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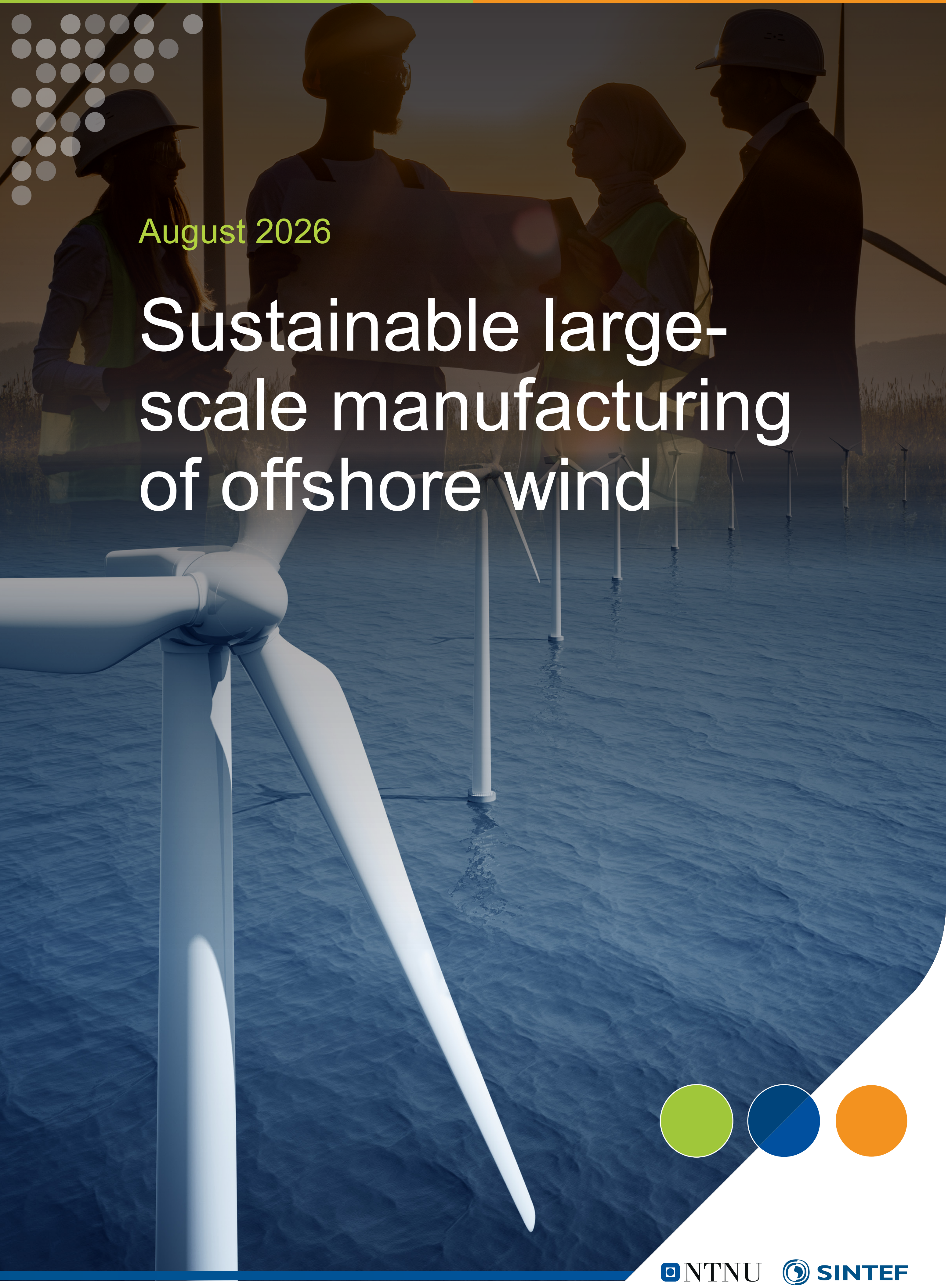
Sustainable large-scale manufacturing of offshore wind



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NTNU Energy Transition Initiative

NORTH WIND

Table of Content

Executive Summary

Sustainable Large-Scale Manufacturing of Offshore Wind

The Challenge

The European Commission estimates that up to 450 GW offshore wind is needed by 2050; North Sea countries have committed to an ambition of 300 GW by mid-century; Norway aims for seabed allocations corresponding to 30 GW by 2040. With current turbine sizes, meeting European targets requires manufacturing, transporting, installing and connecting more than 1,000 turbines per year for 25 consecutive years.

The gap between ambition and current reality is significant. Costs remain high — particularly for floating wind — and supply chains are fragmented. Project delivery still relies on bespoke engineering and one-off logistics rather than repeatable, standardised processes. A structured approach towards standardised serial production of offshore wind is required to become cost-competitive. The challenge is no longer whether offshore wind can be built, but whether it can be built at the scale, speed and cost required.

The Value Chain and Norway's Position

The offshore wind value chain is tightly connected and spans design, manufacturing and fabrication, transport and installation, operations and maintenance, and decommissioning. Cost and risk are determined not only by individual components but by how well the full value chain works together. Norwegian industry generated NOK 60 billion in offshore wind revenue in 2024, but this is dominated by maritime services; fabrication of foundations and floating substructures represents only a small share today. Norwegian industry has recognised strengths in floating structure design, subsea technology, mooring, cables and offshore operations — all transferable to offshore wind and representing clear growth opportunities as deployment scales.

A key structural weakness is fragmentation. Developers, turbine suppliers, yards, vessel operators and grid companies each optimise their own segment, generating coordination failures, late design changes and weak incentives for standardisation. Overcoming this fragmentation is as important as any individual technology advances.

Three Levers for Cost Reduction

Cost reduction is driven by three primary levers that must be applied in coordination across all parts of the value chain:

- **R&D and innovation**. Technology development, design evolution and knowledge generation. Innovation lowers cost by improving technical performance and making components suitable for industrial production, but only when compatible with available manufacturing capacity and supply-chain conditions.
- **Upscaling of capacity**. Expansion of manufacturing, logistics and installation capabilities. Upscaling reduces cost through learning effects, higher utilisation and spreading of fixed costs across larger production runs — but requires mature, repeatable solutions and predictable long-term demand.

- **Standardisation, interface management and value-chain alignment**. Coordination across the many actors in the value chain through standardised components and interfaces, common data formats and clearer allocation of responsibilities. Standardisation reduces complexity and creates the repeatability on which both innovation and upscaling rely, while preserving sufficient design freedom for continued technological development.

Key Findings Across the Value Chain

The detailed analysis in this report covers six value chain segments. The most critical cost-reduction opportunities are:

- **Fabrication and manufacturing**. Manufacturing bottleneck are dominated by labour intensive manufacturing processes for large structures of steel and concrete. One example is the time-consuming arc-welding process used for thick steel tubular wind substructures. New advanced and automated welding technologies - with 10-20 times the productivity of conventional arc welding - and robotic systems for assembly are priority R&D targets. Standardisation of component interfaces and modular design are the primary enablers of serial and automated production; design-for-manufacturability must be embedded in design standards from the outset.
- **Transport and installation**. Reaching 30 GW by 2040 requires installing 3–4 large turbines per week over a sustained decade. Ports must be designed as permanent industrial hubs; fleet strategies must be aligned with stable deployment volumes. Uncoordinated turbine upscaling — which has made entire generations of jack-up vessels obsolete within a few years — creates major investment risk and must be replaced by planned, coordinated size evolution.
- **Operations and maintenance**. O&M accounts for a substantial part of levelised cost of energy. Predictive maintenance through digital twins and condition monitoring is a high-impact R&D priority. Shared vessel pools coordinated across multiple wind farms are a major cost-reduction opportunity. Vendor contracts must require full access to operational data for operators.
- **Decommissioning and end-of-life**. Decommissioning must be integrated into lifecycle design from the outset, not treated as a late-stage obligation. Designing substructures for service lives significantly longer than turbines enables repowering without replacing foundations. Norway, with its oil and gas yard infrastructure and workforce, is well positioned to develop competitive European decommissioning hubs.
- **Electrical infrastructure and system integration**. Electrical infrastructure faces the most acute supply-chain bottleneck in the value chain: subsea cables, HVDC converters and cable-laying vessels are produced by a small number of suppliers with lead times already extending several years. Coordinated, standardised offshore grid architectures are needed to give manufacturers the long-term demand predictability required to invest in new capacity. Multi-vendor interoperability — showing that components from different vendors can function in the same system — is the central standardisation target.
- **Digitalisation and data**. The most important gap is not missing digital tools, but the absence of a shared digital foundation: common data standards, interoperable systems, and governance for data flow across organisations and lifecycle phases. Lifecycle data continuity, predictive digital twins and AI-assisted decision support are priority R&D areas. Data access is also a contractual problem: operators are routinely denied access to turbine performance data held by suppliers.

Two Overarching Conclusions

Two conclusions cut across all segments.

First

Cost reduction requires coordinated use of all three levers. R&D delivers results only when new solutions are compatible with manufacturing capacity and supply chains. Upscaling requires mature, repeatable designs. Standardisation enables both but must preserve room for innovation. There is no shortcut through any single lever alone.

Second

Large cost-reduction opportunities lie at the interfaces between value chain segments, not only within individual segments. Turbine–substructure interfaces, fragmented vessel strategies, late design changes and incompatible data systems are high-cost problems — and they are invisible when each segment is optimised in isolation. An end-to-end value chain perspective is the prerequisite for finding and acting on them.

Roadmap and Priority Actions

The analysis translates into prioritised actions across three time horizons. Stable framework conditions — predictable regulation, long-term seabed allocation plans, and credible project pipelines — are a necessary precondition throughout.

Short term (0–3 years): Enabling conditions. Resolving governance and interface gaps that block coordinated optimisation: turbine–substructure interface standardisation (the single highest-leverage design intervention for floating wind); mandatory vendor data access clauses in contracts; launch of a transnational standardised offshore grid architecture process; regulatory requirements for end-of-life planning from project outset; and definition of common digital naming conventions and semantic standards — the digital offshore wind equivalent of NORSOK.

Medium term (3–7 years): Industrial scale-up. Ramping industrial capacity and demonstrating new technologies: invest in designated Norwegian ports as long-term offshore wind industrial hubs; establish shared vessel fleet governance across multiple operators; deploy fleet-scale digital twins for predictive maintenance frameworks; demonstrate serial manufacturing of steel and concrete substructure; drive investment in cable and converter production capacity through coordinated grid architectures; and qualify new maintenance access technologies for floating wind.

Long term (7–15 years): Structural transformation. Structural transformation of industrial systems and regulatory frameworks: realise a transnational meshed North Sea offshore grid; achieve industry-wide coordination on turbine size evolution; develop Norway's decommissioning capability into a competitive European hub; reform certification frameworks for integrated floating wind systems; develop next generation decision support system based on AI agents enabled by predictive digital twins; and establish European operator control over core offshore wind digital infrastructure.

The detailed analysis and recommendations supporting this summary are set out in the accompanying report (Part 1 Motivation and the roadmap: Chapters 1-4 . Part 2 Detailed analysis of the value chain: Chapters 5–11).

1

Introduction

The transition to a low-emission energy system requires a substantial and sustained expansion of renewable electricity. Offshore wind is expected to be a central pillar of this development. European targets imply a several-fold increase in offshore wind capacity over the coming decades, requiring hundreds of gigawatts of additional capacity by 2050 (GWEC, 2025). In the North Seas there is an ambition to build 300 GW before 2050 in cooperation between 9 countries. In Norway, offshore wind has a dual strategic role: to contribute new renewable electricity to support decarbonisation and electrification. Norway aims to allocate seabed areas corresponding to 30 GW of offshore wind by 2040 (DNV, 2025; GWEC, 2025). These ambitions point to a fundamental shift in offshore wind – from individual projects to continuous, high-volume industrial production. The European Commission has estimated that up to 450 GW of offshore wind is needed before 2050.

From a base of around 37 GW in autumn 2025, this would correspond to an average deployment rate of around 16.5 GW per year over the next 25 years. With turbine sizes of around 16 MW, this implies that more than 1,000 offshore wind turbines would need to be manufactured, transported, installed and connected every year. Offshore wind must be treated not only as an energy technology, but as a large-scale industrialisation challenge requiring upscaling, standardisation and value-chain integration. At these volumes, industrialized modular manufacturing, standardised logistics and dedicated installation campaigns become economically viable — enabling the kind of specialisation and learning-curve effects that have driven cost reductions in other large-scale industries.

Despite significant technological progress, costs remain high – particularly for floating wind – and supply chains are fragmented (IRENA, 2024; Enova, 2025). Project delivery still relies largely on project-specific engineering solutions and one-off logistics approaches, rather than repeatable and standardised processes. As a result, the central challenge is no longer whether offshore wind can be built, but whether it can be built at the scale, speed and cost required.

Already in 2011, Norwegian offshore wind firms drew on the same capital, vessels and skilled labour as the petroleum sector, so resources moved in and out of wind as oil and gas activity fluctuated (Hansen and Steen, 2011). The same pattern is still visible today, with renewable projects struggling to compete with the returns available in oil and gas (DNV, 2025).

That early work also identified a second, more structural tension: the bespoke, high-specification engineering culture inherited from oil and gas sits uneasily with the standardisation and serial production that offshore wind requires to become cost-competitive (Hansen and Steen, 2011). More recent research confirms that this friction continues to inhibit industrialisation and technology transfer across the two sectors (Steen et al., 2024).

Importantly, the cost challenge cannot be addressed in any single part of the value chain in isolation. Cost, risk and performance are shaped by interactions across design, manufacturing, logistics, installation and operations. Decisions in one stage directly influence outcomes in others, and sub-optimisation at interfaces can negate improvements made elsewhere. Offshore wind must therefore be approached as an integrated system, where coordination, standardisation and alignment across the full value chain are essential to unlocking cost reductions and enabling industrial scale-up.

The purpose of this report is to assess how large-scale offshore wind deployment can be achieved in a cost-effective and sustainable manner, by identifying the key cost drivers and the most effective levers for reducing them across the value chain. A central premise is that reaching the required scale depends on a transition from project-based delivery towards industrialised production systems characterised by standardisation, upscaling and improved value chain coordination.

The report aims to provide a foundation for prioritising the research, industrial development, infrastructure investment and policy measures needed to support industrial-scale deployment. The report focuses on the parts of the offshore wind value chain that are most relevant for Norway, particularly where Norwegian industry has existing capabilities or clear potential for growth.

Spatial, environmental and societal considerations – including area use, ecological impact, public acceptance, and the regulatory framework – are outside the scope of this report, but must be considered as binding constraints, shaping not only what can be realised in practice, but also how it can be realised.

Realising the needed scale-up in specialised manufacturing, installation and service capacity depends on market participants being able to see a credible pipeline of projects. A primary lever here is stable framework conditions: clear and predictable regulation, and transparent long-term plans for how national and European resources will be developed. Without this predictability, the investment decisions needed to build specialised value chains will not be made. The analysis centres on the technological and industrial dimensions; policy and regulatory enablers are acknowledged as necessary conditions but not analysed in depth here.

Part 1 of this report contains Chapters 1–4 and is framed as a standalone executive narrative, bringing together the most important insights on the offshore wind value chain and translating them into a coherent set of priorities for cost reductions. The detailed analysis of cost drivers and reduction levers are presented in the digital Part 2 of this document (Chapters 5–10).

2

Overview of the Offshore Wind Value Chain

The purpose of this chapter is to establish a shared understanding of the offshore wind value chain and the main interfaces that shape cost, risk and sustainability. Offshore wind is not a single technology, but a tightly connected set of technical, industrial and operational activities. A wind farm must be designed, manufactured, fabricated, transported, installed, operated, maintained and eventually decommissioned. Cost, risk and sustainability are therefore determined not only by the performance of individual components, but by how well the full value chain works together.

2.1 The Components and Their Place in the Value Chain

The offshore wind system can be divided into main subsystems, each of which plays a role across the value chain. In the following, each subsystem is described in terms of what it is, the materials and design premises it involves, and where in the chain it is designed, fabricated, installed and maintained — together with where Norwegian industry stands.

The turbine system comprises the rotor, nacelle and internal systems such as the drivetrain, generator, and power and control systems. Its main function is to convert wind energy into electrical power and regulate performance and loads. Typical materials include composites (glass and carbon fiber) in the blades, and steel and cast iron in mechanical components and structures (See Figure 1). These components are designed and certified together, and in the Norwegian context the turbine is in practice treated as "given": at present there are no manufacturers of these components in Norway. Norwegian industry has a limited role in turbine manufacturing, but some activity in power and control systems and digital solutions. An important consequence is that the Norwegian design problem becomes essentially one of designing *around* the turbine — developing substructures, balance of plant and operational solutions that take the turbine's loads, motions and rapidly increasing size as a premise. A more realistic and strategically valuable industrial objective for Norway is to further develop strong competence in the assembly, integration and commissioning of offshore wind systems, energy grid systems including cables, substructure fabrication (floating or bottom-fixed), turbine integration, operation and maintenance, and mooring hook-up — areas where existing offshore, electrical and maritime industry skills are directly transferable.

The structural system consists of the tower, substructure and foundation, and is responsible for supporting the turbine and transferring loads from wind and waves. The substructure is one of the main characteristics that differentiate the types of offshore wind systems, with their corresponding value chains, and can broadly be divided into bottom-fixed and floating solutions.

Bottom-fixed substructures include monopiles, jackets (as in figure 1), tripods and gravity-based structures (GBS). Monopiles and jackets are primarily steel structures, while GBS are typically concrete-based. In Europe, large monopiles dominate the market for bottom-fixed structures, while some concrete GBS developments are seen, particularly where seabed conditions or local content requirements are highlighted. The Norwegian market for bottom-fixed offshore wind

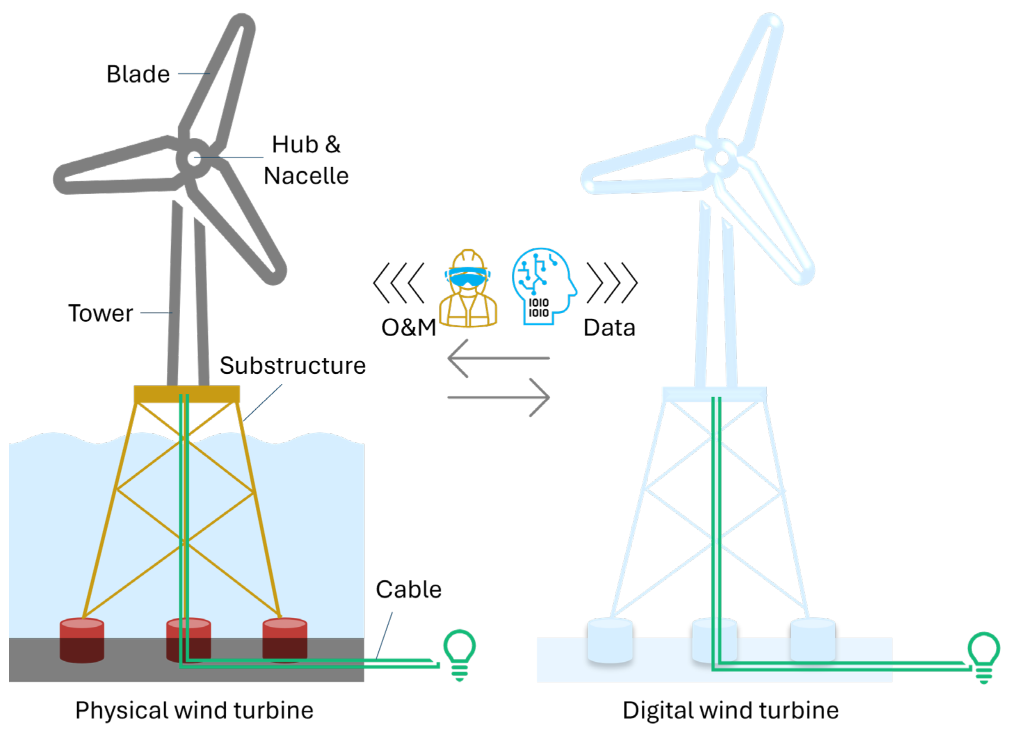


Figure 1: Basic elements of a wind turbine (Xiaobo Ren, SINTEF Industry)

is fairly limited owing to the large water depths in proposed development areas (NVE, 2025).

