Guide to an offshore wind farm

Updated and extended

Published on behalf of The Crown Estate
and the Offshore Renewable Energy Catapult

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The Crown Estate

The Crown Estate manages the seabed around England, Wales, and Northern Ireland. The Energy Act 2004 vests rights to The Crown Estate to license the generation of renewable energy on the continental shelf within the Renewable Energy Zone out to 200nm.

In 2001, The Crown Estate announced the first UK offshore wind leasing round and since has run two further leasing rounds in 2003 and 2008. To the end of 2018, thirty-nine offshore wind farms had been built by the sector, with ambition to grow the offshore wind farm operating capacity from 6.9GW at the end of 2017, to 30GW in the 2030s.

The UK represents the global leading market opportunity for offshore wind, both in terms of operating projects and the development pipeline. To supplement this and ensure increasing demand for offshore wind can be met, The Crown Estate is increasing the depth of an already active portfolio. Last year, The Crown Estate completed its initial assessment of offshore wind farm extension applications, confirming that proposed projects, representing up to 3.4GW of potential new capacity, satisfied application criteria. Subject to the outcome of a plan-level Habitats Regulation Assessment (HRA), successful developers could be granted lease agreements in summer 2019.

It is also currently working with the sector and stakeholders to explore the scale, location and form of proposed new leasing rights. Following this, it intends to confirm plans for a new offshore wind leasing round, to be known as Round 4. This could be launched in the early part of 2019, maintaining a pipeline of projects through to the late 2020s and beyond.

www.thecrownestate.co.uk

Offshore Renewable Energy Catapult

ORE Catapult was established in 2013 by the UK Government and is one of a network of Catapults set up by Innovate UK in high growth industries. It is the UK's leading technology innovation and research centre for offshore renewable energy.

Independent and trusted, with a unique combination of world-leading test and demonstration facilities and engineering and research expertise, ORE Catapult convenes the sector and delivers applied research, accelerating technology development, reducing risk and cost and enhancing UK-wide economic growth.

Active throughout the UK, ORE Catapult has operations in Glasgow, Blyth, Levenmouth, Aberdeen, Hull, the South West and Wales.

www.ore.catapult.org.uk

BVG Associates

BVG Associates provides strategy consulting in renewable energy. We help our clients to do new things, think in new ways and solve tough problems. Our practical thinking integrates the business, economics and technology of renewable energy generation systems. We combine deep wind industry knowledge with skills gained in the world of business consulting. Our purpose is to help our clients succeed in a sustainable global electricity generation mix founded on renewables.

www.bvgassociates.com

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Introduction

The aim of this guide is to help companies develop a greater understanding of the components and processes involved in the development of offshore wind farms that will be built up to 2025, and in doing so help them realise the opportunities that will arise.

There is no single way to build and operate an offshore wind farm and much depends on the specific conditions at the site. The pace of innovation in the wind industry has been rapid over the past decade; however, up to 2025, we can be reasonably confident of the technologies that will be deployed. An important uncertainty is turbine size because although manufacturers are working on designs that will ultimately stretch capacities to greater than 15MW, the timing of their introduction is a complex commercial decision.

Projects vary considerably in their size and their distance from shore. For the purposes of this document, we have assumed a 1GW project of 100 10MW turbines located 60km from shore in 30m water depth and commencing operation in 2022.

We have endeavoured to ensure that the information is as accurate and informative as possible. However, the industry is developing quickly and we at BVG Associates continue to learn. We would value feedback on the content of this document via info@bvgassociates.com.

Where relevant, for each element in the wind farm we cover:

- **Function.** What the component or service does.
- **What it costs.** We provide typical prices for a project with parameters described above. We recognise that there can be quite a range in prices of any element, due to specific timing or local issues, exchange rates, competition and contracting conditions. Prices for large components include delivery to nearest port to supplier and warranty costs. Developer costs (including internal project- and construction management, insurance, typically spent contingency and overheads) are included in the highest-level boxes but are not itemised. The sum of costs in lower-level boxes therefore is often lower than in the highest-level box. Costs, when combined with project life of 25-30 years, capacity factor of just over 50% and weighted average cost of capital equate to the bid prices seen in recent UK Government Contract for Difference auctions.
- **Who supplies them (examples only).** The list of suppliers is indicative rather than exhaustive. We have focused on suppliers with proven capability and generally have not listed suppliers with likely future capability or located distant from the UK (for example in US or China). Nevertheless any omission does not reflect any judgement of a company's capabilities.
- **Key facts.** Description including dimensions / materials where relevant or what is involved in delivering the service / how it relates to other elements and other relevant information.
- **What's in it.** We list the sub-components / services described elsewhere in the guide, or standard components / materials / processes used across a range of industries.

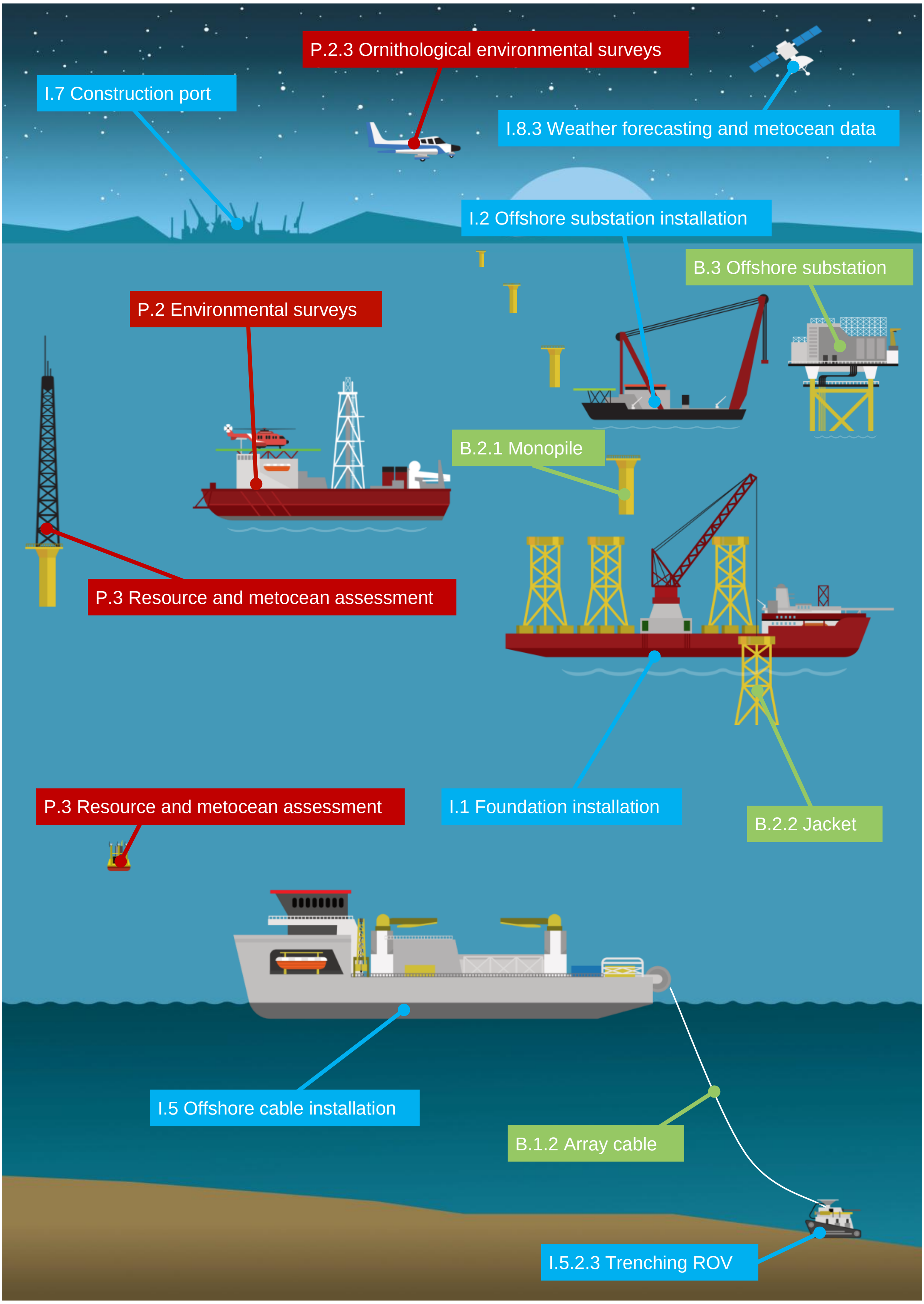
A glossary is provided, recognising that there are many industry-specific or technical terms and abbreviations used in the descriptions.

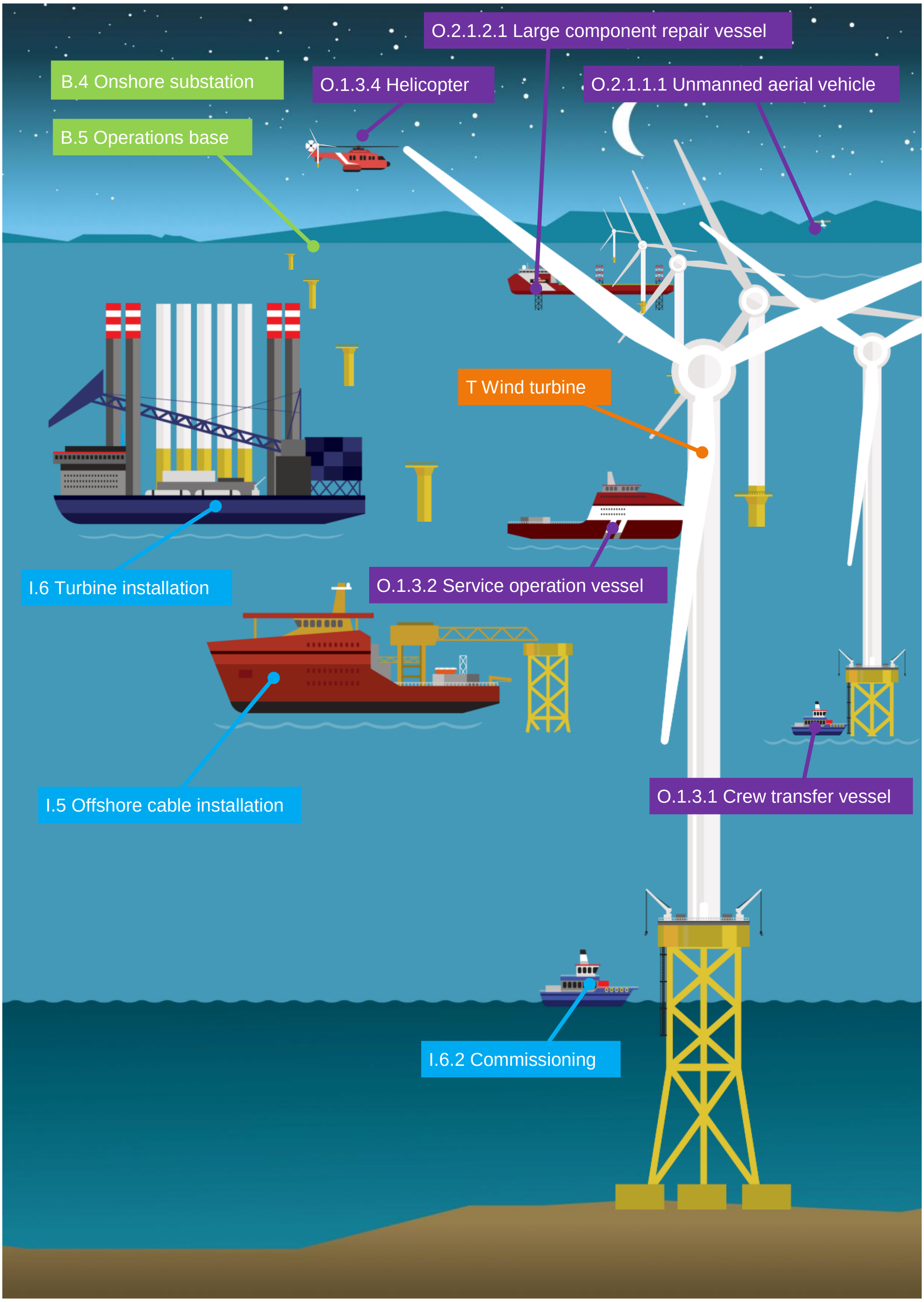
BVG Associates is grateful to the following companies for their help in compiling this document.

- DEME Group
- GE Renewable Energy
- Fugro
- Generating Better
- Innogy
- JDR Cable Systems
- MHI Vestas Offshore Wind
- Natural Power
- Oldbaum Services
- Ørsted
- Senvion
- Siemens Gamesa Renewable Energy
- Siemens Transmission and Distribution
- SNC-Lavalin - Atkins
- Vattenfall

Images

Processes in the development, installation and operation of an offshore wind farm

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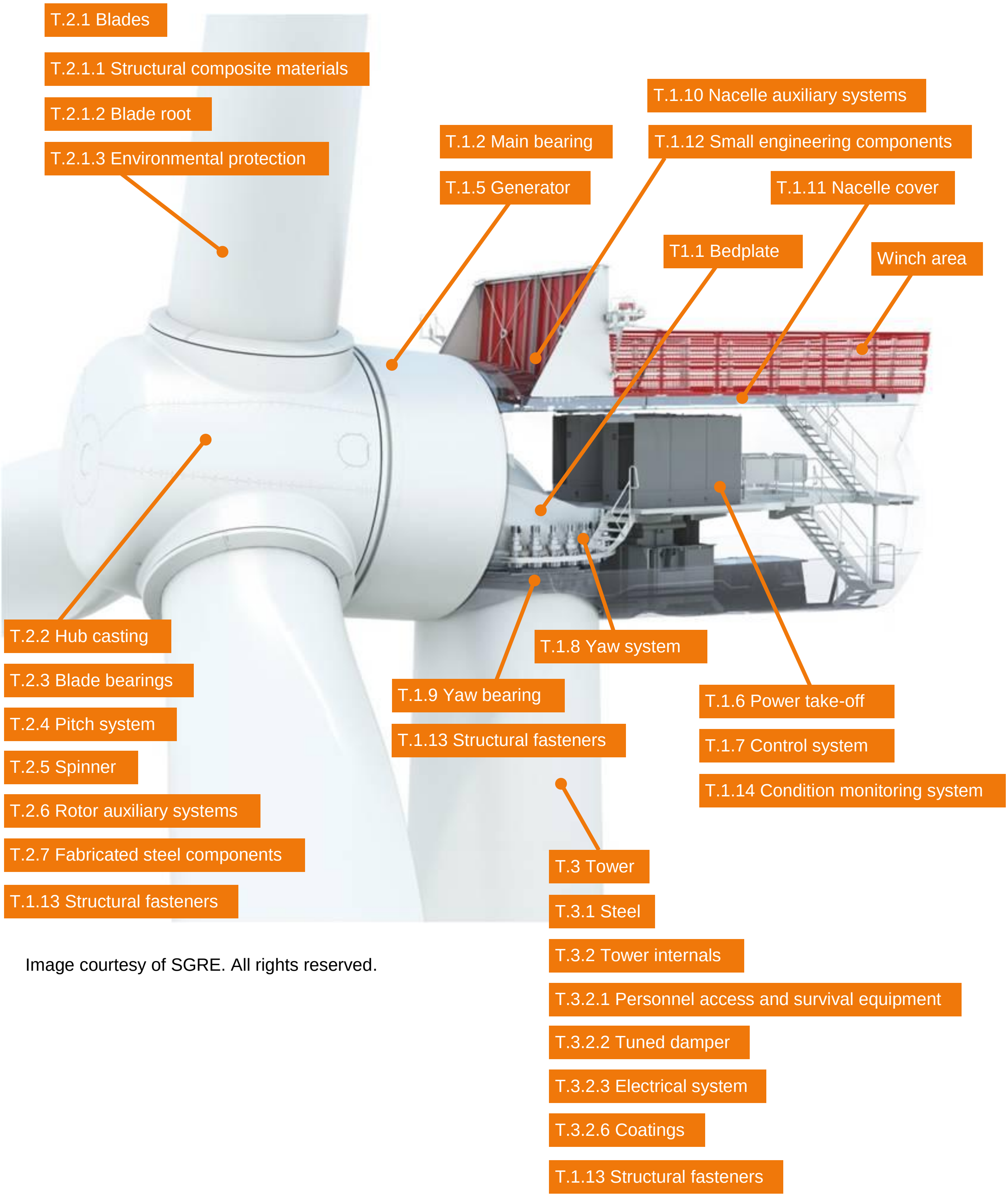
An offshore wind turbine



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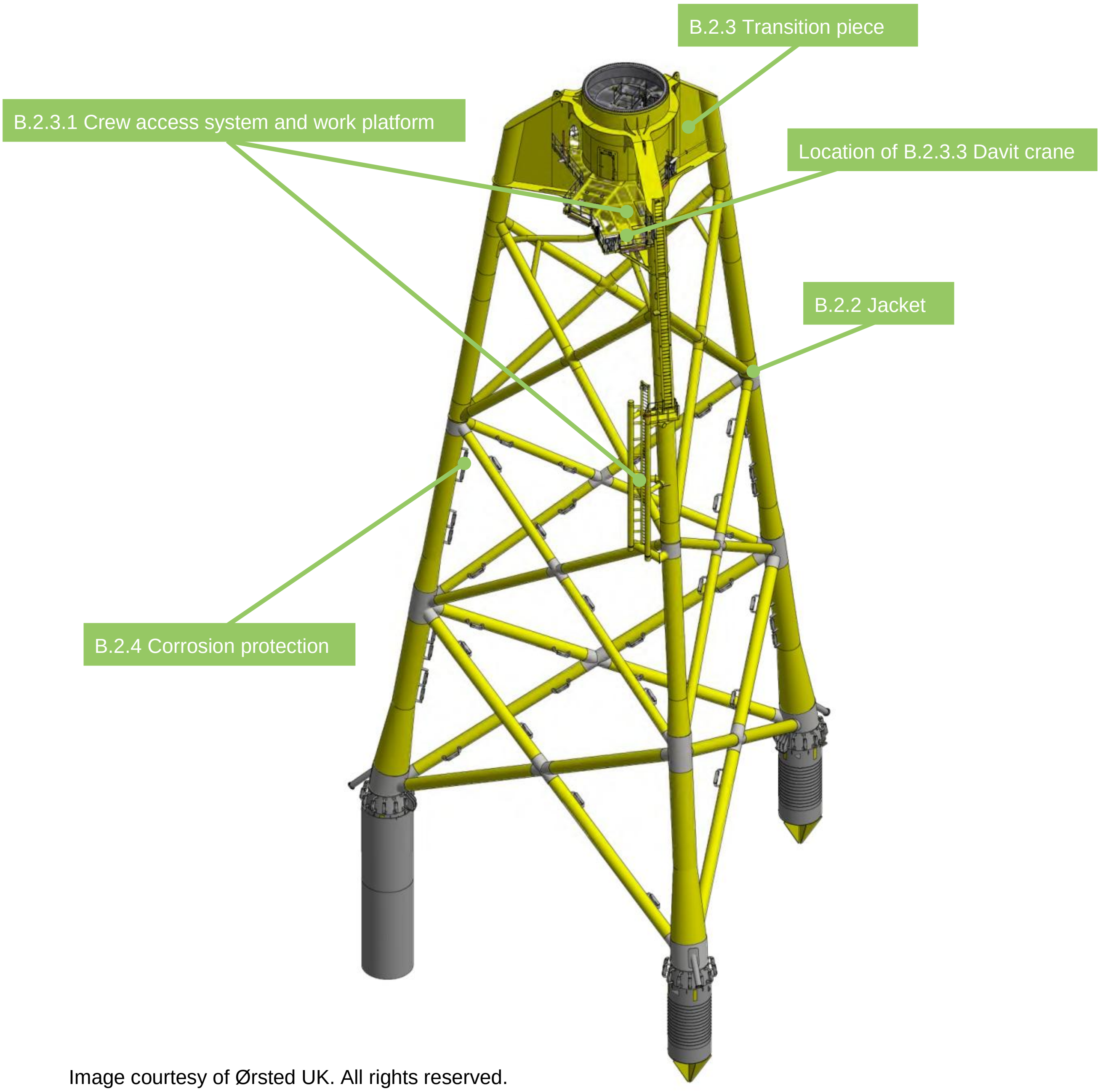
An offshore wind turbine jacket foundation



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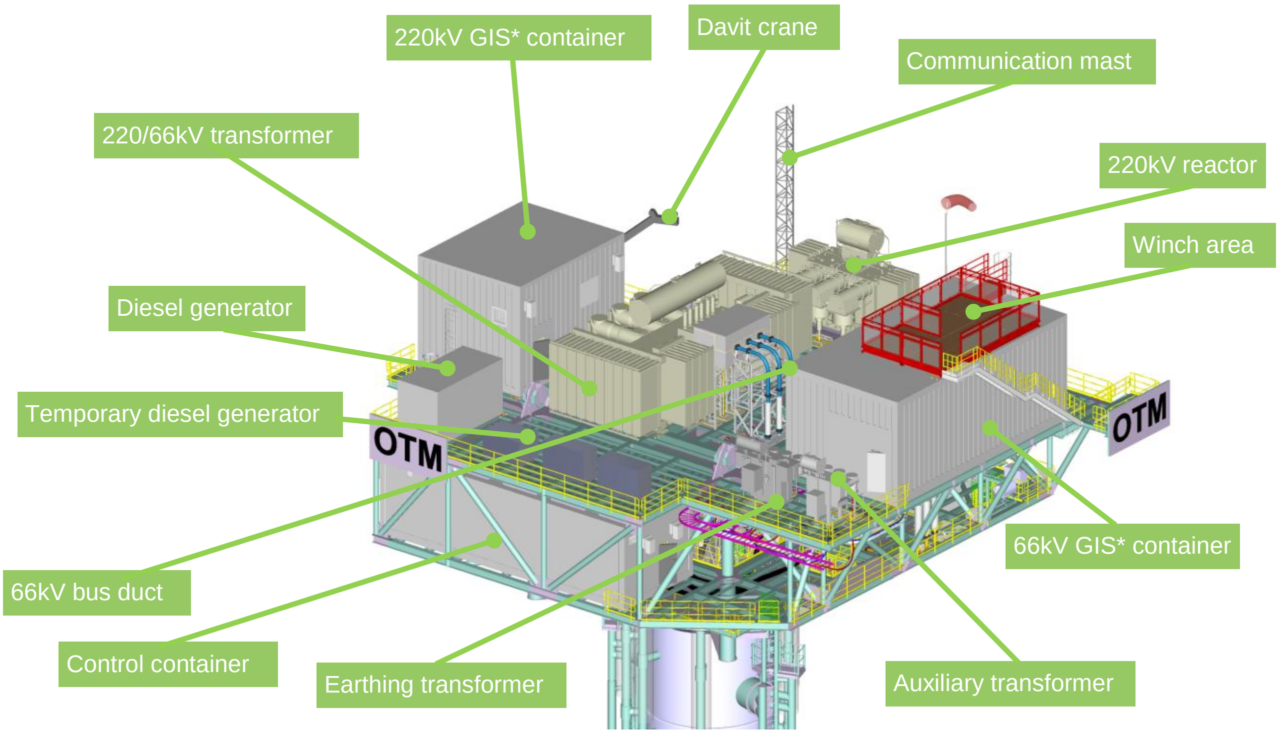
An offshore substation



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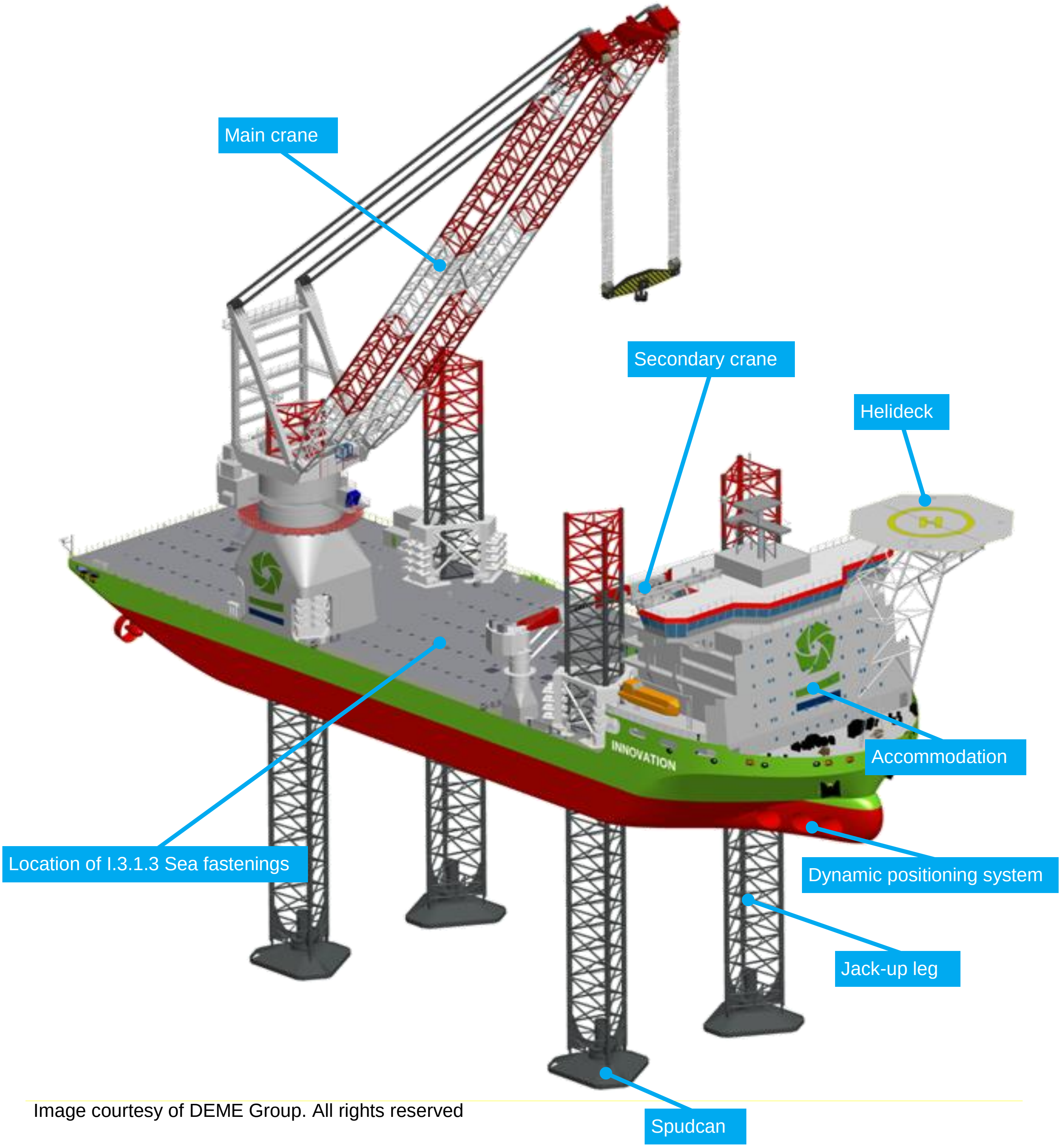
An offshore wind turbine installation vessel



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Glossary

	Definition
Annual energy production (AEP)	The amount of energy generated in a year. Gross AEP is the predicted annual energy production based on the turbine power curve, excluding losses. Net AEP is the metered annual energy production at the offshore substation, so includes wind farm downtime, wake, electrical and other losses.
Array cable	Electrical cable that connects the turbines to each other and the offshore substation.
Availability	The percentage of time the assets are available to produce / transfer power if the wind speed is within the operational range of the turbine.
Balance of plant (BoP)	Includes all the components of the wind farm except the turbines, including transmission assets built as a direct result of the wind farm.
Department for Business, Energy and Industrial Strategy (BEIS)	Government department that is responsible for business, industrial strategy, science and innovation and energy and climate change policy.
Consent	Planning permission.
Cable protection system (CPS)	Cable protection systems protect the subsea cable against various external aggressions. Systems include bend restrictors and bend stiffeners where the cable may be subject to increased loading.
Capacity factor	Ratio of annual energy production to maximum energy production if the turbine / wind farm ran at rated power all year.
Capital expenditure (CAPEX)	Spend on all activities up until works completion date.
Contract for difference (CfD)	Contract where government agrees to pay the wind farm owner the difference between an agreed strike price and the average market price of electricity (reference price). If the difference is negative the wind farm owner pays the difference to the government.
Crew transfer vessel (CTV)	A vessel used to transport wind farm technicians and other personnel to the offshore wind farm turbines either from port or from a fixed or floating base. Vessels operating today are typically specially designed catamarans that accommodate around 12 passengers.
Cross-linked polyethylene (XLPE)	A thermoset material widely used as electrical insulation in power cables.
Doubly-fed induction generator (DFIG)	An electrical arrangement where part of the wind turbine generator power passes via slip rings and convertors to enable a limited variable speed operating range whilst minimising the cost of power electronics.
Decommissioning expenditure (DECEX)	Spend on removal or making safe of offshore infrastructure at the end of its useful life, plus disposal of equipment.

