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Civil Engineering for Offshore Wind Farms



Edited by Trevon M Joseph, Giorgio Giuliani, and Subhamoy Bhattacharya

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Muhammad is a senior geotechnical engineer at KBR and focuses on offshore engineering. He has a doctorate in the critical domain of Technology Readiness Level (TRL) studies, specifically evaluating emerging offshore wind turbine technologies obtained from the University of Surrey. Throughout his career, he has played a pivotal role in various offshore wind projects, contributing to the development of concepts and the execution of detailed designs for a range of foundation types, including jackets, monopiles, gravity-based structures and hybrid structures. His significant contributions have earned him recognition from the Royal Society of Engineering in the field of offshore wind. He has also authored over 20 peer-reviewed journal articles, conference research papers and book chapters in prestigious publications.

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Nicolas is a senior offshore structural engineer at Kent Energies experienced in the structural integrity management of offshore wind farms and oil and gas platforms. In the offshore wind industry, he has conducted fatigue and fracture assessments on operational offshore wind monopile foundations and on offshore wind jacket foundations during their installation, which were all affected by non-design-compliant fabrication defects. He is also experienced in developing offshore inspection plans and reviewing the findings of various offshore inspection techniques. Following completion of an MSc in Data Science, he has used his data analysis and machine learning skills to conduct structural health monitoring assessments using datasets of supervisory control and data acquisition (SCADA) systems, acoustic emission systems and accelerometers.

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safely controlling vessel movement and personnel in the field, O&M analysis using the ECN cost modelling tool and collaborated on projects with Belden and Siemens to develop WiMAX/Wi-Fi infrastructure for offshore wind farms supporting the online information/reporting for all planned and un-planned work through SAP mobile.

James Sweeney MEng AMIME
James is a Structural Engineer with a background in mechanical engineering and a keen interest in structural analysis and artificial intelligence (AI). Since James joined Kent in 2023 he has gained strong experience using SESAM GeniE across multiple projects in the oil and gas and offshore wind industries. James also has strong experience in O&M and has utilised his experience in designing robotic maintenance solutions for nuclear fusion power plants to contribute to Kent's offshore wind O&M team. More recently James has been working as a mechanical engineer in the low-carbon market, analysing biogas compressors and leading a tender evaluation process for a conceptual design project. James's interest in AI was sparked at university but has most recently been built on with his entry into Kent's technical writing competition with a thought piece on how AI will change engineering firms.

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Nick is a mechanical/structural engineer by background and Associate Director at SLPE, London. Nick has many years of experience in the energy sector, with over a decade spent working on the design and analysis of offshore wind monopile and jacket structures. Building on a strong technical background in stress and fatigue analysis, Nick has a broad range of experience in client-facing and interfacing roles. Nick is passionate about the offshore wind industry and about leading and developing teams of engineers to effectively deliver technically challenging projects.

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Wangwen is a leading offshore wind foundation engineer and inventor with over 30 years of experience. He graduated from Imperial College in the 1980s with an MSc and a PhD in structural steel design and structural reliability. The first 15 years of his industrial career were spent in the offshore oil and gas industry, focusing on creating cutting-edge technology. He then moved into the offshore wind industry, holding several senior management positions at Mott Macdonald, ODE, Worley and currently as the Director of Offshore Wind Engineering at AtkinsRéalis and Wind Rider. He is an inventor of the plated transition piece design for offshore wind jacket foundation structures and the rotatable wind turbine. He is a Chartered Engineer and has published over 20 peer-reviewed papers and book chapters on structural design, conceptual engineering, fatigue and fracture, structural reliability and asset management.

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The following list includes those who have participated in some form to the delivery of this book, either by way of contributions to the chapters or in detailed reviews. We take this opportunity to appreciate them again for their efforts.

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Oliver Howell
Wei-Ting Hsu
Guangquan Xu
Wangwen Zhao

And to the families of the contributors and editors, thank you.

We make a living by what we get,
But we make a life by what we give.
Winston S Churchill

Preface

The ambitious global energy transition targets, along with an increasingly mature offshore wind industry, which is now a reality, have prompted the writing of this book. The primary aim is to give an overview of the industry from a civil engineering perspective. This book serves as an introduction for graduates, students, professionals, academics, politicians and anyone eager to gain deeper insight into the offshore wind energy industry. It provides a detailed overview of the key design and project considerations when engineering offshore wind farms (OWFs), making it an invaluable tool for understanding this rapidly growing field.

No offshore wind farm can be developed by an individual or a single team. This is a multidisciplinary process that involves thousands of hours of input from workers across the globe, with the task of delivering a robust and efficient product. In parallel, this book could not be written by an individual, but rather by a multidisciplinary team of engineers dedicated to their specific area of offshore wind farm engineering. The chapters are written by these experienced practising engineers in the offshore wind industry, and the material within them is intended to inform readers of the main considerations in their respective areas. The book includes a wealth of carefully curated references, allowing readers to explore the civil engineering concepts and topics discussed in each chapter in greater depth.

When the book was first envisioned, the idea was to bring together key disciplines within the industry that inform civil engineering. Some of these were quite clear, such as the structural, geotechnical, fabrication and installation disciplines. However, other important disciplines, such as operations and maintenance, offshore wind legislation and economics, were deemed too important to omit. The inclusion of health, safety and the environment was challenging, but it is envisaged to be included in an updated version of this book.