Floating concepts include semi-submersibles, spar-buoy and barges, which may be made of steel, concrete or hybrid material solutions. The choice between concepts depends on water depth, seabed conditions, turbine size, environmental loads, manufacturing capacity, port infrastructure, installation strategy and cost. Here Norwegian industry has a clear competitive advantage, particularly in the design and supply of offshore and floating structures. Norway has direct operational experience through Hywind Tampen, which provides a domestic reference base for floating wind design and performance and demonstrates that floating wind is technically feasible at scale in Norwegian conditions. Relevant state-of-the-art competence exists in structural engineering, marine technology and offshore design, including through institutions such as NTNU and SINTEF.

The seabed and energy system includes seabed survey and preparation, anchoring systems and mooring for floating structures, as well as subsea and electrical infrastructure such as cables, subsea components and offshore substations. These systems ensure both seabed interaction and the transmission of power to shore and into the wider energy system. Floating solutions rely on chains, lines and anchors adapted to seabed conditions, along with dynamic cables and subsea connection systems. For floating turbines the cabling is considerably more expensive, owing to deeper waters, the more complex dynamic cables needed, and the constant motion of the floating turbine. Norwegian industry is strong in subsea technology, cables and mooring systems, and builds on established capabilities toward greater roles in power systems and system integration. The transmission infrastructure represents a significant share of a project's total capital expenditure, and its cost depends on the distance to shore (NVE, 2025), The electrical infrastructure is treated in detail in Chapter 9.

2.2 The Value Chain, Stage by Stage

The offshore wind value chain can be defined as the set of stages (activities and actors) needed to deliver offshore wind systems from early engineering, through offshore installation, to operations and maintenance, and finally decommissioning. An example of a value chain for offshore wind substructures is:

Design → manufacturing and fabrication → logistics and transport → installation → operation and maintenance → decommissioning and end-of-life.

The **early design stage** covers concept development and engineering definition of the chosen type of offshore wind structure. It includes decisions that set the technical baseline for later phases, including concept selection, sizing and design choices.

Manufacturing and fabrication starts from procurement and supply-network activities required to secure materials, components and services, through to the fabrication and assembly of the structures. Early activities include sourcing and contracting decisions, supplier selection and capability considerations, and coordination mechanisms used to manage dependencies across the supply base, as well as how production is organised and how engineering information and interfaces are managed to support predictable fabrication flow.

Transport and installation cover onshore assembly and storage, logistics, transport to site, and offshore installation. It includes the configuration of vessels and port capacity as well as the planning and coordination of offshore tasks under weather and resource constraints.

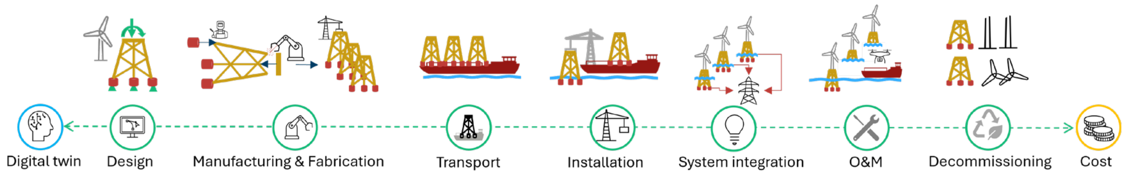
Operations and maintenance include the activities required to keep the system functional, safe and efficient over its lifetime — monitoring and repairing components, harsh marine logistics (vessels, helicopters), predictive maintenance and data analysis.

Decommissioning covers the final, multi-stage, regulated process of removing components at end of life, restoring the site and recycling materials.

2.3 Dependencies Across Stages

Each stage depends on decisions made in earlier stages. Design choices influence material use, manufacturing complexity, transport requirements, installation vessels, maintenance needs and decommissioning options. For example, a substructure design that minimises material use may be more difficult to manufacture or install, while a heavier but simpler structure may reduce fabrication risk and installation time. Similarly, decisions on turbine size, foundation type, cable layout and port strategy affect not only capital cost, but also schedule risk, vessel demand and long-term operational performance.

Figure 2: Illustration of the offshore wind value chain – jacket substructure as an example (prepared by Xiaobo Ren, SINTEF)



OVERVIEW OF THE OFFSHORE WIND VALUE CHAIN

The largest cost drivers vary across the value chain. Turbines, substructures, transport and installation, electrical infrastructure, operations and maintenance, and financing are all major contributors to total cost. However, the relative importance differs between bottom-fixed and floating wind. For bottom-fixed wind, foundation and installation costs are often central. For floating wind, substructure, mooring, dynamic cables, port integration and maintenance logistics become particularly important. Across both technologies, vessel availability, port capacity, weather windows, standardisation and supply-chain maturity strongly influence cost and risk.

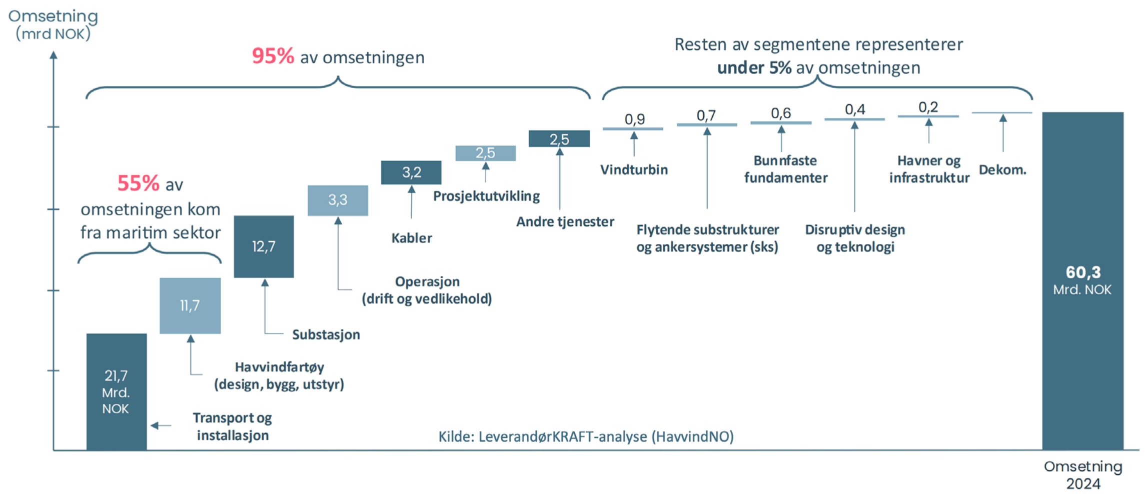
In 2024, total Norwegian activity related to offshore wind was NOK 60 billion (ED og Multiconsult, 2025), distributed across the segments shown in the figure below (LeverandørKRAFT, 2026).

This revenue is dominated by the maritime segments rather than by component manufacturing. Transport and installation, together with offshore wind vessels, account for more than half of total turnover, building on capabilities carried over from oil and gas, while substations and cables — led by HVDC topsides and export cables — add a further quarter (LeverandørKRAFT, 2026). Fabrication of foundations, floating substructures and turbines, by contrast, represented only a small share of 2024 revenue. There are, however, significant year-to-year fluctuations, and the relative share of different segments depends strongly on the types of contracts being delivered. This reflects market timing and limited fabrication capacity rather than a lack of competence: Norwegian industry retains a recognised position in the design and engineering of floating structures, which represents a clear growth opportunity as deployment scales.

2.4 Fragmentation and Lifecycle Thinking

A key challenge is that offshore wind value chains are often fragmented. Developers, turbine suppliers, foundation designers, fabrication yards, ports, vessel operators, grid companies, maintenance providers and regulators may optimise their own part of the system without fully accounting for consequences elsewhere, in

Figure 3: LeverandørKRAFT (2026): How should the supply chain for the offshore wind industry be developed to strengthen Norway's competitiveness and generate greater economic value?, HavvindNO / Norsk Industri.



part because a lead firm's ability to coordinate suppliers varies across different parts of the value chain (van der Loos et al., 2022; Barter et al., 2020). This can lead to coordination failures, late design changes, inefficient logistics, over-conservative requirements, rework and duplication of work, uncertain interfaces and weak incentives for standardisation.

For large-scale offshore wind deployment, lifecycle thinking is essential. Decisions should be assessed not only against immediate investment cost, but also against manufacturability, installation risk, operational performance, maintainability, lifetime extension, decommissioning and circularity. Sustainable manufacturing principles and life-cycle assessment can help identify trade-offs between material choices, emissions, durability, logistics and end-of-life options.

The value chain perspective is therefore central to this report. Cost reductions will not come from one technology or one actor alone (Barter et al., 2020). They require better coordination across design, manufacturing, logistics, installation, operation and end-of-life. Offshore wind must increasingly be treated as an integrated industrial system, where standardisation, digitalisation, circularity and value-chain coordination are prerequisites for cost reduction and sustainable upscaling (Denicol et al., 2020). Design for manufacturability, and for ease of installation and maintenance, depends on coordination across the value chain, and on a gradual and continual upscaling of the industry (Barter et al., 2020; Denicol et al., 2020).

3

Understanding Cost in Offshore Wind through Key Levers

As set out in the previous chapter, the offshore wind value chain consists of interdependent parts – design, manufacturing, installation and operations – with feedback across stages. This value chain must be delivered at a pace and scale not currently seen. This chapter establishes the analytical framework used throughout the rest of the report. It first explains why cost determines the pace, scale and continuity of deployment (3.1), then introduces the three primary levers for cost reduction and the interactions between them (3.2). The relative importance of the three levers varies across these parts, so cost reduction does not follow from applying all levers equally everywhere, but from how they relate to the specific conditions, constraints and opportunities in each part of the value chain.

3.1 Cost as a Driver of Deployment Dynamics

Across markets, the viability, timing and volume of offshore wind development are increasingly determined by whether projects can be delivered at cost levels acceptable to investors, policymakers and end-users. As a result, cost is not only a project-level concern, but a system-level constraint on the realisation of offshore wind ambitions. Cost in offshore wind is often expressed through the levelised cost of energy (LCOE). While useful as a summary metric, LCOE does not fully capture the role of cost in shaping deployment (IRENA, 2024; GWEC, 2026). LCOE reflects only plant-level costs — construction, financing and operation within the boundaries of the wind farm — and does not account for the wider costs of integrating variable generation into the power system, including balancing, grid flexibility and transmission reinforcement, which tend to rise as the share of variable renewables grows (IRENA, 2024; Tande, 2024). It also says nothing about when electricity is produced and therefore cannot reflect the value of a unit of generation, which falls as penetration increases and periods of high output depress market prices (IRENA, 2024; GWEC, 2026). Because no single metric captures all these dimensions, this report frames cost not through one indicator but through the underlying levers that drive it, introduced in section 3.2.

In practice, cost affects offshore wind development through a set of linked mechanisms. Investment decisions depend on expected cost levels and associated risks; project pipelines depend on the viability of individual projects; and industrial scale-up depends on predictable and sustained demand. Because offshore wind is highly capital-intensive, the cost of capital and the risk premium attached to projects are themselves major determinants of delivered cost (IRENA, 2024). Taken together, these relationships imply that cost directly influences the pace, scale and continuity of deployment. High or uncertain cost levels do not only affect individual projects but can slow down or disrupt the broader build-out of offshore wind capacity. Understanding and reducing cost is therefore essential not only for improving project economics, but for enabling large-scale deployment over time.

UNDERSTANDING COST IN OFFSHORE WIND THROUGH KEY LEVERS

3.2 Key Levers for Cost Reduction and their Interactions

Cost developments in offshore wind are shaped by a set of underlying mechanisms that can be influenced through technological, industrial and organisational choices. In this report, these are treated as three primary levers for cost reduction: R&D and innovation; upscaling of capacity; and standardisation, interface management and value-chain alignment. These levers are relevant across all parts of the value chain — design, manufacturing, installation and operations — but their relative importance varies from one part to another, and cost reduction depends on how they are combined and applied in each specific context. The balance between the levers also differs by technology track: for the less mature floating concepts, R&D and innovation carry relatively more weight, whereas for bottom-fixed wind the larger gains come from upscaling and standardising established designs (Tande, 2024).

The first lever, **R&D and innovation**, concerns technology development, design evolution and knowledge generation. It includes improved substructure concepts, larger and more capable turbines, better design standards, new materials, automation and digital tools. Innovation lowers cost both by improving technical performance and by making components and processes more suitable for industrial production. Its effect, however, depends on the industrial context; technological developments deliver cost reductions at scale only when they are compatible with available manufacturing capacity, installation methods and supply-chain conditions.

The second lever, **upscaling of capacity**, concerns the expansion of manufacturing, logistics, installation capabilities and project execution. It includes yard and port capacity, vessel availability, supply-chain depth and the workforce needed to deliver projects at volume. Upscaling reduces cost through learning effects, higher utilisation and the spreading of fixed costs across larger production runs. It depends, in turn, on solutions that are sufficiently mature and repeatable to be produced at scale, and on predictable, sustained demand that justifies investment in capacity.

The third lever, **standardisation, interface management and value-chain alignment**, concerns coordination and integration across the many actors involved in delivering offshore wind. It includes standardised components and interfaces, common documentation and data formats, and clearer allocation of responsibilities between developers, suppliers, yards, vessel operators and grid companies. Alignment reduces complexity, duplication and over-conservative requirements, and creates the repeatability that both innovation and upscaling rely on. Applied too rigidly, however, standardisation can constrain the design space available for technological development, so maintaining room for innovation while enabling standardised solutions is an important balance.

The three levers are closely interrelated and should not be understood in isolation. Innovation must be compatible with industrial capacity to be realised; upscaling requires mature, repeatable solutions and is reinforced by standardisation; and standardisation supports efficiency but involves trade-offs against design freedom and innovation. Cost reduction therefore depends on coordinated development across technological, industrial and organisational dimensions, rather than on any single lever applied alone.

4

Value Chain Cost Reduction: Key Findings and Industrialisation Roadmap

This chapter synthesises the main findings from the detailed analysis of cost drivers and reduction levers presented in the Part 2 of this document (Chapters 5–10). The roadmap reflects expert judgement where direct evidence is not explicitly quantified. The chapter is structured as follows. Section 4.1 summarises the main cost reduction opportunities across value chain segments. Section 4.2 provides a comparative overview of cost reduction potential across segments and levers. Section 4.3 sets out a roadmap with prioritised actions across short-, medium- and long-term horizons, and identifies Norway's specific contribution to European scale-up.

4.1 Main Findings by Value Chain Segment

This section summarises the most critical cost reduction actions across the value chain segments, structured according to the three levers introduced in Chapter 3. The emphasis is on prioritised interventions rather than detailed analysis.

4.1.1 Fabrication and Manufacturing

Fabrication and manufacturing of large structures determine a substantial share of capital cost and are central to whether offshore wind can transition from project-based construction to scalable, industrial production.

R&D and innovation. Manufacturing bottlenecks are dominated by labour-intensive welding of large steel structures and the absence of automated production systems for offshore wind substructures. Advanced welding technologies — including laser-based high-energy-density processes with 10–20 times the productivity of conventional arc welding — and robotic systems for cutting, grinding, NDT (non-destructive testing) and assembly are priority R&D targets. For concrete substructures, serial casting, curing control, dimensional accuracy and durability assurance need equivalent development effort. Digital twin models of the production process, linked to advanced sensors, can eliminate defects and reduce costly rework.

Upscaling. Scaling Norwegian manufacturing capacity to industrial volumes requires a coordinated industry ecosystem, investment in yard infrastructure, and systematic learning from sectors that have achieved high-volume production of large structural components. Greater coordination across manufacturing actors – including yards, material suppliers, equipment providers and research institutions – will be important to support knowledge sharing, strengthen supply chains, and enable investment in advanced production technology. Both steel and concrete manufacturing pathways require attention; they are complementary rather than competing routes.

Standardisation. Standardisation of component interfaces and modular design are the primary levers that unlock serial and automated production. Design-for-manufacturability — ensuring that structural concepts can be produced efficiently in series — must be embedded in design standards from the outset. This requires close coordination between design engineers, fabrication yards and supply chain partners throughout the design process, not as a late-stage check.

4.1.2 Transport and Installation

Transport and installation represent one of the most resource-intensive and coordination-dependent phases, where vessel availability, port capacity and weather constraints strongly influence both cost and schedule risk.

R&D and innovation. The fundamental challenge is integrated design of installation systems. Vessel fleets, port infrastructure, installation processes and design assumptions interact in ways that are not yet well understood at system level. Research on concurrent design of these elements — including fleet composition optimisation under uncertainty and improved metocean modelling for operability and weather windows — is needed. Digital tools for integrated logistics planning, fleet optimisation and risk analysis across multiple projects represent a major opportunity. Environmental impacts of maritime logistics also require further attention as deployment volumes increase.

Upscaling. Reaching Norway's 30 GW ambition by 2040 requires an industrial deployment rate on the order of 3–4 large turbines per week over a sustained decade. This scale demands: coordinated long-term port development, with ports designed as permanent industrial hubs rather than project-specific facilities; fleet strategies aligned with stable deployment volumes; and cross-industry collaboration on siting of manufacturing plants, assembly ports and installation infrastructure to serve multiple projects over time.

Standardisation. Standardisation of turbine size trajectories and installation processes is the prerequisite for repeatable, campaign-based installation and for enabling investment in long-lived, purpose-built infrastructure. With vessel lifetimes of approximately 25 years, uncoordinated and rapid turbine upscaling creates investment risk across the entire installation fleet. Maximising quayside integration for floating wind — transferring work offshore only where necessary — reduces offshore hook-up complexity and improves weather window utilisation.

4.1.3 Operations and Maintenance

Operations and maintenance drive a significant share of lifecycle cost and availability, with performance depending on the ability to manage failure risk, offshore access and maintenance logistics under uncertain conditions.

R&D and innovation. Predictive maintenance — enabled by improved condition monitoring technologies, digital twins and improved failure models — is the highest-impact O&M research priority. A self-learning digital twin framework that integrates maintenance, operations and weather forecasting capabilities is needed. New maintenance access technologies — motion-compensated systems, autonomous inspection, integrated crane systems on floating substructures and helicopter landing facilities — can extend the effective maintenance season and reduce vessel dependency. Planning under uncertainty is needed to optimize maintenance scheduling, weather windows and vessel lead times.