	Definition
Environmental impact assessment (EIA)	Assessment of the potential impact of the proposed development on the physical, biological and human environment during construction, operation and decommissioning.
Engineer, procure, construct and install (EPCI)	A common form of contracting for offshore construction. The contractor takes responsibility for a wide scope and delivers via own and subcontract resources.
Export cable	Electrical cable that connects the onshore and offshore substations, or between an AC offshore substation and a DC converter substation.
Front end engineering and design (FEED)	Front-end engineering and design (FEED) studies address areas of wind farm system design and develop the concept of the wind farm in advance of procurement, contracting and construction.
Final investment decision (FID)	The point at which a developer has in place all the consents, agreements and major contracts required to commence project construction (or these are near execution form) and there is a firm commitment from equity holders and debt funders to provide funding to cover the majority of construction costs.
Floating foundation	A buoyant foundation structure anchored to the sea bed via mooring lines. The term includes several foundation types including spar buoys, tension leg platforms and semi-submersibles.
Gas insulated switchgear (GIS)	Gas-insulated switchgear is often chosen for its compactness and increased reliability over than air insulated switchgear, but has higher cost.
Gigawatt (GW) and Gigawatt hour (GWh)	Unit of power and unit of energy.
Gravity base foundation	A type of foundation designed to be transported offshore as a (normally concrete) hollow structure that is later fixed to the sea bed with the addition of ballast.
High voltage alternating current (HVAC)	An electric power transmission system that uses alternating current for the bulk transmission of electrical power. Alternating current is the form in which electric power is generated by wind turbines and delivered to an end user.
High voltage direct current (HVDC)	An electric power transmission system that uses direct current for the bulk transmission of electrical power. For long-distance transmission, HVDC systems may offer lifetime cost advantages over HVAC systems over long transmission distances. They are currently only used for point-to-point connections.
Highest astronomical tide (HAT)	The highest tidal height predicted to occur under average meteorological conditions and any combination of astronomical conditions.
Horizontal directional drilling (HDD)	Horizontal directional drilling is a low impact (trenchless) method of installing underground cables using a surface-launched drilling rig.
Jacket foundation	See Non-monopile steel foundation.
Levelised cost of energy (LCOE)	Levelised cost of energy is a commonly used measure of the cost of electricity production. It is defined as the revenue required (from whatever source) to earn a rate of return on investment equal to the WACC over the life of the wind farm. Tax and inflation are not modelled.

	Definition
Mean high water springs (MHWS)	The average tidal height throughout the year of two successive high waters during those periods of 24 hours when the range of the tide is at its greatest.
Mean sea level (MSL)	The average tidal height over a long period of time.
Megawatt (MW) and Megawatt hour (MWh)	Unit of power and unit of energy.
Monopile foundation	A type of foundation with a cylindrical tube (normally steel) that is normally driven tens of metres into the sea bed, although it can also be inserted into pre-drilled holes.
Non-monopile steel foundation	Collective term used to describe all steel foundations other than monopiles. Includes braced, welded, space-frame structures (collectively called 'jackets'), tripods and tripiles.
Offshore substation (OSS)	The structure used to transform and transfer the energy collected by the wind turbines to land in the most efficient manner. It may involve increasing the voltage, providing reactive compensation and converting the current from AC to DC. Some wind farms may have more than one offshore substation and equipment may be located on a number of smaller structures and potentially on one or more turbine transition pieces.
Offshore Transmission Owner (OFTO)	An OFTO, appointed in UK by Ofgem (Office of Gas and Electricity Markets), has ownership and responsibility for the transmission assets of an offshore wind farm.
Operational expenditure (OPEX)	Spend on all activities from works completion date until decommissioning.

Operations, maintenance and service (OMS)	OMS comprises wind farm OMS and onshore transmission OMS.
	Definitions of O, M and S are as follows:
	• Operation: day-to-day management including all the work not covered under maintenance and service. For wind farm OMS, this includes cost for port facilities, buildings, management personnel, environmental monitoring and community engagement.
	• Maintenance of assets: scheduled (that is, planned a long time in advance) maintenance, that may be based on suppliers' recommendations or owner's experience. It includes condition-based or time-based maintenance programmes and planned health and safety inspections.
	  • Typical maintenance includes inspection, checking of bolted joints and replacement of wear parts (with design life less than the design life of the project).
	• Service of assets: unscheduled interventions in response to events or failures. Interventions may be proactive (before failure occurs, for example responding to inspections or condition monitoring (CM) or reactive (after failure that affects generation has occurred). Also included are interventions due to major components not lasting the full turbine design life, even if intervention was planned prior to construction.
	  • Service operations include both on site repair and replacement of large and small components.

Remotely operated vehicle (ROV)	ROVs are remotely guided subsea mobile devices. They are usually deployed from a vessel. ROVs can be used for inspections or to carry out handling and repair.

	Definition
Service operation vessel (SOV)	A vessel that provides accommodation, workshops and equipment for the transfer of personnel to turbine during OMS. Vessels in service today are typically up to 85m long with accommodation for about 60 people.
Significant wave height (Hs)	The wave height (trough to crest) of the highest third of the waves over a given period.
Supervisory Control and Data Acquisition (SCADA) system	Data acquisition, transmission and storage system covering all wind farm assets. The SCADA system enable individual wind turbines, the wind farm substations and associated wind farm equipment to communicate operational status including faults. This allows operators to remotely diagnose faults and issue commands to stop, start and reset turbines and other equipment. The SCADA system keeps a full operating history of the wind farm.
Transition piece	A part of the foundation that provides the connection between the foundation and the wind turbine tower. For monopiles, it is usually installed after piling. For non-monopile steel or gravity base foundations, the transition is connected to the main structure before installation.
Turbine rated power	The nominal maximum power output from a wind turbine. Sometimes this is referred to as capacity. The wind turbine is limited to this power output, which typically applies when the wind speed at the hub height exceeds about 12m/s and continues until about 25-30m/s when the wind turbine stops generating to avoid excessive loading. In more benign operating conditions characterised by ambient temperature, main component temperatures, wind speed, turbulence level and grid voltage levels, the output may be allowed to exceed the rated power by about 5%.
Unexploded ordnance (UXO)	Explosive weapons that did not explode when they were released and remain a risk to seabed users.
Weighted average cost of capital (WACC)	The weighted average rate of return a wind farm owner expects to compensate itself and its internal and external investors over the life of a project.
Wind shear	The degree to which wind speed changes with height.
Works completion date (WCD)	Date at which construction works are deemed to be complete and the wind farm is handed to the operations team. In reality, this may take place over a period of time.

1. Development and project management

P Development and project management	
Function	Development and project management covers the activities up to the point of financial close or placing firm orders to proceed with wind farm construction. This includes activities required to secure planning consents such as the environmental impact assessment, and activities required to define the design and engineering aspects.
What it costs	About £120 million for a 1GW wind farm. This includes development and consenting services, environmental surveys, resource and metocean assessment, geological and geotechnical surveys, engineering and consultancy as well as development expenditure incurred by lost projects.
Who supplies them (examples only)	The development and consenting stage is managed by the wind farm developer. The main UK developers are: EDF Renewables, EDP Renewables, E.ON, Equinor, Innogy, Ørsted, Red Rock Power, ScottishPower Renewables, SSE and Vattenfall.
Key facts	Sea bed leasing for existing offshore wind farms has been managed by The Crown Estate through several leasing rounds that began in 2000. In 2017, a new body, Crown Estate Scotland, was formed to own and manage the sea bed in Scottish Territorial Waters and adjacent areas of the United Kingdom Exclusive Economic Zone. The Crown Estate retains responsibility for the sea bed in England, Northern Ireland and Wales. Before the consenting process can begin, the developer must secure a sea bed lease from The Crown Estate or Crown Estate Scotland. These are granted through periodic leasing rounds. Offshore wind projects of more than 100MW installed capacity in England and Wales are defined as nationally significant infrastructure projects (NSIP) and are examined by the Planning Inspectorate. The Secretary of State for the Department for Business, Energy and Industrial Strategy (BEIS) grants or refuses consent based on a recommendation made by the Planning Inspectorate. In England, a Development Consent Order is granted under the Planning Act 2008 (as amended) which incorporates a number of consents, including a marine licence and onshore consents. In Wales the marine licence is determined by Natural Resources Wales. In Scotland, Marine Scotland examines applications for the offshore works and Scottish Ministers grant or refuse consent under the Marine (Scotland) Act of 2010 (up to 12nm from shore) and the Marine and Coastal Access Act 2009 for projects 12-200 nm from shore. A streamlined process incorporates consent under Section 36 of the Electricity Act 1989 in parallel. In Northern Ireland, the Marine Strategy and Licensing team within the Department of Agriculture, Environment and Rural Affairs (DAERA) manages the consent application and decision making process for offshore wind projects. Onshore consent including where the transmission cable landfall is awarded by the relevant local planning authority (LPA), except where a project is handled under an NSIP in England and Wales, in which case the onshore consents are considered within the NSIP process. Developers typically build internal teams of about up to 50 staff during the development phase, which contract specialist packages of work to environmental and engineering consultancies and data acquisition and analysis companies.
What's in it	Development and consenting services [P.1] Environmental surveys [P.2] Resource and metocean assessment [P.3] Geological and hydrological surveys [P.4] Engineering and consultancy [P.5]

P.1 Development and consenting services

Function	Development and consenting covers the work needed to secure consent and manage the development process through to financial close.
What it costs	About £50 million for a 1GW wind farm. This includes developer staff costs, environmental impact assessments and other subcontractor work.
Who supplies them (examples only)	Development services are led by the developer's special purpose vehicle (SPV), which manages the development process and subcontracts work to a range of specialist consultancies. The SPV is a legal entity, which invests in and owns the wind farm project.
Key facts	Developers typically set up a SPV for a wind farm. Should the project advance to construction, the SPV will continue to operate for the duration of the wind farm's life. If the SPV is a joint venture between two or more developers, it is likely that the development team will be based in stand-alone offices to manage confidentiality. The SPV provides a structure to enable external investment, although this investment is most likely to take place at final investment decision (FID) or post construction. In the UK, the SPV manages the design of the wind farm and secures consent for the wind farm and transmission assets. An early formal step in the consenting process is the production of a scoping report, the purpose of which is to scope the level of impact on various receptors in order to properly define the required assessment process and methodologies, and to ensure the environmental impact assessment (EIA) focuses on those impacts that may lead to substantial effects, It also provides an early opinion from the planning authorities to help shape and focus the development activity. Developers will aim to secure planning consent while retaining as much design flexibility as they can. A particular risk for developers is specifying a specific foundation solution or a maximum turbine size, which may prove to be restrictive at the point of procurement and require the developer to request variations to the consent order. With too much design flexibility, the environmental impacts become less certain and more complex to analyse, which may be deemed undesirable by the consenting authorities. The range of options included in the proposed design is known as the design envelope, which includes a clear upper and lower bound on the scale of the project for example in terms of tip height. Developers need to undertake an EIA, which describes the potential impacts with regards to a wide range of environmental factors. The environmental statement is based on a number of detailed analyses. Most offshore wind developers have a predominantly in-house development management capability, with specialist work being outsourced. Specialist suppliers will often second employees into the developer's team for the duration of the development phase. Throughout the development process, developers are obliged to seek the views of a number of statutory consultees. These include a wide range of government appointed consultees and authorities, affected local authorities and those that have an interest in the land affected. Non-statutory consultees with specific interests in the development are also likely to be consulted (such as RSPB). Developers will also seek the views of local communities as part of this process and hold a series of public information and consultation events. Supporting the work will be a range of specialist consultants, covering engineering design, legal issues, land use, environmental and stakeholder relations.
What's in it	Environmental impact assessments [P.1.1]

P.1.1 Environmental impact assessments	
Function	An EIA assesses the potential impact of the proposed development on the physical, biological and human environment during the construction, operation and decommissioning of the wind farm.
What it costs	About £8 million for a 1GW wind farm.
Who supplies them (examples only)	EIA suppliers include AECOM, Arcus, GoBe, Intertek, Natural Power, Ramboll, Royal Haskoning, RPS and SLR.
Key facts	Based on European Legislation, certain projects, such as large offshore wind farms, are required to carry out an EIA. The most recent EIA regulations specify that the assessment must consider impacts on human health, climate change and biodiversity. To determine the impacts, a full suite of environmental surveys is undertaken. After assessing the potential impacts, mitigation measures are defined and applied in order to determine the residual effects associated with the development. A core part of the EIA is the Cumulative Impact Assessment (CIA) where the development's impacts combined with those impacts from other foreseeable projects are assessed. The EIA is used to inform the Environmental Statement (ES) (or EIA Report), which forms the core documentary evidence that is submitted to support a consent application. Consultation with statutory consultees, special interest groups and the local community is performed throughout the EIA process and allows the consenting authority as well as other stakeholders and the public to voice their opinion and concerns. The EIA process can take up to three years to complete, with the main driver being the length of time it takes to complete the required environmental survey work. Under the Habitats Directive and the Conservation of Habitats and Species Regulations 2010 (as amended), developers should consider the potential effects on protected habitats. If the development is likely to affect a designated European site, the developer must provide a report with the application showing the designated European site that may be affected together with sufficient information to enable the decision maker to make an appropriate assessment, if required. A Habitat Regulations Appraisal (HRA) is performed as an integral part of an EIA to ensure that a project conforms to The Conservation of Habitats and Species Regulations (2010).
What's in it	Scoping Assessment Site-specific impacts Mitigation Residual impacts Environmental Statement Habitat regulations assessment

P.2 Environmental surveys	
Function	To determine the environmental impacts, a full suite of environmental surveys of the wind farm location and its surroundings is undertaken. These surveys establish the baseline for the assessment and allow impact modelling to be undertaken.
What it costs	About £4 million for a 1GW wind farm.
Who supplies them (examples only)	Several companies offer a range of environmental surveys: EMU, ERM, Fugro, Gardline Marine Services, Natural Power, Ramboll, RPS, RSK Environment and SLR.
Key facts	Environmental surveys are one of the first tasks to be undertaken at a potential wind farm site and it can take two years or more before sufficient data is collected in order to apply for consent. The surveys include bird, fish, marine mammal and habitat surveys as well as marine navigation studies, socio-economic surveys, commercial fishing, archaeology, noise analysis, landscape and visual assessment and aviation impact assessments. Companies and developers recognise more detailed surveying can reduce costly consenting delays and post construction environmental monitoring requirements. Some surveys need to establish regional behaviours of wildlife, for example bird feeding and breeding patterns and in these cases data may need to be collected for several years. For highly mobile wildlife populations such as birds or sea mammals, it may be difficult to establish whether the predicted impacts during construction will be enduring. Surveys require vessels and aircraft are used to collect the data. Surveys look at the distribution, density, diversity and number of different species. A challenge in the assessments is trying to understand the cumulative impacts of several wind farms, particularly when these are the subject of separate EIA and consenting processes. Some environmental surveys are undertaken by companies that also offer geological or hydrological surveys, in which case the work can be done from the same vessels in parallel. Environmental surveys are typically undertaken by companies from the home market, partly because there is sufficient local resource and partly because some of the wildlife impacts are site specific and require detailed local knowledge and expertise.
What's in it	Benthic environmental surveys [P.2.1] Fish and shellfish surveys [P.2.2] Ornithological environmental surveys [P.2.3] Sea mammal environmental surveys [P.2.4] Onshore environmental surveys [P.2.5] Human impact studies [P.2.6]

P.2.1 Benthic environmental surveys	
Function	Benthic studies survey species that live on the sea bed and in sediment. The survey data and analysis is used to define areas of similar environmental conditions on the sea bed and to inform habitat and species impact studies.
What it costs	About £200,000 for a 1GW wind farm.

Who supplies them (examples only)	Suppliers include ABPmer, APEM, Fugro, Gardline Marine Services and Natural Power.
Key facts	Sampling sites are chosen so as to produce the most effective broad-scale categorisation of the overall region, as well as attempting to investigate smaller scale features such as reefs. Specific attention is given to the presence of particular ecosystems, such as certain reef species, where their presence is of crucial significance to the EIA. Methods include grab and sampling, epibenthic beam trawling and drop down video (DDV). Generally, surveys are designed to ground proof on geophysical data (bathymetry and sidescan), acquired for site characterisation of ground conditions, which has been interpreted to provide predictive habitat mapping.
What's in it	Species identification and counting Laboratory analyses Impact models and reports

P.2.2 Fish and shellfish surveys	
Function	Fish and shellfish surveys establish what species are present in the water column within the proposed wind farm site and surrounding areas. The resulting data is used to inform impact analysis and reporting.
What it costs	About £200,000 for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include ABPmer, APEM, Fugro, Gardline Marine Services, Natural Power and Precision Marine.
Key facts	Beam trawls or otter trawls (dragging a net along the sea bed) are used to sample the species present in the area. In addition other fishing methods such as lobster pots or gill nets can also be used on area where trawling cannot take place. Plankton nets can also be used for fish egg/larval studies (these are required). Surveys are generally undertaken in order to characterise the species present in the area of the wind farm, but also to address specific questions such as whether fish are spawning in the area, should this be an issue for EIA. Surveys can often be done using locally based fishing vessels, providing it can reach minimum safety standards. This approach offers the potential for good engagement with the local fishing community.
What's in it	Species identification and counting Laboratory analyses Impact models and reports

P.2.3 Ornithological environmental surveys	
Function	Ornithological surveys establish the presence and behaviour of birds within the wind farm boundary and surrounding areas. The data from these bird surveys is used to establish the risks to birds that a wind farm may pose.
What it costs	About £1 million for a 1GW wind farm.

Who supplies them (examples only)	Suppliers include ABPmer, APEM, ECON, ESS Ecology, Fugro, Gardline Marine Services, HiDef Aerial Surveying, Natural Power and RPS.
Key facts	Offshore ornithological surveying is normally one of the first tasks to be undertaken at a potential wind farm site because at least two years of data are needed to establish baseline conditions given the high level of spatial and temporal variation in bird abundance and distribution throughout the annual cycle. Furthermore, offshore ornithological constraints can have an important influence on wind farm design. Seabirds, inshore wintering waterfowl, and terrestrial birds on migration are all surveyed to determine how they make use of the proposed area and therefore the different effects that a wind farm may have, including potential collision with turbines, disturbance and displacement, and both direct and indirect habitat loss (for example through effects on prey species). A variety of methods are available for these purposes, each with their own advantages and disadvantages. Boat-based and digital aerial surveys are typically used to establish site-based population estimates and to gather behavioural data including species' flight heights (a key variable used to assess potential collision). Other methods such as GPS tracking, radar and coastal vantage point (VP) surveys can also be used to answer site-specific questions for example to establish connectivity between a specific breeding colony of seabirds and the proposed wind farm.
What's in it	Species identification and counting Impact models and reports

P.2.4 Marine mammal environmental surveys	
Function	Marine mammal surveys establish the diversity, abundance, distribution and behaviour of cetaceans (including porpoises, dolphins and whales) and seals within the wind farm boundary and surrounding areas. Surveys are typically undertaken monthly for at least two years to establish how these variables change across seasons and between years. The data from these surveys is used to establish the potential impacts to marine mammals that a wind farm may pose.
What it costs	About £1 million for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include ABPmer, APEM, Cork Ecology, ECON, ESS Ecology, Fugro, Gardline Marine Services, HiDef Aerial Surveying, Natural Power and RPS.
Key facts	Marine mammals are surveyed to determine how they make use of the proposed area and therefore the different effects that a wind farm may have, including potential disturbance and displacement, physical and auditory injury during pile driving, and both direct and indirect habitat loss (for example through effects on prey species). A variety of methods are available for these purposes, each with their own advantages and disadvantages. The method/s used will be dependent on the species and site in question. Traditional visual surveys using boat and aerial platforms are being supplemented or replaced by new, more accurate technologies such as static and towed acoustic monitoring, tagging of individuals with satellite transmitters and remotely controlled video monitoring.
What's in it	Offshore ornithological and mammal surveying vessels and craft [P.2.4.1] Species identification and counting Impact models and reports

P.2.4.1 Offshore ornithological and mammal surveying vessels and craft	
Function	Bird and marine mammal survey vessels and aircraft provide a platform for surveying to take place.
Who supplies them (examples only)	Vessels: Bay Marine, Enviro-serve, Fugro, Gardline Marine Services and Ocean Marine Services. Aircraft (including, but not limited to): APEM, HiDef Surveying.
Key facts	Traditional visual methods for surveying marine mammals are often undertaken concurrently with offshore ornithology surveys, offering a cost saving. Unfavourable weather and sea conditions have to be considered in the planning of surveys to ensure that the data collected is robust. Multiple crews are used, including experienced and qualified surveyors, who rotate in shifts in order to avoid fatigue and maintain visual acuity. Traditional visual boat-based surveys can be supplemented with a towed hydrophone in order to undertake passive acoustic monitoring for marine mammals. The Collaborative Offshore Wind Research Into the Environment (COWRIE) provides guidance relating to standardised survey methods and vessel specifications. Vessels should provide a stable viewing platform so vessel length and height are important considerations. Whilst traditional visual aerial surveys can be used to record marine mammals, these are not suitable to record marine birds as they fly at relatively low altitudes and can cause disturbance (and therefore the data collected are not representative of baseline conditions). Instead, digital aerial survey aircraft can be used which fly at much higher altitudes, recording both birds and marine mammals. These survey aircraft have a range of remote sensing instruments on board such as high-resolution digital cameras, lidar, video imaging and imaging spectrometers. Twin-engine planes, with long-range fuel tanks and autopilot capabilities allow for extensive surveying offshore without the need for on-board surveyors.
What's in it	Vessels and aircraft Provision of suitably experienced and qualified crew

P.2.5 Onshore environmental surveys	
Function	Onshore environmental surveys consider the potential ecological impact that cable-laying and onshore substations may have on the onshore environment.
What it costs	About £550,000 for a typical 1GW wind farm.
Who supplies them (examples only)	Suppliers include Andrew McCarthy Associates, APEM, BCM Environs, ESS Ecology, Natural Power, RSK Environment and Thomson Ecology.
Key facts	Wildlife surveys are often undertaken by ecological companies who have specialised capabilities for particular species. Skilled ecologists are often deployed. Studies tend to look at the distribution, density and number of different species. Wildlife ranging from badgers to small reptiles are considered, depending on the nature of the proposed site. Fragile coastal ecosystems are a prime area of focus.
What's in it	Surveying Data analysis Reporting

P.2.6 Human impact studies

Function	Human impact studies assess the impact that a proposed wind farm may have on the community living in and around the coastal area near the wind farm.
What it costs	About £350,000 for a 1GW offshore wind farm.
Who supplies them (examples only)	Suppliers include Arcus, Hayes Mackenzie, Hoare Lea, LUC, Royal Haskoning, RPS and SLR.
Key facts	Visual assessments comprise of photomontages from specific viewpoints of what the proposed wind farm will look like. Noise assessments assess that potential noise impacts and determine whether the impact of the proposed wind farm is within the guidance of relevant noise standards. Other areas studies include fisheries and archaeology. The socio-economic study assesses the impacts of a wind farm or coastal infrastructure, for example a port, such as changes in employment, transportation or recreation, or changes in the aesthetic value of a landscape. It estimates the impacts on the local society, not only of these socio-economic changes, but also of the composite of biological, geological, and physical effects caused by the proposed change on the local area. Socio-economic studies include a mix of objective and subjective data. Objective data can include statistics on age, income distribution, ethnicity, mortality, housing type and occupancy, and education. Subjective data can be derived from surveys and observations. These are used to provide systematic estimates of the ways in which various groups perceive their socio-economic environment and thus the impact of the proposed change. Studies consider the onshore cable route and substation.
What's in it	Surveys Consultation

P.3 Resource and metocean assessment	
Function	Resource and metocean assessment is carried out to provide atmospheric and oceanographic datasets to inform the engineering design of a wind farm, the potential future energy production, and to fully describe the likely operating conditions at the proposed wind farm location.
What it costs	Costs for resource and metocean assessment are about £4 million for a 1GW offshore wind farm, assuming no met mast platform is installed. Example costs for elements of this include: • Floating lidar: £375,000 • Lidar mounted on an existing platform: £200,000 • Met masts and platform: £5 million to 10 million • Metocean buoy: £175,000, and • Wave radar: £100,000. The above systems may be used in conjunction or isolation on any particular project, so costs will vary depending on approach adopted.
Who supplies them (examples only)	Resource campaign management and design: Deutsche Wind Technik, DNV-GL, Fugro, K2, Natural Power and Oldbaum Services. Masts: FLI Structures, Fugro, MT Højgaard, Sembmarine and SLP. Lidar units: Leosphere, ZX Lidars. Floating lidars: Axys, EOLOS, EOLFI, Fraunhofer and Fugro. Metocean campaigns and buoys: Axys, Fugro and Partrac. Systems integrators: PowerPoint Technical Services. Reference data provision: The Met Office, StormGeo and Vortex.
Key facts	Wind speed data is required to at least the proposed hub-height of the wind turbines, which will likely be 100m or more above sea level. Measurement systems are installed at the project location to collect wind data (speed, direction) and other relevant meteorological data (temperature, pressure, humidity). In addition, metocean buoys are installed in and around the wind farm site collect metocean data, including wave and tidal characteristics. Long-term reference datasets are required to describe the climatology of the proposed site over a longer period typically in excess of 15 years. These combined data sets are used in the wind farm and system design process, the turbine selection process and to predict the annual energy production (AEP) of the wind farm. Metocean data is also used to inform the vessel selection and operational strategies for the site, and is made available to vessel operators and marine planners during the construction and operational phases. A key interface exists in determining the long term site conditions between wind resource and metocean disciplines. The output from this interface is the extreme wind and wave climate for the proposed site. Hub-height wind masts are founded on the sea bed and require a subsea structure. Masts are usually equipped with cup-anemometers or sonic anemometers. Lidars are remote sensing anemometry devices which use lasers to measure wind speed and direction at up to 300m above sea level. Floating lidars are installed on tethered buoys. Fixed platform masts are becoming less common as floating lidar has now reached a higher level of industry acceptance, and the cost advantages of floating lidar are substantial. A number of offshore wind

	developers have successfully designed, financed and constructed projects based solely on lidar data. Wind lidar can also be positioned on existing infrastructure (such as nearby gas platforms and lighthouses) or in some cases onshore or on nearby islands. When using lidar as the primary measurement instrument, supplementary modelling is used to inform site conditions such as turbulence and horizontal wind gradients. Wind and metocean measurement systems require power supply to run sensors, data storage and telemetry. For low power systems this is often achieved with solar PV panels, small wind turbines and battery storage. Larger systems will use diesel generators or hydrogen fuel cells. Current state of the art campaigns integrate measurement and modelling techniques across both oceanographic and wind resource disciplines. The study can be further broadened to look at further issues such as turbulence, atmospheric stability conditions and the influence of neighbouring wind farms on the proposed site wind conditions.
What's in it	Structure [P.3.1] Sensors [P.3.2] Maintenance [P.3.3]