Hoping to satisfy the curiosity of those with a keen interest in the industry, this book aims to be a reliable reference, providing a platform from which one can pursue further investigation.

The chapters are organised systematically by the civil engineering input required, in chronological order, from feasibility studies through decommissioning. The initial chapters focus on the engineering input for site selection and conceptual design. Based on this knowledge, developers can estimate the basic costs associated with the wind farm to assess the feasibility of continuing the project. Site surveys conducted to expand the available data then feed into the design refinement that are discussed throughout subsequent chapters, culminating in the transportation, installation and operations and maintenance (O&M) stages of the wind farm.

The many legal considerations in offshore wind and the funding for these projects are substantial and the details on these aspects then follow.

For ease of reference, the following is a short summary of the chapters within this book.

Chapter 1: Offshore wind: an overview
This chapter begins by tracing the historical development of wind power and its origin back to 200 BC in China, then used for water and milling grain. The chapter highlights the reason why offshore wind is needed in the context of today's climate crisis and the need for offshore wind energy. Following this, a general overview of projected offshore wind power growth over the next decade in selected countries is discussed. The chapter concludes by giving an insight of wind energy generation and the design stages needed to develop an OWF.

Chapter 2: Preliminary surveys, site selection and feasibility studies
This chapter explores the types of surveys required to collect initial information for the preliminary siting assessment of an OWF. The environmental assessment of wind farm development with the aim of reducing ecological impacts is also discussed. A variety of configurations for the wind farm, the turbines to be employed and the structural forms are assessed and compared including consideration of risk, schedule implications, cost and operability. This chapter also includes some of the specific requirements of stakeholders so that they can be accommodated or mitigated at an early stage.

Chapter 3: Conceptual design
This chapter builds on the preliminary data obtained to assess the impact of this information on the proposed wind farm. How this data is used to determine the potential turbine and cable layout, turbine density, distance from shore, grid connection and the potential capacity of the wind farm is also explored. Areas to avoid, such as locations with archaeological importance, navigation routes through the site and environmental constraints, are also discussed. At this stage of wind farm development, the foundation type is usually selected in an optioneering study developed to identify the most suited foundation to be taken into latter stages of design.

Chapter 4: Geophysical, geotechnical and detailed site investigation surveys
In the development of OWFs, as more data is obtained, the uncertainty reduces. On completion of the preliminary surveys, more site-specific surveys will need to be performed to build on the data. This chapter

discusses the use of desktop studies and the acquisition of geophysical and geotechnical data in the creation of the ground model for the wind farm. This ground model will be improved as more detailed geophysical and intrusive geotechnical investigations are undertaken. The chapter also details the survey strategies used during these campaigns.

Chapter 5: Foundation engineering
Here, the requirements of the geotechnical design of foundations to OWFs are outlined. This includes the essential design principles, stages and best practices. The chapter focuses on the monopile foundation, gravity-based foundation, jacket pile, suction caissons, anchors for floating wind turbines and spudcan foundations for installation vessels. Each section examines critical design considerations, methodologies and the current limitations of design standards while referencing research and development that aims to improve on established methods.

Chapter 6: Structural engineering
This chapter explores the structural engineering activities critical to OWF development, concentrating on the supporting elements of wind turbines. It covers both substructures below the water level and superstructures above it. The chapter discusses the approaches in determining offshore loads on wind turbine generator foundations and the structural analyses required, highlighting the key design drivers during early project phases. Additionally, it addresses specific requirements for jacket and monopile structures at the later design stage and provides insights into secondary steel and substation foundation design.

Chapter 7: Subsea cables
This chapter focuses on electrical cables for OWFs. However, emphasis is on the general civil engineering requirements rather than the details associated with the electrical engineering aspects of cable design. This includes consideration of cable engineering both within the turbine array and along the export corridor, scour assessments, cable burial and cable protection. This topic was considered of high importance due to the large number of insurance claims that arise in offshore wind primarily in offshore cables.

Chapter 8: Fabrication and supply chain: challenges and technological advancements from a fabricator's perspective
Amidst the ongoing growth of the offshore wind sector, the supply chain has been consistently enhancing its capacities to align with the requirements of an expanding array of wind farms and larger turbine installations in deeper waters. This chapter discusses the main aspects, challenges and technological advancements from a fabricator's perspective where

fabrication cost constitutes a significant portion of the overall construction costs. Key topics discussed here include the role of fabricators, materials utilised in the fabrication of large components, welding techniques for foundation components, painting and coating processes, specific challenges pertaining to floating foundations, and considerations of sustainability and decommissioning.

Chapter 9: Installation
This chapter describes the overall installation process of an OWF. Key aspects of transportation and installation of each of the wind turbine generator (WTG) components, the electrical infrastructure, the effect of the weather limits on the transportation and installation as well as logistical and supply chain challenges and how they interact with each other are discussed. A contractor's perspective on the installation of offshore cables is also provided.

Chapter 10: Operations and maintenance
This chapter covers the operations and maintenance (O&M) practices for OWFs, focusing on improving performance while ensuring safety and maintaining assets over their lifetime. It outlines the operational philosophy, highlighting the importance of safe and efficient daily management to minimise downtime and logistical issues. The maintenance philosophy includes statutory, preventative and corrective maintenance strategies to ensure wind turbine reliability and longevity. The chapter also discusses inspection and monitoring methods, such as visual inspections and non-destructive testing, to predict and prevent failures. Energy output optimisation is explored, recommending digital tools and machine learning to reduce revenue losses and improve efficiency. Finally, O&M optimisation strategies are presented, emphasising careful planning and combining tasks through a computerised maintenance management system to minimise disruptions. Overall, the chapter provides a brief outline of the approach to maintaining and improving OWF operations.