Upscaling. Shared vessel resource models — where pools of vessels are coordinated across multiple wind farms and across installation, maintenance and decommissioning activities — are a major cost reduction opportunity. Offshore wind operators could establish a shared reliability and maintenance database (for instance inspired by the OREDA database), alongside coordination of vessel pools and spare-parts supply chains.

This requires governance mechanisms that enable cooperation across competing operators.

Standardisation. Vendor contracts must require that all relevant operational and performance data are made available to wind farm operators, enabling fair competition in outsourced maintenance contracts. Standardisation of O&M documentation and data exchange formats supports efficient workflows, interoperability between operators and vendors, and comparative performance analysis across fleets. Accessibility and repairability must be designed into structures and operational concepts from the outset, also considering trade-offs between towing time and quay capacities, versus local maintenance and repairs based on maintenance access solutions and new crane systems that allows local lifting of components.

4.1.4 Decommissioning and End-of-Life

Decommissioning and end-of-life decisions shape long-term cost, resource use and site availability, and must increasingly be treated as an integrated part of lifecycle design rather than a late-stage obligation.

R&D and innovation. Differentiated design lifetimes — where substructures are designed for significantly longer service lives than turbines, enabling repowering without replacing the foundation — represent a major lifecycle cost reduction opportunity. Integrated end-of-life (EOL) decision support — combining AI-enabled assessment of component condition, residual value estimation and dynamic comparison of decommissioning, repowering and life extension pathways —should be a priority research challenge. This links directly to the digital twin and condition monitoring capabilities described in the digitalisation chapter (Ch 10) . Material recovery research, particularly for composite blade materials where economically viable recycling solutions are still absent, is urgently needed. Advanced reverse logistics models for offshore-to-shore processing, including vessel fleet configuration and integration with downstream circular value chains, are also required.

Upscaling. Coordinated decommissioning campaigns across multiple wind farms in the same region create major opportunities for shared vessel utilisation. Norway, with its existing yard infrastructure and workforce from oil and gas decommissioning, is well positioned to develop dedicated or shared decommissioning hubs — this is a concrete industrial opportunity. Port and yard infrastructure investment is needed now, since vessel and infrastructure constraints will worsen as decommissioning volumes grow with the maturing of the first generation of commercial wind farms.

Standardisation. End Of Life (EOL) planning must be integrated from the earliest design stages, not treated as a distant obligation. Regulatory requirements for decommissioning planning from the outset — analogous to the North Sea oil and gas framework — should be considered for offshore wind. Design for disassembly and circularity should be an explicit criterion in design standards: interface and connection standards that facilitate assembly also facilitate disassembly. Standardised repowering assessment frameworks — covering structural condition, grid compatibility, permitting pathways and economic thresholds — would significantly reduce the cost and uncertainty of EOL decisions.

4.1.5 Electrical Infrastructure and System Integration

Electrical infrastructure and system integration determine how offshore wind connects to and interacts with the wider energy system and are emerging as a critical cost driver due to supply-chain constraints and system-level complexity.

VALUE CHAIN COST REDUCTION: KEY FINDINGS AND INDUSTRIALISATION ROADMAP

R&D and innovation. Grid and market integration is as important as physical connection: offshore wind farms must be able to participate efficiently in electricity markets, contribute system services and integrate with onshore and offshore energy systems, including hydrogen. Research is needed on HVDC breakers for offshore grids, standardised wet-design cabling at higher voltage levels, dynamic export cables for floating wind, and operational strategies that extend component lifetimes through active wind farm control. Transnational North Sea grid models that capture the combined effect of offshore expansion, onshore reinforcement and sector coupling are essential for coordinated investment planning.

Upscaling. Electrical infrastructure is facing the most acute supply chain bottleneck in the entire offshore wind value chain. Subsea cables, HVDC converters, offshore transformers and cable-laying vessels are all produced by a small number of suppliers worldwide, with limited factory capacity and lead times that already extend several years. Addressing these bottlenecks requires investment in new production capacity, qualification of additional suppliers and development of more modular component designs. A precondition is demand predictability: manufacturers require confidence in long-term order volumes before committing to new factories. Coordinated offshore grid architectures across projects and countries are the enabler.

Standardisation. Multi-vendor interoperability — demonstrating that different converters and cable manufacturers can be combined without system failure — is the most important electrical infrastructure standardisation target. Current HVDC connections remain single-vendor, creating lock-in and limiting competition. Modular, standardised wind farm set-ups covering substations and key components are needed. Transnational regulatory coordination on offshore grid standards, roles, and market frameworks is required to realise the full system value of integrated North Sea infrastructure.

4.1.6 Digitalisation and Data

Digitalisation and data enable coordination, optimisation and learning across the value chain, and are essential for reducing cost and enabling industrial-scale deployment in a complex, multi-actor system.

R&D and innovation. R&D should focus on scalable digital solutions that reduce cost, risk and lifecycle uncertainty across projects and vendors. Priority areas include predictive and prescriptive digital twins for offshore wind turbines, subsea cables, structural health, marine operations, wind-farm control and lifetime extension. Digital-twin research should combine physics-based models, operational data, validation and uncertainty quantification, so model outputs can be trusted in real decisions. Research is also needed on reusable digital building blocks, NORSOK-like digital principles, real interoperability between WTG and ESI systems. AI agents should be explored as human-in-the-loop tools for anomaly triage, maintenance planning, vessel scheduling, inspection analysis and control-room decision support. Digital twins and AI agents should be developed together: the twin provides the trusted asset state and constraints, while the agent turns this into workflows and recommendations. RDS-based semantic information architecture should support digital twins, AI and cost modelling by linking assets, functions, documents, data streams and cost elements. Norway should prioritise demonstrators that combine digital twins, AI agents, RDS, cybersecurity and lifecycle data sharing in practical offshore wind use cases.

Upscaling and implementation. Upscaling digitalisation requires organisational, contractual and governance changes, not only new tools. Offshore wind projects should standardise functional behaviour, states, modes, alarms, failure logic and interfaces independently of vendor-specific implementations. Operators and developers should define requirements for data access, interoperability and lifecycle handover early in contracts, reducing dependence on proprietary SCADA, analytics and digital-twin platforms. Digital standardisation must follow the full lifecycle from design and commissioning to operation and modification, supported by common naming conventions, asset hierarchies, event taxonomies, validated AI layers and early integration planning using relevant standards.

Data and sharing. Data access is both a technical and contractual barrier to offshore wind cost reduction. Operators often lack sufficient access to real-time and historical turbine data, especially during warranty periods, limiting independent condition monitoring, fleet-level analytics and benchmarking. Cross-vendor analytics require common formats, APIs, semantic standards and governance rules defining what data must be available in standardised formats. At the same time, digital sovereignty, cybersecurity and commercial confidentiality must be protected. Anonymised operational data, shared industry datasets and public-private data pools can accelerate research, improve failure databases and support better digital twins, AI models and lifecycle decision-making.

4.2 Cross-cutting Insights and Implications

Across the value chain segments, two overarching conclusions emerge from the analysis. These cut across individual technologies and activities and define where the largest cost reduction opportunities lie.

First, cost reduction depends on coordinated use of the three levers – not on any single lever in isolation.

R&D and innovation deliver cost reductions only when new solutions are compatible with available manufacturing capacity, installation methods and supply chains. Upscaling, in turn, depends on designs that are sufficiently mature, repeatable and low-risk to justify large-scale investment. Standardisation enables both innovation and upscaling by reducing complexity and creating repeatability but must be applied in a way that preserves room for technological development rather than prematurely locking in suboptimal solutions. Cost reduction at scale is therefore not a purely technological or industrial challenge, but a coordination challenge across these dimensions.

Second, some of the largest cost reduction opportunities arise at interfaces between value chain segments rather than within individual segments.

Many of the highest costs are generated by misalignments between design, manufacturing, logistics, installation and operations — including turbine–substructure interfaces, fragmented vessel strategies, late design changes and incompatible data systems. These interface costs are often not visible when each segment is optimised in isolation. Taking an end-to-end value chain perspective makes these costs visible and highlights where coordinated interventions can deliver the greatest impact.

Taken together, these conclusions imply that incremental optimisation within individual parts of the value chain will be insufficient to achieve the required cost reductions. The central challenge is to enable coordinated development across the full system — aligning technological innovation, industrial scale-up and value chain integration.

The following roadmap translates these insights into prioritised actions across short-, medium- and long-term horizons.

VALUE CHAIN COST REDUCTION: KEY FINDINGS AND INDUSTRIALISATION ROADMAP

4.3 Roadmap and Priority Actions

Building on the cross-cutting insights above, the following roadmap sets out priority actions across three time horizons. Short-term actions (0–3 years) are those that can be initiated immediately and that are prerequisites for later phases. Medium-term actions (3–7 years) require enabling conditions established in the short term and deliver cost reductions as offshore wind deployment accelerates. Long-term actions (7–15 years) are structural changes to industrial systems, standards frameworks and policy environments that determine the ultimate scale and cost trajectory of offshore wind. Actions span technical, contractual and governance dimensions, reflecting priorities identified across value chain segments and the cross-cutting coordination challenges highlighted above.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Short term (0–3 years): Enabling conditions

Across all value chain segments, the first priority is resolving the data and interface governance gaps that prevent coordinated optimisation.

- **Turbine–substructure interface standardisation**. Initiate a coordinated industry and standards body process to define rational, physics-based limits on turbine motions and interface loads, enabling integrated floater–turbine certification pathways. This is the highest-leverage single design intervention and is prerequisite to most floating wind cost reduction.
- **Vendor data access requirements in contracts**. Establish standard contract clauses requiring WTG vendors to provide operators with full access to operational and performance data. Draw on contract models from oil and gas and other regulated network industries Without this, predictive maintenance and fleet-level analytics remain blocked.
- **Offshore grid architecture and standardisation process**. Launch a transnational process to define modular, standardised offshore grid connection architectures that support multi-vendor interoperability and long-term predictable demand for cable and converter manufacturers.
- **Decommissioning planning requirements**. Introduce regulatory requirements for EOL planning from the outset of project development, as is standard in the North Sea oil and gas sector. This creates the planning horizon needed for circular design and reverse logistics development.
- **Manufacturing innovation ecosystem**. Strengthen coordination across Norwegian yards, material suppliers, R&D institutions and equipment providers to support shared learning and align efforts on automation, robotics and design-for-manufacturability for both steel and concrete substructures.
- **Digital semantic standardisation**. Define common naming conventions, asset hierarchies and event taxonomies for offshore wind digital systems, analogous to what NORSOK achieved for physical systems. This is prerequisite to cross-vendor analytics and operator-controlled digital infrastructure.
- **Cybersecurity requirements for digital infrastructure**. Define minimum cybersecurity requirements for offshore wind SCADA, digital twin and remote-access systems, aligned with standards. Require security-by-design in tenders and establish incident reporting frameworks. Cybersecurity cannot be retrofitted onto operational systems.

Medium term (3–7 years): Industrial scale-up

With enabling conditions in place, the medium term is the window for industrial scale-up — ramping capacity, demonstrating new technologies and establishing repeatable processes.

- **Port infrastructure as industrial hubs**. Invest in and designate key Norwegian ports as long-term offshore wind industrial hubs with sufficient quay length, water depth, load-bearing capacity and laydown and marshalling area to support serial installation, assembly and maintenance for multiple projects over time.
- **Shared vessel fleet frameworks**. Establish governance mechanisms and commercial frameworks that allow multiple offshore wind operators to share installation and maintenance vessel fleets, improving utilisation rates and supporting investment in specialised vessels aligned to stable deployment volumes.
- **Predictive maintenance at fleet scale**. Deploy self-learning digital twin frameworks integrating condition monitoring, failure prediction and maintenance scheduling across multiple wind farms.
- **Concrete floater manufacturing pathways**. Develop and demonstrate serial concrete substructure manufacturing processes at scale, building on Norwegian civil engineering competence and reducing dependence on steel supply chains and large-scale welding capacity. Assess lifecycle costs and embodied emissions against steel alternatives.
- **Supply chain investment in electrical infrastructure**. Drive investment in new cable and converter production capacity, qualified through the standardised grid architectures established in the short term. Target diversification of the supplier base beyond the current two or three global vendors for HVDC systems.
- **HVDC multi-vendor interoperability demonstration**. Deliver a full-scale demonstration of multi-vendor HVDC interoperability — different converters and cable manufacturers operating in the same system without failure — as a precondition for meshed North Sea grid development.
- **Floating wind maintenance access technologies**. Develop and qualify new maintenance access solutions for floating structures, including integrated crane systems, helicopter landing facilities and motion-compensated transfer systems, reducing vessel dependency and extending the effective maintenance season.

Long term (7–15 years): Structural transformation

The long-term horizon covers changes to industrial systems, regulatory frameworks and regional energy infrastructure that determine whether offshore wind can achieve the full cost trajectory implied by the 300+ GW European ambition.

- **Integrated North Sea offshore grid**. Realise a transnational, meshed offshore grid architecture connecting Norwegian, British, Danish, German and Dutch offshore wind resources with each other and with onshore grids, energy hubs and hydrogen production. This requires sustained regulatory cooperation and investment coordination at the highest levels of energy policy.

- **Operator digital sovereignty**. Establish European operator control over the core digital infrastructure of offshore wind operations — including SCADA, digital twins and analytics platforms — through procurement policy, open standards and targeted support for European digital capability. This is both a competitive and a security of supply objective.

- **Industrialised decommissioning sector**. Develop Norway's decommissioning capability into a competitive European hub, leveraging oil and gas yard infrastructure and workforce. Realise circular material flows at scale for steel, concrete and eventually composite materials.

- **Turbine size coordination**. Achieve industry-wide coordination on turbine size evolution — defining stepwise, planned increases with sufficient stability at each step to allow vessel, port and manufacturing investment to be made with confidence. This may require a coordinated industry forum or regulatory framework.

- **Certification reform for integrated floating wind systems**. Reform certification frameworks to enable integrated turbine–floater certification pathways, replacing the current tower-as-fixed-base approach. This will require sustained engagement by NTNU, SINTEF and Norwegian industry with IEC, DNV and other standards authorities.

Part 2

The detailed analysis of cost drivers and reduction levers are presented in the digital Part 2 of this document (Chapters 5–10).

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5

Fabrication and Manufacturing of Large Structures

This chapter examines fabrication and manufacturing and shows how industrial scale-up requires further development and innovation in production technologies and automation, as well as a focus on value-chain integration and standardisation. Since substructure design largely determines the fabrication challenge, this chapter treats the design choices tightly coupled to production, alongside the fabrication itself.

5.1 Context and Current Status

As described in Chapter 2, substructures can be divided into bottom-fixed and floating solutions. Relevant bottom-fixed concepts include steel jackets, steel monopiles and gravity-based structures (GBS) in concrete or steel. Floating concepts include spar buoys, semi-submersibles, barges and tension-leg platforms (TLP), with spar buoys and semi-submersibles the most mature.

Norway has an industrial base relevant to offshore wind, built on oil and gas platform construction, shipbuilding and civil engineering. Existing yard infrastructure, heavy-lift capacity and skilled personnel are important assets for both steel and concrete manufacturing. However, this base should be understood selectively. Norwegian yards are unlikely to compete equally across all substructure types. Monopiles are already a specialised high-volume segment with strong cost pressure, while jackets, floating substructures, concrete GBS and integration work are more relevant opportunities. Jacket fabrication in particular builds on existing offshore competence, and few European yards combine comparable experience, automation potential and heavy-structure handling.

The Norwegian market alone is too small and uncertain to justify a broad build-up of dedicated offshore wind manufacturing capacity. The key implication is that a realistic industrial strategy must combine offshore wind with other offshore markets and assume that Norwegian suppliers compete for European and international projects. This also raises policy concerns, as increasing local-content requirements abroad may limit market access even for technically competitive suppliers.

Steel fabrication typically involves cutting, rolling, welding, coating, inspection, heavy lifting and complex yard logistics. Much of the work remains labour-intensive, with skilled workers performing manual welding and inspections in accordance with offshore oil and gas standards. Concrete offers a complementary route, especially for gravity-based structures and for some floating concepts such as spar buoys (Hywind Tampen). Its fabrication challenges are different and include formwork, reinforcement, prestressing, casting, curing, dimensional control, watertightness and durability assurance.

For jackets, competitiveness depends strongly on the integration of engineering, material flow, welding, inspection and heavy handling. Designs are often developed before the fabricator is involved, which can result in geometries that are structurally feasible but inefficient to produce, such as complex nodes, difficult tolerances, poor access angles or welds that are not suited to automation. Early yard involvement can reduce both steel weight and production hours. The main cost potential lies not in fabrication alone, but in the interface between design, construction method and automation.

Concrete structures require specialist engineering and strict control of geometry, reinforcement, prestressing, curing and durability. At the same time, parts of the construction process can draw on civil engineering supply chains that may be easier to establish locally than specialised offshore steel welding capacity. Serial casting methods such as slipforming may reduce costs for suitable geometries, but require design regularity, strong subcontractor coordination and tight dimensional control. Concrete should therefore not be treated simply as a low-cost alternative to steel; its competitiveness depends on the chosen concept, production site, port access, local material supply, reinforcement complexity, CO2 intensity, and the ability to repeat processes at scale. See also (Windworks Jelsa, 2022; Ocergy, 2026)

5.2 Design Choices That Drive Fabrication and Cost

Several cost drivers are common to bottom-fixed and floating offshore wind, including turbines, financing, installation, and O&M. Financing costs are difficult to influence directly, but uncertainty can be reduced through better modelling, reference projects and larger deployment volumes. For substructures, cost is shaped by site conditions, turbine loads, installation method, manufacturing route and the maturity of the supply chain.

For bottom-fixed wind, both substructure capital and installation costs are significant contributors to LCOE (BVG Associates, 2026). Water depth, seabed conditions, turbine loads, noise restrictions and local-content requirements influence the choice between monopiles, jackets and gravity-based structures. The industry has so far favoured monopiles where possible because they are simple to manufacture, transport and install. Recent designs have also reduced costs by removing the transition piece. Jackets can be more material-efficient, but are harder to manufacture because they contain many tubular members, nodes and welds.

For Norwegian suppliers, jackets are a more realistic industrial opportunity than monopiles. Monopile production has become a specialised, capital-intensive volume business based on dedicated rolling, welding and coating lines. Jackets are more engineering- and labour-intensive, but this gives room for competition through production methods, early design input, modularisation and automation. The relevant question is not whether jackets are preferable in general, but where they can be designed and produced cheaply enough to compete with monopiles, concrete structures or floating concepts.

For floating wind, the largest capital cost contributors after the turbine are normally the substructure, installation and mooring system (Stehly, 2024). Cost depends on floater type, material, size and stability requirements. These are governed by turbine mass, tower loads, environmental loads and dynamic response. Electrical infrastructure can also be affected by the floater concept and park layout.