P.3.1 Structure	
Function	The structure provides the mounting for the meteorological and metocean, sensors and auxiliary systems plus safe access for personnel.
What it costs	About £3 million for a 1GW offshore wind farm, excluding installation.
Who supplies them (examples only)	Foundation and Platform: BiFab, Bladt, MT Højgaard, Sif-Smulders and SLP Energy. Masts: Carl C, Dulas and Francis & Lewis. Floating lidar systems: Axys, Babcock, EOLFI, EOLOS, Fraunhofer and Fugro. Metocean buoys: Axys, Fugro and Gardline Marine Services.
Key facts	Met mast foundations are generally monopiles with transition pieces similar to turbine foundations but of much lighter construction. Jacket structures may be used for deeper water. Platforms consist of a three-beam structure with walkways. Far offshore these structures can also require a helideck for access and a crew refuge. Mountings for wave and current sensors extend outward from the platform. Masts are typically of galvanised steel lattice construction with a personnel climbing facility (including fall-arrest system.) Personnel access to the platform is addressed in the same way as for turbines. Floating lidars are typically small buoys, anchored to the sea bed, with on-board power, data storage and processing and communications. Structures should be equipped with all relevant navigational aids including hazard lighting, fog horn, automatic identification system (AIS) and illuminated identification number panel for shipping.
What's in it	Foundation Platform Mast Buoys

P.3.2 Sensors	
Function	Sensors provide data on meteorological and oceanographic conditions at the site of interest. Data loggers provide data storage, processing and remote communications capability.
What it costs	About £650,000 for a 1GW offshore wind farm including maintenance. Examples of specific sensor costs: Vertical profiling wind lidars cost about £100,000. Class 1 sonic anemometers and cup-anemometer cost about £1,000 each. Other meteorological sensors cost under £1,000.
Who supplies them (examples only)	Meteorological sensors: FT Technologies, Gill Instruments, Kipp & Zonen, NRG Systems, Orga, Thies, Vaisala and Vector Instruments. Wind lidars: Leosphere, Wood and ZX Lidars. Metocean sensors: Datawell, SonTek. Data loggers: Campbell Scientific.
Key facts	Meteorological sensors include wind speed (with instruments at a number of heights or via lidar measuring over a range of heights with one sensor), wind direction, temperature, pressure, humidity, solar radiation and visibility. Measuring wind speeds at different heights provides critical information about the wind speed profile at the site, aiding decisions about the turbine and foundation design. Metocean sensors include wave, sea level and current sensors (for example acoustic Doppler current profiler), sometimes sea bed-positioned. These will record the full wave data spectrum including velocity, direction and period. Multiple sensors are used to provide spatial coverage and redundancy. Bird radar and hydrophones detecting cetacean activity can provide additional information to vessel and air-based environmental surveys.
What's in it	Meteorological sensors Anemometers Metocean sensors Data loggers

P.3.3 Maintenance	
Function	Offshore wind and metocean systems will require maintenance, including inspection, cleaning and refuelling (where diesel generators or hydrogen fuel cells or similar are used).
What it costs	About £300,000 during development for a 1GW offshore wind farm.
Who supplies them (examples only)	System maintenance is typically undertaken by the original system supplier, who will charter vessels for the purpose. Other providers of system maintenance include Deutsche Wind Technik, Dulas and Wood.
Key facts	Maintenance visits will typically be carried out 2-4 times per year. Systems are designed to operate autonomously, with onboard power, data and communications systems.
What's in it	Access vessel Maintenance personnel Equipment and consumables

P.4 Geological and hydrographical surveys	
Function	Sea bed surveys analyse the sub sea bed environment of the proposed wind farm site and export cable route to assess its geological condition and engineering characteristics. The data collected is utilised in a wide range of engineering and environmental studies through the design and development phase.
What it costs	About £8 million for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include Fugro, G-tec, Gardline Marine Services and Horizon.
Key facts	Sea bed surveys consist of two main parts; geophysical surveys of sea bed features and bathymetry; geotechnical surveys of the sea bed characteristics. Sea bed surveys are an important component of the development process and aid a number of processes, such as optimising the foundation design and wind farm layout, as well as minimising risk during installation activities. Environmental and sea bed (geotechnical and geophysical) surveys and data collection start up five years or more before the planned operation of the wind farm. Offshore wind development typically requires more data collection over larger areas but the technical approaches are similar to other sectors, such as oil and gas. The move to auction based systems such as Contract for Differences (CfD) in the UK has placed a greater emphasis on geological and hydrographical surveys as developers require greater design and cost certainty earlier in the development process.
What's in it	Geophysical surveys [P.4.1] Geotechnical surveys [P.4.2] Hydrographic surveys [P.4.3]

P.4.1 Geophysical surveys	
Function	Geophysical surveys establish sea floor bathymetry, sea bed features, water depth and soil stratigraphy, as well as identifying hazardous areas on the seafloor and manmade risks such as unexploded ordnance (UXO).
What it costs	About £1.5 million for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include Bibby HydroMap, Fugro, Gardline Marine Services, Horizon and MMT.
Key facts	Geophysical surveys are non-intrusive and include remote sensing techniques such as seismic methods, echo sounding and magnetometry. The techniques used consist of bathymetry (water depth) mapping with conventional single or multibeam echo soundings or swathe bathymetry, sea floor mapping with side scan sonar, magnetometer for UXO, acoustic seismic profiling methods and high resolution digital surveys. Surveys run along transects across zones within the proposed wind farm site and cable routes. Information from geophysical surveys is used to aid the design and implementation of the benthic and geotechnical surveys, so they are often undertaken near the beginning of the development process.

	Data from geophysical surveys are used to produce charts and maps for GIS systems, which are then used for site layout design. Geophysical surveys can be used to identify unexploded ordnance on or below the seafloor. Geophysical surveys may also consider marine archaeology that may be present in the wind farm site. This is typically dealt with by specialist archaeological survey companies, and is offered as a service in conjunction with the geophysical surveys.
What's in it	Geophysical survey vessels [P.4.1.1]

P.4.1.1 Geophysical survey vessels	
Function	Specialist vessels are used to carry out geophysical surveys of the sea bed.
Who supplies them (examples only)	Suppliers include Bibby HydroMap, Fugro, Gardline Marine Services, Horizon and MMT.
Key facts	Geophysical vessels are typically about 30-70m in length. The vessels must provide a stable platform even in unfavourable sea and weather conditions. Multiple crews, including highly specialised equipment operators, are utilised and the vessel has sleeping berths and living quarters to allow the vessel to have an operational endurance of up to a month. Crew work 12 hour shifts with rotations month by month enable a constant flow of data observation, processing and interpreting.
What's in it	Specialist crew Survey and analysis equipment

P.4.2 Geotechnical surveys	
Function	Geotechnical site investigations are conducted following the geophysical survey to use the information obtained to target soil/rock strata boundaries and engineering properties or specific sea floor features.
What it costs	About £6 million for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include Fugro, G-tec, Gardline Marine Services and Horizon.
Key facts	Geotechnical studies are predominantly intrusive and include such methods as boreholes with soil/rock sampling, and cone penetration testing (CPT). Geotechnical investigation is generally the most expensive part of wind farm survey work, making it a substantial at-risk investment for developers. Typically the geotechnical surveys are performed in phases to add value to the project risk mitigation process. Geotechnical surveys require specialised equipment and skilled personnel. The scope of the investigation depends on the type of foundation being considered and the variability in the sea bed characteristics. Boreholes and CPTs to depths in the order of 50-70m are carried out to investigate the physical characteristics of the sea bed. Surface push CPTs are also used as a rapid method to gather sea bed soil

	stratigraphy. Cable routes are typically investigated using vibrocores and CPTs to a depth of 5m. Offshore laboratories are used to obtain basic soil parameters and the samples taken are then returned to an offshore laboratory for detailed testing. Often soil dynamics tests are performed to monitor the soil behaviour under the constant dynamic loading on the foundation by the wind, waves and current. Resultant data from the geotechnical surveys are combined with results of the geophysical survey, to improve the geological model prior to the design and installation of foundations. Geotechnical data is also used at a later date in combination with heavy lift jack-up vessel information to determine the risks and feasibility of conducting heavy lift construction activities.
What's in it	Geotechnical survey vessels [P.4.2.1]

P.4.2.1 Geotechnical survey vessels	
Function	Specialist vessels carry out geotechnical surveys of the sea bed.
Who supplies them (examples only)	Suppliers include Fugro, G-tec, Gardline Marine Services and Horizon.
Key facts	The vessels are typically 60 -100m length and typically operate their drilling systems through a central moon pool. Some sea bed systems are deployed over the side or stern via A-frames or heavy lift cranes. The vessels are able to operate independently in remote locations. Jack-up vessels can also be used (albeit smaller than those used for foundation and turbine installation) where water depth and sea bed conditions are suitable. The vessels must be able to position themselves at specific locations for borehole sampling using dynamic positioning or anchors and must be able to withstand unfavourable sea and weather conditions. The vessels provide a stable platform for the acquisition of samples and in-situ testing. Due to the expense of hiring these vessels, multiple crews, including highly specialised equipment operators, are utilised and the vessels have sleeping berths and living quarters to allow the vessel to have an operational endurance of over a month. Offshore laboratories also allow for data acquisition and processing onboard. Crew rotations month by month enable a constant flow of data collection, processing and interpreting.
What's in it	Specialist crew Survey and analysis equipment

P.4.3 Hydrographic surveys	
Function	Hydrographic surveys examine the impact of the wind farm development on local sedimentation and coastal processes such as erosion. This is often part of the geophysical survey. These surveys are also part of the post construction monitoring during the operations phase.
What it costs	About £800,000 for a 1GW wind farm.
Who supplies them (examples only)	Specialist hydrographic survey companies such as Bibby HydroMap, Fugro, Gardline Marine Services and MMT perform the surveys and consultants such as ABPmer and HR Wallingford undertake the impact modelling.

Key facts	Understanding the sedimentation environment of the proposed site is of particular importance as it will inform the scour characteristics of the site and subsequent protection measures required.
What's in it	Vessels Crews Survey equipment

P.5 Engineering and consultancy	
Function	Front-end engineering and design (FEED) studies address areas of wind farm system design and develop the concept of the wind farm in advance of procurement, contracting and construction. Earlier on in the process, pre-FEED studies are used to develop an outline concept of the project for the purposes for defining the consent envelope and to inform environmental impact studies. The FEED study is continually refined through the development process and is ultimately used to frame and process substantial engineering and procurement decisions.
What it costs	About £4 million for a 1GW offshore wind farm.
Who supplies them (examples only)	Suppliers include Arup, Atkins, DNV-GL, Mott McDonald, ODE, Ramboll and Wood.
Key facts	Key parameters such as turbine size, foundation type, wind farm layout, substation design, electrical system and grid connection method are considered in order to minimise the project's levelised cost of energy (LCOE). Also included is planning of onshore and offshore operations, port and vessel strategies, determining contracting methodologies and the development of key risk management and health and safety procedures. The FEED study seeks to understand the total wind farm system in an integrated way and to consider the impact of engineering decisions on the LCOE, and to ensure that engineering decisions take full cognisance of environmental and consenting risks and impacts. The FEED study is a multi-disciplinary process that requires extensive communication and coordination, often across multiple teams and organisations. The output of FEED studies is used by construction management teams in order to procure and construct the wind farm. The move to auction based systems such as CfD in the UK has placed a greater emphasis on FEED studies as developers require greater cost certainty earlier in the development process.
What's in it	Layout design and optimisation Turbine selection Foundation type selection Electrical design strategy Interface management Health and safety planning Installation methods Operational strategy

2. Wind turbine

T Wind turbine	
Function	The turbine converts kinetic energy from the wind into three-phase AC electrical energy.
What it costs	The wind turbine cost for a 10MW wind turbine is about £10 million. This includes components as well as assembly and wind turbine supplier aspects of installation and commissioning. These installation and commissioning costs relate mainly to own logistics and staff costs at head office, the construction port, on the installation vessel and on the turbine relating to mechanical and electrical completion, testing and pre-handover checks and trouble shooting. These costs typically exceed £1 million per turbine.
Who supplies them (examples only)	Europe: GE Renewable Energy, MHI Vestas Offshore Wind (MVOW), Senvion and Siemens Gamesa Renewable Energy (SGRE). Asia: Doosan Babcock, Envision, Goldwind, Hitachi, Ming Yang and Sinovel.
Key facts	Most designs have upwind, pitch controlled, variable speed rotors with three blades. Compared to onshore wind turbines, turbines are much larger and there is an increased focus on reliability and maintainability and a decreased impact of noise, visual and transport constraints. Wind turbine suppliers are systems integrators. Blades are typically manufactured in-house, along with a few other components in some cases, depending on the industrial strength and breadth of the supplier. There are fewer offshore turbine suppliers than onshore. The high investment costs, large project sizes but relatively low overall sales volumes make it difficult for new suppliers to challenge the incumbents. A new generation of 12MW+ turbines is being developed. Typically, after a new turbine platform is developed, turbine variants are offered to the market with higher rating (or, more rarely, larger diameter) as their operation is better understood and the platform upgraded. This extends sales lifetime of a given platform while minimising development costs. Wind turbine suppliers prefer to operate just one or two nacelle assembly facilities and blade manufacturing facilities for the European offshore market, as volumes are not that high and fewer turbines are needed per GW as turbine sizes increase. The choice of site depends on the size of the local market, the locations of key suppliers, skills availability and support for local job creation. The design life of an offshore turbine is 25 years. The trend for longer design life on all turbines is due to the maturing of the industry – asset owners now expect to operate wind farms for such periods without the technology becoming obsolete or unsupported by suppliers. The design driver for many components is fatigue loading when generating. Extreme loads due to storms, abnormal events and faults during operation can also be critical. Typically, an offshore turbine will turn for over 90% of the time. Turbines are type certificated by third parties. This confirms that the wind turbine type is designed, documented and key features of performance verified in conformity with specific standards and other technical requirements. Health and safety requirements are increasingly focused on safety by design where the need for people to be put in hazardous environments is minimised or avoided at the design stage.
What's in it	Nacelle [T.1] Rotor [T.2] Tower [T.3]

T.1 Nacelle	
Function	The nacelle supports the rotor [T.2] and converts the rotational energy from the rotor into three-phase AC electrical energy.
What it costs	The nacelle cost for a 10MW wind turbine is £4 million.
Who supplies them (examples only)	Nacelles are assembled by the wind turbine supplier, using components generally sourced from a range of external suppliers.
Key facts	Typical dimensions for a 10MW turbine are 20-25m long x 9-12m wide x 7-9m high, with mass 400-500t including hub. Nacelle mass is kept low to help with overall system dynamics and minimise logistics costs. To keep nacelle mass down, turbine designs may include the transformer and much of the power electronics in the tower base. Mid-grade steels and cast spheroidal graphite (SG) iron are used rather than low-mass materials as they offer the lowest cost per unit fatigue strength. There has been a move away from high-speed gearboxes for offshore turbines. For example, GE Renewable Energy and SGRE have opted for direct drive turbines without a gearbox but instead with a larger and a more complex generator. MVOW has opted for turbines with a medium speed gearbox (600 rpm) and slightly more complex generator. Senvion is the only manufacturer offering a drive train with high-speed generator to the European market in a 5MW+ turbine. Before dispatch, the nacelle undergoes a functional test before being prepared for transport and storage. It is also typically tested with its power take-off hardware. New designs of offshore turbines place a high emphasis on maintainability. This is being achieved through modular designs for large components so more subcomponents can be replaced using the nacelle crane. This minimises the need for jack-up vessels, which are expensive and may have lengthy mobilisation periods. The nacelle incorporates high levels of remote monitoring, heath checking and control.
What's in it	Bedplate [T.1.1] Main bearing [T.1.2] Main shaft [T.1.3] Gearbox [T.1.4] Generator [T.1.5] Power take-off [T.1.6] Control system [T.1.7] Yaw system [T.1.8] Yaw bearing [T.1.9] Nacelle auxiliary systems [T.1.10] Nacelle cover [T.1.11] Small engineering components [T.1.12] Structural fasteners [T.1.13] Condition monitoring system [T.1.14]

T.1.1 Bedplate	
Function	The bedplate supports the drive train and the rest of the nacelle components and transfers loads from the rotor to the tower.
What it costs	The bedplate cost for a 10MW wind turbine is about £200,000.

Who supplies them (examples only)	Bedplates are normally cast SG iron, with a steel fabricated rear section. Casting: Eisengiesserei Torgelow, Felguera Melt, Fonderia Vigevanese, Gusstec, Metso, MeuselWitz, Rolls Royce, Sakana, Siempelkamp and Vestas. Only some of these can manufacture the largest bedplates for offshore turbines today. Fabrications: A reasonable range of steel fabricators exist capable of bedplate manufacture.
Key facts	Frequently, bedplates are manufactured in two parts. The heavier section supports the gearbox [T.1.4] and the yaw system [T.1.8], transfers loads from the rotor [T.2] to the tower [T.3] and is frequently cast. A lighter section supports the generator [T.1.5] and other components at the rear of the nacelle and is normally fabricated. For a direct-drive turbine, the generator takes the place of the gearbox. Bedplates are designed by the wind turbine supplier and generally manufactured by sub-suppliers. Design considerations include fatigue and extreme loads, stiffness and assembly, and maintainability features such as access ways to critical components. Once manufactured, the items are machined, shot blasted, metal sprayed and epoxy painted before delivery to the wind turbine supplier. Material is typically EN-GJS-400-18U-LT grade SG iron or a standard 355-grade steel.
What's in it	Large SG iron or fabricated steel structure Machining and painting

T.1.2 Main bearing	
Function	The main bearing supports the rotor and transfers some of the rotor loading to the nacelle bedplate [T.1.1].
What it costs	The main bearing cost for a 10MW wind turbine is about £200,000.
Who supplies them (examples only)	Liebherr, Schaeffler, SKF and thyssenkrupp.
Key facts	A number of different bearing arrangements exist for offshore wind turbines including a single bearing supporting the generator and rotor. Another approach is to support the main shaft [T.1.3] with a bearing at each end (as for Senvion 6MW turbines). Such arrangements may use a combination of spherical roller bearings (to provide axial location) and a self-aligning roller bearing. Tapered roller bearings, such as the two-row double-outer race (TDO) and tapered double inner (TDI) variants, are also used to manage the combination of radial, thrust and overturning loads. Bearings are often heated prior to mounting on the main shaft in order to provide a robust, stress-concentration free connection. Cast-iron bearing housings provide stiff supports for these bearings and connection to the nacelle bedplate.
What's in it	Forged rolled ring, machined and hardened Rolling elements (spherical, crowned cylindrical / tapered) Rolling element support (cage) Lubricants and seals SG iron bearing housing

T.1.3 Main shaft	
Function	The main shaft transfers torque from the rotor to the gearbox or, for some direct drive designs, the generator. It is supported at the rotor end by the main shaft bearing and at the other end either by the gearbox / generator or separately mounted bearing.
What it costs	The main shaft cost for a 10MW wind turbine is about £200,000.
Who supplies them (examples only)	Brück, Euskal, Skoda and thyssenkrupp.
Key facts	Conventionally, the rotor is flange-connected to the main shaft using a single or double row of structural fasteners [T.1.13]. The main shaft normally also has a ring of holes for use in positively locking the rotor in fixed position for maintenance activities. It normally has a central bore through which control signal, control power supply and electrical or hydraulic power cables are passed to the hub for operation of the blade pitch system. For a large 10MW turbine, the main shaft may have a mass of over 50t and be forged and machined from high-grade steel such as 42CrMo4 or cast hollow from EN-GJS-400-18U-LT. Different turbine concepts require quite different main shaft designs. Even for such a large item, fatigue loading is important as the rotating shaft is supporting the mass of the rotor as well as resisting the aerodynamic torque and thrust loads. It is critical to minimise stress concentrations.
What's in it	Forged / cast shaft Machining, NDT and painting

T.1.4 Gearbox	
Function	Where used, a gearbox converts rotor torque at a speed of 5-15 rpm to a speed of up to about 600rpm for a medium speed gearbox and 1500rpm for a high-speed gearbox for conversion to electrical energy by the generator.
What it costs	The medium speed gearbox cost for a 10MW wind turbine is about £700,000.
Who supplies them (examples only)	Bosch Rexroth, Eickhoff, Hansen, Moventas, Renk and Winergy.
Key facts	The gearbox is a critical item in the wind turbine drive train, with much attention given to the long-term operation given a history of variable quality and reliability. Typically, designs incorporate a planetary first stage followed by a higher-speed parallel (helical) stage. Normally, a brake disk is mounted at the rear (high-speed) end. Design drivers include peak torques coming from a range of load cases; also loads in storms and during braking or other abnormal events, and avoiding high speeds in the gearbox itself. Careful consideration is given to the variation in bearing and gear contact points due to a wide variation in operating power levels during turbine life, including periods of standstill and operation under minimal loading, introducing the possibility of skidding within bearings.

	Design methodologies couple empirical rules of thumb, detailed dynamic analysis and workshop testing. Automatic heating is frequently applied before restart in cold conditions and cooling is designed typically to keep operating temperatures below 70˚C. Cooling systems may be combined with that of the generator. Lubricants specific to wind turbine gearboxes have been developed, with reduced end of life environmental impact. Typically, the gearbox has a bore (say 100mm) in the central shaft (along the axis of the main shaft) to facilitate provision of control signal, control power supply and electrical or hydraulic power cables to the hub for operation of the blade pitch system.
What's in it	SG iron castings (including higher grade (say EN-CJS-700-2U) for items such as planned carrier) and steel forgings Cylindrical, taper and spherical roller bearings; plain bearings Gears Lubricants Sensors

T.1.5 Generator	
Function	The generator converts mechanical energy to electrical energy.
What it costs	The medium speed generator cost for a 10MW wind turbine is about £1 million. The direct drive generator cost for a 10MW wind turbine is over £2 million.
Who supplies them (examples only)	Suppliers include ABB, Elin, GE, Ingeteam, Leroy Somer, VEM and Winergy.
Key facts	Most generators use permanent magnets that need no excitation power. This keeps weight low and dimensions small, lowering transport and installation costs but does rely on the supply of alloys of rare-earth elements. All operate at variable speed, with grid connection via an AC-DC-AC converter. This enables the smoothing of drive train loading and the optimisation of aerodynamic performance without the need for a variable ratio gearbox. Efficiency is critical, especially at part load, as a wind turbine spends many hours generating 20% to 80% of rated power in low-to-medium wind speeds. Water-cooling is common in order to maximise efficiency and compactness whilst limiting noise levels. Generator bearings are designed to avoid passage of electrical current and with special emphasis on lubrication. Typically, these are specialist deep-groove bearings, sometimes with ceramic rolling elements. Related, but not part of the scope of supply of the generator, is the coupling that connects the generator to the gearbox. As both components are flexibly mounted and the wind turbine structure is relatively flexible compared to the loading applied, such couplings generally are able to cope with substantial misalignment.
What's in it	Castings Windings Bearings Sensors Slip rings for doubly-fed induction generators High-speed shaft coupling

T.1.6 Power take-off	
Function	The power take-off receives electrical energy from the generator and adjusts voltage and frequency for onward transfer to the wind farm distribution system.
What it costs	The power take-off cost for a 10MW wind turbine is about £700,000.
Who supplies them (examples only)	Power converters: ABB, AMSC, GE Power Conversion, IDS, Ingeteam, SEG, The Switch and Winergy. Transformers: ABB, GE, CG (Pauwels), Schneider, SGB and Siemens. Switchgear: Areva T&D, CG (Pauwels), S&C and Siemens. Cabling: Draka, Nexans and Prysmian.
Key facts	Most wind turbines have variable speed generators connected to the grid via AC-DC-AC power converters. There is a range of different generator/converter architectures used. With high power density, today's insulated-gate bipolar transistor (IGBT)-based power converters frequently are water-cooled. Critical to consider in the design of power converters are requirements imposed by grid operators for wind turbines to support and stabilise the grid during grid faults and to provide or consume reactive power on demand. Some convertors may be split between nacelle and lower tower section to reduce tower head mass. Where the turbine voltage rating does not match that of the wind farm array, transformers are often placed in the nacelle [T.1], or sometimes at the base of the tower [T.3]. Typically, they transform from low-kV (0.69kV to 3.3 kV) to 33kV or 66kV for distribution around the wind farm array and are of dry (cast resin) design, meeting detailed corrosion, environmental and combustion requirements. Typically, they are forced-air cooled. Switchgear is designed specifically for wind turbine applications, for example gas-insulated for compactness and safety at up to wind farm distribution voltage. Down-tower cabling is routed to enable the cables to twist, allowing the nacelle two complete revolutions of movement by the yaw system [T.1.8] before an untwisting operation is required.
What's in it	Power converter Transformer Switchgear Cables

T.1.7 Control system	
Function	The control system provides supervisory control (including health monitoring) and active power and load control in order to optimise wind turbine life and revenue generation, while meeting externally imposed requirements.
What it costs	The control system cost for a 10MW wind turbine is about £250,000.
Who supplies them (examples only)	Bachmann, DEIF, DNV GL, KK-Electronic and Mita Teknik.
Key facts	The control system carries out regular health checking using 100s of sensors monitoring key components and sub systems. In response to unexpected data, it takes decisions to curtail operation and provides regular reporting to the Supervisory Control and Data Acquisition (SCADA) system.

	The control system also takes control input from the SCADA system, for example to derate wind turbines in response to utility customer requests. Increasing turbines have a power boost capability where they will generate at higher powers in benign conditions when parameters such as temperature and wind shear are in acceptable ranges. Key control parameters for active power and load control are rotor speed, output power and the pitch angle of each blade. Control intelligence may be distributed around the turbine, including in the hub. Control panels contain in-in-house designed and standard panel hardware to interface with sensors and auxiliary systems and combined may weigh up to 500kg. In parallel to the control system, a safety system protects the turbine from control system or operator error. Key sensors for this overriding safety system include speed and vibration sensors. An emergency system with physical press-button and/or chord inputs is provided to bring the rotor to a halt in the event of risk to maintenance personnel. Lidar is starting to be used to measure the incoming wind flow and/or the alignment of the nacelle relative to the wake and provide this data to the control system. Each wind turbine can operate independently from external intervention, starting and stopping in response to changing wind conditions. Control at a wind farm level is used to optimise energy production and minimise loading, for example by avoiding turbines sitting in the wake of turbines immediately upwind.
What's in it	Control panels Control system hardware and software Sensors: Accelerometers, load cells, power meters, strain gauges, thermocouples, and tachometers Safety and emergency systems

T.1.8 Yaw system	
Function	The yaw system orients the nacelle to the wind direction during operation.
What it costs	The yaw system cost for a 10MW wind turbine is about £170,000.
Who supplies them (examples only)	ABB, Bonfiglioli, Bosch Rexroth and VEM.
Key facts	The yaw system typically consists of about 10 geared electric motors mounted on the nacelle bedplate [T.1.1], with gear mounted on their shaft acting on the toothed inner ring of the yaw bearing [T.1.9]. Each drive has mass up to 1 tonne and typically has ratio 200-300:1. To avoid constant varying loading on the drives, a series of about 10 calliper brakes are hydraulically applied to hold the yaw bearing in position, except when movement is required. Even during movement (which may be the order of a few degrees every few minutes in order to align the nacelle to the wind direction), the yaw brakes act to damp movement. Sensors measure the position of the nacelle and limit switches prevent over-twisting of the cables down the tower. Some wind turbines use hydraulically operated yaw motors, providing compliance to relieve tower top loading.
What's in it	Yaw motors and associated gearboxes Yaw brakes Sensors

T.1.9 Yaw bearing	
Function	The yaw bearing connects the nacelle and tower, enabling the yaw system to orient the nacelle to any wind direction during operation.
What it costs	The yaw bearing cost for a 10MW wind turbine is about £70,000.
Who supplies them (examples only)	IMO, Liebherr and thyssenkrupp.
Key facts	Bearings are typically single-row 4-point contact ball bearings made from forged rings of up to 6m diameter for a 10MW turbine, typically of a 42CrMo4 steel, quenched and tempered. Balls are typically material 100Cr6. Total bearing mass may be up to 10 tonnes. Raceways are hard-turned or ground after induction hardening. Bearings see a complex load pattern and operate with long periods of no or only occasional movement over a small proportion of a revolution. Critical to long-term performance is the provision of flat mounting surfaces (so the tower flange will be machined after welding). Bearings incorporate gear teeth to mesh with the yaw drives.
What's in it	Forged rings, machined, hardened and surface finished Balls Cages / spacers Seals Grease Metal sprayed and/or painted finish

T.1.10 Nacelle auxiliary systems	
Function	A number of auxiliary systems facilitate ongoing unattended operation of the wind turbine for the vast majority of the time, and support planned maintenance, which typically should be only on an annual basis.
What it costs	The nacelle auxiliary systems cost for a 10MW wind turbine is about £70,000.
Who supplies them (examples only)	Brake: Siegerland, Stromag and Svendborg. Cooling: Hydac, Windsyn. Air conditioning: Cotes. Anemometry: FT Technologies, Gill Instruments, Kipp & Zonen, NRG Systems, Orga, Thies, Vaisala and Vector Instruments. Lidar: Leosphere, Wood and ZX Lidars. Fire protection: Danfoss, Firetrace and Minimax. Uninterruptible power supply (UPS): AKI Power Systems. Internal service crane: Effer, Hiab, Liftra and Palfinger Marine.
Key facts	Typically, a mechanical brake is mounted at the rear of the gearbox [T.1.4]. Primary braking of the wind turbine in the event of an emergency is achieved by pitching the blades. In some cases also electrodynamic braking is used but a mechanical brake is also present, frequently with a hydraulically applied calliper acting on a disk of about 1m diameter. A rotor lock enables locking of the rotor in a fixed position for maintenance activities. Typically, for large turbines it consists of a peg-and-hole arrangement with manual or automatic hydraulic actuation engaging one or more pegs with holes on the front flange of the main shaft [T.1.3].