Chapter 11: Life extension
This chapter discusses the main civil engineering considerations for OWF life extension. The benefits and barriers within the regulatory landscape are introduced, noting that existing knowledge from the oil and gas industry should be exploited. Focus is placed on fixed-bottom foundations due to their existing prevalence. The technical considerations are then discussed, noting the requirement of a baseline model, which may be used to calculate the structural probability of failure due to different types of damage and deterioration mechanisms. A discussion is conducted on how this should be set up and improved over time. The critical locations on jacket and monopile structures are then highlighted, as well as the

important deterioration mechanisms. These include primarily fatigue and corrosion deterioration, and natural frequency shifts. This is followed by a discussion on the different end-of-life scenarios and options for the operators. This chapter then discusses how relevant risks are defined, as well as how structural health monitoring, inspections, maintenance and repair activities can be used to monitor and calibrate the baseline model's parameters. The chapter finishes with a discussion on the benefits of digital twins and dashboards to better visualise and understand the structural risks and anomalies.

Chapter 12: Decommissioning
This chapter details the decommissioning process for OWFs, addressing various technical, regulatory, economic and environmental considerations. The factors that influence the decision to decommission are discussed such as asset condition, maintenance costs, decommissioning expenses and regulatory requirements. The chapter covers the regulatory framework for decommissioning, emphasising that compliance with the various legislative requirements is essential. The chapter outlines the stages of decommissioning from planning and preparatory work, decommissioning and removal of infrastructure and post-decommissioning monitoring. The chapter also discusses waste management and the reuse and recycling of components to minimise environmental impact. It concludes with a focus on risks and challenges, including structural degradation, vessel availability and technical complexities, indicating the need for careful planning and adherence to best practices.

Chapter 13: Legal aspects of offshore wind
The generation of offshore wind energy is a relatively new industry, and many countries have introduced or are developing legislation to meet their specific needs. In many cases, countries are learning lessons from early starters in offshore wind and using these as a precedent, in part or whole, for their legislation. This chapter summarises key features in selected countries that the civil engineer is likely to be required to address when developing, installing, operating or removing OWFs. The legal side of contract-related challenges is also discussed, an important consideration due to the expenditure required in these projects. Reference is also made to a selection of legal cases that illustrate some of the relevant claims that have developed over the last few years.

Chapter 14: Offshore wind farm economics
This chapter aims to provide the civil engineer with the knowledge of the challenges involved in the financing of an OWF, focusing on the cost models used to determine financial feasibility. The cost categories contained within total expenditure (TOTEX) are examined in detail, such

as capital expenditure (CAPEX) and operational expenditure (OPEX). In addition, life extension, a new category in development, and the cost mechanisms associated with this area are also explored. Financing mechanisms including contracts for difference, feed-in-tariffs and corporate purchasing power agreements are examined to demonstrate the management of risk across different stakeholders.

The editorial team have aimed to ensure this book is fit for purpose based not on their expertise alone but also on that of the contributors. We hope that you enjoy the contents of the book!

The editors.

Glossary

Term	Definition
ABEX	abandonment expenditure
ABS	American Bureau of Shipping
AC	alternating current
AEP	annual energy production
ALARP	as low as reasonably practicable
BLS	boat landing system
BOEM	(USA) Bureau of Ocean Energy Management
BOP	balance of plant
BPI	burial protection index
CA	certifying authority
capacity	rated continuous load-carrying ability of the wind turbine
CAPEX	capital expenditure
CAR	construction all risks
CBRA	cable burial risk analysis
CDM	Construction (Design and Management) Regulations
CfD	contracts for difference
CMMS	computerised maintenance management system
CMS	condition monitoring system
CP	cathodic protection
CPS	cable protection system
DA	drag anchor
DAU	data acquisition unit
DC	direct current
DCO	development consent order
DECEX	decommissioning expenditure
DEPLA	dynamically embedded plate anchors
DEVEX	development expenditure
DFF	design fatigue factor
DGP	drill and grouted anchor pile
DLC	design load case
DP	driven anchor pile
DPA	dynamically penetrating anchors
DWCM	diamond wire cutting machines

Term	Definition
DWW or DWOW	deep-water offshore wind
EA	Electricity Act
EC	export cable
EEZ	exclusive economic zone
EIA	environmental impact assessment
EMC	electromagnetic compatibility
EPC	engineering, procurement and construction
EPCI	engineering, procurement, construction and installation
EWP	external work platform
FCAW	flux core arc welding
FE/FEA	finite element or finite element analysis
FEED	front-end engineering design
FLEPA	flexibly embedded plate anchor
FINEX	financing expenditure
FiPs	feed-in premiums
FiTs	feed-in tariffs
FLS	fatigue limit state
FMEA	failure mode effects analysis
FOWT	floating offshore wind farm
GBF/GBS	gravity-based foundation/structure
GMAW	gas metal arc welding
GRP	glass-reinforced polymer or plastic (fibreglass)
GTAW	gas tungsten arc welding
HSE	Health and Safety Executive
HSWA	Health and Safety at Work Act
HV	high voltage
HVAC	high-voltage alternating current
HVDC	high-voltage direct current
IAC	inter-array cable
ICCP	impressed current cathodic protection
ICE	integrated cold electrode
IEA	International Energy Agency
IEC	International Electrotechnical Commission
ILA	integrated load analysis