For steel floaters, the main cost drivers are steel price, steel weight and labour hours. Weld length, weld accessibility, plate thickness, internal stiffening, coating requirements and tolerances strongly affect fabrication cost. A low-weight design is not necessarily a low-cost design if it creates complicated welds or difficult assembly sequences. This has pushed several concepts towards simpler production geometry, such as box-shaped pontoons and large columns, rather than truss structures with many intersecting members. Optimisation must therefore balance structural mass, weld metres, access, tolerances, inspection effort and yard flow.

For concrete floaters, cost is driven by volume, reinforcement density, hull geometry and production method. Concrete reduces the need for corrosion protection when cracking and water ingress are controlled, and it may enable more local production. However, concrete is not automatically cheaper than steel. Its competitiveness depends on the production site, port access, local material supply, reinforcement complexity, binder cost, CO2 intensity, and repetition at scale.

Several studies indicate lower economic and CO2 costs for concrete platforms (DNV, 2024; BVG Associates, 2026), although these estimates are strongly dependent on the assumptions regarding both steel cost and location for manufacturing. In general, local manufacturing of concrete substructures is an advantage. (Choisnet et al., 2016)

The mooring system is another significant cost item for floating wind. Mooring design depends on bathymetry and seabed conditions and cannot be standardised as easily as the floater. Catenary systems often use steel chains, which are heavy and material-intensive but reduce vertical anchor loads. Synthetic ropes may reduce weight and simplify handling, but have less operating experience. At large deployment volumes, the demand for high-strength steel in towers and moorings could become a supply-chain constraint, making material efficiency important.

Substructure designers respond primarily to turbine loads, not turbine size alone. Thrust, gravity loads and dynamic loads determine the substructure requirements. Larger turbines usually mean larger loads, but the lack of standardised load envelopes across turbine models still complicates design, i.e., the current lack of standardisation in turbine size (mass and maximum thrust) is a major challenge for optimisation of substructures, vessels for installation and maintenance, balance of plant and for modular and serial production.

Requirements are another cost driver. Offshore wind projects often inherit specifications from oil and gas and then add project-specific requirements. In some cases, structures are designed and inspected as if their consequence class were similar to previous offshore O&G projects or standards. Reliability should not be weakened, but requirements should be linked more clearly to the consequences of failure, repairability, redundancy, exposure and personnel presence. Overly conservative specifications increase steel weight, welding hours, inspection scope and lead time and may block automation. Weld accessibility illustrates this problem. Internal welding or inspection may be justified for some joints, but in other cases, it prevents simpler production routes. If equivalent reliability can be demonstrated through design, process control, external welds, qualified non-destructive testing (NDT) or monitoring, these requirements should be reviewed rather than copied from previous offshore projects.

Fabrication scale adds further cost pressure. Jackets can exceed 100 metres in height and weigh more than 2,000 tonnes. Monopiles now exceed 120 metres in length and 10 metres in diameter, with weights above 2,500 tonnes. Floating substructures can be heavier still. These dimensions increase the need for crane capacity, storage area, heavy-transport routes, load-out facilities, and suitable ports. Marshalling-yard area is therefore a limiting factor, especially near ports with sufficient depth and bearing capacity.

Welding remains a major bottleneck in steel fabrication. Jackets still rely heavily on manual welding and inspection, which increases production time, quality variation and repair work. Distortion, residual stress and weld-sequence planning are recurring challenges. Automation can reduce variation, but the design must have sufficient access, repeatable geometry and manageable tolerances. This requires fabrication input before the design is frozen; after that, the opportunity to adapt the structure to automated production is largely lost.

Concrete shifts the industrial challenge from welding to serial casting, curing control, reinforcement, prestressing, quality assurance, heavy handling and marine logistics. Concrete substructures require coastal production sites, quay access, load-out capacity, dry or wet storage and integration with port and installation planning. For floating wind, concrete concepts must also demonstrate reliable control of cracking, water ingress, fatigue, reinforcement corrosion and long-term offshore performance.

A potential advantage is that local aggregates, civil-engineering supply chains and regional construction competence can be used closer to deployment sites.

The comparison between steel and concrete is therefore case-dependent. The relevant question is which production route gives the lowest lifecycle cost for a given concept, site, deployment volume and supply chain. The table below summarises the main fabrication-related differences.

For Norway, the steel pathway is strongest where yard competence, automation and early design involvement can offset high labour costs. The concrete pathway is strongest where local production, sheltered deepwater sites, long service life or limited steel fabrication capacity give an advantage. Hybrid concepts should also be assessed from this production perspective rather than treated as a separate category.

Dimension	Steel substructures	Concrete substructures
Main fabrication bottleneck	Welding, fit-up, distortion, coating, non-destructive testing (NDT) and heavy assembly	Formwork or slipforming, reinforcement, prestressing, curing, geometry control and watertightness
Cost sensitivity	Steel price, plate thickness, weld metres and labour hours	Geometry, reinforcement density, cement/ low-carbon binder cost, production site and repetition rate
Norwegian fit	Builds on offshore fabrication and jacket competence, but depends on scarce welding and inspection capacity	Builds on marine civil engineering and local material supply, but requires suitable coastal production sites and specialist concrete competence
Automation potential	High where design gives access, repeatability and controlled tolerances	High for reinforcement, formwork, slipforming, monitoring and quality-control, if geometry is suitable
Logistics	Established load-out and transport methods, but long-distance transport can add fatigue exposure and schedule risk	Larger and heavier units, with stronger dependence on production site, wet storage, tow-out and port conditions
Lifecycle issues	During service the lifetime is strongly affected by corrosion protection, coating maintenance, fatigue assessment and condition monitoring, For the decommission phase and end-of-life, the steel structures are easily recyclable and technologies for direct reuse are under development.	Durability, cracking, water ingress, reinforcement corrosion, CO2 footprint and end-of-life handling

5.3 Pathways to Cost Reduction and Improvement

Cost reduction in offshore wind fabrication depends on decisions made before production starts. For jackets and floating substructures in particular, design choices, procurement models, and production planning determine much of the final cost. Fabrication improvements cannot be added late if the geometry, tolerances, weld details and inspection requirements have already been fixed. The three levers below span both steel and concrete production and apply to both bottom-fixed and floating substructures, except where noted.

5.3.1 R&D and Innovation

R&D should link structural design more closely to fabrication, assembly, installation, maintenance and decommissioning. For floating wind, this includes integrated turbine–substructure optimisation, better understanding of environmental loads, rational limits for motions and loads, and co-design of mooring and power-cable systems. For both steel and concrete substructures, a key challenge is to design for modular and serial production rather than one-off project execution.

More attention is needed on manufacturability before designs enter procurement. Today, fabrication yards are often involved after the main geometry has been defined. This can leave yards with joints, tolerances, access angles or assembly sequences that are expensive to build. Early manufacturability assessment should compare node designs, brace layouts, weld details, tolerances and assembly sequences before the design is frozen.

Automation should also be treated as a production system issue, not just a replacement for manual tasks. Robotic welding, grinding or inspection will have a limited effect if fit-up, material flow, tolerances and documentation are still managed as one-off project activities.

Improved modelling of environmental loads, material behaviour and system dynamics can reduce design uncertainty. This may also lower financing and contingency costs. Differentiated design lifetimes are another promising route, for example, by designing foundations or floaters with a longer life than the turbine, enabling repowering without replacing the entire support structure.

Mooring systems need further research, especially for long-term qualification of synthetic materials, seabed contact, fatigue and interaction with dynamic power cables. Co-design of moorings and cables may allow larger floater offsets and reduce total system cost.

In line with the EERA JP Wind strategy, important R&D priorities include:

Steel substructures

- Adaptive and autonomous manufacturing technologies, such as robotic cutting, grinding, welding, handling and non-destructive testing, supported by physics-based and data-driven planning tools to eliminate defects and avoid costly rework.
- Flexible automation for jacket components and other part families with variable geometry.
- Serial production of modularised and standardised components.
- Design rules for robot-accessible welds, including access angles, joint preparation, tolerances and sequencing.
- Advanced welding methods, including laser-based high-energy-density techniques, with the potential to increase productivity by 10–20 times.
- Predictive non-destructive testing and process-data-based quality control, linking weld defects to welding parameters, fit-up, temperature, operator input, material batch and geometry.
- Automated handling of heavy parts supported by digitalised supervision.

Concrete substructures

- Serial production methods, including formwork systems, reinforcement and prestressing, curing control, dimensional accuracy, watertightness, fatigue resistance, corrosion protection and low-carbon concrete materials.
- Automation and digital support for reinforcement, geometry guidance, slipforming, curing monitoring and dimensional control.
- Low-carbon concrete materials and binder systems.
- Quality-assurance methods suited to large-scale, repeated production.

Common priorities

- Production automation, AI and digitalisation, including sensors, process monitoring and digital twins.
- Material models linking manufacturing process, microstructure, properties and long-term performance.
- Tender-phase tools such as configurators, cost models and databases of previous designs.
- Better work preparation and documentation flow between engineering, procurement, fabrication and inspection.
- Modular fabrication practices and lessons from shipbuilding and other manufacturing industries.
- Improvements in yard layouts, infrastructure (lifting and transport) and assembly workflows that support high throughput. Increased available laydown space and marshalling-yard capacity.
- Workforce development in welding, NDT, production engineering, automation, HSE and supervision.
- -Modelling of environmental loads
- Mooring system design, particularly for synthetic mooring materials
- Design for production

5.3.2 Upscaling of Industry, Supply Chain and Fleet

Industrial scale-up of Norwegian manufacturing capacity requires coordinated investment in infrastructure, suppliers, labour, vessels and production methods. Design choices that enable serial and modular production are a prerequisite for scaling to volumes consistent with the 30 GW ambition; otherwise, larger volumes will not give the expected learning effects. Relevant actions include:

- Investing in yard infrastructure, advanced production technology, cranes, transport routes, load-out capacity and marshalling areas.
- Strengthening collaboration between fabricators, designers, suppliers, ports and installation contractors.
- Learning from shipbuilding and other industries with experience in serial production of large structures.
- Improving yard logistics to reduce waiting time, temporary storage, repeated lifting and material waste.
- Develop both steel and concrete pathways to reduce dependence on a single material or supply chain.
- Building capacity for production planning, automation support, inspection and quality documentation.

Labour will be a major constraint. Certified welders, NDT personnel, production engineers, planners and supervisors are already scarce, and offshore wind will compete with oil and gas, shipbuilding, infrastructure and defence activity. Automation can reduce some pressure, but it also changes the skills needed in the yard. Training, simpler designs, better work preparation and more stable production schedules will therefore be as important as new equipment.

Experience from serial shipbuilding and other complex assembly industries suggests that learning effects appear when products are repeated, supplier deliveries are stable, and changes are controlled. Jacket production is more variable than a typical assembly line would tolerate, but it can still benefit from grouping components by complexity, using prepared material batches and applying takt-based production principles where suitable.

Norway also has sheltered deepwater locations that may support integration, wet storage, tow-out preparation and turbine assembly. This is relevant for both floating concepts and large bottom-fixed structures. Ports that combine fabrication, marshalling, integration and storage can reduce shuttle transport, repeated handling and schedule risk.

Concrete and hybrid substructures should be developed alongside steel concepts. Concrete may be attractive where local production reduces transport, where steel prices or welding capacity are limiting, or where a long service life provides lifecycle benefits. However, concrete concepts must prove repeatable production, controlled geometry, durable performance and competitive logistics. Steel, concrete and hybrid structures should therefore be treated as complementary industrial options.

5.3.3 Standardisation, Interface Management and Value-Chain Alignment

Standardisation is needed where it reduces cost without removing necessary site-specific design freedom. The most useful target is not full standardisation of complete substructures, but standardisation of interfaces, component families, documentation, qualification methods and production requirements.

At the design level, key interfaces include the turbine, tower, substructure, mooring system and installation method. For floating wind, clearer definitions of turbine loads, motion limits and interface requirements would enable better turbine–floater optimisation and make repowering simpler if support structures are designed for longer lifespans than turbines. Since certification currently treats the tower and rotor as a fixed base and turbine sizes vary, Norway should focus on designing floaters and support structures for efficient manufacturing and assembly, rather than developing floater-specific turbines or support-integrated turbines.

The same issue applies to bottom-fixed jackets. If turbine suppliers provide limited or conservative load information, substructure designers must compensate with heavier designs, larger contingencies and less efficient production planning. Earlier and more standardised exchange of load envelopes, fatigue spectra and interface assumptions would reduce overdesign and improve manufacturability.

FABRICATION AND MANUFACTURING OF LARGE STRUCTURES

Certification and standards should also be reviewed. Offshore wind projects often combine offshore wind standards, customer specifications, EN standards and oil-and-gas practice such as NORSOK. Customer requirements can override or supplement existing standards, creating variation across projects and countries. This increases engineering hours, complicates the qualification of automated production and makes proven solutions harder to reuse. Rational, physics-based limits on turbine motions and interface loads should be established to enable integrated turbine–floater certification pathways. This is as much a regulatory and industrial coordination challenge as a technical one. Industry coordination on turbine size evolution — analogous to the container shipping industry's standardisation of container dimensions — would unlock significant optimisation benefits across the substructure, installation and operations value chain. A clearer requirement hierarchy would reduce unnecessary variation while still allowing site-specific requirements where risk justifies them.

For mooring systems, simpler designs are often possible in intermediate water depths. (200–300 m). Synthetic mooring components, including nylon, may reduce cost and handling loads, but need further qualification and certification. Reliability requirements should reflect actual consequence classes, personnel exposure, redundancy, repairability and park-level risk. Lower safety margins must be justified by reliability analysis, not by cost pressure alone.

At the fabrication level, the most relevant measures are:

- Automation and robotic welding, grinding, cutting, handling, dimensional inspection and non-destructive testing (NDT) have the potential to significantly reduce manual work and save costs.

- Standardise component families rather than complete structures, especially for jackets. Repetition in nodes, braces, legs, lifting points, secondary steel and documentation can support automation without removing site-specific design freedom. Standardise documentation.

- Involve fabrication yards before the main geometry is frozen. Early input can reduce steel weight, improve weld access, simplify tolerances and make robotic welding, grinding and inspection more realistic.

- Design welds and inspection points for access, repeatability and automation.

- Review requirements that drive internal welding, excessive inspection or oil-and-gas-type safety margins where offshore wind risk classes allow other solutions.

- Develop flexible automation and robotisation that tolerates variation in dimensions and geometry found in offshore wind.

- Use process data actively in quality control, linking production parameters, fit-up, material data, environmental conditions, NDT results and repair records.

- Improve digital information flow between design, procurement, fabrication and inspection. Takt-based production requires that material, drawings, work packages, equipment, and personnel are available at the right place and time.

- Develop industrial pathways and assess steel, concrete and hybrid concepts from a manufacturing perspective, including scalability, logistics, local production, automation potential, lifecycle emissions and end-of-life handling.

For Norwegian suppliers, competitiveness will depend on combining offshore structural competence with early design involvement, flexible automation, disciplined material flow and realistic standardisation. The strongest opportunities are likely to be in jackets, floating substructures, concrete or hybrid concepts, and integration work in sheltered coastal locations. These opportunities require predictable demand, but also procurement models that allow production knowledge to influence the design before the main cost drivers are locked in.

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6

Offshore Transport & Installation

Transport and installation cover the logistics chain from manufacturing sites and assembly ports to offshore transport, lifting operations and final installation of offshore wind components. This phase is among the most capital intensive, weather sensitive and coordination dependent stages of the offshore wind value chain. As offshore wind scales towards industrial deployment volumes, transport and installation represent a major opportunity for cost reduction—provided that logistics, vessels, ports and installation processes are treated as an integrated system. Historically, transport and installation have often been planned on a project-by-project basis, with fragmented optimisation across actors and interfaces. This approach limits learning effects, reduces vessel utilisation and increases exposure to weather risk and bottlenecks. A system level perspective—where design, logistics, port infrastructure, vessel fleets and installation processes are developed together—is essential for reducing cost, risk and environmental footprint at scale.

6.1 Context and Current Status

International experience illustrates the importance of a system perspective. Offshore wind deployment in China has been characterised by a higher degree of standardisation, large and coordinated project pipelines, and alignment around a limited number of turbine ratings within each deployment phase. In China, the weighted average total installed cost (WATIC) declined by 71% from 2010 to 2024, reaching around USD 1 520/kW, compared to USD 3 389/kW in Europe (IRENA, 2025). This has supported predictable installation processes, shorter construction periods and substantially lower total installed costs compared to Europe.

While European and Chinese markets differ structurally, the comparison demonstrates the cost reduction potential of coordinated planning across the supply chain, including the siting of manufacturing facilities, assembly ports and installation infrastructure to serve multiple projects over time.

6.2 Key Challenges and Cost Drivers

Installation typically represents a substantial share of total installed cost in offshore wind projects, commonly in the range of approximately 5–25% of total project cost, depending on site conditions and technology choices. Installation costs are primarily driven by three structural factors:

- continued scaling of turbine size and component dimensions,
- increasing distance from shore and harsher metocean conditions, and
- increasing water depths.

These drivers affect bottom fixed and floating wind differently. Bottom fixed projects located close to shore and in shallow waters generally lie in the lower end of the cost range, while floating wind farms in deep water and at long distances from shore are associated with higher installation costs.

A further important cost driver is the availability and utilisation of suitable vessels. Global demand for offshore wind deployment is increasing rapidly, including in emerging markets. This intensifies competition for installation vessels, heavy lift capacity, anchor handling vessels and cable laying vessels, leading to higher day rates and increased schedule risk. Poor coordination between projects can result in low utilisation, long idle periods and costly mobilisation and demobilisation phases.

For bottom-fixed offshore wind, dominant installation cost drivers include foundation installation (pile driving, drilling, grouting), heavy lift operations using jack up vessels, and the sequencing of installation campaigns for foundations, towers, nacelles and blades. Turbine upscaling increases crane demands, jack up vessel leg length requirements and port infrastructure needs, making vessel obsolescence a real risk if fleet design is not aligned with long term deployment assumptions.

For floating offshore wind, cost drivers shift from offshore heavy lifting towards port integration, tow out operations, mooring and anchoring, and dynamic cable installation. Large shares of the work can be transferred from offshore to ports, but this requires industrial deep-water ports with adequate quay length, load bearing capacity and laydown areas. Tow out distance, metocean limits for hook up operations and availability of suitable anchor handling vessels are major contributors to cost and risk.

Transport and installation costs are not only driven by the performance of individual vessels or components, but by how well interacting systems are aligned. This includes the upstream logistics of transporting components from multiple suppliers to fabrication yards and ports, onshore assembly and storage, offshore transport, and installation sequencing.

At sufficient deployment volumes, dedicated and specialised vessels can be highly cost effective due to higher productivity and improved operability—provided that utilisation rates are high. At lower volumes or more volatile deployment rates, larger multi-purpose vessels or reliance on short term charters and spot markets may be necessary, albeit at higher unit cost and with increased uncertainty. The optimal fleet composition therefore depends critically on both total deployment volume and installation rate over time.

Unit cost reductions are not driven by learning effects alone, but by alignment and tuning of interacting systems. This requires a systems design approach that goes beyond the turbine itself. Design should encompass not only physical assets—turbines, foundations, ports and vessels—but also the combined processes in which they interact. For installation, concurrent design of installation processes and fleet configuration can significantly increase vessel utilisation and reduce overall cost.

