and adopting economic models that account for environmental and social impacts beyond financial costs, playing a pivotal role in decarbonising the global OSW industry.

Figure 1: Offshore wind maintenance activity where reducing the carbon footprint of the material inputs and ongoing activities across the project life cycle will be key to decarbonising the industry.

2. Introduction

OSW farms can generate electricity with up to 95% lower carbon emissions than coal-based generation.[1] However, carbon emissions are associated throughout the wind farm's life cycle, including in material inputs, construction and installation, operation and maintenance, and end-of-life and decommissioning.

By the end of 2023, global OSW capacity reached 75.2 GW, marking the second-highest year of installations in history.[2] The installed capacity is expected to increase rapidly, with the International Energy Agency (IEA) estimating that an additional 70-80 GW will need to be installed annually from 2030 onwards to achieve Net Zero by 2050.[3] While the OSW industry is scaling up rapidly to meet this ambitious target, it is crucial that this growth occurs with minimal carbon emissions to align with the future of sustainable energy production. Many stakeholders across the industry widely recognise the challenge of decoupling emissions from the rapid expansion of installed OSW capacity.

An OSW development comprises many constituent parts, each with decarbonisation opportunities to achieve Net Zero. This report identifies these constituent parts, such as material inputs like steel and aluminium, and emissions-producing activities, such as operation and maintenance, releasing emissions through vessel fuels. The report proposes that a comprehensive wind farm level perspective is crucial to guide the industry and inform stakeholders about the potential pathways for decarbonisation.

To address this, the report analyses the individual sectoral pathways to illustrate how emissions across the OSW industry can be collectively reduced. Transitioning to more sustainable and cost-effective Net Zero OSW projects is increasingly vital for meeting climate targets and ensuring a reliable and truly sustainable energy future.

3. Methodology

This report's methodology develops a first-of-a-kind decarbonisation pathway and strategy to accelerate decarbonisation action within the OSW industry. It presents a holistic assessment of emissions across all stages of the OSW project, including material production, manufacturing, construction, operation, maintenance and decommissioning. By combining data-driven analysis with industry insights, this methodology provides a clear framework for aligning the expected growth of OSW installations with global climate goals while minimising carbon emissions. The methodology is structured around the following four steps:

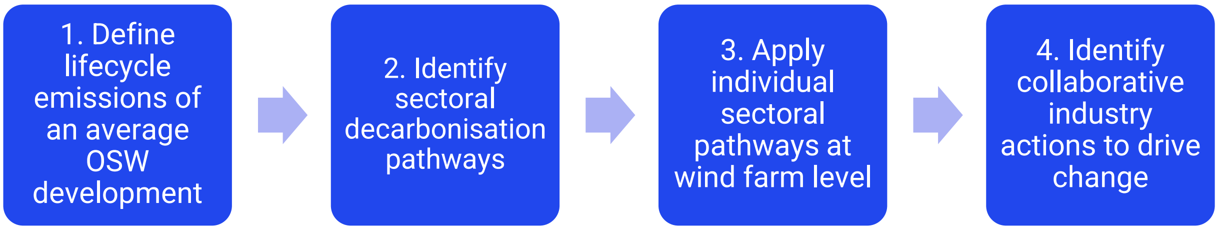


Figure 2: Methodology to arrive at the OSW decarbonisation pathway.

[1] Energy Systems, Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III.
[2] Global Wind Report 2024, Global Wind Energy Council, 2024.
[3] Net Zero by 2050, A Roadmap for the Global Energy Sector, International Energy Agency, 2021.

Step 1. The Carbon Trust established the baseline emission sources for an average OSW development by analysing publicly available studies by Siemens for a development using SGD 14-222 turbines and Vestas for a development using V236-15 turbines.[4,5] These studies provided data on the materials and activities contributing to emissions in each life cycle stage.

Where emissions data for specific materials or activities were available, we directly extracted the stated emission contributions. However, for materials or activities where detailed emissions data was unavailable, the Carbon Trust used mass balance calculations and proxy emission factors from secondary sources to estimate these contributions.

By averaging the extracted and derived data from both studies, we developed a representative baseline emissions profile for the life cycle of an OSW development, broken down into key emission sources. This baseline helps quantify the scale of the challenge and pinpoint where decarbonisation efforts should be prioritised for maximum impact.

Step 2. After identifying the composition of baseline emission sources, we reviewed the individual sectoral decarbonisation pathways for these composition areas relating to the construction and operation phases of the OSW development. The pathways represent sector-level decarbonisation trajectories, indicating what is achievable for each individual sector by implementing various Net Zero-aligned carbon reduction strategies and technologies as defined by industry and research organisations. The sources used for each sectoral decarbonisation pathway are shown in Table 1.

Table 1. Sectoral decarbonisation pathways assigned to key material inputs and activities of a baseline OSW farm.

OSW development material input or activity	Sectoral decarbonisation pathway
Steel	Steel IEA NZE Scenario Pathway
Aluminium	IAI 1.5 Degree Scenario
Plastics	SYSTEMIQ Net Zero System Change Scenario
Copper	ICA Pathway to Net Zero
Cast iron	Steel IEA NZE Scenario Pathway
Construction and installation (vessel fuel)	IRENA 1.5° C Scenario for Shipping Sector
Operations and maintenance (vessel fuel)	ORE Catapult and the Workboat Association O&M vessel roadmap

[4] Electricity from a European offshore wind farm using SG 14-222 wind turbines, Siemens Gamesa Renewable Energy, 2023. The assessment was based on a 1,120 MW capacity plant size, located 50 km from the port, with monopile foundations.

[5] Life cycle assessment of electricity production from an offshore V236-15 MW wind plans, Vestas, 2024. The assessment was based on a 990 MW capacity plant, located 58 Nm from the port, with steel monopile foundations.