	A large offshore turbine is about 92-94% efficient in converting kinetic energy in the rotor to electrical energy, requiring at times up to 800kW of heat to be dissipated from gearbox, generator and electrical system. To protect all nacelle components from corrosion, the nacelle is well sealed and the whole area is served by a local air conditioning system. Mounted on the roof of the nacelle is an anemometry mast with sensors measuring wind speed and direction. Frequently, these functions are combined into sonic devices, rather than using traditional cup anemometers and wind vanes. Frequently, fire protection systems are provided in order to sense and suppress fire in different areas of the turbine. Within electrical panels, nitrogen is used. In open spaces such as the nacelle, fine water spray systems are employed. The fire protection systems have separate control and condition monitoring from the turbine controllers. To facilitate orderly shutdown of the turbine under grid loss conditions, UPS systems are used to power the control, safety and emergency systems and provide emergency lighting in the tower to facilitate safe exit of personnel. In some cases, UPS power is required in order to ensure requirements for rotor warning lights on the tips of blades continue to operate for an agreed period. The internal service crane for a large turbine is designed to lift key turbine components during maintenance activities, typically up to 10 tonnes. The crane is controlled wirelessly and operates through cut-outs in the nacelle cover to lower components to the access platform.
What's in it	Brake Rotor lock Cooling Anemometry Fire protection UPS Internal service crane

T.1.11 Nacelle cover	
Function	The nacelle cover provides weatherproof protection to the nacelle components plus support and access to external components such as coolers, wind measurement equipment and lighting protection devices.
What it costs	The nacelle cover cost for a 10MW wind turbine is about £100,000.
Who supplies them (examples only)	Bach Composites Industry, Eikboom.
Key facts	As well as providing environmental protection, frequently it supports lighting and other auxiliary supplies and acts as a faraday cage to protect nacelle components from lightning damage. It is fitted during assembly of the nacelle, either before or after final test, and plays a valuable role in protecting nacelle components during transport to the wind farm site, as well as during operation. It is designed to withstand wind loading and provide access to lifting points on the nacelle bedplate [T.1.1] for transport and installation. Careful design also facilitates exchange of nacelle components through hatches or hinged openings in the roof, side or floor. The nacelle cover is typically manufactured in a number of sections from glass fibre or steel and may have mass up to 20 tonnes.

What's in it	Fibreglass or steel construction Built-in or post-assembled auxiliary systems (for example lighting) Maintenance support features

T.1.12 Small engineering components	
Function	A range of frequently standard engineering components makes up the rest of the nacelle assembly.
What it costs	The small engineering component cost for a 10MW wind turbine is about £250,000.
Who supplies them (examples only)	Many items are off-the-shelf or can be manufactured by a range of metalworking companies.
Key facts	Guards and flooring and maintenance aids are normally fabricated to drawing from steel or aluminium. A range of cable / hose handing systems, air ducts and similar are needed, depending on nacelle layout. Anti-vibration mounts support the generator [T.1.5] and sometimes other critical components. Standard industrial lighting systems are used to facilitate maintenance work. Fasteners typically vary from M6 upwards and may be grade A4 stainless or galvanised.
What's in it	Guards, flooring, drip trays, cable and hose handing systems and other fixed maintenance aids Anti-vibration mounts Lightning conductors Small fasteners and other accessories and consumables used during nacelle assembly

T.1.13 Structural fasteners	
Function	Fasteners (either bolts or studs) are used in a range of critical bolted joints, for example connecting rotor to main shaft, main bearing housings to nacelle bedplate and yaw bearing to the underside of nacelle bedplate.
What it costs	The structural fasteners cost for a 10MW wind turbine is about £70,000.
Who supplies them (examples only)	August Friedberg, Cooper & Turner, Fuchs & Sanders, Gexpro Services and Wind-Fix.
Key facts	Fasteners for critical structural joints within large turbines are typically of size M30 or M36 and grade 10.9. Often, the fasteners are specified to have threads rolled after heat treatment to improve fatigue properties. Coatings provide corrosion protection. All critical structural fasteners are preloaded either using hydraulic torque tooling or (in the case of studs) hydraulic tensioning. Increasingly, preload indicators or other visual checks on tightness are used.
What's in it	Bolts Studs Nuts

T.1.14 Condition monitoring system	
Function	Condition monitoring systems provide additional health checking and failure prediction capability.
Who supplies them (examples only)	Brüel & Kjær Vibro, Gram & Juhl, SecondWind and SKF.
Key facts	Condition monitoring systems frequently make decisions about individual components (such as the gearbox) via sensors measuring parameters for that component. They also use a range of sensor and controller outputs and make holistic decisions about all drive train components. Condition monitoring systems on the rotor [T.2] are able to assess control behaviour as well as blade health. Turbine and condition monitoring systems send data to cloud-based databases to facilitate analysis over a wind farm and a larger number of turbines. Results of the analysis can lead to changes in control reducing loads on a failing component. Better understanding of the condition of the turbine drive train can lead to increased power output under some conditions where the fatigue life of the turbine allows.
What's in it	Sensors Condition monitoring hardware and software

T.2 Rotor	
Function	The rotor extracts kinetic energy from the air and converts this into rotational energy in the drive train.
What it costs	The rotor cost for a 10MW wind turbine is about £1.7 million.
Who supplies them (examples only)	Wind turbine rotors are usually designed and supplied by the wind turbine supplier as part of the complete wind turbine.
Key facts	The blades [T.2.1] are connected to the turbine drive train via a central hub. In all offshore wind turbines, the blades are mounted on bearings [T.2.3] to allow independent adjustment of the pitch angle of each blade. Fasteners are used to connect the blades to blade bearings and blade bearings to hub. These are typically M30 or M36 grade 10.9 bolts or studs (see [T.1.13]). A rotor for a 10MW turbine has a mass of about 150t and a diameter of 170-200m. There are no fundamental limits to the size of rotors for offshore turbines, though for the same design, mass increases faster than the additional energy generated (because energy capture is proportional to the two-dimensional swept area (square) but the blades increase in size (and mass) in three dimensions (cube). Substantial improvements in blade technology have meant that, so far, the actual increase in mass has been limited to nearer the square than the cube of blade length. New turbine designs have larger rotor swept areas compared to their generator rating to achieve a higher capacity factor. Many offshore wind farms report capacity factors of about 50%, and above that is expected for the next generation of turbines. This compares with capacity factors of about 35% for good onshore sites. As turbine rotor diameter increases, with the same limit on tip speed, the rotational speed will decrease. Lower rotational speeds make it more difficult to design a support structure that avoids resonant frequencies excited by loading from waves and operation of the turbine itself. Rotor speeds are 5 to 12 r/min, resulting in a maximum tip speed of over 100 m/s. In UK, rotor clearance must be at least 22m above mean high water springs (MHWS).
What's in it	Blades [T.2.1] Hub casting [T.2.2] Blade bearings [T.2.3] Pitch system [T.2.4] Spinner [T.2.5] Rotor auxiliary systems [T.2.6] Fabricated steel components [T.2.7] Structural fasteners [T.1.13]

T.2.1 Blades	
Function	The blades capture the energy in the wind and transfer torque and other unwanted loads to the drive train and rest of the turbine.
What it costs	The set of blade for a 10MW wind turbine cost about £1.3 million.
Who supplies them (examples	Most offshore blades are manufactured by wind turbine suppliers. LM Wind Power owned by GE, with coastal facilities in France and Poland, will supply to other

only)	manufacturers.
Key facts	Blades are typically made from fibreglass and epoxy resin, although there are variations between designs, with some using carbon fibre; others use polyester resins. With both cyclically varying aerodynamic and reversing gravity loading, both fatigue and extreme loading inform the design in different regions of the blade. Extreme loads may come from storm loading, specific events such as shutdowns due to control system failure, or from the high number of hours of operating in a turbulent wind field. Natural frequency is another critical design consideration, against a range of driving frequencies due to the rotor rotation, as is deflection stiffness, where avoidance of tower strike is critical. Blades for a 10MW turbine are over 90m long and over 6m wide at their broadest point (maximum chord), with mass 30-40 tonnes. The blade root [T.2.1.2] provides a critical connection to the blade bearing [T.2.3]. A lightning protection system [T.2.1.3] is designed into the blade, including connections to enable lighting to conduct safely through the nacelle and down the tower. Faster tip speeds typically lead to more efficient energy capture. A key limit to achieving this is leading edge erosion where repeated impact by raindrops, particulate matter, hail, ice, and salt erodes the blade causing surface roughness and change in aerodynamic shape. This reduces the performance of the blade and increasing sound emissions from it. If left unrepaired, the damage will continue until it affects the structural integrity of the blade. Reducing the risk of leading edge erosion is an important focus for innovation. One approach is developing better coatings. Another is to incorporate leading edge protection plates similar to those used in helicopter blades but ones able to cope with the larger deflections seen in wind turbine blades. In some applications, aviation lights mounted on the tips of blades are required. These may illuminate only when the blade is oriented vertically upwards. Larger turbine blades interact with a larger volume of flow. It becomes harder to optimise aerodynamics with adjustment of only a single pitch angle and the rotational speed so innovations are being developed to provide more localised control of airflow on blades.
What's in it	Structural composite materials [T.2.1.1] Blade root [T.2.1.2] Environmental protection [T.2.1.3]

T.2.1.1 Structural composite materials

Function	Composite materials are used to provide an efficient, strong and relatively light blade structure.
Who supplies them (examples only)	Airtech, Alcan, Diab, Gurit, Hexel, Owens Corning, PPG, SGL and Zoltek.
Key facts	One type of manufacturing process for a blade is to make two full-length aerodynamic-shaped shells using a resin infusion process, large moulds and consumable vacuum bags. These shells are either glued around a central load-bearing spar or structural elements are incorporated into the blade shells and a strong load-bearing connection between them is provided using glass fibre shear webs. SGRE used a single infusion process to form the whole blade in one step. Some insert the blade root connection prior to infusion whilst some drill and fit this afterwards. Compromises are made between optimum aerodynamic shape (generally low thickness) and optimum structural shape (higher thickness).

	Key parameters that define blade shape along the blade are chord (length of aerofoil cross-section), thickness of aerofoil cross section, twist (angular rotation of aerofoil) aerofoil shape and position of aerodynamic centre. These parameters are optimised during blade design. A stepwise testing strategy for new blade designs is normally employed, where in turn blade materials, structural samples, blade sections and complete blades are tested under fatigue and extreme loads in order to verify design and ensure sufficient strength, a process that takes about 6 months. Repeatable blade quality and manufacturing time are two critical considerations during blade manufacture.
What's in it	Glass fibre, in uni-directional or woven fabric mat and/or prepreg form Carbon fibre (in most cases; generally in prepreg form) Resin, either epoxy or polyester Adhesive Closed-cell foam or balsa bulk fill Consumables

T.2.1.2 Blade root

Function	The blade root acts as the interface between the main composite section of the blade and the steel blade bearing.
Who supplies them (examples only)	An integral element of a blade design, blade roots are designed then manufactured by the blade supplier using bought-in items.
Key facts	The design of the connection to the blade bearing [T.2.3] is critical due to the attachment of a relatively soft composite structure to the stiff bolting and bearing structure. Differing arrangements are used to provide threaded connection for fasteners connecting the blade bearing. In some cases, a ring is set into the root of the blade. In other cases, inserts are either bonded into holes drilled in the root or inserts are infused during manufacture. Finally, other designs use a single or double row of “IKEA-type” threaded bars, set perpendicular to the direction of orientation of studs. The composite structure near the blade root is designed to apply even loading around the blade root as well as smooth transfer of load into each insert. The root of the blade must be sufficiently flat so as not to apply excessive uneven load to the blade bearing. Loading of the root-end and fasteners at the blade root is critical due to the complex geometry, especially of the hub and bearing under load. Development testing of root end strength is common.
What's in it	Metal inserts Composite structure

T.2.1.3 Environmental protection

Function	Lightning protection systems provide a level of protection for the blades and the rest of the turbine. Leading edge tape / metal or ceramic inserts protect blade tips from erosion. Paint or gel coat protects the rest of the surface of the blade against erosion and UV damage.

Who supplies them (examples only)	Lightning protection systems are an integral element of a blade design and the design of other turbine components in the conduction path to earth. They are manufactured by the blade and other relevant component suppliers using bought-in items. Polyurethane Protection Tape: 3M. Coatings: Akzo Nobel, Bergolin and Mankiewicz.
Key facts	Different suppliers have different strategies for the capture and transfer of high currents at high voltages from point of impact through to the hub and rest of the turbine, depending on blade materials and aspects of blade design. Lightning receptors are normally fitted at the tip and other points on the blade. In some cases, a conducting mesh is incorporated into the structure of the blade. It is generally considered advantageous not to allow lightning to pass through blade bearings and into the hub and hence to the main structural load path to tower base. Systems are used to gather data about the severity of lightning strikes.
What's in it	Lightning receptors Lightning conductor arrangement Tape Metal / ceramic inserts Data capture

T.2.2 Hub casting	
Function	The hub connects the blades to the main shaft.
What it costs	The hub casting cost for a 10MW wind turbine is about £150,000.
Who supplies them (examples only)	Eisengiesserei Torgelow, Felguera Melt, Fonderia Vigevanese, Gusstec, Metso, MeuselWitz, Rolls Royce, Sakana, Siempelkamp and Vestas, though only a subset can make the largest of hubs.
Key facts	The hub is made of SG iron and has mass well over 50 tonnes. It houses the pitch system [T.2.4] and provides stiffened support for the blade bearings [T.2.3]. Generally, hubs are approximately spherical, with offset inner and outer surfaces to provide additional strength at the rear of the hub around the connection to the main shaft [T.1.3]. Openings are provided for personnel access. Lifting points for use during installation, support locations for pitch system components and other auxiliary systems and blind tapped holes are generally required. SG iron is typically of grade EN-GJS-400-18U-LT, cast without the need to heat-treat. SG iron is chosen above cast steel due to superior pouring and shrinkage properties.
What's in it	Casting Non-destructive testing Machining Painting

T.2.3 Blade bearings	
Function	The blade bearings enable adjustment of blade pitch angle to control power output from the turbine, minimise loads and start/stop turbine as required.
What it costs	A set of blade bearings for a 10MW wind turbine cost about £200,000.
Who supplies them (examples only)	IMO, Liebherr, Rollix, Rothe Erde and SKF, all based on the continent. Rothe Erde has a subsidiary, Roballo, able to carry out certain processes in UK.
Key facts	Bearings are typically double-row 4-point contact ball bearings or three-row roller bearings made from forged rings of about 4m diameter, typically of a 42CrMo4 steel, quenched and tempered. Rolling elements are typically material 100Cr6. Total bearing mass may be up to 5 tonnes. Raceways are hard-turned or ground after induction hardening. Bearings see a complex, reversing load pattern and operate with long periods of reversing movement over only a few degrees. It is critical to ensure relatively low friction torque to enable safe shutdown of the turbine via 90˚ pitching movements under all conditions. Some designs incorporate gear teeth to mesh with an electric pitch drive. Relatively soft support structures and high loading lead to substantial deflections of bearings during operation. Special greases have been developed in response to lubrication issues due to the high loading and intermittent movement experienced by blade bearings. Seals are made from rubber extrusions with complex cross sections to retain grease whilst minimising friction.
What's in it	Forged rings, machined, hardened and surface finished Balls Cages / spacers Seals Grease Metal sprayed and/or painted finish

T.2.4 Pitch system	
Function	The pitch system adjusts the pitch angle of the blades to control power output from the turbine, minimise loads and start/stop turbine as required.
What it costs	The pitch system cost for a 10MW wind turbine is about £100,000.
Who supplies them (examples only)	See details of hydraulic and electric systems, below.
Key facts	Pitch systems are either hydraulically or electrically operated, with little external difference in functionality. Typically, blade pitch angle is adjusted almost constantly in medium-to-high winds to regulate rotor speed whilst the turbine is extracting maximum (rated) power. Adjustment is over a range of approximately 20˚ at

	rate of a few degrees/second. In lower winds, the pitch system operates to maximise aerodynamic efficiency, which requires substantially less movement. Each blade has an independent pitch system that incorporates a fail-safe function that enables it to pitch quickly through 90˚ without using grid power - from providing power to acting as a brake. This action is independent for each blade to avoid a single failure causing catastrophic damage to the wind turbine. In some cases, blade pitch angles are adjusted independently to different angles on each blade to minimise aerodynamic loading on the rest of the turbine. Power and control signals for the pitch system are provided from the nacelle [T.1] through a bore in any gearbox [T.1.4] and the main shaft [T.1.3].
What's in it	Hydraulic pitch system [T.2.4.1] or electric pitch system [T.2.4.2]

T.2.4.1 Hydraulic pitch system	
Function	The pitch system uses hydraulic actuators to adjust pitch angle of the blades.
Who supplies them (examples only)	Bosch Rexroth, Fritz Schur and Hydratech Industries.
Key facts	Hydraulic actuation uses linear hydraulic cylinders, typically controlled by proportional valves. These actuators are generally trunnion-mounted to the hub and a plate fixed to the inner (rotating) ring of the blade bearing. Maximum pressures are about 250bar and total system mass is of the order of 3 tonnes. Back-up energy to facilitate safety shutdown even without grid power is provided by accumulators. The main hydraulic tank is normally located in the nacelle [T.1], with pressure and return lines passing through the gearbox [T.1.4] and the main shaft along with control signal and control power cables.
What's in it	Power pack Hydraulic actuators Rotating union Manifold blocks Accumulators Hoses Electrical slip rings

T.2.4.2 Electric pitch system	
Function	The pitch system uses geared electric motors to adjust pitch angle of the blades.
Who supplies them (examples only)	MLS, MOOG and SSB.
Key facts	Electric actuation normally uses high-speed DC electric motors controlled by 4-quadrant drives, with total

	peak output up to about 200kW for a 10MW turbine. These motors drive blade bearings [T.2.3] via speed-reducing gearboxes and pinions meshing with either internal or external gear teeth on the blade bearing. Back-up energy to facilitate safety shutdown in the event of no grid power is provided by batteries directly connected to the DC motors. Blade pitch angle is measured through absolute encoders mounted on the pitch drive motors. All electric pitch items are mounted in panels or directly on the hub casting. The electric pitch system for a 10MW turbine has total mass of about 10 tonnes.
What's in it	Motors Gearboxes Electrical panels Batteries Battery chargers Position sensors

T.2.5 Spinner	
Function	The spinner provides environmental protection to the hub assembly and access into the hub and blades for maintenance personnel.
What it costs	The spinner cost for a 10MW wind turbine is about £20,000.
Who supplies them (examples only)	Bach Composites Industry, Eikboom.
Key facts	Generally, the spinner is made from fibreglass in sections and bolted together on a galvanised steel frame. Fibreglass cuffs are frequently fitted round blades to provide environmental protection to blade bearings. Consideration is given to maintenance activities in and around the hub when designing the spinner. In some cases, personnel access is needed between the spinner and hub. The spinner may be up to 6m diameter.
What's in it	Fibreglass mouldings Fabricated steel support frame

T.2.6 Rotor auxiliary systems	
Function	Auxiliary systems may be incorporated to lubricate bearings and provide condition monitoring and advanced control inputs.
What it costs	The rotor auxiliary systems cost for a 10MW wind turbine is about £40,000.
Who supplies them (examples only)	Automatic lubrication systems: Lincoln, SKF. Blade load sensing: Insensys.

Key facts	All offshore wind turbines have automatic lubricated blade bearings [T.2.3]. A central lubrication pump connected to a metering distribution system provides a consistent volume of grease to ports around the circumference of the bearing each day. Grease purged from the system is collected from exit ports to avoid over pressurising seals. Turbines also have blade load measurement as an advanced control input, facilitating reduction in turbine loading, normally at the expense of extra pitch system duty and blade bearing loading. Lighting and other maintenance support features are also provided in the hub.
What's in it	Automatic lubrication system Blade load measurement system Maintenance support features

T.2.7 Fabricated steel components	
Function	Fabrications are often required to stiffen the blade bearing support and provide a connection for hydraulic pitch system actuators. Other items are required for personnel protection, to facilitate access and maintenance activities and to provide a lightning path from the blades into the nacelle.
What it costs	The fabricated steel component cost for a 10MW wind turbine rotor is about £80,000.
Who supplies them (examples only)	These items are supplied by a range of steel fabricators and machinists.
Key facts	Stiffening plates are circular, flame-cut plates of the same diameter as blade bearings, with a ring of boltholes and a central cut-out to provide access from the hub to the blade root [T.2.1.2]. These are metal sprayed and painted. Other steelwork is of simple fabrication from box and other section, galvanised to provide corrosion protection.
What's in it	Steel fabrications Surface treatment

T.3 Tower	
Function	The tower is typically a tubular steel structure that supports the nacelle. It also provides access to the nacelle and houses electrical and control equipment. Also provides shelter and storage for safety equipment.
What it costs	The tower cost for a 10MW wind turbine is about £700,000.
Who supplies them (examples only)	CS Wind, Gestamp Renewable Industries, GSG Towers, Haizea Wind Group, Titan Wind Energy and Welcon.
Key facts	Fabricators manufacture towers to designs provided by wind turbine suppliers, sometimes using free-issue materials (both steel and internal components). Towers are normally made at coastal locations. Once fabricated, the tower sections are shot-blasted and painted before fit-out with other internal components then prepared for transport and storage. The hub height is about 110m above sea level depending on the rotor diameter so each tower is about 100m long and has a mass over 600 tonnes. About 90% of the mass is steel plate with forged steel flanges making up most of the rest. Towers are generally uniformly tapered, with a top diameter of the order of 5-6m for a 10MW turbine and a base diameter of 7-8m. Design is driven by fatigue and extreme loading plus natural frequency requirements and avoidance of bucking. The optimum tower height is normally as low as needed to comply with maritime safety regulations for blade clearance above the water. This is because the wind shear is low offshore (the wind speed does not increase very much with increasing the hub height), meaning there is no cost benefit for using a taller tower. Integrated design of substructures and towers is increasingly seen as desirable with the transition from substructure to tower predicted to be less distinct. The tower, though, continues to be a discrete component supplied with the wind turbine.
What's in it	Steel [T.3.1] Tower internals [T.3.2]

T.3.1 Steel	
Function	Steel is the most commonly used material for the manufacture of towers.
What it costs	The steel cost for a 10MW wind turbine tower is about £600,000.
Who supplies them (examples only)	Corus, Dillinger Hütte, Ilsenburger, Rukki, Salzgitter, Siegthaler and thyssenkrupp. Agents are also used to source and manage supply. Hempel is a key supplier of surface finish products.
Key facts	Towers are manufactured by cutting and rolling steel plate, welding to make typically 3m “cans” then welding these to make tower sections of say 40m, with bolted flanges each end. Steel plate of grade S355J2G3 NL and thickness 10-70mm is typically used.

	Steel thickness is varied for each "can" in steps down to 0.5mm in the upper part of the tower. Thickness is optimised by considering overall natural frequency of the support structure (including foundation) and fatigue life and other design drivers for each "can". Flanges are generally forged and rolled from grade S355 EN10.113-2 NL steel with weld necks in order to improve the weld fatigue class. Tower top flanges are machined post welding to ensure top flange flatness is within tolerances required for the yaw bearing. Other specialised steel is used for the door frame at the tower base, typically of grade S235 J2G3 NL. The frame needs to compensate for the cutaway of important amounts of material for personnel access [T.3.2.1] at this fatigue-critical location. Surface finish is routinely metal spray followed by high build epoxy spray and polyurethane spray finish (total approx. 250 microns).
What's in it	Steel plate Steel flanges Surface finish

T.3.2 Tower internals	
Function	The tower internals provide means of access, lighting and safety for maintenance and service personnel, plus means of transferring hand tools and components to the nacelle. They provide support for control and electrical cables and housing of switch-gear, transformers and other elements of power take-off. Tower internals also provide storage for survival equipment. A tuned damper may be located at the top of the tower to aide damping of tower and structure resonances.
What it costs	The internals cost for a 10MW wind turbine tower is about £70,000.
Who supplies them (examples only)	Various
Key facts	Design of doorways and attachments points for components is critical for the fatigue life of the tower. Magnets are used to attach some components in order to avoid stress concentrations.
What's in it	Personnel access and survival equipment [T.3.2.1] Tuned damper [T.3.2.2] Electrical system [T.3.2.3] Tower internal lighting [T.3.2.4] Coatings [T.3.2.5]

T.3.2.1 Personnel access and survival equipment	
Function	Safe access to the nacelle is required for most maintenance activities. Though ladders are always required, larger turbines also have an elevator. Offshore turbines are usually also equipped with offshore survival equipment in case weather conditions stop the crew leaving the turbine as planned.
Who supplies them (examples only)	Elevator: Avanti, Hailo and Power Climber Wind. Fall arrest: Avanti, Latchways, Limpet Technology and Uniline Safety.
Key facts	Elevators typically operate at rates of up to 20m/min and with load capacities of between 250 and 500kg, though elevators with higher capacity have been used in order to simplify maintenance procedures. Ladders are generally of standard aluminium profile. Fall arrest devices running on rails or wires supported by the ladder and connected to body harnesses are used at all times by maintenance staff. Platforms of aluminium or steel support with checker plates are positioned to meet local health and safety requirements, providing rest points and protection from falling tools etc. Survival kits may contain distress flares, food, drink and other essentials for minimum 3 days.
What's in it	Fall arresters Ladders Elevator Platforms

T.3.2.2 Tuned damper	
Function	In some cases, a large damper is fitted at the top of the tower in order to reduce tower and foundation loading.
Who supplies them	Tuned dampers are generally made from bought-in items.
Key facts	Typically, dampers are liquid-filled. The natural frequency of ‘sloshing’ is tuned to have maximum effect in reducing tower fatigue loading due to varying aerodynamic loads from the rotor and wave loading from the foundation. Dampers can also reduce transient loads during turbine shutdowns.
What's in it	Support structure Liquid container Damping liquid (generally water-based)

T.3.2.3 Electrical system	
Function	All wind turbines have a control panel at the tower base in order to facilitate on-site control of the turbine by maintenance staff without climbing the turbine. For many turbines, the space near the base of the tower is used to mount various elements of the power take-off including convertor and cooling systems.
Who supplies them	These items are generally supplied by the turbine manufacturer to the tower manufacturer for fit-out.