Term	Definition
IMO	International Maritime Organisation
IRENA	International Renewable Energy Agency
KPI	key performance indicator
LCOCE	levelised cost of consumed energy
LCOE	levelised cost of electricity
LIDAR	light detection and ranging
LOSC	common abbreviation for UNCLOS
LPS	lightning protection system
MCA	Maritime and Coastguard Agency
MEL	master equipment list
met mast	meteorological mast
MMO	Marine Management Organisation
MP	monopile
MSA	Merchant Shipping Act
NEPA	National Environmental Policy Act
NGO	non-governmental organisation
NORMS	naturally occurring radioactive materials
NPS	national policy statement
O&G	oil and gas
O&M	operations and maintenance
OEM	original equipment manufacturer
OFTO	offshore transmission operator
OPEX	operational expenditure
OREI	offshore renewable energy installation
OSP	offshore substation platform
OSS	offshore substation
OSW	offshore wind
OWF	offshore wind farm
PA	Planning Act
PISA	Pile Soil Analysis project
PLGR	pre-lay grapnel run
PPA	power purchase agreement
PSHA	probabilistic seismic hazard assessment
PSU	power supply unit

Term	Definition
PUR	polyurethane
R&D	research and development
RBI	risk-based inspection
RCMS	remote condition monitoring system
RCT	risk, cost/compliance, time
REZ	renewable energy zone
RNA	rotor nacelle assembly
SA	suction anchor
SAW	submerged arc welding
SCADA	supervisory control and data acquisition system
SCF	stress concentration factor
SEPA	Scottish Environment Protection Agency
SEPLA	suction-embedded plate anchor
SIM	structural integrity management
SLS	serviceability limit state
SMAW	shielded metal arc welding
SPMT	self-propelled modular transporter
TLP	tension-leg platform
TNUoS	transmission network use of system
TOTEX	total expenditure
TP	transition piece
TSO	transmission system operator
ULS	ultimate limit state
UNCLOS	United Nations Convention of the Law of the Sea
UXO	unexploded ordnance
VHF	very high frequency
VIV	vortex-induced vibration
VLA	vertically loaded plate anchor
VTS	vessel traffic system
WACC	weighted average cost of capital
WELCAR	Wellington Syndicate in April 2001, construction all risks (CAR)
WFO	wind farm operator
WINDCAR	offshore wind, construction all risks (CAR)
WTG	wind turbine generator

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Chapter 1
Offshore wind: an overview

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1.1. History of offshore wind power

The development of onshore wind power has transpired over many decades. However, the capacity of onshore wind farms is dwarfed by the scale of offshore power generation. This is usually due to several onshore limiting factors such as access, geomorphology, availability of high-yielding wind zones and social opposition, while offshore, many of these limitations are not observed. Size is only limited by what can be engineered, fabricated and installed. As a result, the interest in offshore wind is being investigated in full detail.

The design of the wind turbine has developed since the early modern designs with a focus on each component of the structure. With increases in energy demand and specifically in renewable energy, it is generally more cost-effective to build the largest turbine available than a smaller turbine. This has resulted in turbines rapidly increasing in size.

Some sources suggest that wind power was used in China around 200 BC for water and milling grain; however, documented evidence of the harnessing of wind energy to power devices has been dated to 9th century Persia (Al-Hassan and Hill, 1986), where wind was used as a power source for milling various foods and materials. This technology was developed and found its way to Europe, especially in the Netherlands where, from the 12th century, it was heavily used to increase food production and pump water. Later in the 17th century, wind was used to power sawmills which helped increase ship production through automated wood cutting, facilitating the creation of a strong navy. Wind power therefore allowed the Dutch to surpass their European rivals who relied on manual processes.

The harnessing of wind power to create electricity was slowly improving. In the 1850s, Daniel Halladay invented and built several small wind turbines out of the Halladay Windmill Company in Ellington, CT, USA. His associate, John Burnham, sold these turbines to farmers for the extraction of water for livestock, farming and trains. By 1857, the US Wind Engine & Pump Company was formed which industrialised wind turbine generation. From this venture, several patents were created such as one that automatically directed the turbine into the wind and regulated its speed of operation.

In 1883, Josef Friedländer of Austria was the first to generate electricity using wind power. He attached a generator to the Halladay wind turbine and used this to charge batteries to power small electrical appliances. Later, in 1887 in the UK, Prof James Blyth, an electrical engineer, at what is now the University of Strathclyde, developed the first wind turbine in the UK used to produce electricity. In 1888 in the USA, Charles Brush created a 17 m wind turbine to provide electricity to

Figure 1.1 16th century windmills in the Netherlands



his farm. Fast track to 2024 and the industry is installing turbines with diameters of at least 220 m and even larger turbines are planned. We have truly revolutionised the industry! Figure 1.2 shows the timeline of wind power development over the years to 2019.

In 2020, it was thought that by 2025, the largest wind turbine installed offshore would be 12 MW. Over the years, in 2022, 10 MW turbines were installed at the Seagreen OWF; in 2024, 16 MW turbines were installed offshore at the Zhangpu Liuao Phase 2 OWF with a 20 MW demonstrator unit installed in early 2026. Prototype turbines of 26 MW rated capacity have been developed but not yet installed offshore. Figure 1.3 shows the growth in turbine sizes in the 21st century. Although models do vary, as shown, a typical 10 MW turbine will have a rotor diameter of about 160 m and a mass of about 550 tonnes.