Each sectoral pathway identifies several decarbonisation levers that, if implemented, can reduce the associated carbon emissions. Each decarbonisation lever is assigned an emissions impact reduction (EIR), a measure of its potential to decrease emissions relative to the industry baseline's emissions intensity. The EIR quantifies the theoretical decrease in emissions per unit of mass or activity output, assuming the lever is utilised to its full potential. In some cases, the EIR for a decarbonisation lever was directly stated within the sectoral pathway. When this information was absent, the Carbon Trust conducted further research to estimate the approximate EIR.

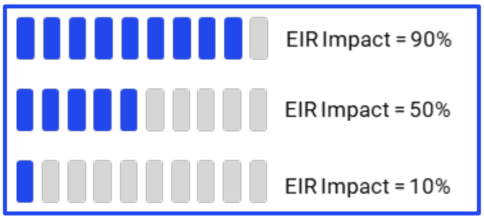


Figure 3: Emissions intensity reduction in $tC0_2$ per tonne material (relative to a baseline value).

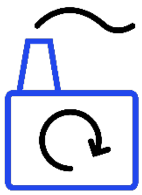
The sectoral decarbonisation trajectory integrates each decarbonisation lever, considering its EIR and practical implementation capacity, influenced by technological readiness and financial constraints. Where the relative lever contributions were not explicitly stated, the Carbon Trust estimated them by combining the EIR with the proportion of emissions it could address within the sectoral pathway.

Step 3. The individual sectoral pathways in Table 1 were applied to the baseline emission source breakdown to show the aggregated emission reduction potential of an OSW development from baseline to 2050, presented in Section 4, Figure 6. Each sectoral decarbonisation pathway was applied to the corresponding material or activity, weighted by relative contribution to the baseline, and the resulting combined decarbonisation pathway demonstrates a possible outcome for OSW if all levers are enacted as per each respective sector-level Net Zero aligned pathway.

The baseline year used as a starting point for each industry decarbonisation trajectory considered in this study varies from 2018 to 2021. For simplicity, it has been assumed that the baseline figure of each separate pathway can be applied to 2020 as a starting point when used in combination with assessing the OSW transition pathway.

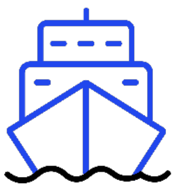
To apply these pathways, we assume there are no restrictions to the ideal pathway scenario as indicated in each source pathway from the analysis, representing an ideal ambitious Net Zero aligned pathway. For example, should the pathway depend on available low carbon materials, we assume these materials are readily available. Therefore, we understand this may be an optimistic scenario.

Step 4. We identified four target areas that could drive industry decarbonisation action. Enacting the OSW decarbonisation pathway requires a recognition of the complex interactions and dependencies between stakeholders to ensure that effective decarbonisation solutions are successfully implemented and that barriers preventing emissions reductions are overcome.



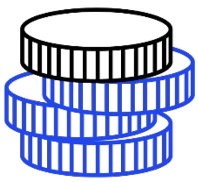
Materials and supply chain

Actions related to driving decarbonisation in the OSW supply chain and associated material inputs



Maritime activities

Actions to decarbonise vessel activities and fuels used during construction & installation and operations & maintenance



Market interventions

Funding, incentives and taxation interventions to facilitate the shift to low carbon developments

Business model innovations

Innovations and changes to OSW development business models

We identified key actions that could take place under each of these categories to accelerate decarbonisation action. Accelerating OSW industry decarbonisation requires action from various stakeholders, who must address the interactions between the systems that create and sustain the OSW industry and the energy sector more broadly rather than approaching each challenge in isolation. We also identified the key stakeholder groups responsible for each action and will need to collaborate to accelerate industry decarbonisation. The stakeholder groups we identified in this analysis include, but should not be limited to:

- **Governments** have a role to play in ensuring that the required technological solutions are incentivised and readily available. Once solutions have been effectively deployed and the actions taken have become well-established, the role of governments is expected to decline.
- **Developers** design and select the technologies to implement into the OSW farm. Developers can also signal the broader industry regarding their intentions and strategic planning for implementing low carbon solutions.
- **Regulators** have a role to play as market-specific and industry-wide regulations are needed to drive action related to directing standardisation or joint industry action.
- **Financial institutions** are responsible for enabling access to capital, which will be required to fund the transition to low carbon solutions in the OSW industry. Significant capital deployment is needed to decarbonise material inputs and maritime activities and support innovations in business models.
- **Supply chains** including but not limited to Original Equipment Manufacturers, foundation suppliers and vessel operators, will provide low carbon solutions to the market and attract sustainable financing options to enable decarbonisation of their own supply chains and assets.

4. OSW decarbonisation pathway

The baseline composition of emission sources for an average OSW development is presented in Figure 4. Having a baseline is a critical starting point for understanding the carbon impact of OSW developments and what the key contributors are for emissions. We note that the emissions profile of OSW developments can vary based on factors such as project size, distance from shore, and the choice of foundation material. As a result, the specific contributions of individual emission sources may differ depending on the design and composition of the OSW development in question.

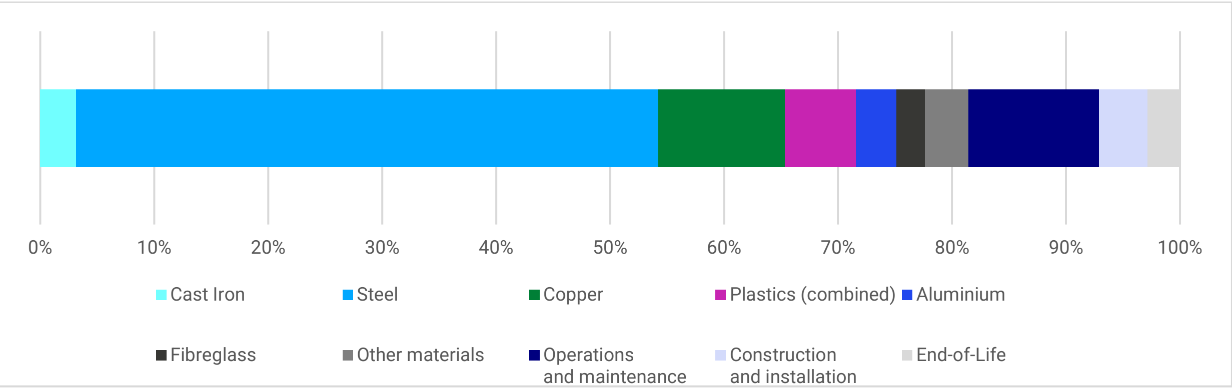


Figure 4: Baseline composition of emission sources for an average OSW development.
Areas in greyscale have not been evaluated as part of this study.