Key facts	The only access to the inside of the tower base is via the access door, so if the transformer is mounted in the tower base, it is essential to be able to replace it via the door in case of failure. If sensitive electrical systems are placed at the tower base, then these are protected by a local air conditioning system.
What's in it	Power take-off [T.1.6] Control system [T.1.7] Tower internal lighting [T.3.2.2] Air conditioning

T.3.2.4 Tower internal lighting	
Function	Lighting is provided to facilitate safe personnel access and egress from the nacelle and tower.
Who supplies them (examples only)	All parts are standard, with many suppliers.
Key facts	Luminaires are frequently fitted to ladders and platforms or in some cases via magnets to the tower wall to avoid welding on lugs (hence introducing stress concentrations) in tower wall sections. In the event of loss of grid, a UPS powers emergency lighting, often a subset of standard lights.
What's in it	Luminaires Low voltage wiring Cable trays Emergency backup including UPS

T.3.2.5 Coatings	
Function	Specialised coatings are used to protect towers, fasteners, hub castings and other components.
Who supplies them (examples only)	AkzoNobel, BASF, Hempel, NOF Metal Coatings Europe, PPG and Teknos.
Key facts	Satisfactorily applied coatings are essential for lifetime protection especially for external surfaces and to avoid putting maintenance personnel in potentially hazardous situations. Specialised coatings have been specifically developed to protect components in the “splash zone”. Coatings are tested and certified against international standards. The component manufacturer usually undertakes the coating application.
What's in it	Resin Metal spray Application equipment

3. Balance of plant

B Balance of plant	
Function	The balance of plant includes all the components of the wind farm except the turbines, including transmission assets built as a direct result of the wind farm.
What it costs	About £600 million for a 1GW wind farm.
Who supplies them (examples only)	See relevant sections below.
Key facts	Much of the benefit of larger turbines is largely realised by the reduction in balance of plant costs. Larger turbines mean fewer structures and less cable. Like-for-like balance of plant costs will increase as wind farms are built further from shore and in deeper water.
What's in it	Cables [B.1] Turbine foundation [B.2] Offshore substation [B.3] Onshore substation [B.4] Operations base [B.5]

B.1 Cables	
Function	The cables deliver the power output from the wind turbines to the grid.
What it costs	About £170 million for a 1GW wind farm.
Who supplies them (examples only)	Cable manufacturers include J-Power, LS Cable, Nexans, NKT, Prysmian and Telefonika Kabel/JDR Cables.
Key facts	A standard subsea cable used in offshore wind is made up of a stranded, profiled conductor with a combination of sealing layers, XLPE (cross-linked polyethylene) insulation and armouring. The mechanical properties of the XLPE are superior to many other forms of insulation, offering greater tensile strength, elongation and impact resistances. Cables are laid up with insulation and armour coating around the conductors. They must have high chemical and abrasion resistance as well as tensile strength to survive the laying process and withstand wave and tidal loading for exposed sections. There are three main insulated power core design types: • Dry, with an extruded lead sheath over the insulation • Semi-wet, with a polyethylene sheath over a non-fully impervious metallic screen • Wet design, without a sheath over a non-fully impervious metallic screen Wet designs have the advantage of being lighter and more flexible but are not yet available at higher voltages. Much of the development of 66kV subsea cables has focused on developing wet designs at high voltages than had been previously possible. Subsea AC cables have threes cores (one for each phase). Onshore AC cables have single cores and are laid in groups of three. DC cables (land and subsea) have single cores (two, positive and negative, for each circuit). The terms low voltage, medium voltage and high voltage are not formally defined by the industry. For offshore wind, high voltage typically refers to any cable rated higher than 66kV and low voltage anything below 11kV. High voltage cables are generally associated with transmission networks and export cables whereas medium voltage is associated with distribution networks and array cables. The wind turbines generate at low voltage with a transformer at the base of the tower stepping up voltage to medium voltage. A single extrusion line can produce around 200km of core per year (this equates to around 40cm per minute). To avoid unnecessary handling, cables that will be installed subsea are ideally loaded directly onto an installation vessel from the factory. Cables have a specified minimum bend radius and failure to maintain this during transportation or installation greatly increases the risk of cable faults. The cable lengths are delivered on drums with sealed ends in order to prevent entry of moisture and other damage. There has been consolidation in the market with the acquisition by Prysmian of Draka and General Cable, by NKT of ABB and by Telefonika Kabel of JDR Cables.
What's in it	Export cable [B.1.1] Array cable [B.1.2] Cable protection [B.1.3]

B.1.1 Export cable

Function	The export cable connects the offshore and onshore substations.
What it costs	About £130 million for a 1GW wind farm.
Who supplies them (examples only)	Export cable manufacturers include Hellenic Cables, LS Cable, Nexans, NKT and Prysmian.
Key facts	An HVAC export cable is 3-core whereas a typical HVDC has a bipolar design with two single-core cables. For a given capacity, HVDC cables are lighter with implications for the ease and cost of installation with subsequent savings in cable costs. HVAC cables suffer important losses over longer distances due to reactive power flow. HVDC is used for long distance transmission because the full capacity of the cable system can be used for transferring active power (because there is no reactive power flow). HVDC converter stations are expensive and the savings from the use of HVDC cable are not realised until the cable route between the substations is around 80-100km. Even beyond this distance, project-specific considerations can make final concept choice complex. AC export cables are typically rated between 132kV and 245kV, allowing export of 350-400MW per 3-core cable. The voltage chosen balances the cost of the cable per km, the number of circuits for the grid connection and the number of substations needed. The trend towards wind farms further from shore has been associated with an increase in export cable voltage and 220kV is increasingly the standard. Medium voltage cables may be used for export for small wind farms close to shore. Their use for commercial scale projects in the future is therefore unlikely but medium voltage export is attractive for demonstration projects, for example at the Blyth Offshore Demonstrator, the European Offshore Wind Deployment Centre (Aberdeen Offshore Wind Farm) and Hywind Scotland. For HVDC systems, a pair of single-core 320kV cables can export up to 1,200MW per and in time, this maximum power will increase. A 220kV three-core copper AC export cable has mass of approximately 90kg/m. A 320kV single-core DC copper export cable has mass of approximately 40kg/m.
What's in it	Cable core [B.1.1.1] Cable outer [B.1.1.2] Cable accessories [B.1.1.3] Cable jointing and testing [B.1.1.4]

B.1.1.1 Cable core

Function	The cable core transfers the power through the conductor.
Who supplies them (examples only)	Cable cores are typically manufactured by the cable manufacturer. Usually, the core is made on the same site to avoid transport costs and limitation on core length if it needs to be moved by road.
Key facts	The core is typically made up of the conductor, a screen, the XLPE insulation and a protective sheath. The sheath has historically been lead but alternatives are being developed on environmental grounds. The conductor may be stranded copper or aluminium. Both have low resistance, excellent conductivity, are ductile and relatively resistant to corrosion. Copper has higher conductivity, 60% greater than

	aluminium, but is more expensive and the price is more volatile. Aluminium is lighter and therefore easier to handle. Overhead power cables are typically aluminium for this reason. The cable should at least have a conductor cross section adequate to meet the system requirements for power transmission capacity. Energy losses can be reduced by using larger conductor but at a greater capital cost. Three-core subsea cables usually have steel wire armour. Single-core cables have non-magnetic armour. Single-core cables can be laid separated or close. Close laying gives lower losses. Separation eliminates mutual heating but means higher losses in the armour. A 66kV subsea cable core has a cross-sectional area of between 150mm^2 (14mm diameter) and 800mm^2 with 13mm of insulation. A 220kV subsea cable core has a cross-sectional area of between 800mm^2 (32mm diameter) and 1600mm^2 with 23mm of insulation. A 320kV DC cable core has a cross-sectional area of between 1,000mm^2 (40mm diameter) and 2500mm^2 with 25mm of insulation. The conductor screen is a semiconducting tape that surrounds the conductor and maintains a uniform electric field and minimise electrostatic stresses on the cables. For offshore wind, XLPE cables are typically preferred to paper-insulated cables. XLPE cables are typically cheaper and lighter but are not currently available at as high a voltage as paper-insulated cables, which means that international interconnectors often still use paper-insulated cables. This is expected to change with market demand and developments in cable design. Surrounding the insulation is a further screen, similar to the conductor screen.
What's in it	Conductor Conductor screen XLPE insulation Insulation screen Lead sheath

B.1.1.2 Cable outer	
Function	The cable outer surrounds the core are materials to protect the cable and house the fibreoptic cable.
Who supplies them (examples only)	Commodity suppliers. Fibre optic manufacturers: Hexatronic, Huber+Suhner. Fibre optic jointers and systems: Aceda, CCL UK.
Key facts	For a three-core core, the cores are packed with non-conductive filling material made from polypropylene. Its purpose is to maintain the cable’s shape and surrounding by binding tape. The armouring includes the bedding, the armour and the serving application. A layer of polypropylene string is applied over the assembly as bedding for the armour wires. The armouring is usually made up of helical metal wires, often steel, surrounding the cable. The choice of armouring is important as will impact its protective and handling properties. Bitumen may be applied over the armouring to protect against corrosion and provide additional adhesion. A layer of polypropylene string is applied over the armour as cable serving to provide against abrasion and to reduce cable friction during laying. A polypropylene serving is applied with a black and yellow pattern to make the cable easily visible during laying.

	A fibre optic cable is integrated into the power cable for communications. The cable is multimodal, meaning that it can carry a wide range of data at different frequencies, typically for voice, turbine, switchgear and security information. The typically has 48 strands.
What's in it	Bitumen Polypropylene strings Steel wire

B.1.1.3 Cable accessories	
Function	Cable accessories are used to provide electrical termination and mechanical support for cables both during and after installation.
Who supplies them (examples only)	Interface plugs: Pfisterer, Ridderflex and TE Connectivity. Hang-off clamps: BMP, Voss Prodect and WT Henley. Cable connectors: see cable manufacturers [B.1.1].
Key facts	Pulling heads enable the safe installation of the cable to the platform. It typically connects directly onto the cable armouring to ensure that all mechanical forces associated with pulling the cable via the J-tube are borne by the armour rather than the core. They are usually made from machined steel and hot dipped galvanised and zinc plated. Kellums Grips are often used for lighter weight or lower tension installations The termination hang offs ensure that the cable is mechanically secured after installation to ensures the mechanical stresses expected to occur during service life are safely borne by the cable structure. Offshore junction cabinets is used as a disconnecting point for internal tower cable to external subsea array cables and made from marine grade stainless steel. Coupling connectors link the cable with the switchgear. These are insulated using ethylene propylene diene monomer (EPDM). J-tube seals are used to seal the interface between the inside of a J-Tube and the riser. Water containing a corrosion inhibitor is normally introduced into the J-tube void. Cable protection systems (CPS) are often employed to ensure the cable is not subjected to excessive loadings through the cable route as the cable departs the foundation and continues onto the sea bed.
What's in it	Interface plug Hang-off clamp Cable connector, T-connector Cable cleats Cable trays CPS

B.1.1.4 Cable jointing and testing	
Function	Jointing the segments of cable and testing during manufacturing.
Who supplies them (examples only)	In house by cable manufacturers. Independents: Maillefer, PCSL and WT Henley.

Key facts	There are two types of joints: • The factory flexible joint connects individual segments of cable core into one continuous length during the lay-up process. Crucially, the joint must have the same electrical, mechanical and thermal properties as the rest of the cable and result in a joint that it does not hamper installation or increase the risk of cable failure. • The field rigid joint is a manufactured product. It may be supplied to the wind farm owner or the offshore transmission owner (OFTO) with the cable in case of failure during operation or supplied as a planned joint to link sections of the export cable. Field rigid joints have generally been bespoke products because of the substantial variations in cable design between wind farms. There is growing interest, particularly by OFTOs, in developing joints that are suitable for a range of designs. Cables undergo a series of tests before dispatch, dependent on the cable type and voltage class, including: • Cable (and accessories) pre-qualification tests • Cable (and accessories) type tests • Cable routine electrical tests on each manufacturing length before jointing and armouring • Sample tests • Routine factory splice tests, and • Tests on complete cable lengths including factory installed joints (if any).
What's in it	Joints Electrical test and diagnostics devices

B.1.2 Array cable	
Function	The array cable creates loops or individual strings connecting all wind turbines to the offshore substation.
What it costs	About £35 million for a 1GW wind farm.
Who supplies them (examples only)	Array cable manufacturers include JDR Cable Systems, Draka (Prysmian), Hellenic Cable, Nexans, NKT and Twentsche Kabelfabriek.
Key facts	Each turbine has of the order of 1km of array cable on either side associated with it, depending on turbine size and spacing. Array cables are now typically rated at 66kV. The first generation of offshore wind farms typically used 33kV but the high voltage has been a major focus of technical development because they enable more capacity to be connected on a single string, reducing the length of cable required and reducing the number of switchgear bays needed on the substation. With the deployment of larger turbines above 6MW this has driven an increase in conductor sizing, in addition to the elevated voltage. Whereas for earlier 33 kV wind farms included 630mm^2 copper as the largest array cable sizing, projects in construction and planning phase are moving to 66 kV 800mm^2 or larger for both copper or aluminium. Array cables are typically supplied with cable accessories, although the manufacture of accessories may be outsourced. Cable protection may also be included in the supply scope but it is more often part of the installer’s scope. Cables may be supplied as pre-cut lengths or as a continuous length, depending on the project’s requirements. Several cable manufacturers have cable installation equipment and vessels but turnkey cable packages have typically led by marine contractors. This is mainly because different wind farms have contrasting technical requirements associated with the soil conditions or water depth and these are not necessarily a

	good fit with the manufacturer's equipment.
What's in it	Conductor Insulator Electrical screen Optical fibre cable Mechanical and chemical protection

B.1.3 Cable protection	
Function	Cable protection provides protection to cables at vulnerable locations, from the wave and tidal action and when the cable enters the wind turbine or offshore substation aperture or J-tubes.
What it costs	About £2 million for a 1GW wind farm.
Who supplies them (examples only)	Suppliers for cable protection include Blue Ocean, Seaproof, Subsea Protection Systems , Synthetex, Tekmar, Terram, Trelleborg and Vos Prodect.
Key facts	J-tube seals provide a seal at the ends of the J-tube to prevent seawater entering the J-tube. Passive seals consist of a series of disks that are pulled up into the J-tube. Active seals require inflation after they have been pulled through into the J-tube, requiring a remotely operated vehicle (ROV). Seals are not used in all cases, but a sealed J-tube may be filled with a corrosion inhibitor. A bend restrictor prevents damage caused by excessive bending. Cable stiffeners or CPS are also used for protection. If made from steel, they effectively weigh down the exposed cable. The CPS is typically positioned at the exit of the J-tube to the sea bed, or designed to protect the cable through ballast or scour protection, and also through to any planned cable burial position. Cable mats are also used to protect exposed areas of cable, such as when cables cross and they cannot be buried. Mats are typically made of concrete or polyurethane. Some suppliers offer a J-tube-less solution for monopile foundations by providing a clamp that enables the cable to be routed through a hole in the monopile.
What's in it	J-tube seals Bend restrictors Bend stiffeners Cable mattresses Rock placement

B.2 Turbine foundation	
Function	The foundation provides support for the wind turbine, transferring the loads from the turbine at the tower interface level (typically around 20m above water level) to the sea bed where the loads are reacted. The foundation also provides the conduit for the electrical cables, as well as access for personnel from vessels.
What it costs	About £280 million for a 1GW wind farm of 10MW turbines using monopiles at 30m water depth. About £350 million for a 1GW wind farm of 10MW turbines using jackets at 40m water depth.
Who supplies them (examples only)	Design: Ballast Nedam, COWI, LICengineering, OWEC Tower, Ramboll and SNC-Lavalin Atkins. Monopiles: Ambau, Bladt Industries, EEW SPC, Haizea, Navantia Windar, Sif and Steelwind Nordenham. Transition pieces: Bladt Industries, EEW OSB, Smulders, ST^3 Offshore and Wilton. Jackets and other space frames: BiFab, Bladt Industries, Harland and Wolff, Lamprell, Navantia Windar, Smulders and ST^3 Offshore. Concrete: BAM Nuttall, Jan de Nul and Vici Ventus.
Key facts	Foundation design is a complex engineering task. Design requirements include gravity load, thrust and associated overturning moment, natural frequency, fatigue strength, verticality (over time), personnel access, cable entry and support. Design needs to take account of both wind and wave loading and in some circumstances must consider other environmental conditions such as earthquakes, typhoons and sea ice. Over 80% of offshore wind capacity installed to date has been supported by monopiles driven into the sea bed, with jacket (and other space frame) foundations representing approximately 15%. Gravity bases are the least common design and most were deployed at early offshore wind farms in water depths of less than 10m. Monopiles require more steel than jackets but they are easier to manufacture and install in volume and they are well suited to the geology of the North and Baltic Seas. For larger monopiles, a key design driver is their stiffness, as the natural frequency of the complete wind turbine structure needs to be kept between blade passing frequencies over a range of wind speeds and above wave loading frequencies in order to minimise dynamic magnification and control fatigue loading. For larger turbines and in deeper water, the cost of monopiles rises substantially. At around 35m water depth, jacket designs become cost competitive. For a 10MW turbine at 30m water depth, indicative mass for a monopile (including transition piece) is around 1,650 tonnes. For a 10MW turbine at 40m water depth, indicative mass of a jacket (including pin piles) is 1,450 tonnes. It is easier to design a stiffer jacket structure for turbines of 10MW and above in order to meet natural frequency requirements, giving such structures the edge over monopiles. Jackets can also be used in a wider range of ground conditions, where the ground is either too hard or too soft to suit monopiles. In shallow waters and benign ground conditions, gravity bases have been used successfully. The Blyth Offshore Demonstrator Project used concrete gravity bases in waters of 36-42m, but at relatively high cost, with a mass of 15,000 tonnes for the concrete base, steel shaft and substrate ballast. Concrete material prices generally are less volatile than steel, meaning that when steel prices are high concrete is more attractive. In some regions, they can also offer higher levels of local content. The use of suction buckets for attaching the foundation to the sea bed is being explored and has been commercially deployed in only a handful of offshore wind farms such as Borkum Riffgrund 2 (Germany) and European Offshore Wind Deployment Centre (UK). These can be used with either jacket structures, or with monopiles (a “mono-bucket”). The main advantage is avoiding the loads associated with driving the monopile or pin piles into the sea bed. This both reduces noise for sea creatures and allows foundations to be installed completely assembled with all secondary steelwork. In water depths greater than about 60m, floating solutions are expected, with the potential for commercial

	deployment in the mid-2020s.
What's in it	Monopile [B.2.1] Jacket [B.2.2] Transition piece [B.2.3] Corrosion protection [B.2.4] Scour protection [B.2.5]

B.2.1 Monopile

Function	The primary function of a monopile is to support the static and dynamic loads of the wind turbine through anchoring it firmly to the sea bed using the embedded part of the monopile. Secondary functions include supporting the wave loads on the monopile itself and enabling cable entry.
What it costs	About £150 million for the monopiles for a 1GW wind farm.
Who supplies them (examples only)	Manufacturers: Ambau, Bladt Industries, EEW SPC, Haizea, Navantia Windar, Sif and Steelwind Nordenham.
Key facts	Monopiles are the most commonly used foundation type to date and are considered to be a proven technology by the offshore wind industry in water depths up to approximately 40m. Typically, for a 10MW turbine, the dimensions will be up to 10m diameter, 120m overall length and 2,000 tonnes. A number of suppliers have the capability to mass-produce this type of monopiles. The monopile is a cylindrical steel tube that is usually driven into the sea bed. The embedded section of the monopile is of constant diameter to allow entry into the sea bed. A monopile will normally have a transition piece between it and the bottom of the turbine tower, which supports secondary steel work such as a boat landing, cable J-tube and personnel access systems. Monopiles have typically been joined to their transition pieces using a long joint, either cylindrical, with shear keys, or conical, filled with grout. Jacking points allow adjustment to ensure that the transition piece is vertical before the grout is poured. A separate transition piece also avoids pile driving on the flange below the turbine tower, and allows secondary steelwork to avoid pile-driving loads. There is a trend towards bolted joints between the top of a monopile and the bottom of a transition piece where a grouted joint is swapped for a bolted joint, which is faster to install. In some cases, a transition piece is not used. Monopiles have evolved to be relatively simple cylindrical structures and as such are now made in highly automated factories with little work on top of rolling and welding of parallel cans. Two thirds of the cost is steel. They do not generally have a surface finish to resist corrosion. Monopiles need to withstand the impact of pile driving into the sea bed. The pile needs to be designed to account for these impact loads, which will use up a percentage of its fatigue life. As it is a simple cylindrical structure it is relatively easy to transport and move into its vertical orientation. Although monopiles are considered an established technology, innovation continues: • To better understand actual loads in order to support or improve the design guidelines currently in place. For example, the PISA (Pile Soil Analysis) joint industry project recommended use of shorter monopile embedded depths, achieved through a more accurate modelling of the soil supporting the structure. • To design monopiles that take further advantage of innovative water-aided pile driving installation methods that reduce piling fatigue. These may allow for design of monopiles that contain necessary secondary steelwork without the need for a separate transition piece. The monopiles may also be thinner if less of the fatigue life is used up in the piling process. • To avoid piling by using a single large suction bucket instead of the embedded part of the monopile, which also allows the use of a fully assembled foundation, for example as used on selected

	foundations at the Borkum Riffgrund 2 offshore wind farm. • To improve corrosion resistance by using new types of coating.
What's in it	Steel plates Flange Joints

B.2.2 Jacket	
Function	The primary function of a jacket is to support the static and dynamic loads of the wind turbine by anchoring it firmly to the sea bed using a set of pin piles. Secondary functions include supporting the wave loads on the jacket itself and enabling cable entry. A jacket foundation does not have a separate transition piece. The upper part of the jacket performs many of the functions of the transition piece, which are described in [B.2.3] and its sub-sections.
What it costs	About £310 million for the jackets for a 1GW wind farm at 40m water depth. This cost includes the pin piles and the upper part of the jacket, which performs many of the functions of the transition piece.
Who supplies them (examples only)	Jacket suppliers include BiFab, Harland and Wolff, Lamprell, Navantia Windar, Smulders and ST^3 Offshore.
Key facts	Jacket foundations make up approximately 15% of current installed capacity and are typically used at depths greater than 30m. There are several different versions of jacket structures, including three legged, four legged, “twisted” and “true X-braced”. Three and four legged versions are currently the most widely used. Typical overall jacket size for a 10MW turbine: 22m by 22m footprint, 60m height, with jacket mass of 1,100t and total pin pile mass of 350t. The supply of 100 jackets, as would be required for a 1GW offshore wind farm with 10MW turbines, is likely to require multiple fabricators. Jacket foundations are used for a number of reasons other than where the sea bed depth is too deep for monopiles to be economically viable: • Where ground conditions are too hard for monopiles, because it is easier to drive small piles than large monopile foundations into the sea bed. • Jacket foundations can also be used where ground conditions are too soft for monopiles and the load can be more effectively transferred to the ground by a jacket due to it having a wider footprint and is spreading the loading across at least three piles. • Driving smaller diameter pin piles creates less noise than driving a single monopile. In locations where noise regulations exist, a jacket may therefore be preferred over a monopile. • For sites where shallow bedrock means that driven piles are not a viable solution, jackets can be used in conjunction with drilled and grouted piles or other foundation solutions such as suction caissons (see below). A recent innovation has been to use suction buckets, also known as suction caissons, to secure the jacket to the sea bed (with one suction bucket supporting each jacket leg instead of piles), as used in the offshore oil and gas sector. During installation, the weight of the structure is combined with differential hydrostatic pressure created by pumping water out of the bucket, to draw the foundation down to penetrate the sea bed. Suction buckets have the advantage of little or no piling noise. They can only be installed in certain soil conditions, preferably sand or clay that is neither too dense or hard nor too loose or soft. Sites with shallow bedrock or the presence of boulders in clay soils are not suited to suction buckets. To maintain verticality, the caisson can be compartmentalised so that differences in pressure can be applied across the base of the structure. High-pressure jets positioned around the skirt can also

	help the levelling process. A challenge is the lack of evidence showing how a suction bucket structure will behave under long-term cyclic turbine aerodynamic and wave loading. Manufacturing savings can be achieved because a jacket design uses less steel than an equivalent monopile to support a 10MW turbine. This improvement is partially offset by the increased complexity of the welded nodes, the joints between pin piles and jacket base and the transition at the top between the lattice structure and the tubular tower base. Jackets may make up a higher percentage of future installed capacity if: • The cost of steel increases, • Further automation can reduce the cost of fabrication, • There is an increase in the proportion of sites with more than 40m water depth, or • The combination of load sets at a particular site with 10MW+ turbines favours them as a design solution.
What's in it	Steel lattice Struts Nodes Pin piles Protective coating

B.2.3 Transition piece	
Function	The transition piece provides the connection between the foundation and the tower, typically extending around 20m above mean sea level (MSL). It also supports secondary steelwork which provides functions such as allowing personnel access via a work platform, supporting cables and supporting the corrosion protection system.
What it costs	About £100 million for the transition pieces for a 1GW wind farm using monopile foundations. Where jacket foundations are used, the function of the transition piece is fulfilled by the upper part of the jacket structure. The cost is therefore included in the supply of the jacket.
Who supplies them (examples only)	Transition piece suppliers include Bladt Industries, EEW OSB, Smulders, ST^3 Offshore and Wilton. Often supplied through a joint venture with the monopile supplier.
Key facts	All foundation types have an upper part which is described as a transition piece. Monopiles usually have a separate transition piece (bolted or grouted). For jackets or concrete gravity base foundations this will be an integral part of the structure. Typically, the top of the transition piece needs to be approximately 20m above the highest astronomical tide (HAT) to keep the working platform above the worst expected combination of wave height, splash height, tide height and storm surge. It is finished at the top with a flange that will mate to the flange at the base of the turbine tower. For a 10MW turbine, a monopile transition piece will weigh approximately 500 tonnes and have an upper diameter of about 7m. The transition piece for monopile foundations will have a joint at its base; either a grouted joint or a flange for a bolted joint. Grouted joints require a number of jacking fixtures to correct any variation in the verticality of the installed pile prior to grouting to ensure a level flange on which to install the turbine and may require other features such as grout lines and shear keys. Transition pieces with bolted joints require the monopile to be installed to within a small deviation from vertical. The transition piece is also the part of the foundation to which most of the secondary steelwork is attached by welded or bolted joints. Secondary steelwork can include boat landings, external access ladders, the external work platform, internal work platforms, the cable entry and support system and the corrosion protection system.