With vessel lifetimes of 20–25 years, long term assumptions regarding turbine size and installation concepts are decisive. Rapid turbine upscaling in the past has rendered several generations of installation vessels obsolete after only a few years. Future deployment strategies therefore require either stabilisation of turbine size over extended periods or planned, stepwise upscaling for which vessel and port designs are prepared in advance.

Weather windows represent a fundamental constraint. Installation operations involve transitions from one safe state (port) to another (installed offshore), and these transitions require metocean conditions within relatively tight limits. The number of available weather windows—particularly in the North Sea winter season—is limited. The interaction between turbine design, installation process, fleet capability and port buffering capacity therefore becomes a key system level design driver.

6.3 Pathways to Cost Reduction and Improvement

The three levers below treat the installation system as a whole — fleet, ports, processes and industry coordination — across both bottom-fixed and floating deployment.

6.3.1 R&D and innovation

Key R&D challenges span the integrated design of installation systems, port capacity planning, metocean and operability modelling, digital logistics tools, and the socio-economic governance frameworks needed to enable coordination at deployment scale.

A fundamental challenge is the integrated design of installation systems. Vessel fleets, port infrastructure, installation processes and design assumptions interact in ways that are not yet well understood at system level. Research is needed on how concurrent design of these elements can improve vessel utilisation, reduce weather exposure and lower overall installation cost. This includes methods for fleet composition optimisation under uncertainty, where both total deployment volume and installation rate over time are critical design drivers.

Port capacity and infrastructure represent a growing bottleneck. As turbine sizes increase and floating wind requires new port capabilities, research is needed on how ports can be designed and operated as long-term industrial hubs rather than project-specific facilities. This includes quay length, water depth, laydown area, load-bearing capacity and the integration of port planning with upstream manufacturing and downstream installation logistics.

Weather windows are a fundamental constraint on installation operations, particularly in the North Sea. Better modelling of metocean conditions, operability limits and the interaction between vessel capability, installation process design and port buffering capacity is needed to improve planning accuracy and reduce weather-related delays and costs. This is especially relevant for floating wind, where tow-out and hook-up operations introduce additional sensitivity to sea state conditions.

Digital tools for integrated logistics planning, fleet optimisation and risk analysis represent a promising area for development. Current planning approaches are often fragmented across actors and project phases. Improved decision-support systems that integrate weather forecasting, vessel scheduling, port operations and installation sequencing could significantly reduce cost and schedule risk at scale.

Finally, the environmental impacts of maritime logistics — including emissions from installation vessels, underwater noise and seabed disturbance — require further attention as deployment volumes increase and environmental requirements tighten.

Furthermore, a central research challenge is how to enable and incentivise coordination and cooperation. This is not primarily a technical challenge, but a socio-economic, regulatory and market design problem. It requires new approaches to:

- governance and coordination mechanisms across actors and value chains,
- market structures and incentives that reward collaboration rather than fragmentation,
- data governance frameworks that enable secure and effective data sharing,
- long term planning of infrastructure and industrial capacity, and
- risk sharing models that support joint investments in vessels, ports and industrial systems.
- Transport and handling of oversized components, including permitting and safety requirements

- Heavy lift operations under tighter safety, weather and efficiency constraints

6.3.2 Upscaling of industry, supply chain, and fleet

Reaching 30 GW by 2040 requires an industrial deployment rate on the order of 3–4 large turbines per week over a sustained decade. This scale cannot be delivered efficiently using project specific installation solutions, but demands coordinated long-term port development, fleet strategies aligned with stable deployment volumes, and cross-industry collaboration across the full value chain.

- Align deployment volume and installation rate with fleet strategy. High, stable volumes favour specialised vessels on long term contracts; lower or uncertain volumes favour flexibility but at higher cost.
- Design ports as long-term industrial hubs. Ports must support serial installation, buffering capacity and multiproject utilisation rather than single project optimisation.
- Pursue coordinated planning between industry actors and policymakers on the siting of manufacturing plants, assembly ports and installation infrastructure to serve multiple projects over time.

A transition towards a more industrialised and cost-efficient offshore wind sector requires stronger coordination in several key areas:

- Cross value chain collaboration — Closer interaction between designers, manufacturers, logistics providers, installation contractors, operators and decommissioning actors is necessary to ensure that solutions are optimised for the full lifecycle rather than for individual project phases.
- Data sharing and digital integration — Improved access to operational and performance data across projects and actors can significantly reduce uncertainty, enable better decision making and support more efficient operations, maintenance and logistics planning.
- Coordinated infrastructure development — The development of ports, yards and logistics infrastructure must be aligned with the pace and scale of offshore wind deployment. A lack of coordination in infrastructure investments can lead to bottlenecks, suboptimal transport routes and inefficient use of assets both upstream and downstream.
- Fleet sharing and fleet specialisation across projects — Vessel fleets should be planned and utilised across multiple wind farms rather than dedicated to individual projects. This allows higher utilisation rates and supports the development of more specialised, cost-efficient vessels tailored to overall system needs.

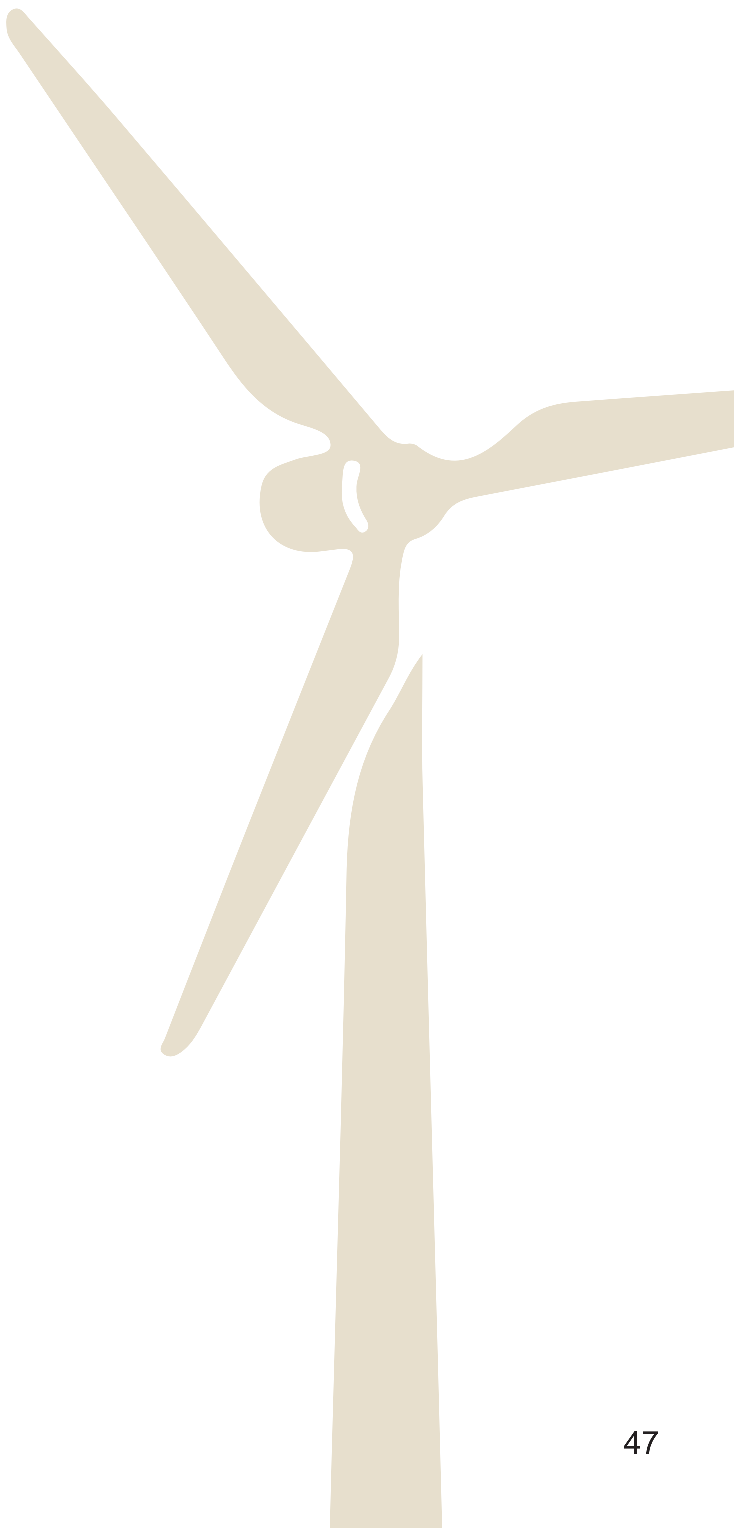
6.3.3 Standardisation, interface management, and value chain alignment

Standardisation of turbine size trajectories, installation processes, and vessel–port interfaces is the prerequisite for repeatable, campaign-based installation and for enabling investment in long-lived, purpose-built infrastructure.

- Treat installation fleet and processes as a single systems design problem. Vessel type, number, contract strategy and installation sequence should be designed together, not decided sequentially.
- Stabilise or plan turbine size evolution. Avoid uncoordinated upsizing that risks early vessel obsolescence.
- Maximise quayside integration for floating wind. Transfer work offshore only where necessary; reduce offshore hook-up complexity wherever possible.
- Increase fleet utilisation through standardisation and campaign-based installation. Repeatable operations improve safety, productivity and cost predictability.

With vessel lifetimes of about 25 years, the target turbine size becomes a decisive factor. The rapid increase in turbine size in the early 2010s made many jack-up installation vessels obsolete after only a few years. Thus, either the turbine size should be fixed at the start of the programme, or there should be a planned, stepwise increase for which the vessel designs are prepared for.

Alignment on turbine size development — Uncoordinated and rapid turbine upscaling creates investment risk, particularly for vessels and lifting equipment with long lifetimes. A more predictable and coordinated approach to turbine size evolution would improve investment incentives and avoid premature obsolescence of critical infrastructure.



7

Operations & Maintenance (O&M)

Operations and maintenance (O&M) cover the activities required to keep offshore wind farms operational throughout their lifetime, including inspection, monitoring, repair and component replacement. As offshore wind scales towards industrial deployment volumes, O&M represents a major opportunity for cost reduction through predictive maintenance, improved logistics, shared vessel resources and better utilisation of operational weather windows. The potential for cost reductions will depend on system-level coordination between maintenance planning, vessel fleets, weather forecasting and digital infrastructure, enabling higher availability and more efficient use of offshore resources.

7.1 Context and Current Status

O&M costs broadly account for up to 25% of the levelized cost of energy. For fixed bottom plants and floating plants, the OPEX is estimated to 17.8% and 26.9% respectively. Maintenance accounts for around 60% of the O&M costs (IRENA, 2025), highlighting the importance of efficient maintenance over the wind farm lifetime.

O&M costs for offshore wind are significantly higher than for their onshore counterparts (IRENA, 2025). While offshore siting provides higher and more stable wind speeds, harsh and uncertain weather conditions make planning of marine logistics and maintenance activities considerably more complex.

7.2 Key Challenges and Cost Drivers

In harsh weather there are limited weather windows where vessels can operate to perform maintenance, and these are hard to forecast, with uncertainty increasing with longer planning horizons. At the same time, the increasing number of offshore wind farms globally means that highly specialised vessels, such as jack-up and crane vessels, have a long lead time and must be chartered well in advance. This means that these vessels are often chartered for extended periods, despite low utilisation rates. Further, HSE regulations limit accessibility to the turbines, driving maintenance costs.

In the current industry practice the vendors of major components such as the generator, the gearbox and the nacelle determine and execute the maintenance program for the first five years. This gives the vendors the freedom to implement costly maintenance programs to avoid failures in the warranty period. But more importantly, this practice also gives the vendors an opportunity to collect maintenance and reliability data that competing maintenance contractors cannot access, and hence maintenance outsourcing is ineffective.

An additional challenge is that turbine vendors themselves often have limited empirical failure data for their most recent turbine designs. Continuous upscaling of turbines and frequent introduction of new turbine generations mean that components are deployed at scale before long operational histories have been established. As a result, historical failure data are sparse, making it difficult to develop robust failure models and reliable predictive maintenance strategies.

Predictive maintenance is a data-driven maintenance approach where data from condition-monitoring systems and operational data are used to predict component failures and optimise maintenance timing. This approach is in general not implemented in offshore wind and most tasks are based on calendar time. Predictive maintenance aims to yield cost reduction, reduce HSE risk and increase lifespan.

Major component replacement (MCR) represents one of the largest and most uncertain cost drivers in offshore wind O&M. Replacement of heavy components such as gearboxes, generators and blades requires specialised crane or jack-up vessels and acceptable weather windows. For floating wind structures, additional complexity is introduced through towing operations, disconnection and reconnection of mooring and cable systems, or offshore heavy-lift operations under dynamic conditions. The need for MCR occurs infrequently but can lead to long production stops and high vessel costs. As turbine sizes continue to increase, MCR is becoming increasingly challenging due to heavier lifts, larger crane requirements and limited vessel availability. Reducing the need for major replacements through improved reliability, condition monitoring and predictive maintenance therefore represents a significant cost-reduction opportunity.

The Kincardine floating offshore wind farm provides a concrete illustration of MCR cost challenges for floating structures: because of design choices, a maintenance operation required the entire floating installation to be towed to the Netherlands, and the towing operation alone took 53 days. This highlights how costly and time-consuming O&M can become when repairs cannot be performed effectively offshore or close to the field, and underscores the importance of designing for offshore maintainability from the outset.

7.3 Pathways to Cost Reduction and Improvement

The three levers below address predictive and data-driven maintenance, shared fleet and supply chain coordination, and standardisation of data access, documentation and operational concepts — across both bottom-fixed and floating assets.

7.3.1 R&D and Innovation

Key R&D priorities span digital twin development for maintenance and operations planning, self-learning failure models, integrated logistics and marine operations research, and new maintenance access technologies tailored to offshore and floating structures.

O&M optimisation depends on access to relevant condition monitoring data, short- and long-term electricity price forecasts as well as short- and long-term wind and weather forecasts. A key element is to synchronize with operational plans taking available weather windows into account. This requires a digital twin framework where the “maintenance-”, “operations-” and “weather-” twins interact in a consistent manner. A wide range of mathematical models exist within each of these domains, but no standard data exchange and “what-if-inquiries” protocols exist to ensure communication between the various “twins”.

A key feature of a digital twin is its ability to learn and update models based on the real-time data flow. Such updating models range from “white box” models requiring a sound understanding of the underlying material degradation mechanisms to “black box” models utilizing AI and machine learning. A systematic review of existing models is required to implement a “self-learning” digital twin that can translate operational data into meaningful health states and ultimately provide reliable Remaining Useful Life (RUL) predictions to support maintenance decisions.

Manhour- and vessel-costs are significant contributors to the OPEX of offshore wind farms. Improved logistics and marine operations are required to reduce these costs. For vessels used in offshore wind operations, particularly larger vessels such as crew operation vessels (COVs) used for routine inspections and minor maintenance, and jack-up and heavy-lift crane vessels used for major component replacement, a shared vessel fleet among operators could enable economies of scope and scale. A framework for how to share the vessels between operators, but also between installation, maintenance and decommissioning activities must be developed for efficient use of vessels and tools. Research will be needed on integrated planning of maintenance operations, vessel utilisation and offshore access under uncertain weather conditions. This includes improved decision-support systems, stochastic optimization methods, offshore access strategies, walk-to-work solutions, autonomous inspection technologies and flexible vessel concepts adapted to large-scale offshore wind operations.

New technologies for marine operations should be developed and implemented to improve accessibility and lower vessel cost. This includes autonomous and remotely operated inspection systems, improved walk-to-work solutions, offshore charging and energy systems, motion-compensated lifting systems and new concepts for major component replacement. Better integration between vessel design, maintenance strategy and operational planning can significantly improve vessel utilisation and extend the effective maintenance season.

A shift from “predetermined” to “predictive” maintenance should take place. This requires more monitoring capacities, so a detailed analysis of which sensors are cost/beneficial to install is required. Sensors should be data-friendly, meaning remotely accessible, and maintenance-friendly, meaning they should not significantly increase inspection requirements. Moreover, for cost efficiency, the sensors should be installed onshore/in the yard when possible. Furthermore, increased modelling competence is required, both in failure prediction models and in stochastic decision-support models that use failure predictions as input to support maintenance planning under uncertainty in both component failures and weather conditions. Digital twins embedding these capabilities should be developed to synchronize maintenance with operational demands and weather conditions.

Possible maintenance access innovations include integrated crane systems on the floating substructure — enabling component lifts from the turbine itself without a dedicated crane vessel — and helicopter landing facilities providing direct crew transfer to the turbine without vessel-based transfer operations. These solutions could significantly reduce vessel dependency, extend the effective maintenance season and improve emergency access for floating wind structures.

- Climbing crane systems integrated on the turbine or substructure for component access
- 3D motion-compensated vessel cranes for offshore lifting operations
- Improved motion compensation equipment for maintenance access and personnel transfer
- Onboard support systems for crew and equipment on floating structures
- Simulation and model testing for new maintenance and access concepts
- Full-scale demonstration of new maintenance technologies
- Improved operational planning tools and decision-support systems

7.3.2 Upscaling of industry, supply chain, and fleet

Cost-efficient O&M at scale requires shared vessel resources, coordinated spare-part supply chains, and industry collaboration frameworks that allow operators to plan jointly across multiple wind farms and across installation, maintenance and decommissioning activities.

Wind farm operators should establish a pool of various types of maintenance vessels to reduce vessel cost. By a large pool of vessels, the various farms can coordinate activities and adjust maintenance plans to best utilize the fleet of available vessels.

Operators should learn from the OREDA project (https://oreda.com/) — a long-running, member-led collaboration between energy companies established in 1981 to improve safety, reliability and performance through shared operational experience.

Standardization and efficient spare part optimisation also require methods and models to be developed. Considering the current geopolitical situation, more focus on resilient supply chains is required. There is a need for operators to collaborate on the supply chain of both components for new wind farms and spare parts for existing. For example, continuing attacks on Ukrainian infrastructure have resulted in shortages of transformation stations, a challenge for all grid operators both onshore and offshore.

7.3.3 Standardisation, interface management, and value chain alignment

Standardisation of data access rights, maintenance documentation, operational protocols and maintenance access concepts is required to enable efficient outsourcing, fair competition and systematic learning across the fleet.

In vendor contracts it should be stated that all relevant data shall be available for the wind farm operators such that fair outsourcing of maintenance contracts can take place. Vendors shall provide a documented maintenance program based on RCM or similar structured methods.

Walk-to-work operations present significant challenges in harsh offshore conditions, but improved motion-compensation equipment and onboard support systems can extend operability and improve access windows. The fundamental principle is that accessibility and repairability must be built into the structure and operational concept from the outset, not addressed as afterthoughts.

Standardisation of O&M documentation and data exchange formats — including IEC 82045 for document management — supports efficient maintenance workflows, enables interoperability between operators and vendors, and provides a foundation for data sharing and comparative performance analysis across fleets.

8

Decommissioning and End-of-Life

Decommissioning and end-of-life (EOL) management are integral parts of the offshore wind value chain and should be considered from the earliest design and planning stages. Offshore wind farms are long-lived assets, but they do not operate indefinitely. Decisions taken at the EOL have implications for cost, environmental impact, resource efficiency, and future use of offshore space. As the industry scales, decommissioning must transition from a project-specific activity to a predictable, industrialised process aligned with circular economy principles.