From the studies reviewed for this report, the baseline composition shows that:

- **Steel** contributes over 50% of life cycle carbon emissions for an average OSW development. This relates to the embodied carbon associated with producing the material and represents the area where the most significant reductions are required to achieve Net Zero.
- Embodied emissions from **other materials** (copper, plastics, cast iron, and aluminium) contribute 24% to a development's footprint.
- 15-20% of emissions are produced by construction and installation and operation and maintenance activities throughout an OSW development's lifetime. This largely reflects the emissions associated with **vessel fuels** required for these activities.

Individual sector decarbonisation pathways show the emission pathway reduction potential between 2020 and 2050. Figure 5 shows one potential decarbonisation trajectory, modelled by the IEA, for the iron and steel sector aligned with reaching Net Zero by 2050, which relies on an assumed interplay between a combination of decarbonisation levers.

The pathway indicates how the average steel emissions per unit purchased for an OSW development could decrease between 2020 and 2050. Several decarbonisation levers are listed, along with their EIR compared to business-as-usual production, contributing to the overall sector emission reduction potential. To maximise the decarbonisation of steel used in OSW developments, the material availability of steel produced under each of the decarbonisation lever methods will be an influencing factor.

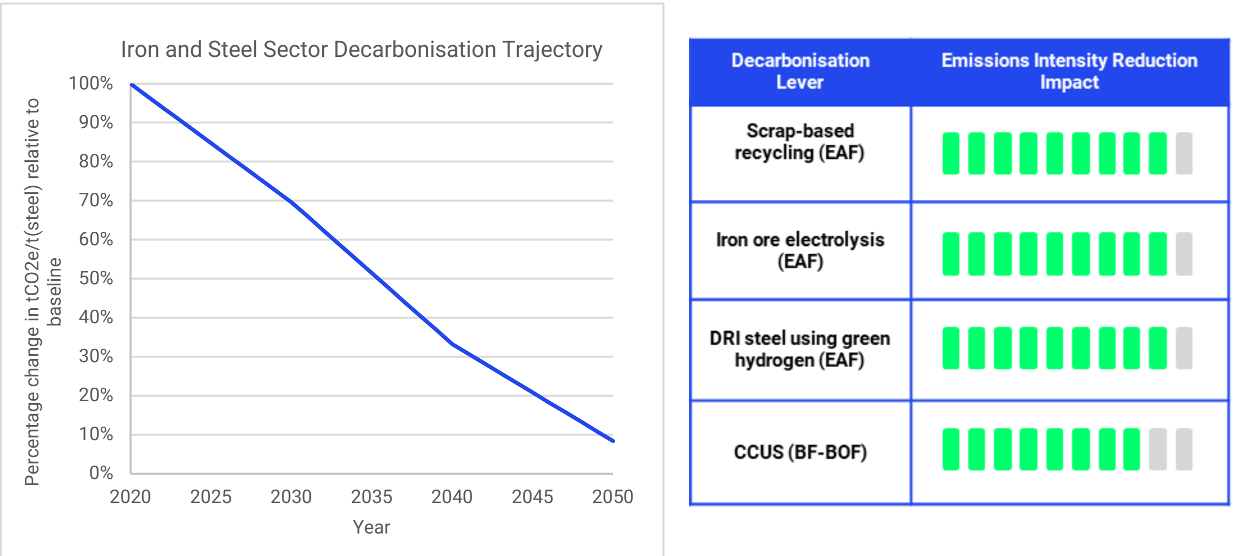


Figure 5: Iron and steel sector decarbonisation trajectory and the impact of emissions intensity reduction based on decarbonisation levers. Data source: IEA NZE Scenario.
EAF = Electric Arc Furnace

To create the first-of-its-kind OSW decarbonisation pathway presented in Figure 6, we combined the individual sectoral pathways for each of the component parts in Table 1, and applied them to the baseline OSW emission breakdown in Figure 4.

The applied sectoral decarbonisation pathways represent the average emissions within an ambitious Net Zero aligned scenario. The developed OSW pathway may represent an optimistic scenario dependent upon the availability of the low carbon materials identified within the material decarbonisation pathway.

Applying the sectoral decarbonisation pathways to the OSW baseline demonstrates that these separate input pathways, such as steel, copper, and plastics, can be combined to significantly decarbonise the overall OSW farm emission profile when a range of low carbon technologies and Net Zero manufacturing processes are used. **A reduction of 90% is achievable by 2050** should all ambitious decarbonisation pathways be possible. This would be equivalent to achieving a cross-sector SBTi-aligned Net Zero target.