	Protective surface coating is mandatory in the atmospheric zone (that part which is exposed to air) and splash zone (that part which is exposed to both sea and air), which accounts for nearly all of the transition piece. They are normally painted a bright yellow colour for visibility. Most projects have installed davit cranes on the transition piece to transfer equipment, small replacement parts and consumables from the support vessel.
What's in it	Crew access system and work platform [B.2.3.1] Internal platforms [B.2.3.2] Davit crane [B.2.3.3] J-tubes, I-tube or monopile entry point [B.2.3.4]

B.2.3.1 Crew access system and work platform	
Function	The crew access system and work platform enable operations service personnel to gain safe access to the turbine platform and allows loading, unloading and storage of equipment.
Who supplies them (examples only)	The crew access system and work platform are usually supplied as part of the transition piece, see suppliers of transition pieces [B.2.3]. In practice, the steelwork for the crew access system and work platform may be subcontracted to a smaller steelwork supplier.
Key facts	Adverse weather conditions can limit access to turbines and delay essential maintenance, leading to revenue loss. Currently, most crew transfer vessels (CTV) (such as a catamaran) are able to offload crews in wave heights of 2m. Some turbines have systems to enable helicopters to drop crew but if used routinely, this is an expensive solution with health and safety concerns. The simplest and cheapest option for turbines located close to shore is to use a small CTV. In this case, the vessel will press up against the boat landing, which consists of a pair of strong parallel vertical beams (known as "bumper bars") mounted onto the transition piece. This allows the service personnel to step across to a ladder located between and slightly behind the boat landing, clip into the fall arrest system, and hence gain access to the main work platform and the turbine. Intermediate rest platforms may also be included between the boat landing and platform access. This method of access is limited to significant wave heights (H_S) of approximately 1.5-2.0m. There are a number of systems which extend the range of sea conditions under which it is safe for personnel to transfer across to the access ladder. Service personnel may also arrive on a larger service operation vessel (SOV) equipped with a motion compensated gangway. In this case, they can step straight from the gangway onto the main work platform. Motion compensated gangways allow turbine access with H_s of up to approximately 3.0-4.0m. The main work platform is typically located about 25m above MSL in order to be clear of splashes during storm surges, even at high tide. It is sized to allow the storage of small ISO containers, which are frequently used to transfer parts and equipment to offshore wind turbines. They could also be used to store a generator, which is commonly needed before the turbine is connected to the grid. The main work platform is surrounded by guardrails and will have lights and textured non-slip decking to provide a safe working environment.
What's in it	Steel framework Decking Guardrails

B.2.3.2 Internal platforms	
Function	Internal platforms are used to support equipment housed in the transition piece and to provide personnel access for installation and maintenance purposes. They are also used to seal the upper reaches of the

	transition piece from the sea and any harmful gases from the corrosion protection system.
Who supplies them (examples only)	These are usually supplied by the supplier of transition pieces [B.2.3]. In practice, the steelwork for the internal platforms may be subcontracted to a smaller steelwork supplier.
Key facts	The upper platform provides access to the bolted connection between the transition piece and the tower base. The lower platform allows a seal to be made between the lower internal part of the monopile and the upper internal part of the monopile. This is because hazardous gases can accumulate inside the lower part of the monopile from the corrosion protection system. Further platforms may be included: • To provide access to the bolted connection between the monopile and transition piece, or to allow adjustment of the transition piece relative to the monopile before grouting, or • To support the turbine transformer, switchgear and a personnel refuge, although these can alternatively be located in the lower reaches of the turbine tower.
What's in it	Lightweight structural steel frame and decking

B.2.3.3 Davit crane	
Function	Davit cranes are used to lift equipment from a workboat up to the main external work platform.
Who supplies them (examples only)	Suppliers of davit cranes include CraneSolutions, Demag Cranes, Granada Material Handling, Liftra, Palfinger Marine and Sparrows Group.
Key facts	A davit crane is a crane, which can lift loads from a workboat and slew them around in order to lower them onto the main work platform. They have become almost universally adopted on offshore wind turbines to lift tools, auxiliary generators and smaller spare parts of up to approximately one tonne. They are particularly useful when a small CTV is used to access the wind turbine, as these vessels do not have a crane capable of lifting onto the main external work deck. Tools and parts can also be moved onto offshore turbines using a motion compensated gangway, vessel crane or helicopter.
What's in it	Steelwork

B.2.3.4 J-tubes, I-tube or monopile entry point	
Function	The J-tube or I-tube routes the array cables from the outside to the inside of the foundation and provides protection to the cables from wave action.
Who supplies them (examples only)	These are usually supplied by the supplier of jacket [B.2.2] or transition piece [B.2.3]. In practice, the steelwork for the J-tubes or I-tube may be subcontracted to a smaller steelwork supplier. A monopile entry point will be formed in the monopile by the monopile supplier.

Key facts	For a monopile, a J-tube is a steel tube of diameter approximately 300mm attached to the transition piece extending from platform level to a few metres above the sea bed. It is called a J-tube because the lower end is curved like a letter J so that the cable bends smoothly towards the horizontal, where it will enter the sea bed. Both ends of the J-tube have a bell mouth shape to allow easy cable entry. The cable will enter the lower end close to the sea bed, pass up through the tube where it will be protected from the action of waves, and will commonly exit around the level of the top of the transition piece. There are a variety of ways for the array cables to pass from the outside to the inside of the wind turbine. Both ends of the J-tube are normally sealed after the cable has been pulled through – see cable protection [B.1.3]. In deeper water, the top of the monopile finishes higher above the sea bed so an I-tube can be used. An I-tube has a vertical lower end, because it is many metres above the sea bed. A cable protection system will need to be used for the exposed cable between the buried section and where it enters the I-tube to stop it flexing in tidal currents. Another alternative is to have a monopile entry point in the side of the monopile a couple of metres above the sea bed. This will be sealed after the cable has been pulled in. These same options are used to route and protect cables for jacket foundations and for gravity base foundations.
What's in it	Tubular steel

B.2.4 Corrosion protection	
Function	Corrosion protection protects the foundation from corrosion to the extent that is required.
What it costs	About £20 million for the foundation corrosion protection for a 1GW wind farm using monopiles. About £30 million for the foundation corrosion protection for a 1GW wind farm using jackets.
Who supplies them (examples only)	Suppliers of corrosion protection coatings suitable for use on offshore foundations include Hempel, International Paint and Jotun. Suppliers of cathodic protection systems include Cathelco, Imenco Corrosion Technology and Impalloy.
Key facts	Corrosion protection is an integral part of the overall wind turbine design and is essential to achieving the intended lifetime. Several distinct zones need to be considered for corrosion protection, these are the atmospheric zone, the splash zone, the submerged zone and the buried zone (that part which is below the sea bed). Methods for corrosion protection include cathodic protection and corrosion protective coatings. Other methods for corrosion control, such as corrosion allowance and use of corrosion resistant materials, are important considerations in the design of foundations but are not covered in this section. Corrosion protection must also account for fabrication, transport and installation to avoid damage even before the wind turbine is operational. The corrosion protection system mitigates general and localised wall loss and is a prerequisite for attaining the fatigue of the structure. The external surfaces of the atmospheric and splash zones are normally coated with high performance marine coatings. Although the atmospheric zone coating can be accessible for repair, it is costly to repair any coating offshore, more so in the splash zone. For this reason, the coatings are combined with a design corrosion allowance to give maintenance-free service at least for the foreseen lifetime of the wind turbine. Cathodic protection systems are typically used to provide corrosion protection to the part of the foundation in the submerged zone. The application of a negative current to the steel structure reduces the voltage on the structure to a level at which oxidation, and hence corrosion, is suppressed. Galvanic anode cathodic protection systems (GACP) comprise a number of sacrificial anodes made of aluminium or zinc-based alloys that are fixed to the steel structure below the waterline. The more active

	alloy in the anodes is consumed in preference to the structural steel. This galvanic action provides a self-regulating current source that protects the structural steel and other metal components of the foundation. The zinc or aluminium bars can be designed to be replaced periodically to extend the useful lifetime of the corrosion protection. A variation of cathodic protection is the impressed current cathodic protection system (ICCP). This uses an external power source and rectifier to supply a negative current to the structure and a corresponding positive current to non-consumed anodes mounted adjacent to the structure. An ICCP is substantially lighter than GACP and causes less drag in the water than the numerous sacrificial anodes required by a traditional cathodic protection system. A reliable power supply and associated instrumentation is required, and the design needs to be robust enough to withstand possible damage from sea conditions such as waves and currents as well as from maintenance and operational activities. Unprotected structures, particularly embedded in the upper layers of the sea bed, may be subject to microbiological influenced corrosion related to naturally occurring bacteria. The resultant damage can reduce fatigue life of these areas. Reactions between the foundation, the sea and the sea bed material, together with reactions from the cathodic protection system can generate noxious gases, which will accumulate inside a monopile. The lower deck of monopiles will be sealed for the safety of maintenance technicians working above, whilst gas detection and ventilation systems may be used to monitor and safely vent the concentrations of the noxious gases. In closed internal compartments, such as in jacket tubes, which have been welded shut, corrosion may be mitigated by control of humidity or depletion of oxygen. The inside of a monopile is not considered to be a closed internal compartment.
What's in it	Paints and thermal metal spray coatings Zinc or aluminium based sacrificial anodes Impressed current cathodic protection systems

B.2.5 Scour protection	
Function	Scour protection prevents scour of the sea bed caused by the speed-up of water moving around the foundation, which safeguards the performance and integrity of the foundation.
What it costs	About £10 million for a 1GW wind farm.
Who supplies them (examples only)	Rock installation firms: Boskalis, Peter Madsen Rederi, Tideway (DEME Group) and Van Oord Offshore Wind. Scour mat suppliers: Naue, Norfolk Marine and SSCS.
Key facts	Scour is erosion caused by the presence of a structure changing flow patterns and increasing sediment transport locally around the structure. Scour is therefore an important factor for all foundation types. If sea bed material around the foundation is removed by the action of scour then: • For a monopile or jacket foundation, the loads from the turbines will be resisted by a shorter embedded length of pile in the sea bed. This will reduce the stiffness of the foundation and will reduce the maximum load the piles can withstand. • For a gravity base foundation, the foundation could rest on a smaller footprint, which increases the chances of leaning, or in the worst case, toppling. • For any foundation type, the action of scour will change the frequency response of the structure and may push it into closer to wave or blade driving frequencies, which would amplify loads and accelerate fatigue. The ground conditions have a consequential impact on the scour assessment and scour protection design. The particle size distribution and the strength are key considerations for both. Non-cohesive sediments (such as sand) do not resist scour whereas cohesive sediments (clay and silt) and bedrock are

	better able to resist it. Other key factors are waves, currents, water depth and the structure dimensions. All of these need to be considered when estimating scour depths. In non-cohesive sediments scour depth increases with pile diameter, with design scour depth applied as 1.3 times the diameter of the pile. Scour will therefore be a bigger problem with larger turbines, which require larger diameter piles to transfer loading into the ground. Depth of non-cohesive sediments is therefore very important in determining accurate scour depths as these inhibit scour. Jacket structures are expected to be less susceptible to scour due to the smaller diameters of the pile footprint. However, total scour around the foundation also needs to consider the spacing of the vertical legs and lower horizontal members. The rate of increase in scour depth slows with time until it reaches an equilibrium depth, typically within the first year. Once an estimate of the scour depth has been calculated, a decision can be made to design the foundation to cope with the scour estimate including an allowance for the scour depth, or design and install scour protection (which will prevent the scour from occurring). The additional cost of initial scour protection and repairs over time should be balanced against the cost of designing to cope with the anticipated level of scour. This highlights the importance of estimating the scour depth as accurately as possible. Routine monitoring is required in either scenario to monitor the scour depth development or the effectiveness of scour protection to avoid the risk of movement to the foundations structures. Crushed rock is most commonly used for scour protection. However, in some cases, rocks can sink into the sediment, and secondary scour around the scour protection can also occur which needs to be considered in the design. Alternatives to rock are available, for example concrete mattresses and geotextile sand containers. Options for installation of scour protection vary according to design and include pre-pile installation, post installation or a combination of the two. Scour protection, as well as the turbine structures, become habitats for a number of marine species. However, this may not always be seen as a positive impact as the habitats created, and thus the species inhabiting the habituates, are different to the baseline environment. In 2018, European scour researchers kicked off PROTEUS, a new EU Hydralab+ project, which aims to improve the design of scour protection around offshore wind turbine monopiles and future-proof them against the impacts of climate change.
What's in it	Rock or geotextile sand containers

B.3 Offshore substation	
Function	Offshore substations are used to reduce electrical losses before export of power to shore. This is done by increasing the voltage, and in some cases converting from alternating current (AC) to direct current (DC) The substation also contains equipment to manage the reactive power consumption of the electrical system including the capacitive effects of the export cables.
What it costs	About £120 million for a 1GW wind farm, considering an HVAC system.
Who supplies them (examples only)	Electrical components: ABB, CG Power, GE, Schneider and Siemens. Structure: Babcock, Bladt Industries, Chantiers de l'Atlantique, Harland and Wolff, Heerema, Hollandia, Navantia, SLP Sembmarine and Smulders. Systems integrators: Engie Fabricom, Iberdrola, Ørsted, Petrofac and Semco. Structural designers: Arup, Atkins, ISC and Ramboll.
Key facts	Substations are often delivered as one element of a contract to connect the wind farm generating assets to the onshore transmission grid. An HVAC substation topside (everything above the substructure) weighs between 1,200 and 3,000 tonnes. A 1GW wind farm is likely to have two or three substations. An HVDC substation topside weighs between 12,000 and 18,000 tonnes. A 1GW wind farm would only have one HVDC offshore substation but will often be connected to the turbines by several AC convertor stations which would transform the 66kV output from the turbines up to 132kV or higher to feed the HVDC substation. Developers typically work closely with their chosen supplier after the turbine has been chosen to optimise the transmission system as a key opportunity to reduce the cost of energy. By reducing the number of circuits, the substations need less switchgear and fewer transformers. This provides an opportunity to dispense with a substation or to reduce platform and foundation costs. Standardisation of substation design offers the potential to lower costs, although few developers have the project pipelines to justify the upfront costs. With the introduction of 66kV subsea cables, near shore wind farms up to 300MW can be built without an offshore substation A typical HVAC platform is about 25m above the sea and has an area of 800m². Typically, a single substation can support the input of about 500MW. In some circumstances, the greater cost of higher capacity cables can be offset by savings on substation hardware. Although many substations are not being used primarily as service platforms, they will still have a modestly equipped workshop and frequently a helideck. The offshore substation is ultimately owned and operated by a transmission operator (OFTO in the UK); although the wind farm owner has access and responsibility for the array cable entry and wind farm switchgear.
What's in it	Electrical system [B.3.1] Facilities [B.3.2] Structure [B.3.3]

B.3.1 Electrical system	
Function	The electrical system integrates AC power output from individual turbines and transforms voltage from for example 66kV to 275kV for export to onshore substation, else converts to DC for onward transmission.
What it costs	About £45 million for a 1GW wind farm.
Who supplies them (examples only)	ABB, GE and Siemens. Wind farm substation transformers: above plus Tironi.
Key facts	Offshore substations located more than 80-100km from the onshore substation may use HVDC to reduce transmission losses. Concerns about the reliability of offshore HVDC convertor stations, and the higher capital costs have led some developers to implement technology solutions to allow AC transmission to be used over longer distances. Some sites have used additional reactive power compensation equipment, located on offshore platforms part way along the offshore cable route, or in onshore substations close to the coast. Key components include: • HV switchgear sets to isolate and protect each array and export connection to the substation • Transformers (if AC) in order to transform to higher voltage for onward transmission. A typical offshore substation will have two or more transformers to improve availability. Transformers are oil cooled, requiring the use of fire and blast protection • Converters (if HVDC) in order to convert AC to DC for onward transmission • Passive and active reactive power compensation, typically large coils and power electronics, to improve stability of the local grid system • Earthing systems including lightning protection connecting electrical components and the substation structure • Cable trays, tracks, clamps and supports to protect electrical items.
What's in it	HVAC system [B.3.1.1] or HVDC system [B.3.1.2]

B.3.1.1 HVAC system	
Function	An HVAC system converts and transmits the electrical power generated by the wind turbines, at say 66kV AC, to the onshore substation through the export cables at say 275kV AC. Transformers in the onshore substation may increase the voltage further to say 400kV for connection to the onshore transmission grid.
Who supplies them (examples only)	ABB, Schneider Group and Siemens. Transformers: above plus Tironi.
Key facts	An HVAC transmission system, including the export cables and offshore and onshore substation, typically offers a lower lifetime cost (when also taking into account electrical losses) than the equivalent HVDC system for wind farms where the distance to the onshore substation is less than about 80-100km. The factors used in making the choice between HVAC and HVDC, however, are complex. HVAC electrical systems use standard technology and systems, which may be customised for use in a marine environment.
What's in it	HVAC switchgear Transformers Passive and active reactive power compensation

	Earthing systems Auxiliary electrical, control and monitoring systems Industrial waterproof enclosures Cable trays, tracks, clamps and supports to protect electrical items

B.3.1.2 HVDC system	
Function	An HVDC system converts and transmits the electrical power generated by the wind turbines, at 66kV AC, and transformed to say 132kV AC by AC convertor stations, to the onshore substation through the export cables at say 375 kV DC. Equipment in the onshore substation converts the voltage back to say 275kV or 400kV for connection to the onshore transmission grid.
Who supplies them (examples only)	ABB, GE and Siemens.
Key facts	An HVDC transmission system, including the export cables and offshore and onshore substations, typically offers a lower lifetime cost (when also taking into account electrical losses) than the equivalent HVAC system for wind farms where the distance to the onshore substation is greater than about 80-100km. The factors used in making the choice between HVAC and HVDC, however, are complex. HVDC systems use relatively new technology and systems which are custom designed for the transmission of high power, say over 750MW, over long distances. HVDC systems currently only operate point-to-point and require the use of a matched pair of converters at each substation (one onshore and one offshore).
What's in it	HV AC and DC switchgear Transformers Converters Passive and active reactive power compensation Earthing systems Auxiliary electrical, control and monitoring systems Industrial waterproof enclosures Cable trays, tracks, clamps and supports to protect electrical items

B.3.2 Facilities	
Function	Auxiliary systems that support the operation and maintenance of the substation and enable some wider wind farm maintenance activities.
What it costs	About £20 million for a 1GW wind farm.
Who supplies them (examples only)	Building monitoring systems (fire and gas detection, CCTV, access, security) suppliers include • Communications and networking: Atos, Cisco, Cobham Wireless, Motorola and Semco Maritime • Crane: Demag, Granada and Kenz Figee • Diesel generator: Aggreko, Caterpillar, Iveco, Midas and Mitsubishi • Fire and blast protection: Mech-Tools (steel) and SCS (composites) • Heating, ventilation and air conditioning: Heinen & Hopman, Oteac, and • Helicopter fuelling systems: Imenco Supply of general facilities is often local to assembly of the substation.
Key facts	Like any other complex industrial facility, this offshore building needs fire detection and suppression

	systems along with security, safety, communications and other monitoring systems. Fire and blast protection is required because the transformers contain oil and coolants and present a fire risk. They need to be protected from fires elsewhere on the platform. Siemens Offshore Transformer Module HVAC substation uses Ester as the transformer cooling system. This is a non-combustible, biodegradable fluid that has eliminated the need for active fire suppression. A standby generator is required to provide auxiliary power and lighting in the event of loss of connection to the onshore substation, and to provide power to restart and reconnect to the onshore substation. An on-board crane to lift from a service vessel typically has a load capacity of around three tonnes. Also required are a control room, health and welfare and refuge for visiting crews, clean and black water systems, fuel tanks, low-voltage power supplies, navigational aids and safety systems.
What's in it	Auxiliary electrical systems Monitoring systems Communication system Fire and blast protection systems Standby generator (normally for HVDC substations) Crane Control room & refuge Clean and black water systems (normally for HVDC substations) Fuel tanks (normally for HVDC substations) Heating, ventilation and air conditioning equipment

B.3.3 Structure	
Function	The structure provides support and protection for the electrical and other systems.
What it costs	About £60 million for a 1GW wind farm.
Who supplies them (examples only)	Structure: BiFab, Bladt Industries, Harland and Wolff, Heerema and McNulty Offshore. Helideck: Aluminium Offshore, Bayards and other suppliers to the oil and gas industry.
Key facts	The steel structure is complex, with many safety considerations and services incorporated. For a small substation, the foundation may be similar to a turbine foundation [B.2], but with a different loading pattern. For a large substation, distributed piles or a jacket is preferable. A helideck is generally specified to enable helicopter landing. Offshore helidecks are generally aluminium to minimise corrosion and weight. An accident during take-off or landing can result in hundreds of litres of jet-fuel spilling from ruptured fuel tanks so stringent safety regulations are in place with the requirement for an integrated fire-fighting system. The use of helicopters for crew transfer is an integral part of maintenance and service operations for some, but may only be used for emergency access or egress by others. Access by vessel is similar to that for a turbine.
What's in it	Helideck and/or heliwinch Steel structure

B.4 Onshore substation

Function	The onshore substation transforms power to grid voltage, for example 400kV. Where a high voltage DC export cable, the substation will convert the power three phase AC.
What it costs	About £30 million for a 1GW wind farm. This includes the buildings, access and security as well as electrical systems.
Who supplies them (examples only)	They are generally contracted to the same main contractor as the offshore substation [B.3].
Key facts	Many of the electrical components will be similar in specification to the offshore substation, but constraints on weight and space are not as critical. The substation will contain metering equipment to measure electricity exported to the grid. The area of the onshore substation is likely to be about 5ha for a HVAC system and 7.5ha for a HVDC system. The onshore substation is ideally located close to the offshore export cable landfall to limit the length of the onshore cable route, but it may be up to 60km from landfall. The onshore substation is often the first part of the wind farm to be built, about a year before offshore construction. In some cases, work may start ahead of final investment decision for the wind farm to mitigate the risk of stranded generation assets. Typically, they are two parts to the substation: the wind farm side owned by the offshore transmission owner (OFTO, in the UK) and the grid side owned by relevant grid operator (National Grid Electricity Transmission in England and Wales, SSE Networks or SP Energy Networks in Scotland, or Northern Ireland Electricity Networks). The wind farm part of the substation is much the larger, consisting of high voltage switchgear, transformers (to step up from the export cable voltage to grid transmission voltage (400kV), reactive power management systems and a building with a control room, office and storage. The grid-side substation may be an extension to an existing facility or a new one if this is not practical. The onshore substation is likely to be contracted to a supplier of transmission systems with a substantial amount of the work contracted to a civil engineering contractor.
What's in it	Buildings, access and security [B.4.1]

B.4.1 Buildings, access and security

Function	Buildings, access and security provide physical protection and security for the onshore electrical equipment that connects the wind farm to the onshore transmission network
What it costs	About £8 million for a 1GW substation.
Who supplies them (examples only)	Buildings: any provider with a suitable track record of constructing architect-designed industrial buildings can respond to a tender to construct the building and compounds. Access and security: industrial fencing, security including CCTV, access control systems, industrial LV systems, HVAC (short for heating, ventilation and air-conditioning) will be put out to tender and can be supplied by any pre-qualified supplier.

Key facts	The buildings and associated compounds will be custom designed to suit the specific technical and planning requirements of the project. For an HVAC substation, indoor space is required for housing some of the switchgear, monitoring systems and associated low voltage systems and welfare facilities for visiting technicians. Often about the same area of outdoor space is required for compounds for outdoor HV switchgear, termination of HV overhead lines, storage and car parking. For an HVDC substation, indoor space, typically at least two storeys high, houses the HVDC converter, monitoring systems and associated low voltage systems and welfare facilities for visiting technicians. Outdoor space is also needed for compounds for outdoor HV switchgear, termination of HV overhead lines, storage and car parking.
What's in it	Monitoring systems Auxiliary and low voltage system Welfare facility

B.5 Operations base	
Function	The operations base supports the operation, maintenance and service of the wind farm.
What it costs	About £3 million for a 1GW offshore wind farm.
Who supplies them (examples only)	The wind farm owner is likely to choose a local construction company for the construction of the operations base. Examples are Hobson and Porter, R G Carter Construction.
Key facts	The specification for an operations base depends on whether the owner has chosen a shore-based maintenance and service strategy (using crew transfer vessels) or an offshore maintenance and service strategy (using service operation vessels). For a shore-based strategy, the operations base consists of offices, warehousing, workshops, car parking and vessel berths. The total area of the site is likely to be about 8,000m^2. A 1GW wind farm with a shore-base strategy is likely to require up to 10 CTV berths. Fewer than this will be needed on a day-to-day basis but the owner will want to ensure that there is capacity to support peak turbine maintenance and service activity and for the use of balance of plant maintenance contractors. CTVs use purpose-built concrete pontoons with mooring, electrical and water systems and a fast fuelling system. One CTV needs a berth of about 30m. The berths are likely to be built ready for the construction phase before being reutilised for operation. For an offshore maintenance and service strategy, a base may be used to support several wind farms. Although, an SOV will only visit port every 14 or 28 days, the owner is likely to want a dedicated berth of about 100m. In theory, the administration of the wind farm does not need to be within the port but it is likely that owners will choose to locate it close to offshore operations.
What's in it	Warehouse Workshop Vessel berths

4. Installation and commissioning

I Installation and commissioning	
Function	All installation and commissioning of balance of plant and turbines, including land- and sea-based activity. For offshore activities, the process starts by transporting components from the nearest port to manufacture to either the construction port [I.7] or straight to site. Activities are complete at the wind farm construction works completion date, where assets are handed over to operational teams.
What it costs	About £650 million for a 1GW wind farm. This includes the installation of the balance of plant and turbines, offshore logistics as well as developers insurance, construction project management and spent contingency.
Who supplies them (examples only)	Installation: Suppliers listed in relevant sections below. Full engineer, procure, construct and install (EPCI) services: Boskalis, DEME Group (A2Sea, GeoSea and Tideway), Jan de Nul, MPI Offshore, Subsea 7 (Seaway Heavy Lifting, Seaway Offshore Cables) and Van Oord Offshore Wind.
Key facts	Today, the typical process for installation is to install the wind farm in the following sequence, with overlaps where possible: • Onshore substation and onshore export cables • Foundations • Offshore substations • Array cables • Offshore export cables, and • Turbines. The installation period for a 1GW wind farm is typically three years from the start of onshore works. Weather downtime is a key cost consideration for any offshore activity with a third of time often lost through waiting on weather. H_s is the most widely used measure of limitation offshore. In reality, this needs to be combined with wave periodicity, direction, persistence (the length and frequency of suitable weather windows), wind speed and direction and tidal flow to define the fraction of workable and non-workable days for different activities. Sites with deeper water and farther from shore are typically associated with more adverse weather conditions and higher weather downtime. Increases in the size of turbines and foundations have an impact on the weather downtime unless these are accompanied by developments in equipment and processes. The opportunity for innovation to reduce costs is substantial and increasing the operating range of offshore operations is key as this increases vessel utilisation and shortens project installation time. Already, the season for installation is being extended, even though this increases weather downtime. There can be considerable risk in introducing new processes and technologies to reduce weather downtime and demonstration will be difficult in some cases. A concern is that some innovations in installation aimed at reducing costs tend to push the boundaries of what can be achieved in adverse conditions. Addressing health and safety considerations need to remain a focus. Installation services are supplied on a day rate or lump sum basis, principally for the vessel or vessels and the crew and equipment onboard. Additional costs are fuel and harbour dues. Developers vary in strategy but contracts are usually let for the cable laying (separately for subsea export and array, and onshore), offshore and onshore substation installation, foundation installation and turbine installation. They may award a single EPCI but this has been less favoured in the UK, particularly by experienced developers that can manage the interface risks between packages.

What's in it	Foundation installation [I.1] Offshore substation installation [I.2] Onshore substation construction [I.3] Onshore export cable installation [I.4] Offshore cable installation [I.5] Turbine installation [I.6] Construction port [I.7] Offshore logistics [I.8]

I.1 Foundation installation	
Function	Foundation installation consists of the transport and fixing of foundation in position.
What it costs	About £100 million for a 1GW wind farm.
Who supplies them (examples only)	Boskalis, Fred. Olsen WindCarrier, GeoSea (DEME Group), Jan de Nul, Jumbo Offshore (transition pieces only), SAL Heavy Lift (transition pieces only), Saipem, Scaldis Salvage & Marine, SeaJacks, Seaway Heavy Lifting (Subsea 7), Swire Blue Ocean and Van Oord Offshore Wind.
Key facts	The process involved varies with the foundation technology employed. Offshore substation foundations may be installed in a similar way to turbine foundations but are substantially larger. *Monopiles* Monopiles may be installed from a jack-up vessel or a floating vessel. The transition piece is usually lifted and grouted or bolted in place from the same vessel but two-vessel strategies have been used successfully. Monopiles (up to 10m diameter) are generally moved into position using the main crane and upending tool and held in position by a gripper tool. They are the driven into the sea bed using a hammer and anvil system before mounting and grouting transition pieces. Transition pieces are usually carried and installed by the same vessel, although a two-vessel strategy in which transition pieces are installed by a separate vessel has been used on several occasions. This focuses the utilisation of the monopile installation vessel, which is likely to have higher day rates than the transition piece vessel. A disadvantage is the costs of mobilising and demobilising two vessels. Feeder strategies have been used for monopiles, notably with Van Oord's *Svanen*, which has no useable deck space for transporting components. In this case, the monopiles are floated to site using tugs or transported using platform supply vessels. An approximate timetable for installation once at the wind farm site is: • Transport and positioning: 2 hours for floating vessels; 4 hours for jack-ups • Preparations: 1 hour • Lifting and pile positioning: 1 hour • Driving: 6 hours, and • Grouting: 2 hours. The full cycle time is 2-3 days per monopile, a figure that takes into account mobilisation and demobilisation, loading and waiting on weather. Under some ground conditions, monopiles are grouted into a pre-drilled rock socket. Under conditions with boulders, a combination of drilling and driving is required. *Jackets* Jacket foundations may be installed by floating vessels or jack-ups. Installation usually involves pre-piling using a reusable template. The jacket is then lowered into place over the pin piles and grouted. Post-piling, in which the pin piles are driven (or lowered into pre-drilled sockets) through a sleeve on the jacket legs, may alternatively be used. Pre-piling has the advantage of decoupling the piling and jacket installation, enabling a lower cost vessel to be used for piling and maximising the use of deck space of the main jacket installation vessel. An approximate timetable for installation once at the wind farm site is: • Transport and positioning: 2 hours for floating vessels; 4 hours for jack-ups • Preparations: 1 hour • Lifting and pile positioning: 4 hours • Driving: 8 hours, and • Grouting: 2 hours.