At the end of their service life, offshore wind farms generally face three main EOL options: complete decommissioning, extended operation, or partial or full replacement through repowering. The choice between these options has major implications for cost, resource use, and the long-term availability of offshore sites. These options are typically defined within permitting frameworks and must balance regulatory requirements, economic considerations, technological progress, and environmental impacts. The optimal pathway depends on site-specific conditions, asset integrity, infrastructure compatibility, and broader system-level considerations such as grid integration and emerging offshore energy uses.

8.1 Context and Current Status

Decommissioning concepts and system overview

Decommissioning is a complex, multi-stage process that involves offshore operations, logistics coordination, and onshore processing. It is not simply the reverse of installation, but a system-level challenge that requires coordination across actors, assets, and environments. A typical decommissioning workflow includes planning and permitting, preparation of assets, offshore dismantling, transport to shore, and post-decommissioning processing.

Planning activities include environmental assessments, regulatory approvals, contracting, and detailed logistics design. Asset preparation involves disconnection from the grid and substations, removal of hazardous materials such as oils and hydraulic fluids, and preparation of lifting interfaces. Offshore dismantling operations include disassembly, cutting, unbolting, lifting, and loading of components such as blades, nacelles, towers, substructures, and cables. These operations are followed by transport to shore and subsequent sorting, reuse, recycling, or disposal.

The requirements and constraints differ between bottom-fixed and floating wind systems. Bottom-fixed structures often require partial or full removal of foundations, depending on regulatory requirements, which can involve cutting below seabed level and handling heavy structures. Floating wind systems involve disconnection of mooring systems, towing of structures, and handling of dynamic cables. While floating systems may offer advantages in reversibility and retrieval, they introduce additional complexities in offshore handling and logistics. The decommissioning strategy for floating wind is less established than for bottom-fixed, and requires specific attention as the first commercial-scale floating projects approach their end of life.

Across both concepts, decommissioning operations are highly sensitive to weather conditions, vessel availability, and safety constraints. As a result, the efficiency of decommissioning depends not only on individual operations, but on the coordination of the entire system.

Material recovery and circularity pathways

EOL management presents a significant opportunity to improve resource efficiency and reduce environmental impact. Offshore wind farms contain large quantities of materials, including steel, concrete, composites, copper, and critical materials, which can potentially be recovered and reintegrated into industrial value chains. The scale of future decommissioning — combined with global demand for steel and critical materials — makes material recovery both an economic opportunity and an industrial responsibility.

Circular pathways include reuse of components, remanufacturing of subcomponents, recycling of materials, and, where necessary, energy recovery or disposal. Steel structures are relatively well suited for recycling, while composite materials, particularly blades, remain a major challenge due to limited economically viable recycling solutions. Advancing circularity therefore requires both technological development and improved design practices.

Design for disassembly is a key enabler. Decisions made during design influence how easily components can be dismantled, separated, and processed at end-of-life. Integrating circularity considerations early in the lifecycle can reduce future decommissioning costs and improve material recovery rates. Decommissioning should therefore be understood not only as an operational activity, but as an outcome of earlier design, manufacturing, and material choices. This creates a direct link to the design and manufacturing chapters of this report — choices made there determine what is recoverable at end-of-life.

Environmental and regulatory considerations

Decommissioning activities are subject to environmental and regulatory constraints that vary across regions and are still evolving. Requirements typically include the safe removal of infrastructure, management of hazardous materials, and protection of marine ecosystems during offshore operations.

Environmental impacts must be assessed across the entire decommissioning process, including offshore dismantling, seabed disturbance, transport emissions, and onshore processing. In some cases, partial removal of structures may be allowed to reduce environmental impact, but this must be balanced against long-term ecological and navigational considerations.

A lack of harmonised and dedicated decommissioning regulations remains a challenge. Uncertainty regarding requirements, responsibilities, and acceptable practices can increase risk and cost for developers and operators. Early integration of regulatory considerations into project planning is therefore essential. The regulatory gap is particularly pronounced for floating wind, where decommissioning requirements are not yet defined in most jurisdictions.

8.2 Key Challenges and Cost Drivers

Decommissioning costs are driven by the complexity of offshore operations and the need to coordinate multiple interdependent activities under uncertainty. Key cost drivers include the technical complexity of removing turbines, foundations, cables, and associated infrastructure under site-specific conditions, as well as the availability and cost of specialised vessels and equipment.

Weather dependency plays a major role, as limited operational windows can lead to delays and low vessel utilisation. Logistics and transport distances between offshore sites and onshore processing facilities further influence cost, particularly when suitable port infrastructure is limited. Yard capacity constraints and the handling of large volumes of materials, including hazardous substances and difficult-to-recycle components, also contribute significantly.

Extended periods of non-use during decommissioning and re-installation phases, particularly in repowering scenarios, increase overall economic cost. This is a cost driver that is often underweighted in lifecycle analyses — lost production during a repowering campaign can run to years.

Vessel and infrastructure constraints

Decommissioning relies on specialised vessel fleets and offshore equipment, similar to installation but with different operational constraints and objectives. The selection and coordination of vessels are critical, as they must match lifting requirements, component sizes, and environmental conditions. Key vessel types include:

- Jack-up vessels and installation vessels for stable lifting operations
- Heavy-lift vessels and floating cranes for large components
- Shear-leg crane barges for high-capacity lifts
- Transport vessels for offshore-to-shore logistics

Operational feasibility depends on crane characteristics such as lifting height, reach, and capacity, as well as turbine size, dismantling strategy, and sea state conditions. Inefficient vessel utilisation, long standby times due to weather, or mismatches between vessel capabilities and operational needs can significantly increase costs. As turbine sizes increase, many vessels currently available for early-generation decommissioning will be undersized for next-generation assets — the vessel fleet challenge is therefore not only about availability today but capacity adequacy in the future.

Onshore infrastructure is equally critical. Efficient decommissioning requires access to deepwater ports and yards capable of handling large components, enabling temporary storage, material sorting, and integration with downstream processing. Limited port capacity or insufficient yard infrastructure are already visible bottlenecks in the North Sea and will worsen as decommissioning volumes grow.

Link to cost and sustainability objectives

Decommissioning is closely linked to the overarching challenges identified in this report. From a cost perspective, efficient decommissioning strategies and logistics optimisation can reduce lifecycle costs and improve economic performance. From a resource perspective, effective EOL-management is essential for enabling circularity and reducing material demand. Circularity is not only an environmental objective — recovery of steel, copper and critical materials from decommissioned assets reduces future raw material demand and supply chain risk.

The finite availability of offshore space requires efficient use of existing sites over time, making repowering and life extension important strategic options. At the same time, rapid technological development challenges the competitiveness of older assets, requiring careful evaluation of when to extend, replace, or remove infrastructure. This evaluation is non-trivial: the economics of repowering depend on site conditions, grid connection capacity, remaining foundation life, and future turbine technology — all of which are uncertain.

Uncertainty remains a central issue. Limited data, evolving regulations, and variability in asset condition increase risk and complicate decision-making. Reducing uncertainty through better data, models, and coordination is therefore essential for improving EOL outcomes.

8.3 Pathways to Cost Reduction and Improvement

Cost reduction and improved performance in decommissioning and EOL management depend on progress across all three levers: R&D to address technical and decision-making gaps, upscaling of vessel and infrastructure capacity, and standardisation to reduce uncertainty and improve predictability.

R&D and innovation

Integrated EOL decision support: A central research challenge is the development of integrated methodologies that support decision-making across EOL options — decommissioning, life extension, and repowering — under varying technical, economic, and environmental conditions. Current approaches are often fragmented and lack the ability to capture interdependencies across the value chain. This creates a need for advanced decision-support frameworks that combine engineering models with data-driven approaches.

In particular, there is a strong opportunity to develop AI-enabled decision support systems that can integrate operational data, inspection results, environmental conditions, and economic parameters to support more informed and adaptive EOL strategies. Such systems could enable predictive assessment of component condition, estimation of residual value, and dynamic comparison of alternative pathways such as reuse, remanufacturing, recycling, or repowering. The link to digital twins and condition monitoring — developed in Chapter 10 — is direct: high-quality operational data is a prerequisite for credible EOL decisions.

Reverse logistics for offshore wind: Research is needed to design and optimise reverse supply chains, including vessel fleet configuration, transport strategies, port utilisation, and integration with downstream material recovery and industrial processes. This requires a system-level perspective that links offshore operations with onshore circular value chains.

Material recovery and recycling: Material recovery remains a major area of research, particularly for composite materials such as blades, where economically viable and scalable recycling solutions are still limited. Advancing recycling technologies, as well as developing design strategies that enable easier material separation and recovery, are essential to improving circularity. There is also a need to better understand how early design decisions influence EOL outcomes, including dismantling complexity, recoverability of materials, and potential for reuse or remanufacturing.

Offshore operations under uncertainty: More advanced models that integrate environmental data, operational constraints, and real-time information could significantly improve planning accuracy, reduce downtime, and increase efficiency. Current planning approaches often rely on simplified assumptions about weather windows and vessel availability.

Regulatory frameworks and standardisation: Research should address how regulatory requirements, environmental considerations, and industrial practices can be aligned to enable safe, cost-effective, and sustainable EOL management. The current lack of harmonised regulations creates uncertainty and may lead to suboptimal or overly conservative solutions.

Upscaling of industry, supply chain, and fleet

Coordination of logistics and vessel operations should be improved, potentially through shared fleet concepts and better alignment across projects. The timing of decommissioning campaigns across multiple wind farms in the same region creates opportunities for coordinated vessel utilisation — reducing idle time and improving economics for all parties.

Investments in port and yard infrastructure are needed to support large-scale decommissioning and material processing. The development of dedicated or shared decommissioning hubs may be necessary to support future offshore wind volumes. Norway, with its existing yard infrastructure from oil and gas decommissioning, is well positioned to develop such hubs — this is a concrete industrial opportunity that should be developed further.

Standardisation, interface management, and value chain alignment

EOL planning should be integrated early into offshore wind project development, including permitting processes, design decisions, and lifecycle cost assessments. This is not happening systematically today — decommissioning is often treated as a distant obligation rather than a design input. Regulatory requirements for EOL planning from the outset (as in North Sea oil and gas) should be considered for offshore wind.

Design for disassembly and circularity should be promoted to enable more efficient dismantling, material separation, and recovery. This includes consideration of material choices, connection methods, and component standardisation. This links directly to the design and manufacturing chapters: interface and connection standards that facilitate assembly also facilitate disassembly — this should be an explicit criterion in design standards.

Repowering should be considered as a strategic option to balance modernization, cost efficiency, and resource use. Standardised assessment frameworks for repowering decisions — covering structural condition, grid compatibility, permitting pathways, and economic thresholds — would reduce the cost and uncertainty of these evaluations.

Synergies with emerging offshore systems, such as hydrogen production or multi-use infrastructure, should be explored where technically and economically feasible. Repowered sites with retained grid connections are potentially attractive for offshore hydrogen or energy storage, reducing stranded infrastructure risk.

9

Electrical Infrastructure and System Integration

In this chapter we look at the electrical infrastructure offshore and its integration with onshore systems and market. Electrical infrastructure is often treated as the final connection task in an offshore wind project, but it is rather a system integration architecture. It determines how offshore generation is collected, converted, transmitted, traded, balanced and protected. The main cost question is therefore not the price of components such as cables, transformers and converter stations, but the total system value of different connection concepts: radial export to one country, hybrid interconnectors, integrated offshore grids, power-link islands, or offshore energy hubs with/without hydrogen production. This distinction is important because the lowest-cost component solution for developers may be expensive for society if it creates congestion, curtailment, weak access to flexibility, or poor utilisation of offshore wind resources in terms of market access.

9.1 Context and Current Status

Meeting European offshore wind targets will require a massive expansion of electrical infrastructure across four interconnected system levels: within individual wind parks, between wind parks and nodes in an offshore grid, across the offshore grid itself, and in the links between the offshore grid and onshore transmission systems.

At the wind park, the collection system gathers power from individual turbines and delivers it to the offshore substation. Each turbine contains a generator — typically 15–20 MW today — with a built-in transformer that steps voltage up from 690 V to medium voltage (33–66 kV). Turbines are connected in strings by inter-array cables, typically operating at 33 kV or 66 kV AC; 120 kV is under development, and 132 kV (Um 145 kV) wet-design cables are under active industry discussion. The strings feed into an offshore substation (OSS), which steps voltage up to transmission levels for export — by standard IEC component terminology anything above 36 kV is 'high voltage', though the term is sometimes used differently in power systems planning. As turbines grow larger and farms extend further from shore, demands on the collection grid — voltage levels, cable ratings, protection systems — increase accordingly.

Between wind parks and nodes in an offshore grid, export infrastructure carries power to shore or to offshore hub structures. Export cables run from the OSS as either HVAC (High Voltage Alternating Current) or HVDC (High Voltage Direct Current). The transition point between the two depends not only on distance but also on the volume of power to be transmitted: at sufficient scale a bipole HVDC system becomes more competitive than a three-phase AC system on conductor count and cross-section alone. For projects near the distance threshold, mid-point AC compensation is increasingly used to avoid long HVDC component lead times. Where HVDC is applied, an offshore converter station converts AC to DC using VSC (Voltage Source Converter) technology; an onshore station converts back to AC. Component supply chains at this level — cables, converter stations, installation vessels — are already constrained, with order lead times extending several years.

In the offshore grid, a coordinated network of subsea cables and converter stations would allow power from multiple wind farms to be routed across national boundaries and to offshore energy hubs. This infrastructure level does not yet exist at scale: current offshore wind connections are predominantly radial, linking individual projects point-to-point to a single national grid.

In the links towards the onshore system, export cables come ashore via horizontal directional drilling under the beach zone, then run through cable trenches to an onshore substation that steps voltage down to transmission grid levels. The Point of Connection (POC) is where the wind farm formally connects to the national grid via the Transmission System Operator (TSO). Offshore expansion and onshore grid reinforcement must be planned together — congestion or capacity gaps onshore can prevent offshore generation from reaching consumers.

The offshore grid is therefore not simply a connection task. A coordinated offshore grid enables power to flow to where it is most needed in the integrated European power system — from areas with abundant generation to markets and consumption centres where it is needed most. This is what makes the offshore grid a prerequisite for large-scale offshore wind to deliver its full system value.

System integration needs: For Norway, offshore wind infrastructure is more than a connection issue. Radial connections may add renewable generation but coordinated offshore grid architectures can also support security of supply, industrial electrification, hydrogen production and regional market integration (Haaskjold and Seljom, 2024; Svendsen et al., 2024). Effective scale-up requires decisions at three levels: project-level optimisation of wind farm connections, system-level coordination with onshore grids and markets, and sector-coupling with hydrogen, industry, ports and maritime fuel demand. Without such coordination, savings in one part of the system may reappear as higher congestion costs, lower capture prices, increased curtailment or reduced system resilience.

Integrated North-Sea offshore grid and transnational cooperation: North Sea offshore grid analysis highlights the need to assess offshore wind infrastructure from a transnational and cross-sectoral perspective. Offshore wind should be evaluated in combination with cross-border transmission, electricity market dynamics, hydrogen demand and long-term investment decisions (Kristiansen et al. 2018; Durakovic et al., 2023; Svendsen et al., 2024). The key policy insight is that grid connection design affects not only export costs, but also offshore wind utilisation, capture prices, curtailment risk and overall system value (Jåstad and Bolkesjø, 2023). International collaboration on common solutions for offshore grid and electricity market integration (roles, regulations, standards, alignment across countries) is needed.

9.2 Key Challenges and Cost Drivers

For large offshore wind farms, the electrical system normally consists of four functional layers. First, the inter-array grid collects power from individual turbines and transports it to an offshore substation. Second, the offshore substation transforms voltage or converts AC to DC. Third, the export system connects the offshore asset to shore, to another country, or to an offshore hub. Fourth, the operational layer — protection, control, communication, condition monitoring and market dispatch — determines how the physical infrastructure is used in real time.

The cost of offshore electrical infrastructure can be understood by examining how technical, logistical, and market related risks emerge within each layer. These risks include long component lead times, the complexity of marine installation, limited availability of converters and transformers, the operational and economic consequences of cable failures, the duration and cost of outages, interoperability challenges between equipment supplied by different vendors, and uncertainty regarding future market design and regulatory arrangements. This layered perspective provides a useful basis for identifying the main cost drivers of offshore wind integration, where component level challenges must be considered together with broader system level requirements such as coordinated onshore and offshore grid expansion, balancing needs, multi-vendor interoperability, and the technical readiness of future offshore grid architectures.

- Grid expansion is one of the main bottlenecks of increasing the share of wind power in Europe. It is expected that going forward the onshore grid expansion and offshore grid design must be aligned within Europe.

- Grid integration and system solutions for large-scale offshore wind (farm-to-shore, farm-to-farm, meshed grid, system operation, energy hubs) are still outstanding issues requiring both technological and regulatory developments.

- Large-scale deployment of offshore wind will affect the need for balancing services and storage or alternative production. A system that relies on consistent output can be disrupted during low-wind periods when farms produce little or nothing. This is a challenge with potentially considerable cost to the overall system development. This cost can be reduced through targeted design and implementation of system services by offshore wind farms on an inter-park level.

- Interoperability of multi-vendor equipment and reliability of grid components will contribute to reduced costs and give possibilities for stage-wise expansion of the system.

- For inter-array connections, reliable and cost-effective cabling and connectors operating at the desired voltage levels are necessary. With voltage levels moving up, wet-design AC cables and wet-mate connectors need to keep up.

- Diversification in vendors for electric infrastructure and increase in production capacity are also needed.

- Use of subsea hubs changes collection grid design and improves reliability (star design instead of radial design). This requires technology development, for example subsea breakers and switchgear at 66 kV and above.

- New protection schemes will likely be required.

- Offshore multi-terminal HVDC grids will likely require HVDC breakers, which are not available at the desired voltage levels (for a grid, assumed to be 525 kV).

- Redundancy planning for seabed cable failures.

- Technology developed for oil and gas must be adapted to the marine environment and, for floating wind, to continuous platform movement. This adaptation requires qualification work (GCOFW, 2025).

9.3 Pathways to Cost Reduction and Improvment

9.3.1 R&D and innovation

Grid and market integration: As offshore wind scales up, the ability to operate wind farms efficiently within electricity markets and across energy system boundaries becomes as important as the physical grid connection itself. Offshore wind farms do not operate in isolation: they interact with grid tariff structures, connection regimes, balancing markets and, increasingly, with other energy carriers through offshore energy hubs. Research is needed to develop models and operational strategies that reflect this complexity — covering how wind farms participate in short-term markets, manage imbalance costs, apply active control to extend component lifetimes, and integrate with onshore and offshore energy systems. Without this, the full system value of offshore wind will not be realised, and individual wind farm economics will remain disconnected from broader power system needs.