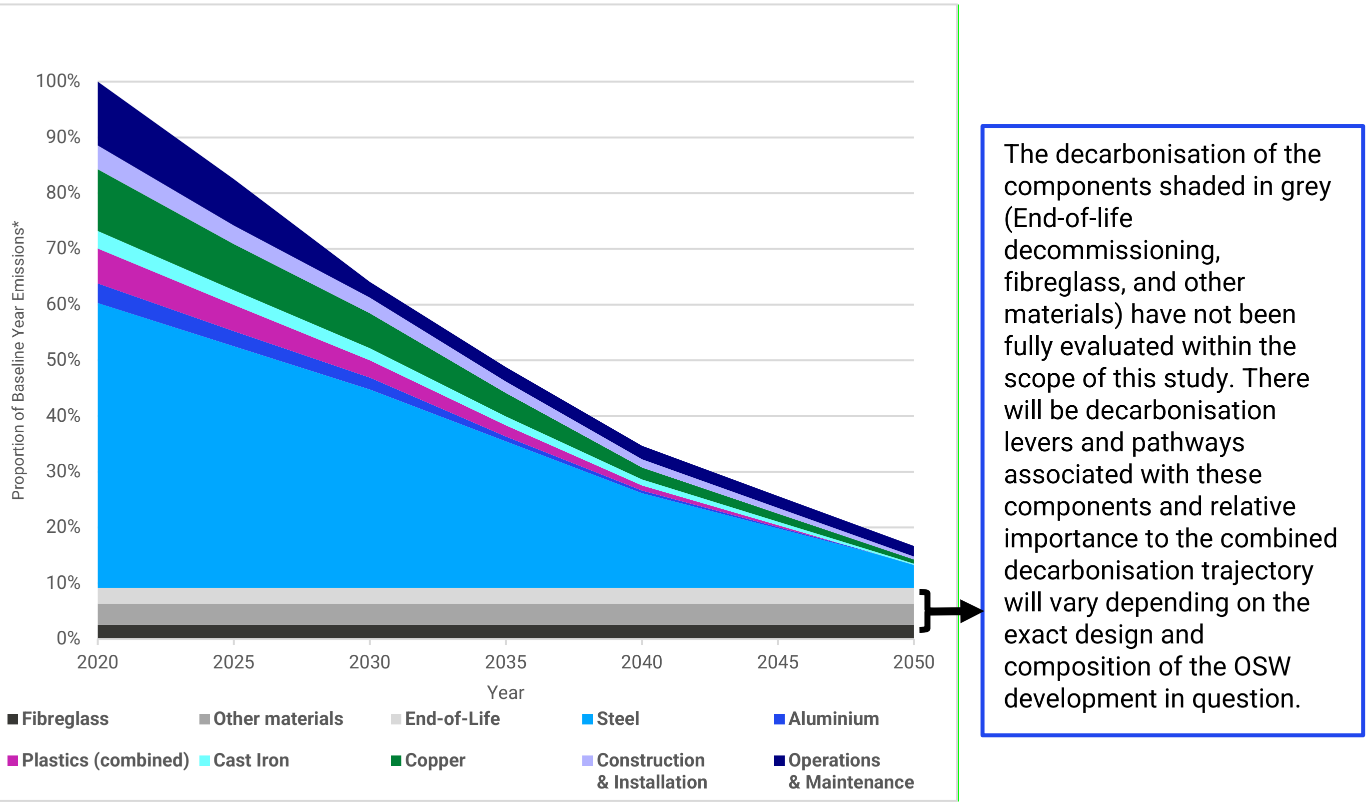


Figure 6: OSW decarbonisation pathway from 2020 - 2050 broken down by emission source.

The transition pathway and emissions reduction of 90% is in no way guaranteed, as its realisation will rely on the diligent actions of developers and other stakeholders. There is an opportunity for stakeholders across the OSW industry to come together, prioritise their efforts and align timelines. Without alignment on an OSW decarbonisation pathway, there is a risk that efforts are duplicated and fragmented across the materials and activities, resulting in limited carbon reductions in actual OSW developments. Hence, the decarbonisation pathway will ultimately rely on the cumulative actions and significant collaboration of stakeholders throughout the value chain of an OSW development. The following section presents key findings from a stakeholder actions assessment which would bring forth the realisation of the OSW decarbonisation pathway.

5. Actions for key stakeholders

The OSW decarbonisation pathway provides critical insights into the range of carbon emissions sources and how these relate to the associated sectors. Leveraging carbon reduction levers across sectors will be key for the OSW industry to align with Net Zero by 2050. While there is an important detailed list of actions across the short, medium, and long-term until 2050 summarised in Figure 7, in this report, we focus on key activities within the short-term, the next 4-5 years, to shift the pathway for 2030 onwards**.**