1.2. Why is offshore wind needed?

Over the last few decades, meteorological and other scientific observations have noted changing trends in our climate. Based on these, predictions have concluded that if we continue along the same path with nothing done differently, this will only exacerbate the climatic effects in the future. The main driver of this has been society's reliance on the use of fossil fuels to provide energy to support industrial development and economic growth. Due to the cost, efficiency and reliability of fossil fuels to meet energy demands, alternative means of energy production have not been readily adopted.

There are numerous alternative means of generating the energy required to support industrial and societal development. These include renewable sources such as the harnessing of solar, wind, waves, tidal, hydro and geothermal energy. Alternatively, nuclear energy is an option that does not add to either carbon or greenhouse gas emissions. The costs associated with the development of these green industries have, over the years, been governed by the relative cost against that of producing energy from fossil fuels. Given the clear scientific observations, it has therefore been the responsibility of governments to initiate the required procedures to input the necessary laws thereby forcing the industry to rethink the historical energy-producing methods.

Figure 1.2 Evolution of wind power technology from 1887 until present (adapted from Nikitas, 2020)

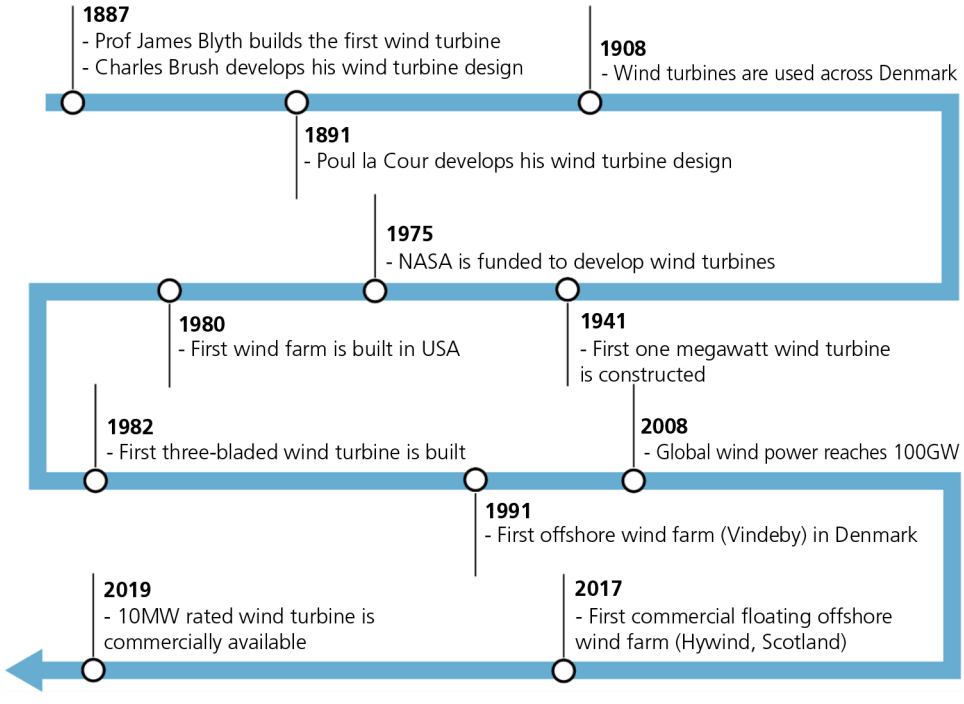
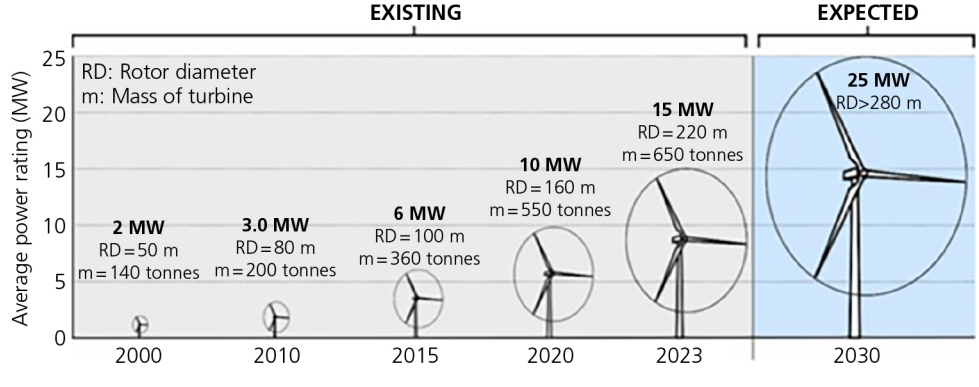


Figure 1.3 Evolution of offshore wind turbines and projections (Nikitas, 2020)



Economics has played a part in the means of generating energy in each country. As a result, some are more advanced than others in terms of the infrastructure available to develop certain renewable industries. Also, for other strategic reasons, some countries have developed a variety of energy-producing industries and in doing so, the risk associated with dependency on one form of energy is diminished.

Of the variety of energy-producing sources, countries determine which is the best form for their use. It can be expected that those with large waterways, such as China and Brazil, or those with an abundance of sunlight, such as those surrounding the Sahara Desert, will be able to harness the power of these sources if it is in their best economic interests. Countries with large open fields and a surplus of fast winds can harness the power of wind. Those with an abundance of coastline, such as the UK and China, can harness the power of offshore wind.