- Market and operational models for wind connected to grid and consumption (connection regimes, tariffs, interface offshore-onshore, connection with other energy system)

- Operational strategies for economic operation in the market (start–stop, imbalance costs, active wind farm control) and that extend the lifetime of wind turbines and electrical components in wind farm control

- Combination with other energy carriers in Offshore Energy Hubs

System services and storage: There is an increasing awareness of the need for system services associated with the introduction of intermittent renewable energy sources. As the share of these sources increases, the need for services such as storage and balancing capabilities is growing. Without proper implementation of such services the power system may experience more severe price fluctuations and blackouts. It is therefore important to look beyond the LCOE of each individual wind park and also take into consideration supporting technologies and sub-systems (such as energy hubs) that need to be developed to enable the high shares of offshore wind that are anticipated to penetrate the European power system.

Design and operation of wind farms for system services: Offshore wind farms have traditionally been optimised for maximum energy production. As their share of total generation grows, this is no longer sufficient. Large-scale offshore wind affects system frequency, voltage stability, balancing needs and the spatial distribution of generation capacity — all of which have cost implications beyond the individual project. Research is therefore needed on how wind farms can be designed and operated to contribute actively to system services, and how their geographical placement and incentive structures can be aligned with system needs rather than developer preferences alone. This includes exploring how offshore wind can be coupled with flexible demand, storage or hydrogen production to increase system value beyond what energy-only metrics capture.

- Shift focus from optimising only energy production in a wind farm to rather optimise for the needs of the power system. For example, some overall production may be sacrificed for increasing production during low wind scenarios.

- Overall strategy for wind farm placement, ensuring incentives for developments sufficiently draw them to areas where there is the greatest need.

- Investigate the possibility for novel large-scale benefits of integrated energy systems where the energy from the farms may be carried to consumption centres or stored in the form of hydrogen or NH3 offshore.

The need for highly reliable electrical components: The rapid expansion of wind energy requires highly reliable electrical components to ensure stable and efficient grid connection of increasingly large and remote wind farms. Key challenges include improving the durability and performance of subsea cables, transformers, power electronics, and offshore substations operating under harsh marine conditions. Research is needed to enhance fault detection, condition monitoring, and insulation technologies, as well as to increase the resilience of HVDC and HVAC transmission systems. Advancing reliable grid connection components will reduce failures, minimise downtime, and support the large-scale integration of wind energy into future power systems. Although focusing on offshore connection, this includes the onshore interface since ENTSO-E's offshore network development planning couples offshore expansion with the onshore connection and onshore grid needs (ENTSO-E ONDP 2024).

- Robust power electronics components for offshore transmission and connection (standardisation, HVDC-switches, connectors, components for intra-national connections)

- An understanding of the impact of increased use of power electronics on the neighbouring components (transformers, cables, terminations, etc.)
- HVDC breakers for an offshore grid
- Standardised wet-design cabling at higher voltage levels
- Dynamic export cables (AC or DC)
- Wet-mate connectors at higher voltage levels
- Load monitoring and power flow control (for an offshore grid)
- Submarine/bottom-fixed/floating substations (AC & DC)
- More environmentally friendly components/cables

9.3.2 Upscaling of industry, supply chain, and fleet

Manufacturing and supply chain: Scaling up offshore wind electrical infrastructure is also a manufacturing and supply chain problem. The components required for large-scale grid connection are produced by a small number of suppliers worldwide, with limited factory capacity and lead times that already extend several years. Subsea cables, both HVAC and HVDC, are manufactured by a handful of companies. HVDC converters are dominated by two or three vendors globally. Offshore transformers and switchgear face similar constraints. Offshore substations remain largely custom-built, with few fabrication yards qualified to deliver them. Cable-laying vessels are a separate bottleneck: the specialist fleet is small, heavily booked and expensive, and repair vessels for subsea cable faults are even scarcer, making fault recovery a significant cost and reliability risk.

Addressing these bottlenecks requires investment in new production capacity, qualification of additional suppliers and development of more modular component designs that allow broader manufacturing. One precondition for industrial scale-up is demand predictability. Manufacturers face volume risk when investing in new cable factories or converter production lines without confidence in long-term order volumes. Another prerequisite is standardization. HVDC can be built in the same way as HVAC — with on-the-shelf components from various manufacturers and not as closed, single-vendor solutions. This is where the system perspective becomes essential: coordinated, standardised offshore grid architectures, rather than bespoke project-by-project connections, make predictable volume manufacturing viable. Standardisation and coordinated planning are a regulatory challenge but also enablers of the industrial scale-up that cost reduction requires.

System integration as a prerequisite for scale-up: A prerequisite for achieving the deployment volumes that justify supply chain investment is that offshore wind is well integrated into the existing power system. Without coordinated grid architectures — across projects, countries and energy sectors — each wind farm remains an isolated export connection, unable to generate the predictable, long-term demand signals that manufacturers need when investing in new production capacity. System integration is therefore not only an energy system requirement; it is an enabling condition for industrial scale-up.

Security of supply: The offshore and onshore power system is one system and should not be planned and optimized independently as two separate systems. Concepts such as dimensioning faults, N-1 criteria strategy and balancing markets need to be further developed as the framework conditions are changing with the introduction of large-scale offshore wind. In addition, attention should focus on how offshore wind farms can interact with the wider energy system beyond electricity.


Adobe Stock

Hydropower can provide valuable flexibility for wind-dominated systems, but only if sufficient transmission capacity and effective congestion management allow this flexibility to reach relevant markets (Farahmand et al., 2015). Offshore grid expansion, onshore reinforcement and hydropower dispatch should therefore be planned as part of one integrated system. While offshore wind farms are a potential target for physical attacks due to their more remote location, the distributed power production can also be beneficial.

- Enhanced energy security with distributed power production from hydro, onshore wind and offshore wind power
- Robustness and emergency preparedness, linked to wind and related infrastructure (cable security, access offshore, supply chains, raw materials)
- Tools and analysis models to handle risks in systems (including energy security and connection with remaining power system)
- Standardization and cooperation around the North Sea within emergency preparedness and mitigation capabilities may significantly reduce cost and increase the ability to both protect against and restore the system after harmful events.

9.3.3 Standardisation, interface management, and value chain alignment

Functional interoperability and standardization: Faulty electrical components have a large impact on power transmission. While onshore equipment can be replaced more easily, the offshore location incentivises the development of highly reliable and (almost) maintenance-free components [ref economic cost]. There is a need to enhance reliability by improving system and component design and multi-vendor interoperability. As an example, HVDC links in Europe are still point-to-point, single component vendor (within each component category) projects. There is a need for functional interoperability, i.e. showing that we can use different converters or different cable manufacturers and not have our connection break if there is a fault. This also applies to fault detection methods, monitoring data flows and communication between all the various distributed components with sensing systems.

Modular, standardised wind farm set-up — covering substations and key components — is a key lever for reducing the cost of design, manufacturing and installation. This requires multi-vendor interoperability.

A system perspective is essential for industrial scale-up: Figure 2 illustrates how electrical infrastructure choices simultaneously affect investment cost, reliability, curtailment risk, access to balancing resources, market value and security of supply. This underlines the need to plan offshore connections, onshore reinforcements and sector-coupling solutions as parts of one coordinated energy system.

ELECTRICAL INFRASTRUCTURE AND SYSTEM INTEGRATION

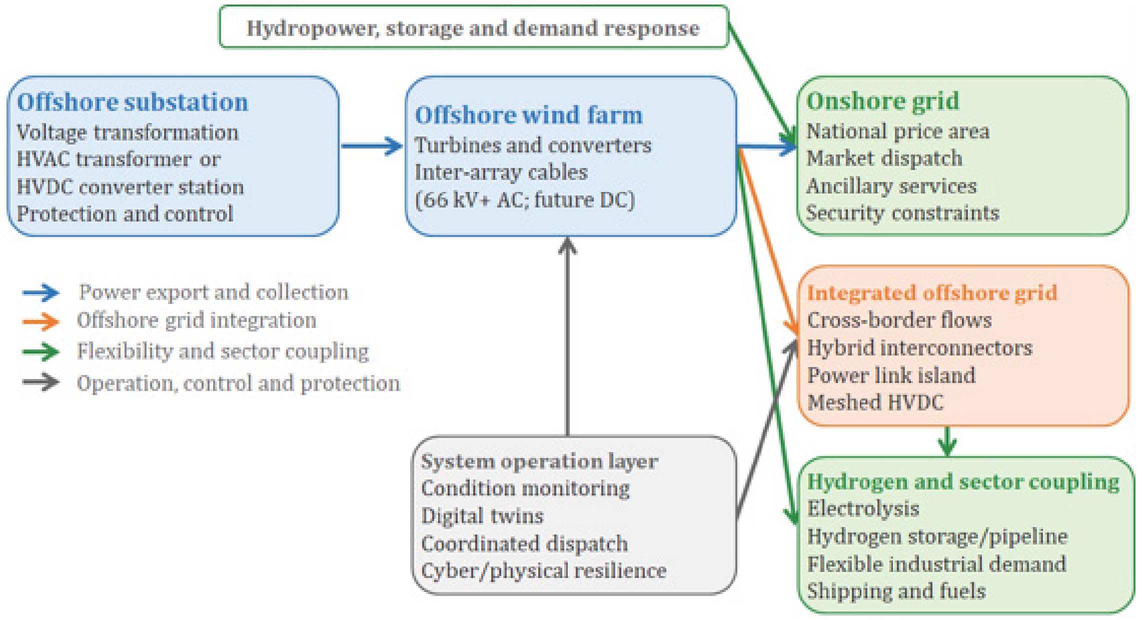


Figure 4: Electrical infrastructure and system integration pathways for offshore wind.

10

Digitalisation and Data

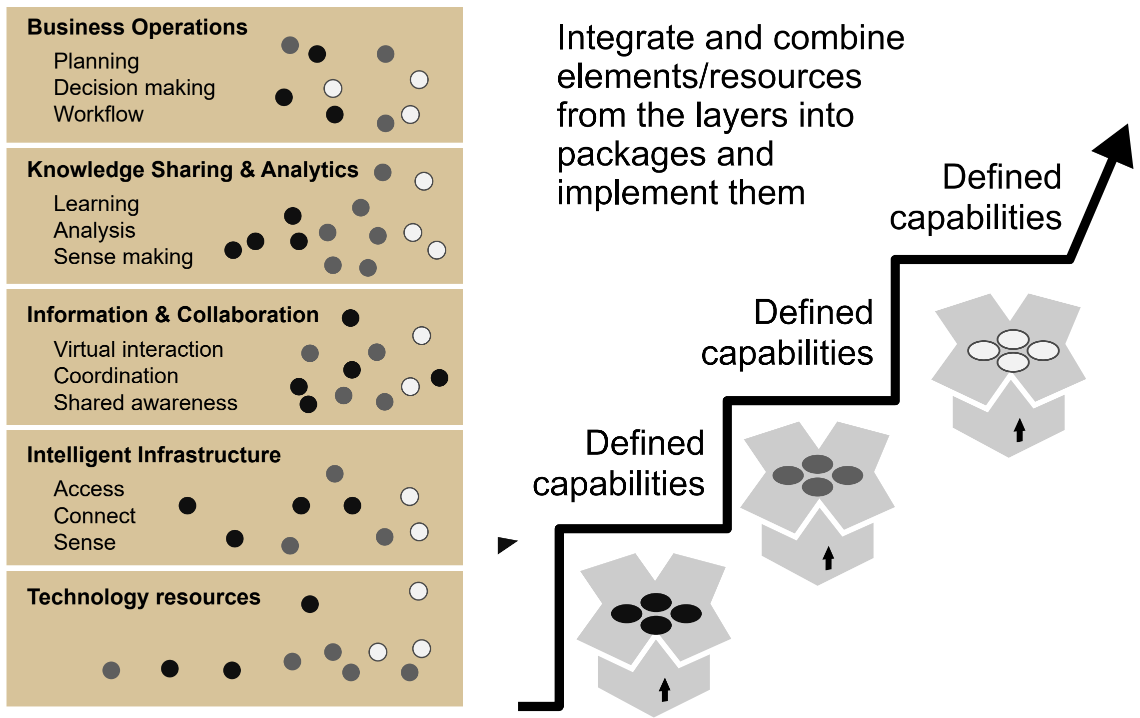
Digitalisation is a cross-cutting enabler for cost reduction, safety and productivity across the offshore wind value chain. As the sector scales from bespoke projects toward industrial deployment, competitive advantage will depend on the ability to collect, structure and share data across the full lifecycle — from site assessment through decommissioning.

Offshore wind assets are remote and safety-critical, with no permanent personnel on turbines or substations and all monitoring performed from onshore. This operating model depends on five interdependent digital infrastructure layers:

- technology resources for power generation, conversion, communication and transfer;
- intelligent infrastructure for sensor data, condition monitoring and automated surveillance;
- information and collaboration platforms that enable data exchange between actors;
- analytics and knowledge-sharing tools for forecasting, diagnostics and O&M planning
- business operations and decision-support processes that turn data into performance.

The upper layers — analytics and business operations — receive most attention through digital twins and AI applications, but depend entirely on the layers below, as illustrated in Figure 5.

Figure 5: Stack model with layers (from Rosendahl and Hepsø, 2013).



10.1 Context and Current Status

Digitalisation in offshore wind has developed rapidly. Tools now cover the full project lifecycle, from wind-resource assessment, design simulation and spatial planning through SCADA, condition monitoring, asset management and inspection, to marine-operations planning and early AI/ML applications. They are increasingly important for reducing offshore interventions, improving vessel use and enabling remote operation.

The most important gap is not that tools are missing, but that they are weakly connected and the absence of a shared digital foundation: common data standards, interoperable systems, secure architectures and governance for data flow across organisations and lifecycle phases. Digital twins, AI and predictive maintenance can reduce cost and risk, but only when built on this foundation. Information generated during early site work, engineering or fabrication is often not available in a machine-readable and trusted form during commissioning and operation. Similarly, operational experience is rarely transferred systematically back to future designs, procurement requirements and standards. A lifecycle view of data is therefore essential.

Despite progress, the sector remains fragmented across developers, turbine suppliers, electrical infrastructure, vessel operators and yards — each with different data structures, naming conventions and interfaces. Norway has strong capabilities from oil and gas, maritime, simulation and industrial software, creating an opportunity to build digital requirements into early projects rather than retrofit them later.

For Norway, a relatively small domestic market can become a learning arena for the wider supplier industry. The opportunity lies in combining offshore engineering, maritime operations, subsea competence, yards, research communities and industrial software capabilities. Early projects should generate reusable knowledge — not only electricity.

Lifecycle phase	Current digital use	Main gap
Planning and design	Wind-resource and metocean models, GIS, wake models, aero-hydro-servo-elastic simulation and design optimisation.	Design assumptions are not always traceable into procurement, commissioning and operation.
Manufacturing and yards	CAD/PLM systems, digital work packages, quality records, dimensional control and yard-flow planning.	Supplier documentation, deviations and quality data are not standardised for later use.
Installation and logistics	Weather-window tools, vessel tracking, lift planning, port scheduling and marine-operation simulations.	Plans are often optimised within single contracts rather than across the full project chain.
Operations and maintenance	SCADA, condition monitoring, alarm logs, inspection data, CMMS, remote-control centres and analytics pilots.	Cross-vendor data access, common semantics and fleet-level analytics remain limited.
Lifetime extension and end-of-life	Asset registers, inspection histories, material data and structural assessment models.	Data is rarely organised early enough to support circularity, reuse, recycling or repowering decisions.

10.2 Key Challenges and Cost Drivers

The main barriers to effective digitalisation fall into five categories: system fragmentation, vendor lock-in, lifecycle inconsistency, operational inefficiency and contractual misalignment — compounded by interoperability gaps, digital complexity and the challenge of safely integrating AI into safety-critical systems.

Many of these cost drivers emerge during project execution. Signal lists may arrive late, making control-room design, alarm handling, and integration testing more expensive. Vendor-specific tools may work well within one package but create costly workarounds when combined with others. Pilot projects may demonstrate promising analytics but fail to scale when ownership, data quality, model maintenance, and operational responsibility are not clarified. The largest cost impact may come from lost learning. If data from design, fabrication, installation and operation cannot be compared across projects, the industry repeats engineering work and over-relies on bespoke solutions.

Cybersecurity deserves particular attention. Offshore wind farms combine remote operation, operational technology (OT), grid interfaces,

Cost driver	Effect on offshore wind
System fragmentation and integration complexity	Separate WTG and ESI SCADA systems with limited interoperability require costly signal mapping, alarm alignment and naming conventions; late signal lists add engineering cost and integration risk.
Vendor lock-in and proprietary solutions	WTG vendors provide proprietary SCADA, analytics and digital twins; warranty-bound O&M services and limited access to real-time and historical turbine data restrict operator control.
Lifecycle inefficiencies	Inconsistent standards across design, commissioning, operation and modification make heterogeneous WTG and ESI systems costly to maintain and update; digital solutions often remain pilots rather than scalable lifecycle tools.
Operational inefficiencies	Fragmented monitoring and alarm systems across vendors prevent fleet-level analytics across mixed WTG suppliers, increasing manual workarounds, vendor-specific processes and labour cost.
Contractual and governance constraints	Split WTG and ESI contracts weaken operator influence over functional definitions and data ownership, while vendor incentives are misaligned across vendors and lifecycle phases.
Sector-wide digital complexity	A heterogeneous ecosystem of PLC/DCS, SCADA, cloud, historians, AI/ML and digital twins create complexity when data models, APIs, software lifecycles and semantic frameworks are inconsistent.
Lack of interoperability and standard adoption	IEC standards such as IEC 62541 OPC UA exist but are implemented inconsistently; real WTG-ESI interoperability is lacking, and installed systems and vendor incentives slow technology adoption.
Vendor dominance vs. operator power	Vendors control systems and functional definitions, creating strong silos. Operators lack enforcement mechanisms comparable to oil and gas/NORSOK, and adaptation of such mechanisms should be explored.
Safety and trust in AI-driven systems	Safety-critical systems require deterministic, auditable behaviour, while resistance to black-box AI creates a need for explainability, validation and fail-safe behaviour.
Cybersecurity exposure	Remote, unattended offshore wind farms connected to critical energy infrastructure are attractive cyberattack targets. Geopolitical risks, including attacks on subsea cables and energy infrastructure, make cybersecurity strategic; retrofitting security is costlier than designing it in.

cloud services, supplier access and vessel connectivity. In the current geopolitical environment, cybersecurity is a strategic risk as well as a compliance issue.

10.3 Pathways to Improvement

The strategic goal is a Norwegian offshore wind digital ecosystem that is secure, interoperable and export-oriented — strengthening domestic project delivery while creating products and services for European markets.

10.3.1 R&D and innovation

R&D should focus on digital solutions that can scale across projects and vendors, not only on isolated pilots. The highest-value research areas are:

- AI in safety-critical systems: combine deterministic rule-based logic with AI/ML for forecasting, anomaly detection, optimisation and advisory functions. Research is needed on explainability, safe states, validation and audit trails.
- Standard digital building blocks: define reusable, vendor-neutral logic for states, modes, alarms, events, APIs, resilience rules and test cases. This is the digital counterpart to standardised physical interfaces.
- Interoperability at scale: reduce late-stage integration work by requiring signal lists, data models and interface definitions early in the project lifecycle. Demonstrators should include multi-vendor WTG and ESI environments.
- Lifecycle robustness: design digital systems that survive software upgrades, component replacements, cyber updates, organisational changes and long asset lives.
- Cybersecurity R&D: develop threat models and security-by-design frameworks for remote, unattended offshore installations, aligned with IEC 62443 and IEC 62351.