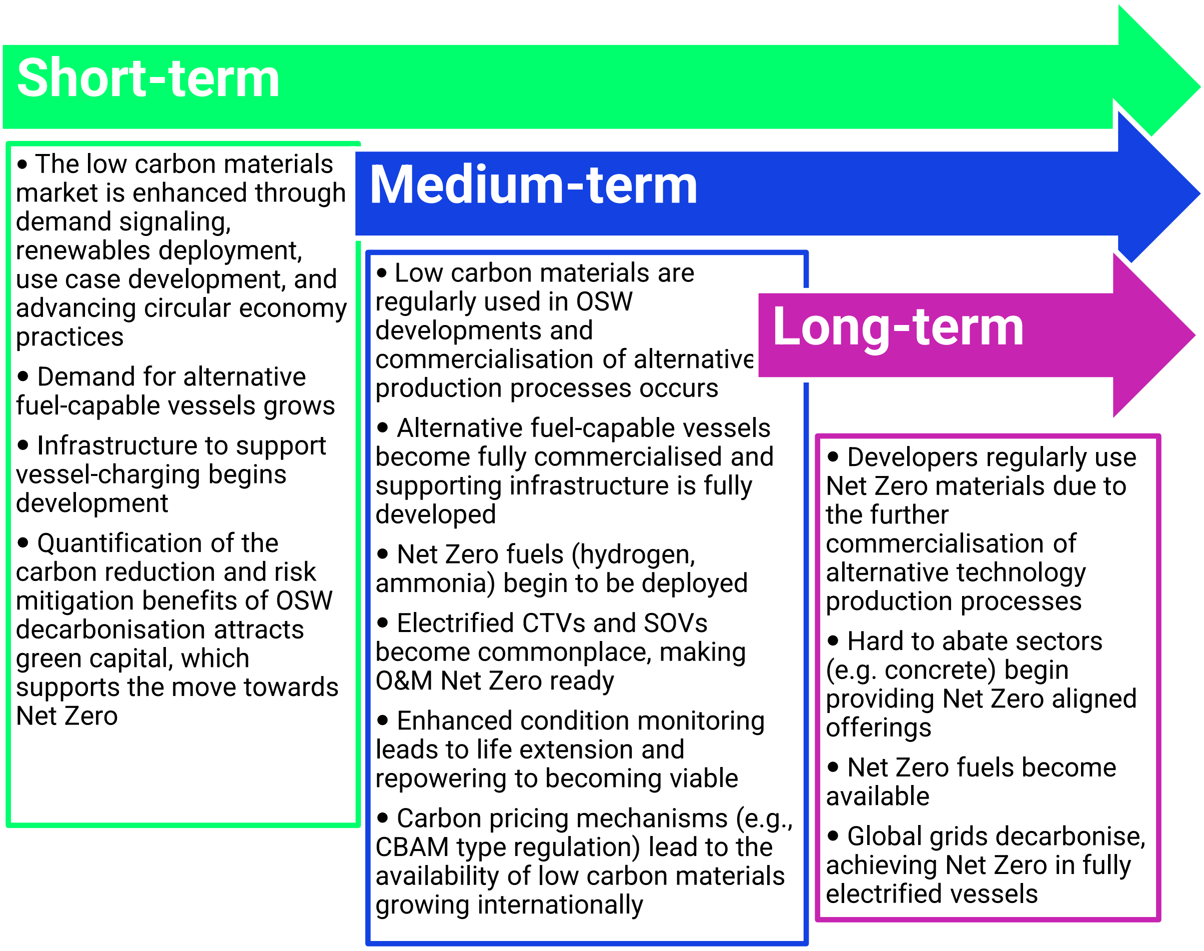


Figure 7: Overarching industry decarbonisation actions until 2050, where this section focuses on enabling the next short-term outcomes.

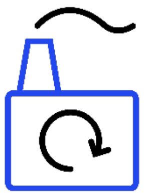
The specific emissions associated with any OSW development depend on the mix of components used in that wind farm. Tracking and accounting for emissions associated with each component is essential, with a clear need to monitor the emissions of the materials used in production.

Throughout Phase 1, we engaged numerous stakeholders, including regulators, governments, supply chain companies, academics and industry associations. It is promising to note that our engagement activities suggest that many players in the OSW industry are already measuring their associated carbon emissions, whether of the wind farm, as a life cycle assessment, or at the component level.

The Sustainability JIP partners recognised the significant challenge in harmonising the measurement approaches to calculating the carbon footprint of an OSW farm and the transparency of data information. In response, the programme commissioned the 'Offshore Wind Industry Product Carbon Footprinting Guidance' to standardise how an OSW farm footprint should be calculated. There is an opportunity to use the methodology to support consistency in individual reporting. In combination with the OSW decarbonisation pathway, we can collaboratively identify how the industry can reduce its footprint over time by selecting the most efficient and impactful interventions and levers.

Next, we discuss how the four identified target areas can facilitate decarbonisation action in the OSW industry. We highlight the challenges, possible solutions and examples of industry action to drive change. Although we discuss the four target areas individually it must be noted that they should be considered as part of a whole systems approach to accelerate change fully.

5.1. Materials and supply chain



The baseline composition of emission sources (Figure 4) indicates that 60-80% of emissions stem from the material inputs used in an OSW development. Increasing the supply and demand of 'green' materials is essential for decarbonising OSW farm projects.

Setting individual targets for material demand and production by developers and suppliers will improve the market's transparency and establish clear expectations for suppliers to adapt to the demand for low carbon materials. Exploring long term agreements between developers and suppliers could forge strategic relationships and ensure the future availability of green materials.

The availability and price of green materials remain key challenges in scaling their use, particularly as demand from other industries impacts supply. Significant coordination is needed to drive decarbonisation action given the range of materials and inputs and their individual decarbonisation pathways (Table 1). Governments, financial institutions, and regulators will play important roles in supporting a transition to greener materials through the use of reporting mechanisms, access to capital for investments in the supply chain, and improving the regulatory environment for the quality of green materials. Several actions related to this topic are discussed in Section 5.3 as each area is part of the wider system change.

Table 2. Stakeholder actions related to the materials action area.

Grouping	Developers	Regulators	Governments	Supply chain	Vessel operators	Financial Institutions	Action	Examples
Cross cutting							Set 'green' material use targets independently or through organising bodies to stimulate demand for low carbon materials.	Climate-focused initiatives such as SteelZero aim to drive substantial change across industries by setting clear targets.[6] Organisations that join SteelZero commit to sourcing and using 100% Net Zero steel by 2050 or earlier.
							Aggregate demand for green materials and communicate future commitments and	Promoting the business case for lower carbon emissions materials (which commonly carry a green premium) within energy companies also relies on support through market interventions and internal

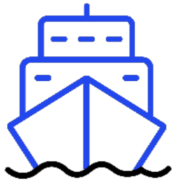
[6] About SteelZero | Climate Group.

	●	●		●			expectations around material use to support supply chain planning.	business model innovations. The Rocky Mountain Institutes' Sustainable Steel Buyers Platform aims to aggregate green steel demand across North America to support the investment required for cleaner steel production.[7]
	●	●		●			Mark materials with their classification/grade and produce a materials passport to increase re-use, improve the quality and quantity of recycled materials and minimise reprocessing requirements.	Material passports are gaining traction in other industries and play a pivotal role in advancing the circular economy by treating infrastructure and buildings as material banks (known as BAMB). By maintaining comprehensive digital records of the materials used for an OSW development and conditions assessments, significant increases in the potential for reusing, recycling or upcycling materials can be realised.
Steel	●		●				Increase OSW and other renewable energy capacity to facilitate green hydrogen production and the deployment of electric arc furnaces required to decarbonise the steel sector.	Renewable energy generation needs to increase to be able to accommodate demand once low carbon production technologies become commercially available. Setting ambitious renewable energy targets, such as the UK's 50 GW by 2030 and Germany's 40 GW by 2035 will support renewable generation.
	●	●		●		●	Identify and support low carbon steel manufacturers with high-impact capital investment roadmaps.	Steel manufacturer Dillinger has near-term plans to adopt low carbon technologies (EAF by 2030). The company offers reduced-emission products under its Pure Steel+ concept in collaboration with Saarstahl.[8] This concept allows for CO_2-reduced steel to be recognised and marked to their products. This approach ensures that low carbon steel is not only recognised but also integrated into product offerings.
	●	●		●			Increase the use of scrap steel within the manufacture of heavy plate steel.	The Ørsted and Vestas's partnership is an example of how scrap steel can be increased in the manufacturing process. This pioneering circular solution involves the procurement of low carbon steel wind turbine towers and blades made from recycled material.[9]
Aluminium	●		●	●		●	Target OSW and other renewable development to supply aluminium facilities with low/zero carbon electricity.	Alinta Energy in Australia plans to power the Portland Aluminium Smelter with up to 100% renewable energy provided by the Spinifex OSW development.[10]