In 1997, the historic Kyoto Protocol was agreed between nations across the globe. This was an agreement, which was the first of its kind, whereby countries acknowledged the impact of climate change and agreed to reduce their carbon and greenhouse gas emissions by challenging targets from agreed base years. Many developed nations have taken decisive actions and, in this context, have set ambitious targets to reduce greenhouse gas emissions. Some that have pledged to attain net zero by 2050 have identified that a practical way to achieve this target is to supply energy produced mainly from renewable sources, thereby decarbonising the economy. Many countries have since pushed the boundaries of their attainable renewable energy targets and have opted to develop offshore wind as a strategy to fulfil their increasing energy demands. As the agreements and targets continuously change, it is expected that more changes will occur even after the publication of this text. For more on this please see the annual updates by the Global Wind Energy Council (GWEC, 2026).

1.3. Regional offshore wind

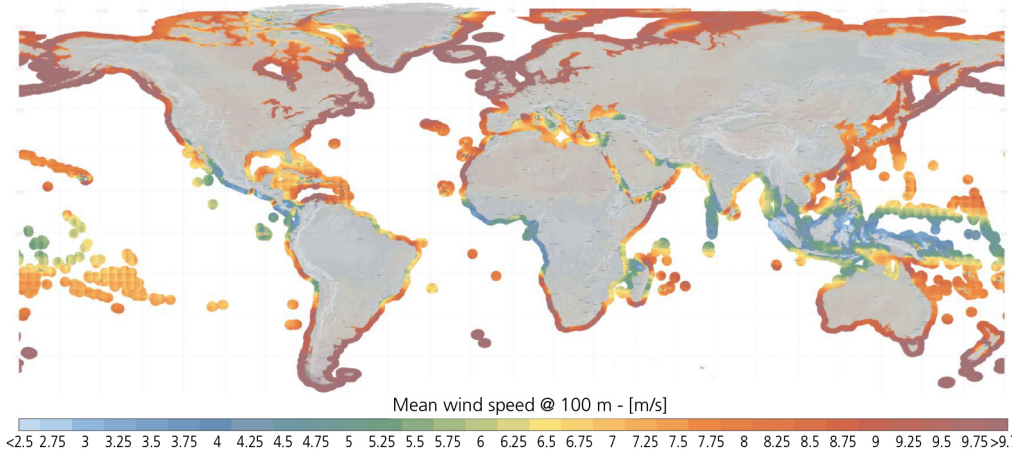
The harnessing of wind power was, in general, a more costly means of producing energy than carbon-rich sources such as fossil fuels. However, through investment, research into each turbine component and industrial development, the cost of wind energy has dramatically reduced. This reduction in cost has received the attention of many countries worldwide who wish to reduce their dependency on fossil fuels for energy production.

After steadily increasing from the first offshore wind farm (OWF) in Vindeby in 1991, by the end of 2013 there was about 7 GW of offshore wind capacity installed globally, with Europe accounting for about 90% of this and the rest coming from the Asia-Pacific (APAC). By the end of 2021, there was 56 GW of offshore capacity installed and, for the first time, almost the same amount of installed offshore wind capacity in Europe and APAC. However, since 2021 the installed capacity of the APAC region has been steadily surpassing that of Europe. This demonstrated the beginning of the shift in the leadership of offshore wind installations. By the end of 2023, the total worldwide offshore wind power capacity was about 75 GW, with a split of 34 GW from Europe and 41 GW from the Asia-Pacific (APAC) region. Estimates predict that by 2035, there will be 420 GW of offshore wind capacity installed (GWEC, 2026), with approximately 40% coming from Europe, 50% from Asia and 10% from the rest of the world.

In terms of offshore wind capacity, Figure 1.4 gives an indication of the mean wind speed at 100 m above sea level. These wind speeds have been derived based on high resolution wind speed data supported by modelling. This is limited to around the coastline of countries. Figure 1.4 shows where the hotspots for offshore wind are situated. In general, there are larger offshore wind speeds closer to poles in both hemispheres; however, there is a large amount of offshore wind resource available across the globe.

The following sections briefly outline the expected growth in offshore wind power over the next decade in a few countries. Initially, the authors aimed to give an idea of the growth in offshore wind per country over the next decade, but installed capacity and targets published were found to

Figure 1.4 Offshore wind resource map, mean wind speed (Source: Global Wind Atlas, n.d.)



be quickly superseded in this rapidly growing market. Within this section is also identified locations in which fixed or floating structures could potentially be installed and these are also subject to change depending on the technologies available at any given time. Also, as technologies develop, the threshold depth for changing from fixed to floating structures is also being updated which will again result in a modification of the statistics over time. The indication of the change from fixed to floating is therefore adopted as 50 m water depth.

1.3.1 Europe

Offshore wind was dominated by Europe for many decades. The UK has been the leader in terms of offshore wind investment since 2009, followed by Germany, the Netherlands and Denmark. Each European country was required to set clean energy targets by 2030 as part of a 10-year European Union (EU) initiative and delivered in a National Energy and Climate Plan (NECP). Many EU countries adopted a specific level of offshore wind to contribute to their clean energy portfolio. Notable targets as part of the NECP are indicated in Table 1.1. These are considered to be mainly from fixed-bottom structures; however, floating structures are slowly being developed.