R&D should also include methods for evaluating digital benefits. Many digital solutions are justified by expected reductions in downtime, vessel days, spare parts, engineering hours or risk, but the evidence base is often weak. Demonstrators should therefore include measurable baselines, common KPIs and post-project learning. This is important for public funding as well as for private investment decisions.

Floating wind is a particularly important case. Mooring systems, dynamic cables, platform motion, access constraints, and harsh-weather operations create new monitoring and modelling needs that are not well covered by existing digital tools. Norwegian digital demonstrators should connect sensor systems, structural models, marine operations and control-room decision support from the start, with common data requirements and shared learning objectives.

NORSOK reduced physical-system variation in oil and gas; offshore wind now faces the same challenge digitally. A digital NORSOK equivalent should not copy oil and gas standards directly but define common principles for functional behavior state machines.

- Develop a digital standardisation approach inspired by NORSOK principles, focused on behaviour, semantics, interfaces and testability.
- Prioritise demonstrators in floating wind, subsea cables, marine operations, yards, structural health monitoring, wind-farm control and lifetime extension.
- Build cross-disciplinary competence in offshore engineering, simulation, data science, operations, cybersecurity and industrial data governance.

Digital twins can support the shift from bespoke project delivery to industrial deployment by connecting data, simulation models and operational experience across the lifecycle of assets and projects. A digital twin can be understood as a virtual representation of a physical asset or process, enabled by data and simulators, for real-time prediction, optimisation, monitoring, control and decision-making (Stadtmann et al., 2023; Rasheed et al., 2020). The term covers a spectrum, from standalone design models and descriptive/diagnostic twins to predictive, prescriptive and autonomous twins. For offshore wind, the immediate priority should not be full autonomy. The highest near-term value is likely to come from predictive and prescriptive twins with human-in-the-loop decision-making, especially for safety-critical systems and marine operations.

Offshore wind will not be served by one monolithic digital twin. It needs an interoperable ecosystem of twins at component, asset, wind-farm, logistics and grid level — covering turbines, blades, drivetrains, foundations, floating systems, moorings, cables, vessels, substations and environmental monitoring. Their value depends on shared identifiers, metadata, interfaces and governance. Digital twins should be developed around concrete decisions and value drivers, not around software platforms or 3D models. Priority use cases include:

Use case	Decision supported	Industrial value
Design and certification	Loads, fatigue, wake effects, installation limits and safety margins.	Reduced uncertainty, faster design iterations and less over-engineering.
Manufacturing and yards	Digital work packages, quality traceability, dimensional control and production flow.	More serial production, lower rework and better scale-up capability.
Installation and marine operations	Weather windows, vessel plans, lifting/ transport risk and port logistics.	Fewer vessel days, safer operations and better use of scarce installation capacity.
Structural health and predictive maintenance	Inspection timing, failure risk, remaining useful life and spare-part planning.	Lower downtime, fewer offshore interventions and improved lifetime utilisation.
Floating wind, moorings and cables	Dynamic response, fatigue hot spots, seabed interaction and degradation risk.	Better control of high-cost and high-risk subsystems.
Wind-farm control and grid integration	Wake control, curtailment, power output, loads and grid constraints.	Higher production, reduced component stress and increased system value.
Lifetime extension and end-of-life	Whether to extend life, repair, repower, reuse, recycle or decommission.	Lower material demand and stronger circularity.

DIGITALISATION AND DATA

Predictive twins cannot be delivered through modelling alone. They require a shared data foundation: consistent asset identifiers, standardised metadata, machine-readable documentation, quality-assured sensor data, traceability from as-designed to as-built and as-operated states, open interfaces, model version control and clear governance for data ownership, access and sharing. Without this foundation, digital twins risk becoming project-specific tools that cannot support industrial learning across the value chain.

Hybrid analysis and modelling is especially important for offshore wind. Physics-based models provide structure and interpretability, reduced-order models make high-fidelity simulations fast enough for operational use, and data-driven methods can update models from sensor measurements and operational experience (San et al., 2021; Quarteroni et al., 2016). The key research priority is therefore not only higher model accuracy, but also validation, uncertainty quantification and clear communication of model confidence. A digital twin used for decision support must be traceable, validated and transparent about its assumptions and limits.

One of the most strategic roles of digital twins is to close the learning loop between research, innovation, design and operation (RIDO). In offshore wind, long project cycles and limited operational feedback can slow product development, standardisation and process optimisation. A lifecycle twin can connect design assumptions, manufacturing deviations, installation records, inspection data, SCADA data, condition monitoring, metocean data and maintenance logs, so that operational experience is fed back into future concepts, standards, fabrication methods and maintenance strategies. For Norway, shared and trusted digital-twin environments could connect wind-farm operators, offshore suppliers, yards, maritime service providers, research institutes and universities. Early Norwegian offshore wind projects, including floating-wind demonstrators, should therefore be treated as learning platforms for the wider supplier industry, not only as individual energy projects.

The main barriers are not only technical. They include fragmented data ownership, inconsistent data quality, proprietary systems, weak incentives for data sharing, cybersecurity exposure and insufficient combined offshore-wind and digital competence. These should be addressed through project design, procurement and regulation — not as add-on IT issues late in the project.

Cybersecurity and data governance must be designed in from the start. As twins connect to OT systems, cloud platforms and supplier networks, access control, data integrity and incident response become essential. Governance models should distinguish between open data, shared industry data, anonymised benchmark data, and confidential project- or supplier-specific data.

Digital twins should be treated as industrialisation infrastructure for offshore wind. Their success should be measured by whether they reduce cost, risk, downtime, material use and delivery time; whether they improve safety and system value; and whether they accelerate learning across projects and the supply chain. The central task is therefore to build not only individual digital twins, but a shared digital foundation that enables offshore wind to scale as a data-driven, standardised and continuously improving industry. Achieving this requires sustained investment in validation, uncertainty quantification, cybersecurity and human-in-the-loop decision support before expanding towards autonomous functions.

AI agents are an emerging next step in offshore wind digitalisation. Unlike conventional analytics tools that present information to human users, an AI agent observes data, reasons about alternatives, plans workflows and executes digital tasks with a degree of autonomy. This makes them relevant for a sector that depends on complex coordination across operations, maintenance, logistics, weather windows, suppliers, and grid constraints (Wang et al., 2024; Guo et al., 2024).

In offshore wind, AI agents could support tasks such as anomaly triage, maintenance planning, spare-part coordination, document control, inspection analysis, vessel scheduling, permitting support and fleet-level performance optimisation. For example, an agent could monitor alarms and condition data, compare them with inspection history and weather forecasts, propose a maintenance campaign, check vessel availability, estimate production losses and prepare a decision package for the control room. In yards and manufacturing, agents could support production planning, quality documentation and coordination between engineering, procurement and fabrication.

AI agents are closely linked to digital twins. A digital twin provides the structured, validated representation of the physical asset — defining asset state, constraints and uncertainty — while the AI agent uses this to reason, plan and act. Agents in turn increase twin value by turning model outputs into workflows and coordinated decisions. Data quality, model validity and industrial acceptance become even more critical when agents are allowed to recommend or execute actions.

The main position should therefore be cautious but forward-looking: AI agents should first be used as human-in-the-loop decision-support tools in well-defined workflows. For safety-critical functions, they must operate within deterministic boundaries, with explainability, validation, audit trails, cybersecurity and fail-safe behaviour. Their long-term value will depend less on autonomy itself and more on whether they reduce manual coordination, accelerate learning, improve decisions and enable more scalable offshore wind operations.

Relational Database Services (RDS) can provide a structured data backbone for digital twins and cost modelling in offshore wind. By organising technical, operational and commercial data in linked tables, RDS-based modelling supports the move from document-centric exchange toward shared digital architectures, standardised information models and stronger interface management across OEMs, developers, designers, certification bodies and software vendors. In a digital twin context, RDS can connect asset hierarchies, design assumptions, sensor data, maintenance records and cost elements, making it easier to trace how technical choices affect CAPEX, OPEX, risk and lifecycle performance. This is particularly valuable where fragmented systems, inconsistent data models and limited interoperability currently increase integration cost and reduce fleet-level learning.

10.3.2 Upscaling and implementation

Implementation at scale requires organisational and contractual change in addition to technology development. Six actions are particularly important:

Digitalisation challenges in offshore wind are not only technical: they are procurement, governance and lifecycle-management problems — and solutions must address all three.

Make digital twins use-case driven: start with the decision to be improved and the cost, risk, safety or sustainability value to be created.

- Standardise behaviour and interfaces: define states, modes, alarms, failure logic and data interfaces independently of vendor implementation.
- Adopt lifecycle-based digital standardisation: require consistency from design and commissioning through operation, modification, lifetime extension and decommissioning.
- Strengthen operator-driven governance: give operators sufficient control over functional definitions, data access, interoperability requirements and long-term maintainability.
- Enable semantic standardisation: standardise meaning through naming conventions, asset hierarchies, event taxonomies and alarm semantics, not only file formats or tools.

- Use hybrid architecture for AI: keep deterministic rule-based core systems for safety-critical functions and layer AI/ML around them for prediction, optimisation and advisory decisions.
- Plan interoperability early: define SCADA integration, signal lists, APIs, alarm structures and test cases before procurement and detailed engineering decisions lock in vendor-specific solutions.

Implementation should follow the project timeline. In early development, digital requirements should be included in concept selection, tender documents and contract models. During detailed engineering and commissioning, the focus should be on verified data structures, interface testing, alarm rationalisation and secure remote access. During operation, the priority should shift to model maintenance, lifecycle documentation, performance benchmarking and continuous improvement. This prevents digitalisation from being retrofitted after key design and procurement decisions are locked in.

Developers and operators should be able to specify required behaviours, interfaces, data rights, testability and handover obligations — not only which software platforms they want. Such requirements enable supplier innovation while ensuring systems can be integrated and maintained across the asset life.

Public authorities can support implementation by making interoperability, machine-readable documentation, cybersecurity and data handover explicit requirements in tenders and support schemes. Industry can contribute through shared test environments, common terminology and trusted data-sharing arrangements. Research institutions can validate models, develop open reference datasets and train engineers who combine offshore-domain knowledge with data science and cybersecurity.

Cybersecurity must be dedesigned from the start — into architecture, procurement, testing and operating procedures. Retrofitting it onto legacy systems is more expensive and less reliable.

Relevant international standards include: IEC 61131-3 (PLC programming), IEC 61784/62769 (industrial communication), IEC 62541 OPC UA (interoperable data exchange), IEC 61400-25 (wind-power communication), IEC 62351 (power-system security) and IEC 62443 (industrial automation and control-system security). The challenge is less the absence of standards than inconsistent implementation, insufficient contractual requirements and weak governance of how standards are applied.

10.3.3 Use and sharing of data

AI for fleet-level optimisation is a priority beyond individual turbines. Cross-site analytics, wake and curtailment optimisation, and fleet-wide anomaly detection have significant potential, particularly for mixed-vendor portfolios. This requires algorithms and governance models that make data available in standardised, secure and legally usable formats.

Access to data is both a technical and contractual challenge. Operators often lack access to real-time and historical turbine data held by WTG suppliers, particularly during warranty periods. This limits independent condition monitoring, benchmarking, fleet-level analytics and innovation. At scale, weak data access becomes a structural barrier to cost reduction.

Contract frameworks should define data access rights, the boundary of legitimate vendor intellectual property, data use conditions during and after warranty, and cybersecurity obligations. Standard clauses for data access, machine-readable handover and lifecycle documentation should be required in tenders, support schemes and contracts.

Cross-vendor data integration is essential for industrial learning. Common APIs, data formats, semantic standards and asset identifiers should

RDS point	Effect on offshore wind, digital twins and cost modelling
Semantic interoperability	Semantic interoperability enables offshore wind to scale as an industrial system by aligning meaning across actors, tools and lifecycle phases. It should be treated as a prerequisite for industrialisation, not only as an IT concern.
RDS as common digital language	The IEC/ISO 81346-based Reference Designation System (RDS) provides stable reference designations for functions, products, locations and lifecycle phases, enabling consistent identification of assets, systems, documents and data.
TIMWind as implementation pathway	TIMWind can translate RDS principles into wind-industry guidance, manuals and examples that make the approach usable in projects, contracts and software implementation.
RDS4X as industry governance	RDS4X can bring developers, OEMs, suppliers, software vendors, system integrators and research organisations together around shared implementation challenges and interoperable practices.
RDS as vendor-neutral backbone	RDS should not be presented as a software product or platform. It is a vendor-neutral semantic and structural backbone that existing tools can map to and use for consistent information exchange.
RDS and cost reduction	RDS reduces cost indirectly by lowering integration effort, reducing rework, improving data quality, enabling automation and making handover between lifecycle phases more reliable.
Interface management	Many offshore wind cost drivers arise at interfaces. RDS can make interfaces explicit, traceable and machine-readable across turbine, substructure, electrical, installation and O&M domains.
Digital twins and digital thread	Digital twins become more trustworthy when every asset, function, document and data stream is anchored to stable identifiers, making RDS a practical foundation for lifecycle digital twins and the digital thread.
AI readiness	AI applications in engineering, maintenance and cost modelling require structured, semantically consistent data. RDS-based information models can improve explainability, traceability and confidence in AI-assisted decisions.
Developer and operator data requirements	Developers and operators should specify data, naming, handover and interoperability requirements contractually. Without this, vendors are likely to optimise within proprietary silos.
PLM and enterprise-system integration	RDS needs to be implemented in practical systems such as PLM, ERP, SCADA, asset management and document management, where lifecycle interoperability becomes real rather than theoretical.
Offshore substations as use case	Offshore substations are complex multi-discipline systems and a strong use case for demonstrating RDS-based functional and product structures, cost modelling and handover.
Reusable reference architectures	Reference architectures should combine RDS with relevant standards for documents, asset management, digital twins and enterprise integration, reducing reliance on bespoke project-specific data models.
RDS4X.org as scaling channel	Standards do not scale through publication alone. RDS4X.org can support implementor forums, shared use cases, vendor roadmaps, guidance, feedback loops and evidence from pilots.
RDS-based information architecture	Norwegian offshore wind projects should be required or strongly encouraged to define an RDS-based information architecture from early concept through design, procurement, installation, operation and decommissioning, with measurable data handover and interoperability requirements.

allow operators to compare performance, failures and maintenance needs across turbines, sites and suppliers. Trusted data-sharing models should distinguish between open public-interest data, shared industry data, anonymised benchmark data and confidential project- or supplier-specific data.

A practical governance model should define data categories, access levels, retention rules, quality requirements and responsibilities for model updates. It should also clarify how data can be used by researchers, suppliers and authorities without exposing commercially sensitive information or creating cybersecurity vulnerabilities. The goal is not maximum openness, but controlled access that creates learning and trust.

Digital sovereignty should also be considered. Offshore wind will become critical energy infrastructure, and dependency on external suppliers for core operational software, cloud services, algorithms or remote access can create strategic risk. Procurement should promote secure, interoperable and controllable architectures while still allowing access to best-in-class technology.

Finally, anonymised operational data for research can accelerate learning on reliability, failures, environmental effects, maintenance strategies and floating-wind performance. Public-private data pools, trusted research environments and clear incentives for participation could help Norwegian and European actors turn early deployment into shared industrial learning:

- Establish common data architecture, asset identifiers, metadata and lifecycle handover requirements.

- Develop trusted data-sharing models for benchmarking, reliability analysis, environmental learning and R&D while protecting commercially sensitive information.

To avoid digitalisation becoming a collection of pilots, projects should define measurable indicators from the start that connect digital investments to industrial value and lifecycle learning. Relevant indicators include data-handover completeness, machine-readable documentation share, manual signal mappings at commissioning, cross-vendor API coverage, alarm rationalisation quality, cybersecurity test results, and model-update lead time after hardware or software changes.

Operational indicators should include unplanned downtime, number of offshore interventions, vessel days per maintenance campaign, spare-part waiting time, alarm load per operator, quality of failure classification and forecast accuracy for production, weather windows and component degradation. For lifecycle learning, projects should track whether operational findings lead to changes in design assumptions, procurement requirements, inspection plans or standards. This turns digitalisation into a feedback mechanism for industrial improvement, rather than only a tool for monitoring existing assets.

These indicators should be reported in a format that supports comparison across projects without exposing commercially sensitive data. Over time, such benchmarking can help identify which digital solutions reduce cost and risk in practice, which requirements should become standard in future tenders, and where further research or industrial investment is needed.

Main position: *Offshore wind does not need digital twins for visualisation alone. It needs decision-support and learning infrastructure that reduces uncertainty, downtime, material use and risk across design, manufacturing, installation, operations, lifetime extension and decommissioning.*

11

Industrial Scaling and Work Safety

The scaling of offshore wind in Norway will require careful considerations of work safety related to construction, transport, installation and operation. While the chapters in this report have mainly focused on cost reductions, the discussions and recommendations in the previous chapters must be seen in light of health and safety standards. This should be considered already in the design phase and in a full value chain perspective and not be isolated to specific value chain tasks. This report does not go in detail on work safety, but we illustrate some important aspects below.

Construction, transport and installation at the scale required will introduce high work activity, require extensive cooperation between actors and involve complex value chains, conditions that are generally known to challenge work safety (Kongsvik et al., 2026). In the operational phase, offshore wind will imply new work contexts and tasks, and the introduction of new and unfamiliar risks. Norway's ambitions should be guided by the ALARP principle — the risk should be as low as reasonably practicable. From a regulatory perspective, this means that necessary safety measures should be undertaken provided that the costs are not in 'gross disproportion' to benefits (Jones-Lee & Aven, 2011).

Some incident data are available for offshore wind from the Global offshore wind health and safety organisation (2025). There were 1967 incidents reported in 2024, and 245 of these were considered high potential. Most incidents happened during construction (60 %), followed by incidents during the operational phase (34 %). Jack-up vessels/barges and Walk-to-work systems stand out regarding incidents.

Construction work in general has a high risk due to the high levels of energy involved. This is reflected in the most common types of incidents; falling objects, falling from heights, crushes etc. Offshore wind construction will require strong safety management practices, high-quality training of personnel and the mitigation of known safety challenges related to organisational complexity, e.g. time pressure, goal conflicts, role ambiguity and competence (Milch & Laumann, 2016).

Some research addresses work safety in the operational phase. Wind technicians perform operational and maintenance tasks in remote environments, often with limited supervision and communication. Hazards include weather conditions, noise, vibration, long shift patterns, work pressure, isolation, poor communication, and contract uncertainty (Roberts & Flin, 2025). Critical tasks identified include transfer from the vessel to the facility, ascending the internal ladder and manoeuvring through hatches (Milligan et al., 2019).

Safety management principles in current offshore wind operations are to a large extent taken from the petroleum industry (ibid.). Still, the hazards are different and appear in a new context, requiring adapted approaches. Safe operation of offshore wind in Norway will require substantial investments in competence and training for technicians and management and learning from other countries' experience (e.g. Denmark, UK, Netherlands).

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