[7] Sustainable Steel Buyers Platform, Rocky Mountain Institute.
[8] Pure quality, pure innovation: Pure Steel+.
[9] Ørsted and Vestas in industry-first pioneering partnership towards net-zero wind farms.
[10] Alinta lands powerful new partner for offshore wind project – and identifies a site near smelter | RenewEconomy.

Concrete							Increase the use of recycled concrete when developing OSW sites, where appropriate.	Examples of developments using recycled concrete include the Kunsthaus Zurich building extension, which used 98% recycled concrete, significantly reducing the environmental impact related to construction activities.[11] There is opportunity to use recycled concrete in OSW developments.
							Explore the suitability and application of geopolymer binders within gravity-based and floating OSW foundations.	Geopolymers are commonly used within the construction sector with benefits to improve strength and waterproof properties, ultimately protecting the concrete and reducing associated carbon emissions in the manufacturing. Research has been conducted to explore the suitability of geopolymers for OSW monopiles, but are currently in concept stage.[12]

5.2. Maritime activities



The baseline composition of emission sources (Figure 4) indicates that around 15% of emissions originate from operations and maintenance and construction and installation activities, which are driven by vessel fuel emissions.

The wide variety of vessels used throughout the life cycle of the OSW development presents a coordination challenge. Driving maritime decarbonisation requires collaboration among diverse stakeholders, with developers, vessel operators, governments, regulators and financial institutions all needing to play a role. This area presents a significant opportunity for the OSW industry to lead in decarbonising offshore logistics.

Green hydrogen, e-methanol, bio-methanol, and electrification are seen as particularly promising decarbonisation levers for decarbonising operation and maintenance vessels. While electrification holds significant promise for decarbonisation, it faces physical constraints such as battery energy density and cost, which pose challenges, particularly for the complete electrification of larger vessels. As a result, electrification is expected to be primarily applicable to crew transfer and service operation vessels. Yet, there remains uncertainty as to whether decarbonisation will be achieved mainly through vessel electrification or fuel-switching.

[11] Using Recycled Concrete for Sustainable Construction, Bloomberg, 2021.
[12] A new concept for offshore turbine tower construction, Wind Systems Magazine, 2020.

Table 3. Stakeholder actions related to the maritime activities action area.

Grouping	Developers	Regulators	Governments	Supply chain	Vessel operators	Financial Institutions	Action	Examples
Construction vessels	■	■	■				Install shore power connections in ports and provide renewable energy options.	The Tyndall Centre's report on shore power highlights three actions to drive uptake in the UK over the next 5 years. The actions provide a clear roadmap for practical deployment and one notable recommendation is transitioning from conventional diesel to clean electricity sourced from OSW farms.[13]
	■	■	■		■		Expand methanol dual fuel engine fleet capacity through retrofit and new builds.	Expanding the use of methanol-fuelled ships within fleet capacity will significantly lower emissions, using specialised engines. DNV has highlighted the growing momentum for methanol adoption and underscores the opportunity to procure DNV-certified vessels.[14]
Low/zero carbon bunker fuel infrastructure		■			■		Skills and training development across vessel operators and key ports on safe and effective low/zero carbon fuel handling.	The Seafarer Training and Skills for Decarbonized Shipping report by the DNV outlines the impact of decarbonisation on the shipping industry and the training needs required for crew members.[15]
		■			■	■	Low carbon bunker fuel pumping tool infrastructure deployment in key construction ports.	Since the summer of 2023, the Port of Rotterdam has facilitated methanol bunkering to sea-going vessels.[16] This happens at a shipping-vessel level, and OSW vessel operators must signal demand.
		■	■				Industry body-led identification of suitable ports for low-cost infrastructure development e.g. where methanol is already held for transport.	The Methanol Institute has identified that methanol is available at more than 100 ports around the globe. Of these, 47 ports have the facilities to store over 50,000 tonnes of methanol. Such

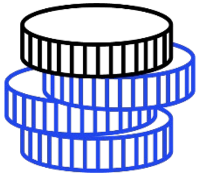
[13] Barriers and solutions for UK shore-power, Tyndall Manchester, 2020.
[14] Record Number of Methanol-Fueled Ships Ordered Reports, DNV, 2023.
[15] Seafarer training and skills for decarbonized shipping, DNV, 2022.
[16] Port of Rotterdam to fuel ships with methanol on a regular basis from summer 2023, Offshore Energy, 2023.