	The full cycle time is 3-5 days per jacket, a figure that takes into account mobilisation and demobilisation, loading and waiting on weather. Under some conditions, suction buckets may be used as the sea bed connection. This technology offers potentially lower installation costs because less equipment is needed. Suction buckets have been deployed commercially with jacket foundations but can be used with monopiles as well. *Gravity bases* Gravity base foundations may be installed by floating crane vessels (such as a sheerleg crane vessel) or specialist barges to support float out. Concrete gravity foundations can weigh substantially more (3,000 tonnes) than steel foundations and may be floated out to position before being submerged. The sea bed must be levelled to receive such foundations. Large scale installation of gravity bases has not been attempted in UK waters. Cycle times are likely to be similar to jackets, but floating transportation can result in considerably more weather downtime and requires more onshore manufacturing space. *Floating foundations* The installation strategies for floating foundations are still evolving and will vary with the specific foundation concept. In general, the aim will be to install the turbines on the foundations at the quayside or in sheltered waters before being towed to site and moored to pre-installed anchors. *Scour protection* Scour protection is generally provided by dumping of rocks or bags of stones or other materials (such as tyres) around the base of the structure. Rock dumping may use a fall-pipe vessel that are widely used in the dredging industry. Bags are likely to be lowered into position using an offshore construction vessel.
What's in it	Foundation installation vessel [I.1.1]

I.1.1 Foundation installation vessel	
Function	The foundation installation vessel transports the foundations from the quayside fabrication facility or construction port [I.7] to the site and secures them to the sea bed. Heavy lift vessels, floating sheerleg vessels and self-propelled jack-up vessels are all used.
What it costs	Day rates for high specification floating heavy lift vessels are likely to be about £200,000, depending on market conditions and the vessel type. Rates exclude specific foundation installation equipment and investments (for example hammers, pre-piling templates).
Who supplies them (examples only)	Operators: Boskalis, Fred. Olsen WindCarrier, GeoSea (DEME Group), Jan de Nul, Jumbo Offshore, SAL Heavy Lift, Saipem, Scaldis Salvage & Marine, SeaJacks, Seaway Heavy Lifting (Subsea 7 Group), Swire Blue Ocean and Van Oord Offshore Wind. Vessel manufacturers: as for turbine installation vessels [I.6.1].
Key facts	The foundation installation vessel fleet has overlapped with the turbine installation fleet in the past but the fleets are diverging due to the increasing size and mass of components and the relative merits of jack-ups and floating heavy lift vessels. Foundation installation has made considerable use of vessels originally built for other sectors, including oil and gas, bridge building and near-shore construction. With the mass of monopiles increasingly exceeding 1,000t, few jack-up vessels have the necessary lifting capacity. With the jacking process lasting several hours and the lower weather sensitivity of the installation process (compared with turbine installation), a floating installation vessel has notable advantages. Disadvantages have been the relatively high charter rates and low availability of heavy lift vessels with a

	maximum crane capacity of 1,500t or greater. The recent investments in heavy lift vessels for the offshore wind market by Boskalis and GeoSea are considerable. A typical specification for a latest generation heavy lift vessel is: • Length: 260m, beam: 50m, draft: 12m • Crew berths: 150 • Crane: 2,000 tonnes • Maximum transit speed: 14 knots • Component capacity: Up to 7 foundations, and • Dynamic positioning system. Jacket foundations are typically lighter than monopiles and the choice of vessel is driven by a number of factors including deck space and lift capacity. Installation using jack-ups is affected in particular because the position of the legs limits the flexible use of deck space. One of the advantages of three-legged jackets is that they enable better use of deck space. There is growing interest in suction bucket foundations, particularly under jackets. These are potentially faster and therefore cheaper, to install and avoid the need for expensive noise mitigation.
What's in it	Foundation handling equipment [I.1.1.1] Foundation installation equipment [I.1.1.2] Sea fastenings [I.1.1.3] Crane Auxiliary cranes Dynamic positioning system Propulsion systems Jack-up system Spud cans Helideck Gangway

I.1.1.1 Foundation handling equipment	
Function	Foundation handling equipment is used to manoeuvre the foundations into position before driving them into the sea bed.
What it costs	The crane, upending frame, pile gripper, pile guiding positioning frame and monopile plug are part of the contractor's equipment. As for the lifting tools, these are usually rented and cost about £10,000 per day.
Who supplies them (examples only)	Suppliers include IHC IQIP, Houlder and Temporary Works Design.
Key facts	Monopiles are transported in the horizontal position. A lifting tool grips a flange at the top of the monopile, to which the crane hook is secured. The base of the monopile is gripped by an upending frame while the monopile is raised into the vertical position. The crane then lifts the monopile and moves into position for piling. A pile guiding and positioning frame is used to position the monopile accurately and ensure verticality. The pile must be installed within 0.25° of vertical. If a floating vessel is used for piling, a motion-compensated pile guiding and positioning frame may be used. If the monopile is floated out to site, a monopile plug is used to maintain buoyancy and provide a towing

	point. Jackets are transported in the vertical position if a heavy-lift vessel with deck space is used. If the jacket is to be installed in relatively benign conditions, a sheer leg crane vessel may transport a single jacket to site from port. Equipment may be designed and built for a specific project or installed more or less permanently on the vessel with the flexibility to be used for a range of different projects. Equipment may be owned or rented by the installation contractor.
What's in it	Crane Lifting tool Upending frame Pile gripper Pile guiding and positioning frame Monopile plug

I.1.1.2 Foundation installation equipment	
Function	Foundation installation equipment is used to secure the foundation to the sea bed.
What it costs	If rented, the rate is about £50,000 per day for all the equipment and third party crew to operate, but excluding other rental rates for bolting tools or grouting spread, generators, survey equipment and ROV.
Who supplies them (examples only)	Piling equipment: Cape Holland, Fistuca, IHC IQIP, Menck and PVE. Noise mitigation: IHC IQIP and W3G Marine.
Key facts	Vessels have a range of onboard tooling, depending on type of foundation to be installed. For monopiles, on-board hammer and anvil systems are used to drive the piles. On-board drilling systems are used where hammering is not possible due to ground conditions or environmental restrictions. In such conditions, monopiles are then grouted into position. A hammer and anvil system may be rated up to 4,000kJ and deliver 30-60 impacts per minute via a steel ram. Hammers can pile up to 9m diameter piles. Larger piles may be tapered at the top to avoid any constraint. A novel system in development is the use of a water column to drive the pile. The reported benefits are lower noise, fewer moving parts and less installation fatigue. Vibro piling has also been trialled and offers the potential of less noise and faster, lower impact piling. Turbine locations are typically chosen to avoid areas where piling is likely to be problematic. For some sites, a vessel will be mobilised with drilling equipment to mitigate the risk to the project schedule in cases of pile refusal. For pre-piled jackets, a reusable piling template is lowered to the sea bed and the pin piles hammered into the sea bed using the same process as for monopiles. There is concern about the ecological impact of pile driving on marine mammals and the harbour porpoise in particular. Piling restrictions have been most common in Germany and the Netherlands. There are three approaches to minimising the environmental impact of piling: avoidance, deterrence and mitigation. For avoidance, the aim is to choose foundation technologies (for example, jackets or suction piles) and installations strategies (for example, timing or vibro piling) that have reduced impact. For deterrence, the aim is to displace animals from areas of high noise levels by means of a ‘soft start’ or

	using a deterrence device. ‘Pingers’ emit aversive sounds into the marine environment for about 40 mins before piling. ‘Seal scarers’ are similar but emit higher density sounds for about 30 mins before piling. The two main mitigation technologies are bubble curtains and noise mitigation screens. Other approaches are foam-wrapped piles, hydrosound dampers and resonator systems. Mitigation systems are expensive both in terms of equipment and time and there has been a large amount of research to understand the enduing impacts of piling on marine mammal populations. Projects may monitor impacts during installation as part of this activity.
What's in it	Hammer Anvil system Noise mitigation equipment

I.1.1.3 Sea fastenings	
Function	Sea fastenings are used during the transport of heavy and costly components from the construction port [I.7] to site.
What it costs	Included in installation subcontract cost.
Who supplies them (examples only)	Suppliers include AIS, ALE, Durham Sheet Metal, ESG MC Construction, Semco Maritime and Temporary Works Design.
Key facts	Sea fastenings are typically designed and fabricated specifically for a project, although there is increasing interest in reusable sea fastenings that reduce cost of design and manufacture of the sea fastenings and shorten mobilisation time. Turbine component sea fastenings are well suited to this approach because the dimensions do not vary substantially for a particular turbine model. Sea fastenings are typically welded steel structures that are welded to the vessel deck during mobilisation. They have locking devices to ensure safe transit and rapid release at the installation site.
What's in it	Monopile cradle Transition piece cradle Crane sea fastening

BVGassociates

I.2 Offshore substation installation	
Function	The installation of the offshore substation consists of the transfer of the substation from its quayside fabrication site and the installation on the foundation.
What it costs	About £35 million for a 1GW offshore wind farm.
Who supplies them (examples only)	The installation often forms part of the substation supply contract. Marine contractors include Boskalis, Saipem, Scaldis Salvage & Marine, Seaway Heavy Lifting (Subsea 7 Group).
Key facts	Offshore substation installation is a heavy lift operation (2,000t plus) requiring vessels with sufficient crane capacity. Vessels with the necessary lift capacity typically do not have the deck space to accommodate a substation platform. The substation is therefore floated out of the substation fabrication facility on a barge, usually directly to the wind farm site. The substation foundation, which is installed prior to the topside structure, may be a monopile or a jacket and the installation may form part of the turbine foundation installation package.
What's in it	Substation installation vessel [I.2.1]

I.2.1 Substation installation vessel	
Function	The substation installation vessel allows the transport and lift of offshore substation, in order to position it on pre-installed foundation.
What it costs	Included in the substation installation contract. Day rates for most substation installation vessels are about £180,000. Semisubmersible vessels may typically have day rates greater than £450,000 but if the oil and gas market is quiet then rates may be more competitive.
Who supplies them (examples only)	Operators include Bonn & Mees, DBB, Huisman, Saipem, Scaldis Salvage & Marine and Seaway Heavy Lifting (Subsea 7 Group).
Key facts	Four main types of vessel may be used: • Sheerleg crane vessel • Barge • Heavy lift vessel, and • Semisubmersible vessel. The choice of vessel is likely to be driven by market factors and, in many cases, the vessels serve other markets. As a result, there has been little investment in vessels for the offshore wind market specifically. Heavy lift vessels used in offshore wind include *Rambiz*, *Stanislav Yudin* and *Samson*. Crane ratings are from 900 tonnes to over 3,000 tonnes.

What's in it	Crane Auxiliary cranes Dynamic positioning system Propulsion systems Helideck Gangway

I.3 Onshore substation construction	
Function	The construction of the onshore substation consists of the construction of the infrastructure and the installation of electrical equipment.
What it costs	About £25 million for a 1GW wind farm.
Who supplies them (examples only)	Balfour Beatty, J Murphy and Jones Bros.
Key facts	Enabling works to level the site and provide road access are completed early, to ensure that the work can begin promptly. They may also address constraining features of the site, such as the existence of overhead power lines or underground pipes. Subcontracted work may include fencing, curbing, tree cutting and the demolition of existing structures. This work may form part of the main civil construction contract. The civil contractor will typically work to an engineering design supplied by the main contractor. About 20-25% of the work will be subcontracted, including steelwork, flooring, fencing and sealing roads and car-parking areas, access tracks, gravel paths and hard-standing. Local suppliers will generally be used unless there are specialist requirements, as they have valuable knowledge of local contractors and good contacts in the local authority and Environment Agency office. Contractors will recruit local operatives and hire local equipment if they are operating at large distances from their fleet's base. Electrical works and commissioning will typically be led by the main electrical supplier but substantial work is likely to be subcontracted to a high voltage electrical contractor.
What's in it	Civil works Electrical works

I.4 Onshore export cable installation	
Function	The installation of the onshore export cable completes the connection between the offshore export cable and the onshore substation.
What it costs	About £5 million for a 1GW wind farm, depending on distance and complexity of route.
Who supplies them (examples only)	Various construction companies such as Balfour Beatty, J Murphy and Sons.
Key facts	The subsea cables terminate a short distance inland at the transition joint bay. This could be located on the beach, behind a sea defence, or up to 1km inland. Onshore cabling is generally underground to address local concerns over the siting of overhead power lines. There are a range of local services used before and during the cable installation. These include wheel washing, road cleaning, traffic management, signage and temporary bridges over rivers and ditches. At least one site compound will be established along the cable route. These sites will provide equipment storage, car parking and welfare facilities for staff. Typically, they will be 100m by 100m in size. Before construction, site investigation and environmental work is undertaken to plan the installation and minimise impact on the surroundings. A cable corridor is used during installation, which comprises the cable trench, storage for spools and access road. Installation can be carried out using open trenches, typically around 1 metre wide and up to 1,000 metres in length (depending on the cable) or by placing ducts into the trenches and covering them over more quickly. With ducting, it is typical to use medium density polyethylene (MDPE) ducts which are laid in the trench and the cable pulled through the ducts at a later time in up to 1,000m lengths. This option allows excavation, duct installation and backfilling to be completed in sections of up to 120m in a day. This minimises the amount of excavation left open outside working hours, which can help reduce environmental, and safety concerns. Where the cable crosses obstacles such as roads or railways or encounters difficult or highly sensitive conditions, directional drilling may be used to route and pull the cable under the obstacle without the need for trenching. Specialist drilling equipment creates a bore that passes the obstacle and can be up to 1,000m in length. Drilling mud is used as lubrication and this is recycled through a temporary mud lagoon during construction and disposed of after construction. Once drilled, a cable duct is then pulled through and the cable is then pulled through again using specialist equipment. The cable is tested to ensure a complete circuit is in place. Once fully installed, an energised test is carried out to verify operation at or close to the intended voltage. Care is taken to reduce the impact on endangered species, including species such as newts, bats and dormice, which might require specialist environmental monitoring and/or mitigation.
What's in it	Drilling equipment Trenching equipment Cable-laying equipment

I.5 Offshore cable installation	
Function	The installation of array cables enables the connection of the wind turbines to the offshore substation whilst the installation of the export cable enables the connection between the offshore and onshore substations.
What it costs	About £220 million for a 1GW wind farm. This includes cable-laying vessel, cable burial, cable pull-in and electrical testing and termination as well as survey works, route clearance and cable protection systems.
Who supplies them (examples only)	Marine contractors: Boskalis, DeepOcean, Global Marine, Jan de Nul, Prysmian, Seaway Offshore Cables (Subsea 7), Tideway (DEME Group) and Van Oord Offshore Wind.
Key facts	Cable installation activities are preceded with a survey to define the route and identify any UXO. This is followed by a pre-lay grapnel run (or alternative method) to clear debris from the cable route. All offshore cable installation (export and array cables) involves the following activities: • Cable lay • Cable burial • Cable pull-in (to turbine, substation or shore), and • Electrical testing and termination. There are different strategies involving one or two vessels, and the chosen approach depends on sea bed conditions and equipment available to the contractor. Pre-trenching and simultaneous lay and burial using a cable plough [I.5.2.2] is often preferred if the soil is suitable as immediate burial and protection is obtained in a single pass which reduces costs. In other cases, a two-stage process may also be used where the cable is laid on the sea bed, after which a vessel with trenching ROV [I.5.2.3], vertical injector or jetting sled [I.5.2.4], undertakes the burial. Export cable installation starts with the shore pull-in (first-end pull-in). The installation vessel then moves off, laying the cable as it goes. Export cables are laid in as long sections as possible, of up to 70km in length, to avoid expensive subsea joints. At the substation, the cable will be either set down and wet-stored for subsequent pull-in to the substation, or immediately installed by the cable-lay vessel, which is preferred. A more detailed description of this in provided in the cable pull-in box [I.5.3]. Array cable installation starts with the first-end pull-in at the substation (subsequent first-end pull-ins are done at each turbine). Array cables are usually installed in a spider arrangement with a series of strings of turbines connected to the substation or in a series of loops (strings connected together away from the substation). Strings of turbines may be 6 to 10 turbines long, depending on cable size and turbine rating. The cables may be carried as a single length then cut offshore, or pre-cut. Using pre-cut lengths can save time offshore but because turbine spacing is not uniform, it limits the order in which the cables are installed. This can lead to important delays if there is a problem at one of the turbine locations. Cables are typically buried to 1-4m below sea bed to ensure long-term cable integrity and to prevent damage, for example by fishing vessels, ship anchors or sea bed movement. The required burial depth is based on a cable burial risk assessment (CBRA) (and a burial protection index (BPI)). For more details on cable burial, see [I.5.2]. Cable protection typically falls within the installer's scope of work. This consists of bend restrictors or stiffeners to limit fatigue loading on the cables and cable entry systems that lock and seal the cable as it enters the foundation. Other techniques like rock dumping and mattresses are also used to ensure burial and protection on cable crossings. Export cable manufacturers usually subcontract the cable installation; however, companies are increasingly investing in their own fleet (for example Nexans and Prysmian). For array cables, it is usually the cable installation contractor that subcontracts the cable manufacturing.
What's in it	Cable-laying vessel [I.5.1]

	Cable burial [I.5.2] Cable pull-in [I.5.3] Electrical termination and testing [I.5.4]

I.5.1 Cable-laying vessel	
Function	The cable-laying vessel lays the cables between the wind turbines and offshore substation and between the offshore and onshore substation.
What it costs	Included in the offshore cable installation contract. A typical day rate for a cable-laying vessel is about £90,000.
Who supplies them (examples only)	Marine contractors include Boskalis, CWind (Global Marine Group), DeepOcean, Jan de Nul, Seaway Offshore Cables (Subsea 7), Tideway (DEME Group) and Van Oord Offshore Wind.
Key facts	The same vessels may be used for export and array cable installation, although export cable-laying vessels will typically have larger carousels to accommodate longer cables. The vessels may need to have a shallow draft to install the cables in shallow water. Simultaneous lay and burial can be carried out with a variety of burial tools. In that case, the cable is buried during the lay to obtain immediate protection. Otherwise, a post-lay burial is required. See [I.5.2] for more details on cable burial. Cable-laying vessels are characterised as follows: • Up to 30m (breadth) by 140m (length) and can operate at a speed up to 14kn (transit speed). • Accommodation for a crew of up to 90. • The current capacity of carousels is of up to 7,000t. Some contractors offer vessels with a double carousel (for example Jan de Nul's *Isaac Newton*). • Likely to be equipped with a 3D motion compensated crane with up to 25t and a 25t A-frame. • Generally equipped with a personnel transfer gangway (for example Ampelmann system) and a helideck.
What's in it	ROV [I.5.1.1] Cable-handling equipment [I.5.1.2] Crane Personal transfer gangway

I.5.1.1 ROV	
Function	ROVs have many uses including visual inspections of subsea structures such as cable entry locations on foundations or cable routes, feeding the cable through the J-tubes and monitoring operations such as grouting of piles.
What it costs	Included in the installation contract.
Who supplies them (examples only)	ROVs are usually provided offshore contractor. Manufacturers include Forum Energy Technologies, Louis Dreyfus Travocean, Saab Seaeye and SMD.
Key facts	ROVs are generally used not only to monitor the subsea structures but also to assist the laying and pull-in

	of the cables during which they carry out a touchdown monitoring. Cable installation contractors usually seek to avoid using ROVs to minimise costs. In deeper water, the use of ROVs avoids the high costs associated with the use of divers to work at depths requiring specialist equipment and extended decompression.
What's in it	Propulsion system Control system Remote camera Lighting system Power supply Manipulator arm

I.5.1.2 Cable-handling equipment	
Function	The cable-handling equipment ensures that the cable is safely deployed from the vessel to the sea bed.
What it costs	The equipment is usually provided by the cable installation contractor; in that case, it is either part of the vessel or can be rented. Typical day rates for a 2.5t carousel used for array cables are about £4,500.
Who supplies them (examples only)	Cable-handling equipment is usually provided by the cable installation contractor; in that case, it is either part of the vessel or must be mobilised. Manufacturers: Aquatic, Ecosse Subsea, Fraser Hydraulic Power, Hulst Cable Equipment, Royal IHC, MacArtney and Sparrows. Rental: Caley Ocean Systems, CWind (Global Marine Group), Demanor, Drammen Yard, Ecosse Subsea, Osbit, RentOcean and Sparrows.
Key facts	Cable handling equipment is designed to protect the cable's integrity and to ensure the cable is deployed in a controlled manner and at the correct speed. The cable is stored either on a carousel, in a static tank or on a reel. To exit the storage area, a tensioner is used to grip and move the cable toward the chute where the cable is deployed onto the sea bed whilst ensuring no bending at less than the minimum allowed bend radius. During a second-end pull-in or pull-in at the substation, a quadrant is used to deploy the end of the cable on the sea bed before it is pulled in.
What's in it	Cable storage: carousel, tank or reel Cable lay equipment: tensioners, cable highway (rollers), chute and quadrant

I.5.2 Cable burial	
Function	The cable is buried to a predefined depth under the sea bed to ensure protection from external aggression (for example fishing and anchoring) as well as to prevent exposure due to sea bed mobility.
What it costs	About £50 million for a 1GW offshore wind farm.
Who supplies them (examples only)	The burial and burial tools are usually provided by the cable installation contractor. Vessel contractors: Assodivers, Boskalis, Canyon Offshore (Helix ES), Global Marine, Jan de Nul and Van Oord Offshore Wind.

	Manufacturers include Canyon Offshore (Helix ES), Osbit, Royal IHC and SMD.
Key facts	Burial can be achieved either at the same time as the lay of the cable (simultaneous lay and burial) or afterwards (post-lay burial). If the former method is used, a cable plough [I.5.2.2] is used simultaneously during the cable lay to create a trench in which the cable falls and is immediately buried. In the case of a post-lay burial, the vessel will move along the laid cable, using a trenching ROV [I.5.2.3] or vertical injector or jetting sled [I.5.2.4] to fluidise the sediment and allowing the cable to be buried. Burial depths are determined based on an industry standard (burial protection index and/or cable burial risk assessment). Generally, cables are buried at a depth of 1-4m below the sea bed.
What's in it	Cable burial vessel [I.5.2.1] Cable plough [I.5.2.2] Trenching ROV [I.5.2.3] Vertical injector [I.5.2.4]

I.5.2.1 Cable burial vessel	
Function	The cable burial vessel undertakes cable burial post laying of the cable on the sea bed.
What it costs	These costs are usually included in the cable burial contract. A typical day rate for a cable burial vessel is about £95,000.
Who supplies them (examples only)	Cable burial vessels are provided by a number of offshore vessel operators such as Canyon Offshore (Helix ES), Global Marine and Van Oord Offshore Wind.
Key facts	Burial vessels vary in size based on the required burial tools to be mobilised and the water depth. Generally, most types of vessels can be utilised as long as burial tools can be mobilised. Dynamically positioned vessels are generally used although barges may be used in shallower waters in the case of near-shore burial work. Post-lay burial is undertaken using a trenching ROV [I.5.2.3]. Vertical injectors [I.5.2.4] can also be used.
What's in it	Crane or A-frame Personnel transfer gangway Burial tools and equipment

I.5.2.2 Cable plough	
Function	A cable plough is normally used to simultaneously lay and bury a cable but it can also be used in post-lay burial and pre-trenching.
What it costs	The provision of the cable plough is usually part of the cable installation contract scope. When hired, a typical day rate for a cable plough is about £5,000.
Who supplies them (examples only)	The cable plough is usually provided by the cable installation contractor, either as part of the vessel or mobilised specifically. Manufacturers: ETA Subsea Specialists, Osbit, Royal IHC and SMD. Rental: ETA Subsea Specialists and Pharos Offshore.

Key facts	Cable ploughs can bury the cable down to 3-4m below sea bed level. The plough will require a tow force to pull the plough through the soil depending on the soil conditions and the required burial depth. Using a barge (for shallow water operations), this force is supplied by an anchor or a tow tug. For a dynamically positioned vessel, a specialist vessel with an appropriate bollard pull is required. It is often not possible to plough close to the turbine or substation. In that case, a trenching ROV [I.5.2.3] may be used.
What's in it	Plough share High pressure jetting nozzles Skids Bell mouth Cable depressor

I.5.2.3 Trenching ROV

Function	A trenching ROV forms a trench in which to bury the cable. This tool is generally used in post-lay burial but can be used during simultaneous lay.
What it costs	The provision of the trenching ROV is usually part of the cable installation contract scope. When hired, a typical day rate for a trenching ROV is about £10,000.
Who supplies them (examples only)	The trenching ROV is usually provided by the cable installation contractor, either as part of the vessel or mobilised specifically. Manufacturers: Forum Energy Technology, Louis Dreyfus Travocean, Osbit, Royal IHC, SIMEC and SMD. Rental: Dockstr, Ecosse Subsea and James Fischer Marine Services.
Key facts	ROVs can have either a jetting system or a mechanical cutter. A high pressure jetting system is used to fluidise the sea bed and allow the cable to sink to the required depth (only in sandy sediments and softer clays). For rocky or hard clay sea bed conditions, a mechanical cutter is used.
What's in it	Pressure and flow water jetting system and/or mechanical cutter Power supply and control system Propulsion system Camera and lighting system Sonar Cable tracker

I.5.2.4 Vertical injector and jetting sled

Function	Vertical injectors and jetting sleds are used to bury the cable where the sediment can be fluidised (for example sand, soft clays). Vertical injectors are used for simultaneous lay and burial of the cable. Jetting sleds are mostly used for post-lay burial.
What it costs	The provision of the vertical injector or jetting sled is usually part of the cable installation contract scope. When hired, a typical day rate for a vertical injector is about £10,000 and £8,000 for a jetting sled.
Who supplies them (examples only)	The vertical injector or jetting sled is usually provided by the cable installation contractor. Manufacturers: Miah, Royal IHC and Seatools. Rental: ETA Subsea Specialists, Global Marine and Modus.