Offshore wind potential maps for fixed-bottom and floating structures are provided for the UK and for Germany. As indicated, the areas suitable for offshore wind are changing as technology develops and, as a result, although some indication is provided here, these will most likely require updating in the near future.

1.3.2 China

China is one of the leaders in wind turbine technology and has the world's largest wind supply chain. For many years, the energy mix of China comprised the use of mainly fossil fuels, but was also supported by hydropower, solar and wind. China requires a large supply of energy, especially to support its large manufacturing industry. Many of these manufacturing hubs are situated along the eastern side of the country and efforts to curb the reliance on fossil fuels along with the scale of energy required have been sought. Offshore wind is considered to be an ideal source of energy to support the eastern areas.

Table 1.1 Targets for selected European countries (continued on next page)

European country	Offshore wind target by 2030
UK (HMG, 2025)	• 45 GW from fixed • 5 GW from floating The UK initiated many rounds of offshore wind. Round 1 targeted the shallower areas and, with the later releases of rounds 2 and 3, wind farm sites by the Crown Estate in deeper waters. Figure 1.5 shows an outline of the potential of fixed and floating OWF locations across the UK. As can be clearly seen, there is a much larger potential for offshore floating, which remains untapped
Germany (GWEC, 2026)	• 30 GW is the target, although less being fed into the grid by 2030 • 40 GW by 2035 • 70 GW by 2045 Figure 1.6 shows the technical potential and suitability of fixed-bottom and floating OWFs in Germany
Denmark (GWEC, 2026)	• 12.9 GW – the official national target for offshore wind capacity
France (Enerdata, 2024; Montel News, 2024a, GWEC 2026)	• 3.6 GW • 15 GW by 2035 Originally indicated as 1.5 GW in 2023, the 2024 NECP indicated that it would double its target.
Poland (Norton Rose Fulbright, 2025; GWEC, 2026)	• 5.9 GW • 18 GW by 2040 Poland intends to stimulate industrial growth by a significant investment in renewable energy
Ireland (Department of Enterprise, Trade and Employment, 2024)	• 5 GW of grid-connected offshore wind and 2 GW of non-grid connected offshore wind is anticipated by 2030 • 20 GW by 2040 • 37 GW by 2050
Belgium (Brussels Time, 2024)	• 6 GW Of the offshore space available in the North Sea for Belgium, about 15% of this space is available for wind development due to the protected nature reserves at sea. However, to meet the renewable energy targets, about 25% is required. To rectify this, additional engineering or reductions to the target will be required
Spain (Asociación Empresarial Eólica, 2022)	• 3 GW by 2030 • 17 GW by 2050 The NECP was updated to be more ambitious for the 2023 to 2030 period. The original plan aimed for 1 GW
Greece (Herema, 2022)	• 2.7 GW Under the NECP, Greece is aiming to install these offshore wind farms by the use of Herema (Hellenic Hydrocarbons and Energy Resources Management Company)

Table 1.1 Continued

European country	Offshore wind target by 2030
Italy (Ion Analytics, 2024; Montel News, 2024b; TEHA, 2023)	• 2.1 GW Italy has the potential to be a leader in floating offshore wind. This is due to the water depths and the reduced environmental impact. As a result, hundreds of offshore wind projects are being investigated across Italy
Portugal (GWEC, 2026)	• 2 GW This is intended to be delivered by way of floating offshore wind
The Netherlands (Navingo, 2024a)	• 21 GW This was intended to be connected by the end of 2030; however, due to issues with connectivity to the grid, this is now deemed possible only by 2032

Figure 1.5 Overview of offshore wind farms in the UK (Source: GWEC, 2026)