								infrastructure is pivotal in supporting the shipping industry's transformation to a greener future.[17]
Methanol							Support and promote the development of e- and bio-methanol facilities through demand signalling.	The Danish renewable developer European Energy has received €53 million for its upcoming Power-to-X facility, which will become the largest e-methanol production plant in the world. This facility is powered by renewable energy from a nearby solar park, contributing towards clean fuel production.[18]
Vessel electrification							Increase the use of hybrid service operation vessels (SOV) and crew transfer vessels (CTV) to generate demand signals for fully electrified vessels once costs are reduced.	Damen's fully electric Service Operations Vessel demonstrates the potential for significant reductions in emissions related to the maintenance of OSW farms. Damen's vessel uses a 15 MWh battery, sufficient to power the vessel during a full day of operations. The battery is lithium iron phosphate making the most out of the vessel's sustainable credentials.[19]
Vessel electrification infrastructure							Survey grid capacity at key SOV and CTV ports to identify where additional infrastructure is needed to supply an electrified fleet.	Identifying where additional infrastructure may be required could be done using calculation tools. For example, the National Grid has partnered with Siemens to develop a free online tool to help UK ports forecast the future infrastructure needed to meet the potential rising demand for zero-emission vessels.[20]
							Develop grid infrastructure or battery installations to enhance the supply capabilities of key ports.	Many ports do not have sufficient grid capacity to charge multiple vessels. Alternative methods of energy storage, such as battery solutions, can be implemented to provide low carbon electrification support. Solutions like those provided by Connected Energy can provide battery storage for ports and harbours.[21]
							Ensure new OSW developments are equipped with vessel charging capabilities.	OSW developments currently being installed will be in operation for the next 25-30 years. Installing vessel charging capabilities will future proof the industry and mitigate challenges of battery range. The charging systems could enable all offshore support vessels to connect in the field to a 100% green energy source. The Port of Blyth harbour trials, using the Tia Elizabeth crew transfer vessel

[17] Methanol already available at more than 100 ports says institute, Container News, 2020.
[18] World's largest e-methanol facility gets €53 million boost, Offshore Energy, 2022.
[19] Damen introduces fully electric SOV with offshore charging, Damen, 2023.
[20] New online tool will help UK ports transition to net zero, National Grid Group, 2021.
[21] Battery Storage For Ports & Harbours, Connected Energy.

								(CTV), is an example where this type of charging system is being tested.[22]
Standardisation							Alignment of the interface geometries, so vessel types can consistently dock across different turbines and platforms.	Ensuring all vessels can dock efficiently at all platforms requires precise and well-planned geometry. The Carbon Trust provides a recommended design for optimal boat landing geometry, addressing practical challenges faced by vessels and crews.[23] By prioritising safety and operational efficiency, this recommended design demonstrates the importance of innovation in increasing the adoption of sustainable, low carbon vessels.

5.3. Market interventions



Transitioning to a low carbon economy requires significant market interventions to create the necessary push and pull factors to drive the transition. In the OSW industry, such interventions will likely include funding initiatives, taxation measures and other incentives.

In the short term, funding will need to come from an increased availability of sustainable finance and sustainability linked loans or bonds. Tailored financial instruments to support the transition to a low carbon emissions economy can allocate funds and provide favourable interest rates for green projects. Access to such capital reduces debt expenses associated with green initiatives, strengthening their viability.

The supply chain also requires significant capital investment to produce necessary green materials. As such, developers and the supply chain will need to quantify emission reduction potential to attract capital, especially given the broader application of low carbon materials to other sectors besides OSW. The recently published OSW industry PCF guidance will help quantify the carbon abatement opportunities that sustainable finance is already contributing to or could contribute to.[24] Measuring the carbon emission savings through this approach will enable lenders to see the achieved or prospective benefits of funding green decarbonisation levers.

Governments and regulators must be the primary stakeholders in initiating the required incentive-related stakeholder actions, introducing opportunities to support industry decarbonisation.

[22] Offshore charging facility for electrified vessels set to revolutionise offshore operations, ORE Catapult, 2020.
[23] Design for recommended boat landing geometry, The Carbon Trust, 2018.
[24] Standardising offshore wind carbon footprinting, The Carbon Trust, 2024.

Table 4. Stakeholder actions related to the market intervention areas

Grouping	Developers	Regulators	Governments	Supply chain	Vessel operators	Financial Institutions	Action	Examples
Sustainability linked bonds/loans	✓			✓	✓	✓	Financial incentives/disincentives are defined as a reduction (step-down) or increase (step-up) against bond coupon or loan interest rate. The quantum of the step-up/step-down can also be structured to mitigate the variable impact of higher/lower interest rate environments.	Green loans can be used as an attractive financing instrument. Landesbank Baden-Württemberg (LBBW) is a German bank and is an example of how bilateral or syndicated loans can be made green. LBBW's positive incentive loan enables the support of a green economy for customers such as developers, giving them a price advantage.[25]
				✓	✓	✓	Increase the issuance of GSS+ loans (loans with fixed use of proceeds requirements) for both suppliers and developers to incentivise the necessary capital expenditure.	Significant investment is needed in the OSW industry to incorporate low carbon solutions. Financial institutions will need to make loans available to support this transition. The Glasgow Financial Alliance for Net Zero (GFANZ) is a global coalition of leading financial institutions all committed to accelerating the decarbonisation of the economy.[26]
Sustainable finance				✓	✓	✓	Apply sustainable finance frameworks with eligible assets related to OSW ecosystem decarbonisation to enhance access to capital for supply chain decarbonisation.	The Barclays Sustainable Finance Framework sets out a methodology for classifying financing as sustainable to integrate sustainability into financing practices. The framework highlights the importance of transparency through rigorous reporting and impact measurement. This framework will allow suppliers to enhance their capital and support decarbonisation activities.[27]
				✓	✓	✓	Quantification of the sustainability benefits of OSW ecosystem decarbonisation use of proceeds, to increase access to capital for the sector through enhancing the visibility of decarbonisation benefits to lenders.	AIB's green bond impact report (2023) outlines the type of green investment reporting undertaken by financial institutions and lenders.[28] Estimated annual emissions avoided are often reported. Quantification of green initiative benefits by OSW supply chain

[25] Green loans: How green finance pays off, LBBW, 2019.
[26] Glasgow Financial Alliance for Net Zero, GFANZ.
[27] Barclays Sustainable Finance Framework, Barclays, 2022.
[28] Green Bond Report, AIB Group plc, 2023.

								partners or other parties involved can support this and help to raise further investments.
Risk mitigation							Quantify risk mitigation benefits related to OSW industry decarbonisation to incentivise investment in the ecosystem.	The Task Force on Climate-related Financial Disclosures (TCFD) set out a framework in 2017 for organisations to analyse, understand and disclose climate-related financial information. The framework sets out recommendations on how organisations can assess risks and opportunities related to climate change.[29] Climate risk assessments have since been adopted in numerous standards and reporting requirements (ISSB, CSRD). Evaluating the reduced risk exposure can support a business case for climate mitigation initiatives.
OSW auctions							Enhance the weighting of carbon-related criteria in incentive mechanisms and tendering frameworks.	The Department for Energy Security and Net Zero (DESNZ) in the UK has plans to introduce the Clean Industry Bonus mechanism, which will allow CfD applicants to access extra CfD support if they provide evidence of supporting more sustainable supply chains.[30] Such policy shifts could enable higher-priced bids to be successful so long as the additional cost is going towards cost-effective carbon reductions.
							Increase the use of non-price criteria for auctions, factoring in sustainability and innovation.	The auction design for the 2022 Hollandse Kust West site in the Netherlands included non-price criterion worth 50% of total marks supporting the positive contribution to ecology of the North Sea. Similar design elements can be adopted to support aspects contribution to emissions reduction, increased circularity or other sustainability principles.[31]
Supply chain							Government supply chain support mechanisms to help the development of sustainable manufacturing infrastructure.	One example of available support is the UK's Industrial Energy Transformation Fund (IETF). The fund supports the development and deployment of technologies. The IETF launched in 2020 and is in 3 phases, with £500 million of funding available up until 2028. This will enable businesses with high energy use to transition to a low carbon future.[32]

[29] Task Force on Climate-related Financial Disclosure (TCFD), HM Treasury UK Gov, 2024.
[30] Contracts for Difference (CfD) Allocation Round 7: Clean Industry Bonus framework and guidance, UK Gov, 2024.
[31] Government Gazette of the Kingdom of the Netherlands, 7101 n1, Overheid.nl, 2022.
[32] Industrial Energy Transformation Fund, UK Gov, 2019.

5.4. Business model innovations

Innovations and adjustments to business models can be implemented to prioritise the sustainability and longevity of OSW assets. Individual companies will likely need to implement these changes, tailored to their specific business strategies.

There is no universal approach for making business decisions to facilitate OSW decarbonisation. Nevertheless, by integrating circular economy principles and designing to repair, repurpose and dismantle, companies can improve designs, extend the asset's lifespan, repower, and effectively decommission developments, significantly reducing the carbon impact of OSW farms. Whilst these business model innovations will unlock emission reduction potential, they must be paired with technological advancements to ensure full implementation.

Producing the low carbon materials necessary for future OSW developments will require a large quantity of high-quality scrap. Therefore, improving the availability and quality of scrap through better mainstream decommissioning practices could meet this demand while creating new commercial opportunities for developers in the recycled materials market.

Table 5. Stakeholder actions related to the business model innovation area.

Grouping	Developers	Regulators	Governments	Supply chain	Action	Examples
Repowering					Explore the implications of designing with repowering in mind. For example, to determine whether installing larger platforms that can accommodate future larger turbines when repowering is beneficial. This would reuse existing infrastructure, increasing circularity.	Futureproofing OSW developments for potential repowering could allow the reuse of existing infrastructure, reducing emissions. However, this must be balanced with the increased embodied emissions of installing oversized infrastructure. Innovative repowering design have the potential to dramatically increase power generation within the footprint of the existing project site. Governments could enable this action by supporting innovation tenders targeting repowering.
					Incentivise investments for repowering by lengthening seabed leases. Issue 50-year OSW leases to encourage life extension and repowering.	The Crown Estate updated the lease agreements for Round 4 sites from a 50-year lease to a 60-year lease to allow for two full operational life cycles.[33]

[33] Information Memorandum, Leasing Round 4, The Crown Estate, 2019.

Decommissioning					Investigate decommissioning processes for foundations that could enhance the availability of material for recovery and recycling.	Monopile decommissioning is an example area where more innovative approaches should be explored to support material recovery, low carbon operations, and circularity. Currently, monopiles are often cut at the base and extracted, leaving a large portion of the monopile underwater. Current research is exploring ways to commercialise the extraction of full monopiles from the seabed, which would help increase recycling rates (HyPE-ST 1.2).[34]
Life extension					Conduct regular condition assessments and install monitoring equipment on new and existing turbines.	OSW developments already incorporate various technologies to monitor assets, which are typically costed into the overall projects and business assessment. Advances in technology now enable more precise predictions of asset conditions, further enhancing operational efficiency and reliability.

[34] Hydraulic Pile Extraction Scale Tests 1.2 (HyPE-ST 1.2), GROW, 2021.

6. Conclusion

Decarbonising the OSW industry will require significant cross sectoral collaboration. The pathway to achieving Net Zero emissions will require action from developers setting clear targets, suppliers providing technology solutions, governments incentivising change, and financial institutions facilitating access to capital. While significant progress has been made at the individual sector level and by each industry, a holistic view of all parts of the OSW value chain is essential to unlocking the full decarbonisation potential.

The OSW decarbonisation pathway identified that a life cycle emission reduction potential of up to 90% is possible by 2050, should all decarbonisation levers be implemented without barriers (Figure 6). This is based on an analysis of emission sources of a typical OSW project (Figure 4) and publicly available sectoral decarbonisation pathways (Table 1). While targeting high emissions areas like steel production can deliver significant reductions, achieving Net Zero ultimately requires the reduction of emissions across all areas of the value chain as OSW relies on a range of inputs. Decarbonisation aligned with Net Zero goals is achievable within the OSW industry, but it relies on the committed actions of stakeholders to address the most emissions intensive areas of the value chain.

Although the emissions from OSW represent a small fraction of the total emissions associated with electricity generation, every industry must take accountability for exploring pathways to Net Zero and adopting economic models that account for environmental and social impacts beyond financial costs. Achieving Net Zero alignment will require fully integrating low carbon materials and practices into OSW designs and development processes. This will be a gradual, collaborative process, but in the short term, this OSW decarbonisation pathway acts as a starting point to seek deeper cooperation and action between the listed stakeholders in the near-term, from governments and regulators, to supply chain companies and vessel operators.

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