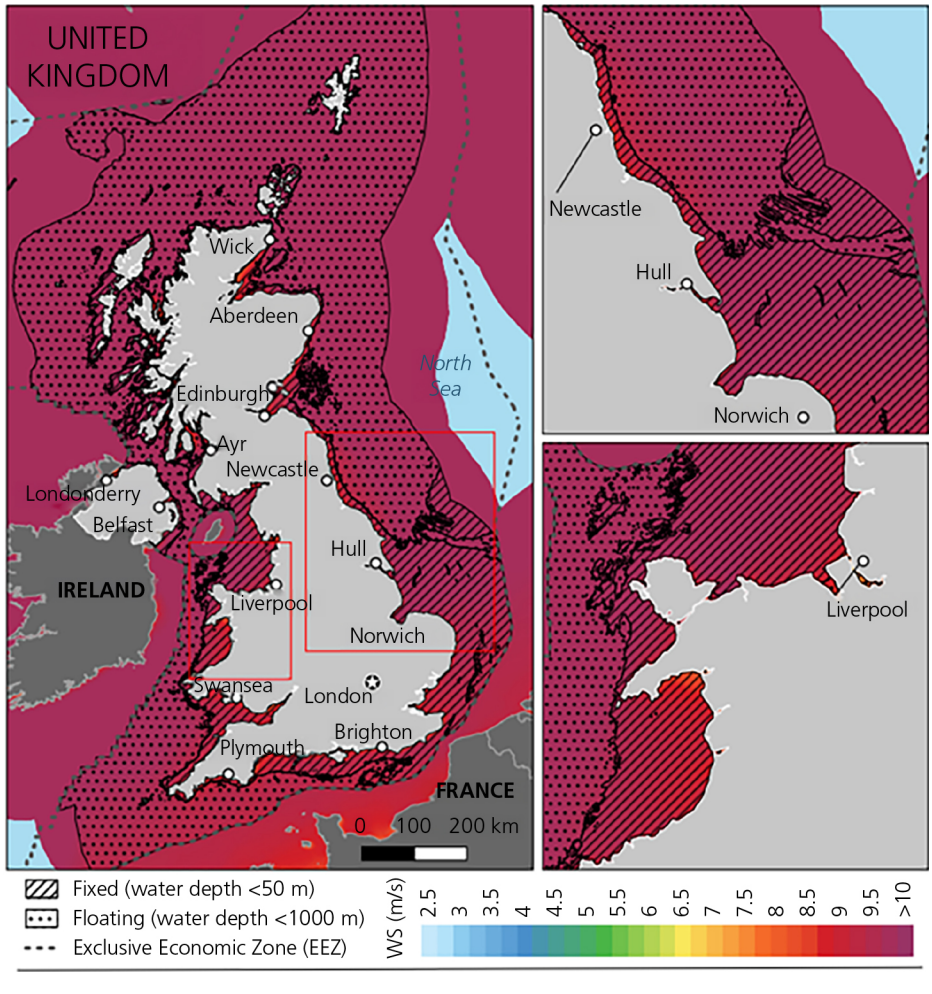
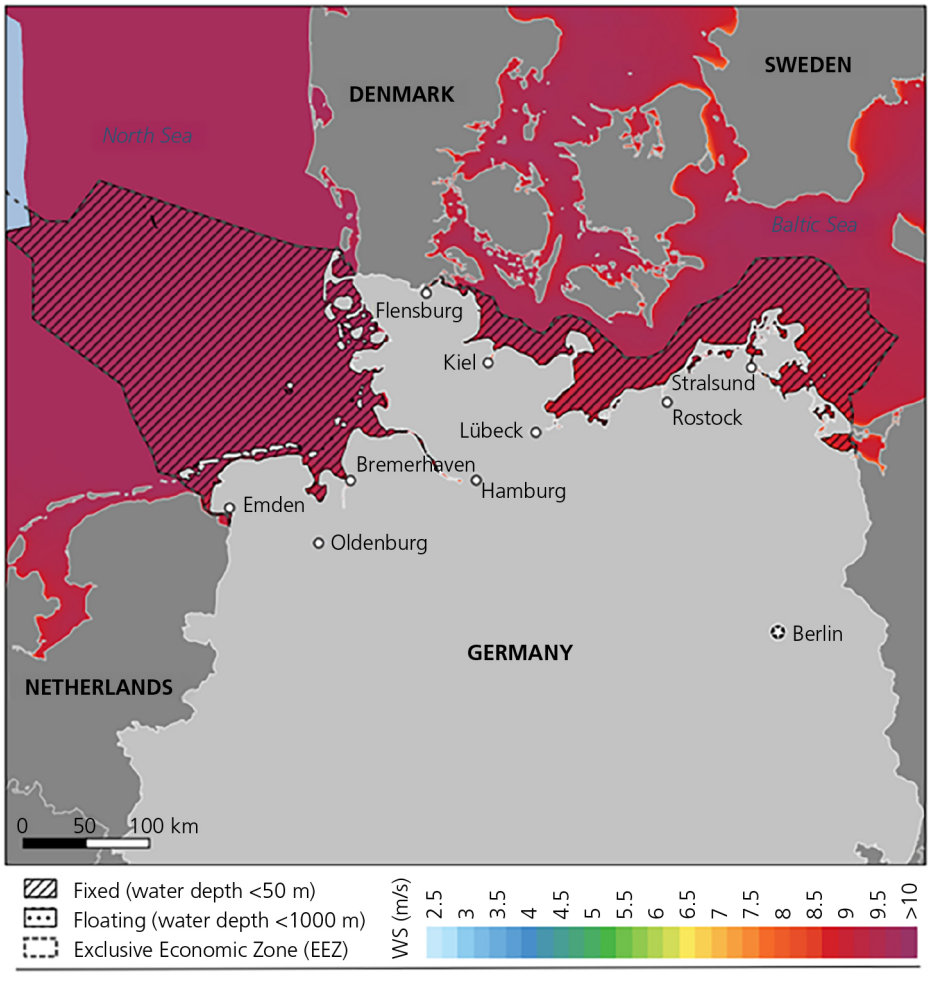


Figure 1.6 Overview of offshore wind farms in Germany (Source: GWEC, 2026)



Up to the end of 2024, China accounted for 60–70% of the global offshore wind market share of nacelles and key component production, with more than 15 wind turbine manufacturers active in China. In order to achieve this, China plans the construction of several 10 GW offshore wind farms off the eastern coast. Moreover, the Chinese wind industry released an initiative during the Global Offshore Wind Summit-China 2022 (GWEC, 2023) that set targets of 100 GW of offshore wind in China by 2025 (although by the end of 2025 only 48.4 GW was installed), 200 GW by 2030 and 1000 GW by 2050. These were very ambitious targets, but set the stage for China to dominate this industry.

Figure 1.7 shows the ambition of offshore wind development in China, which is targeting large installations in the provinces of Fujian, Shandong, Zhejiang and Jiangsu (S&P Global, 2024). In long-term development, China aims to target a potential 2982 GW of offshore wind power with 1400 GW from fixed-bottom structures and 1582 GW from floating structures.