Key facts	Vertical injectors can bury the cable down to 10m below sea bed level using a high pressure jetting system in soft sediment. They are generally fixed on the side of the vessel. A vertical injector is made up of a header and extension section as well as a burial section, the shoe injector, which contains the jetting nozzles. Jetting sleds can bury the cable down to 4m below the sea bed. They are usually equipped with a hydraulic actuation system that ensures the cable is buried at the required depth. An eduction system allows the removal of excess material in the trench once the fluidisation has been carried out. Jetting sleds are deployed using a crane and can therefore be mobilised on a large range of vessels.
What's in it	Shoe injector High-pressure jetting nozzles Cable depressor detector Pressure sensors Skids Positioning system receptor

I.5.3 Cable pull-in

Function	For the array cable, the pull-in consists of the pulling of the cable into the substation or turbine foundation. For export cables, the pull-in consists of pulling the cable to shore as well as into the substations.
What it costs	About £8 million for a 1GW offshore wind farm.
Who supplies them (examples only)	The cable pull-in is usually provided by the cable installation contractor (see [I.5]).
Key facts	The installation of the export cable starts with the beach pull-in. During this, the cable vessel is anchored offshore and the cable winched on floats or through a pre-laid duct to the onshore transition joint pit, where it will eventually be jointed to the onshore cable. The installation vessel then moves off, laying the cable as it goes. Depending on the landfall site, some projects require horizontal directional drilling (HDD) which may extend to the first short length of burial offshore. In other cases, the cable may be transferred to a third party shallow draft barge or amphibious vehicle to bring the cable to shore. At the offshore substation, the cable will be either set down and wet-stored for subsequent pull-in to the substation, or immediately installed by the cable-lay vessel, which is preferred. It may however be necessary to wet store the cable if for example the substation is not installed yet or if the lay vessel is not equipped to conduct the second-end pull-in at the substation. The installation of each string of array cable starts with the pull-in at the substation. The second-end pull-in consists of pulling the cable into the turbine foundation transition piece. After this, the crews pull in the first end of the next cable at the wind turbine location: a messenger wire is used so that the ROV finds the cable entry hole at the base of the foundation; the cable is then pulled up into the foundation. The vessel then moves off to the next location, laying the cable as it goes and pulling it in once it arrives at the following location. For second-end pull-ins, a quadrant is generally used.
What's in it	Barge Amphibious vehicle ROV Messenger wire J-tubes Horizontal directional drilling Winches Quadrant Floats

I.5.4 Electrical testing and termination	
Function	The electrical testing is designed to test and prove cable integrity whilst the termination enables the electrical connection between the offshore cable and either the wind turbine, the substation or the onshore cables.
What it costs	About £10 million for a 1GW offshore wind farm.
Who supplies them (examples only)	The electrical testing and termination is usually provided by the cable installation contractor (see [I.5]). Manufacturers of electrical testing equipment and termination tools: Baur, Megger Pfisterer, Tekmar and WT Henley.
Key facts	After the cable is pulled into the substation or wind turbine, a hang-off clamp is fitted and the cores of the cables are stripped back and connected to a termination plug. The plug will then be interfaced into a designated junction box or switchgear using a connector. A similar procedure is conducted for the fibre optic cable. Prior to the termination, a series of electrical tests are performed to prove the cable's electrical integrity. These include very low frequency (VLF) tests, insulation resistance (IR) tests, time-domain reflectometry (TDR) tests and optical time-domain reflectometry (OTDR). After the cable is pulled into the transition joint bay on shore, it is terminated at the beach joint.
What's in it	Test and diagnostics device Connection cables Power supply Termination plug Cable trays Hang-off clamp

I.6 Turbine installation	
Function	Turbine installation involves transportation of the turbine components from the construction port [I.7] and installation of the turbine components onto the foundation.
What it costs	About £50 million for a 1GW wind farm.
Who supplies them (examples only)	A2Sea/GeoSea (DEME Group), Fred. Olsen WindCarrier, Jan de Nul, MPI Offshore, Seajacks, Swire Blue Ocean and Van Oord Offshore Wind.
Key facts	Installation methods vary depending on the turbine supplier and the relative size of turbine and vessel. Installation methodologies aim to reduce as far as practical offshore operations. Typically, the turbine tower is pre-assembled onshore and transported with the nacelle and blades for final assembly offshore. Three variations in the rotor installation process have been used repeatedly: • Placing the nacelle on the tower then lifting the pre-assembled rotor in one piece to mate with the nacelle (a single rotor lift) • Mounting the hub and two blades on the nacelle "bunny ears" at port, before mounting the nacelle on the tower onsite and then fitting the final blade, and • Placing the nacelle plus hub on the tower then lifting individual blades to mate with the hub, turning the rotor each time to repeat the same lift three times. The third method is current preferred practice, even though this involves more offshore operations. Tower sections are typically preassembled onshore with any internal components and the completed structure is transported vertically to site for installation. Offshore turbine installation is undertaken by jack-up vessels due to the need for a stable platform to perform offshore lifting operations and mating of components at height. The installation of a turbine from positioning the vessel at the site to departure takes about 24 hours, depending on location and weather conditions. The cycle time is between 1.5 and 4 days, depending on the project (factoring in mobilisation, demobilisation, loading and waiting on weather). A constraint during transportation and installation is the acceleration limit defined by the turbine supplier to avoid damaging the turbines and invalidating warranties. This is typically about 0.5g. Blade installation is constrained not only by the operating range of the vessel but also the wind speeds, and the limit has been gradually increased with innovations in blade lifting equipment. The current maximum is normally 13m/s at hub height and any increases beyond this may be limited by health and safety risks. Whole turbine installation, in which the complete turbine, including the tower, is assembled onshore, then transported and lifted into place on the foundation, reduces the number of offshore lifts as well as avoiding much of the offshore commissioning process. A number of new concepts are in development. The approach is most commonly associated with concrete gravity bases. The concepts typically involve the investment in a bespoke vessel. Due to the considerable improvements in the installation time when using conventional approaches by the turbine suppliers, the business case for full turbine installation is less strong. There has also been slow progress in the commercialisation of deep water gravity base foundations. A step change in turbine installation could be achieved through the use of floating vessels for turbine component installation, which could shorten installation times further. The movements of the lifting hook at hub heights greater than 110m on a floating vessel have the potential to be substantial, however. Progress on floating installation methodologies will depend on collaboration between turbine suppliers and installation contractors. Turbine installation is undertaken jointly by the turbine supplier technicians and the installation contractor. The turbine supplier is usually responsible for the lifts along with mechanical and electrical completion.

What's in it	Turbine installation vessel [I.6.1] Commissioning [I.6.2]

I.6.1 Turbine installation vessel	
Function	The turbine installation vessel transports the turbine components to site and supports the erection of the turbine on the foundation. Similar jack-up vessels are used to those for foundation installation.
What it costs	These costs are typically included in the turbine installation contract. Day rates for vessels range between £90,000 and £130,000, excluding fuel, crew and equipment. Depending on the transit distance, fuel can cost up to £20,000 per one-way sailing to wind farm site.
Who supplies them (examples only)	Operators: A2Sea/GeoSea (DEME Group), Fred. Olsen WindCarrier, Jan de Nul, MPI Offshore, Seajacks, Swire Blue Ocean and Van Oord Offshore Wind. Vessel manufacturers: generally in China, Korea, Singapore or the Arabian Peninsula.
Key facts	Recent turbine installation on commercial-scale projects to date has normally been undertaken with a self-propelled jack-up vessel designed primarily for the purpose, though in some cases, jack-up barges have been towed with tugs. Vessel contracts are typically placed by the wind farm developer or the turbine supplier. An example of specification for these vessels is: • Length: 130m, Beam 40m, Draft 5m • Crew berths: 100 • Crane: 1,500 tonnes • Carrying capacity: 9,300 tonnes • Maximum transit speed: 12 knots • Jack-up depth: 45m • Wind turbine component capacity: 5 sets • Number of jack-up legs: 4-6 • Jack up speed: 1m/min, and • Dynamic positioning system (DP2). Most of the vessels in operation have been used for both turbine and foundation installation. Increasingly the fleets are diverging. The increase in turbine capacity (and therefore rotor diameter) is associated with a higher hub height. At the same time, foundation mass is increasing and they can now be installed more rapidly from a floating vessel. The current fleet of turbine installation vessels was designed to install 6-10MW turbines. Investment in new vessels requires careful consideration due to: • Developments in turbine size are associated with a declining vessel market because vessel carrying capacity in MW increases with turbine rating and installation time per MW drops • Turbine ratings are likely to continue to increase, meaning that vessels become obsolete for installation, and • Investment costs for a vessel suitable for turbine and foundation installation are high but lower cost vessels can only target one or other of the markets. A number of vessel cranes have undergone modification but unless upgrades were considered in the original design, they can have an impact on other aspects of the vessels' performance. Feeder vessels could be used to limit the transit time of the main installation vessel but this is only likely to be cost effective if the transfer of turbine components from low cost floating feeder vessels can be achieved without increasing risk and if the feeder vessel has a considerably lower charter rate than the

	main installation vessel. Floating vessels are considered a natural next step for turbine installation, offering theoretically faster installation than jack-ups. Hook height movements at 110m or higher can be important, thereby limiting the operability of the vessel for installation work. A floating installation vessel could also be used efficiently for foundation installation thereby reducing investment risk. Vessels no longer suitable for turbine installation in Europe could be further utilised in the service market and in new installation markets such as Asia, where turbine size has so far lagged behind that in Europe.
What's in it	Turbine handling equipment and sea fastenings [I.6.1.1] Crane Auxiliary cranes Dynamic positioning system Propulsion systems Jack-up system Spud cans Helideck Gangway

I.6.1.1 Turbine handling equipment and sea fastenings	
Function	Turbine handling equipment is used to assist in the lifting and manipulation of turbine components during loading in port and installation offshore. Handling equipment is typically developed by the turbine supplier to be specific to a given task and component. There are several handling tools required for offshore installation including tower handling tools, nacelle handling tools and blade handling tools. Sea fastenings are used during the transport of heavy and costly components from the construction port [I.7] to site.
What it costs	Included in turbine installation cost.
Who supplies them (examples only)	Component handling tools are often provided to the offshore contractor by the turbine supplier as the tool is specific to a turbine type and installation methodology.
Key facts	There are several approaches to reducing the sensitivity of turbine component lifts (especially the blades) to high winds, thereby reducing weather downtime: • The blade still hangs from the crane hook, but is supported in a frame with a hydraulic assembly to allow the blade to be rotated remotely to the preferred orientation, the position of the blade also being constrained by a series of remotely controlled ropes • A lifting tool with a four-part attachment: two tag lines from the crane and a third running from a bracket fixed to the tower enables the blade position to be controlled in wind speeds up to 13m/s regardless of direction • Rigid support of the blade so that at no point is its position influenced by wind loading, and • Hook stabilisation tools that reduce hook movements due to wind. Currently, blades can be lifted in winds in wind speeds up to 13m/s. Although this limit could be raised in theory, there comes a point where high winds make work on deck hazardous, even if the turbine installation can, in theory, be continued. Sea fastenings are structures located on the deck of the installation vessel, which allow for the safe transportation of turbine components from the construction port [I.7] to the installation location. Typically, large steel fabricated structures and frames secured to the main deck of the installation vessel. Sea fastenings are designed to transfer the load of the component into the vessel structure and keep the component in position without damaging the component or vessel. Sea fastenings must also be designed

	to allow safe access of technicians both during transportation for inspections and to release the component to allow lifting.
What's in it	Remotely controlled electro mechanical systems Remote controls operated by installation technician on deck of the vessel Winches Turbine frame Blade rack sea fastening Tower grillage Crane sea fastening Tag-line systems

I.6.2 Commissioning	
Function	After installation, commissioning is the process of safely completing mechanical and electrical assembly, putting all systems to work and addressing punch lists before handover.
What it costs	These costs are included in the wind turbine / substation supply contract.
Who supplies them (examples only)	Generally led by the wind turbine supplier and substation supplier.
Key facts	The key steps in commissioning the offshore substation and cabling include visual inspection, mechanical testing, protection testing, electrical insulation testing, pre-energisation checks, trip tests and load checks. Assuming grid connection to the turbine is complete, key steps in turbine commissioning include: • Check of installation activity and documentation • Mechanical and electrical completion • Check of communication systems (SCADA, VHF radio) • Energisation of all subsystems • Testing of each link in safety and emergency system chains • Exercising of all safety-critical and auxiliary systems • Slow rotation of the rotor to confirm balance and smooth operation of the drive train • Overspeed sensor and other safety-critical checks • First rotation then first generation and checks on normal operation of all systems, and • Checks on critical components and connections after a period of attended operation, then after a longer period of unattended operation. Even after first generation, it is routine to have several punch lists for each turbine and substation containing outstanding issues that need to be addressed before handover to the customer and operation, maintenance and service (OMS) teams. Handover will also normally require demonstration of performance and reliability over an agreed length of time.
What's in it	Electrical testing device Generator

I.7 Construction port	
Function	The construction port is the base for pre-assembly and construction of the wind farm. Separate locations may be used for feeding foundations and the wind turbines to a wind farm. Location is critical as it affects the time spent in shipment and sensitivity to weather windows.
What it costs	Included in installation contracts.
Who supplies them (examples only)	UK ports used so far include Able Seaton, Barrow, Belfast, Great Yarmouth, Harwich, Hull, Mostyn and Sheerness. Non-UK ports used for UK projects include Cuxhaven, Eemshaven, Esbjerg, Ijmuiden, Ostende and Vlissingen.
Key facts	Construction port requirements are typically: • At least 8 hectares suitable for lay down and pre-assembly of product • Quayside of length 200-300m length with high load bearing capacity and adjacent access • Water access to accommodate vessels up to 140m length, 45m beam and 6m draft with no tidal or other access restrictions, and • Overhead clearance to sea of 100m minimum (to allow vertical shipment of towers). Sites with greater weather restrictions or for larger scale construction may require an additional lay-down area, up to 30 hectares. Large areas of land are required due to the space taken when turbines are stored lying down on the ground.
What's in it	Quay Lay-down area Cranes Workshops Personnel facilities

I.8 Offshore logistics	
Function	Offshore logistics involves coordination and support of offshore installation and commissioning activities.
What it costs	About £3.5 million for a 1GW wind farm.
Who supplies them (examples only)	High-level coordination is typically undertaken by the developer. Construction management services: DNV-GL, K2 Management, LOC Renewables, Natural Power, ODE, RINA and SeaRoc.
Key facts	Offshore logistics covers all the work needed to ensure that construction proceeds smoothly, safely and on time. Construction management covers a wide range of services including contract management, health and safety and marine coordination. In many cases, contractors are embedded in the construction management team. In addition, in order to fulfil the insurer's requirements, a marine warranty surveyor (MWS) has to be appointed. The MWS ensures that all activities are compliant with the approved procedures and delivers the Certificate of Approval (CoA). Specialist software tools are available to plan and monitor offshore activity. Weather and metocean forecasting services provide visibility of weather windows a few days in advance. While meteorological buoys are typically owned and operated in the UK by the MetOffice, third-party providers with their own forecasting algorithms also offer services. Support vessels include guard vessels (potentially drawn from local fishing fleets), crew transfer vessels and accommodation vessels. These vessels may be contracted by the developer of the marine contractor.
What's in it	Sea-based support [I.8.1] Marine coordination [I.8.2] Weather forecasting and metocean data [I.8.3]

I.8.1 Sea-based support	
Function	A number of vessels are used to support the installation process. These may include CTVs, anchor handling, barges, dive support and ROV handling vessels.
What it costs	About £2.5 million for a 1GW wind farm.
Who supplies them (examples only)	Vessel operators: Holyhead Towing, Iceni Marine Services, MPI Offshore, Offshore Wind Power Marine Services and Windcat Workboats. Vessel manufacturers: Alicat, Alnmaritec, Arklow Marine Services, Ctruck and South Boats.
Key facts	Specialist vessels are used for crew transfer to the wind farm for installation and commissioning tasks. These are typically 15-20m workboats of the kind regularly used during wind farm maintenance. ROV support vessels are 80-100m DP2 vessels with a moon pool and deck crane.
What's in it	CTV Barge ROV

I.8.2 Marine coordination	
Function	Marine coordination is necessary in order to manage heightened marine traffic as well as multi-vessel activity on an offshore construction site.
What it costs	About £850,000 for a 1GW wind farm.
Who supplies them (examples only)	Marine coordination is usually carried out by the developer or a subcontractor, for example SeaRenergy, SMC and WindandWater. Suppliers of marine management system software include James Fischer Marine Services, SeaRoc and Systematic.
Key facts	A marine coordinator, usually located at the base harbour or operations base [B.5], is responsible for the coordination, control and exchange of information between all contractors working on the site. A marine management software system is used to plan and monitor vessel and personnel movements. The main tasks of the marine coordinator include: • Monitor all vessel and personnel (as well as helicopter) movement from, to and inside the offshore wind farm perimeter • Ensure no conflict from simultaneous operations • Ensure the authorisation and access of appointed persons on the site, and • Communicate with all vessels and helicopters.
What's in it	Marine management system software Marine coordination centre

I.8.3 Weather forecasting and metocean data	
Function	Weather forecasts are needed for short-term planning of offshore activities (for example vessel transfers and lifts) and the closer the forecast is to the activity, the more reliable it gets. Metocean data recordings are used to provide real time data to support offshore activity, to verify forecast tools and to resolve disputes regarding weather downtime. Key metocean parameters that impact installation and commissioning activities are wind speed, wave height and current.
What it costs	About £300,000 for a 1GW wind farm. The weather forecast supplier usually offers several options (both in the number of forecasts per day as well as forecasts for the different locations). For example, forecasts for the base harbour and the offshore site or a complete forecast for base harbour, the offshore site and transit route. Metocean measurement devices can be rented or purchased.
Who supplies them (examples only)	Suppliers for weather forecast services: Fugro, MetOffice, MetoGroup and StormGeo. Suppliers for current and wave buoys: Axys, Datawell and OSIL. Suppliers for anemometers and lidars: Axys (floating lidar), EOLOS (floating lidar) Gill Instruments (anemometer), Leosphere (Vaisala) (lidar) and ZX Lidars (lidar). In addition, the vessel contractor generally provides wind measurements (for example via anemometer mounted on crane boom or lidar).
Key facts	Weather plays a crucial role in offshore installation and commissioning activities as it has an influence on the sequence and duration of planned activities (which need to be conducted safely that is all offshore activities have weather limits, exceeding these would be unsafe) and may lead to delays, which result in

	elevated costs. Weather forecasts are generated through global meteorological models that may be improved in their accuracy with finer resolution local models. Forecasts usually include several different meteorological parameters such as wind speeds at different heights, wave and swell height and period as well as general weather information (for example visibility, lightning risk, fog, water and air temperature and rain). The forecasts are used to plan activities based on when weather windows are available. Wind parameters are usually measured with a lidar (on a fixed or floating meteorological station) or an anemometer (rotary or ultrasonic) on a fixed metrological station with tall mast. The advantage of the lidar is that wind speed and direction at different heights can be determined. Ocean parameters can be measured with a wave buoy or current meter although there is a trend towards complete systems that combine both wave and current measurements.
What's in it	Weather forecast report (and online access) Wave buoy Current meter Lidar Anemometer

5. Operation, maintenance and service

O Operation, maintenance and service	
Function	Operation, maintenance and service (OMS) are the combined functions which, during the lifetime of the wind farm, support the ongoing operation of the wind turbines, balance of plant and associated transmission assets. OMS activities formally start at the wind farm construction works completion date. The focus of these activities during the operational phase is to ensure safe operations, to maintain the physical integrity of the wind farm assets and to optimise electricity generation.
What it costs	About £75 million per annum for a 1GW wind farm, including insurance and internal asset owner costs.
Who supplies them (examples only)	The wind farm owner will oversee and fulfil overall site operations activities. In terms of wind turbine planned maintenance and service in response to faults, wind turbines are typically under warranty for the first five to ten years of operations and the wind turbine suppliers offer a service level agreement during this period to provide turbine maintenance and service. After this initial warranty period, the wind farm owner may maintain and service the wind farm using an in-house team, contract to a specialist company or develop an intermediate arrangement where turbine technicians transfer to the wind farm owner at the end of the warranty period.
Key facts	The focus of OMS is to maximise the financial return from the owners' investment. Owners aim to optimise the balance between operational expenditure and turbine yield. By scheduling downtime during the summer months and low wind speed winter periods, owners can secure high availability during the winter months when wind speeds and energy outputs are typically higher. Contractual arrangements, which award energy production, are increasingly common. Turbine availability is the percentage of time the wind turbine is ready to produce power if the wind speed is within the operational range of the turbine. Modern onshore turbines have a technical availability of around 98%. The performance of offshore wind turbines has improved with optimised design, and offshore turbines often have availabilities in a similar range to onshore. The planning of logistics and access is vital to securing higher availabilities. Where there are access restrictions then availability may be in the range 95-98%. Operational support is provided to the wind farm 24 hours a day seven days a week, 365 days a year, including responding to unexpected events and turbine faults, weather monitoring and live turbine monitoring. Outside normal operating hours this support is provided from remote control rooms which monitor wind farm SCADA data. Maintenance and service includes scheduled and unscheduled activities and requires the regular transfer of personnel and equipment to the wind turbines and offshore substation. Safe access to the turbines is a critical area for further focused innovation. If required, specialist staff from the wind turbine supplier (more commonly) or 3rd party providers (less common) will carry out major repairs and replacement of main components. The wind turbine supplier and other third parties will carry out repairs of turbine blades. In the UK, transmission assets (substations and export cables) are transferred to an OFTO within 18 months of wind farm commissioning. The OFTO may contract some maintenance and service functions to the wind farm owner because it has onsite personnel and has a strong interest in minimising transmission downtime. In other European territories, typically a transmission operator is responsible for building the offshore transmission.
What's in it	Operations [O.1] Maintenance and service [O.2]

O.1 Operations	
Function	Operations relate to management of the asset such as health and safety, control and operation of the asset including wind turbines and balance of plant, remote site monitoring, environmental monitoring, electricity sales, administration, marine operations supervision, operation of vessels and quayside infrastructure, and back office tasks.
What it costs	About £25 million per annum for a 1GW wind farm. This includes training, onshore and offshore logistics support and management, overheads, health and safety inspections and insurance.
Who supplies them (examples only)	The owner of the wind farm typically creates a special-purpose vehicle to operate the project. This may have several shareholders, one of which is likely to take a lead role. Operations tasks for offshore wind farms are typically provided by the majority wind farm owner. Some aspects of wind farm operations are contracted to companies such as Deutsche Windtechnik, James Fisher Marine Services and 3Sun.
Key facts	An onshore control room provides access via SCADA and other systems to detailed real-time and historical data for the wind turbines, substation, met station, offshore crew and vessels. Systems ensure that the operations duty manager knows where all personnel and vessels are located. Wind farms are monitored remotely on an ongoing basis using SCADA and condition monitoring systems and periodically by way of active inspections, including of subsea infrastructure. A senior authorised person (SAP) is available at all times with coordination responsibility for the switching operations of all high voltage equipment. Review of SCADA data and prognostic condition monitoring can help to time preventative maintenance before failure occurs. The industry is steadily adopting more advanced data driven approaches to maximising asset value, including the increased use of performance analytics, performance benchmarking and integrated digital systems. In addition to hardware-related activity, environmental monitoring to understand the effect of the wind farm on the local environment and wildlife is also carried out. Wind farms can be broadly categorised as having: • An onshore base (at an OMS port), with day-to-day access to the wind farm via CTVs. An onshore base is typically used if the wind farm is less than 40nm from shore or if the wind farm is less than about 400MW (where the number of technicians does not justify the cost of an offshore base), or • An offshore base, for wind farms greater than about 40nm and greater than 400MW, which is likely to be a SOV, although fixed platforms have been used. In practice, wind farm operators adopt a flexible approach, particularly during peaks of activity. In both cases, helicopters may be used in addition to CTVs and SOVs. Careful planning of routine and unscheduled activities with due consideration of weather conditions and availability of spares and specialist vessels is critical.
What's in it	Training [O.1.1] Onshore logistics [O.1.2] Offshore logistics [O.1.3] Health and safety inspections [O.1.4]

O.1.1 Training	
Function	Training ensures that OMS personnel are qualified to fulfil the roles needed by the wind farm while ensuring their own safety and those of colleagues.
What it costs	About £500,000 per annum for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include AIS, ARCH, B&FC, CWind, Falck Safety Services, Heightec, Maersk Training, MRS Training and Rescue, National Wind Farm Training Centres, Offshore Marine Academy and ProntoPort. The Global Wind Organisation (GWO) training standards are now widely adopted in the offshore wind industry. The GWO is a non-profit body founded by leading wind turbine suppliers and/or operators.
Key facts	Training is related to both technical aspects and to health and safety skills and awareness. A number of certificates are required by all personnel likely to be present on the wind farm site, including: • Emergency first aid and advanced medical training • Offshore survival training, including marine transfer • Helicopter winch training • Working at height • Working in confined spaces • Wind turbine rescue • Manual handling • Lifting and hoisting, and • Electrical safety awareness. The technical training required is dependent on the requirements of the client, but as a minimum will cover specific technician training for the relevant turbine model. Other key training qualification requirements includes operational safety rules for high voltage switching and wind turbine operations
What's in it	Training courses Training examinations Certification

O.1.2 Onshore logistics	
Function	Onshore logistics involves support and resources to the wind farm operations, including quayside infrastructure, warehousing, logistics and operational planning.
What it costs	About £450,000 per annum for a 1GW wind farm.
Who supplies them (examples only)	The wind farm operator will establish OMS port facilities during the installation process, as many support vessels active during the operational phase will operate from local ports. The wind farm owner will typically occupy quayside facilities, operating on a long-term lease with the owner of the port infrastructure.
Key facts	Typically, wind farm owners will look to use the nearest port that meets its specifications to minimise transfer times and reduce the risk of time being lost due to bad weather. Nevertheless, owners will typically competitively tender the contract for the provision of port services. For wind farms further from shore, the use of offshore accommodation and other facilities (possibly shared with other wind farms) becomes more attractive. Port location is critical – far from shore port requirements will differ from a wind farm that is operated using CTVs and workboats only.

	Consideration is given to the scope for future expansion to support additional project phases. Port facilities are required to be flexible to accommodate variable demand with maintenance and service campaigns and site activities. Ideally, the warehousing and logistics buildings are close to the quayside to minimise the time loading support vessels. 24/7 access from a chosen port in all states of tide will increase flexibility to perform maintenance and service operations without delay to enable weather windows to be exploited – this may require port agreements to include requirements for dredging to maintain adequate water depths. Safe means of transfer onto vessels is needed – this often requires the installation of pontoons to ensure a level access route in all tidal conditions. A 1GW wind farm may employ up to 100 people onsite, of which about half will be turbine technicians. The availability of skilled and experienced technicians is a crucial factor in the successful operation of an offshore wind farm for wind farm owners and operators. OMS facilities need 24/7 access, 365 days a year. As well as the port facility, operators will use remote land based support, such as specific engineering advice and support, performance monitoring and 24/7 control room monitoring. Each support vessel will need a berth of up to 30m. A 1GW wind farm may require the operation of between four and seven vessels, depending on the distance from the wind farm to shore and the maintenance and service strategies chosen, although up to 10 berths may be specified in order to provide capacity for peak periods. Uninterrupted access requires the availability of a non-drying harbour with minimal tidal restrictions. An onshore base consists of: • Administration facilities and operations room • Lifting equipment, for example forklifts (600kg) and small cranes (1 t) to move components from the harbour to the vessel • Workshop facilities, workbench areas and tool storage • Stores, with small components that do not need specialist vessels to facilitate use • Wet and dry rooms, with space for personal protection equipment • Oil store, gas bottle store and waste management facilities • Fuel bunker, and • Parking spaces.
What's in it	Facilities management

O.1.3 Offshore logistics	
Function	Offshore logistics involves management and coordination of all marine based activities and operations.
What it costs	About £1.6 million per annum for a 1GW wind farm.
Who supplies them (examples only)	The wind farm owner will setup and manage a marine operations centre at the main OMS port. Third party suppliers of marine coordination services and software include SeaRoc, Vissim, and Windandwater.dk.
Key facts	Marine coordination involves the 24/7 monitoring of the locations of all vessels and personnel within the vicinity of the project, including the supply and interpretation of specialist tools such as marine coordination software. Cameras are often located on selected offshore structures to enable CCTV feeds to review conditions and monitor offshore activities. Operators a need to make judgements about the priority of activities based on the scheduled maintenance and unscheduled service workload and weather forecast. The industry is increasingly adopting software

	simulation tools to maximise operational efficiency in relation to scheduling tasks and deploying resources, taking account of weather conditions, sea state, vessel capability and operational priorities. Bigger wind farms further offshore and with more complex operational systems will increase the logistical challenge. Robust communication equipment and infrastructure is a key element of offshore logistics in order to ensure live communication between all personnel.
What's in it	Crew transfer vessels [O.1.3.1] Service operation vessels [O.1.3.2] Turbine access systems [O.1.3.3] Helicopters [O.1.3.4] Weather forecasting and metocean data [I.8.3] Marine planning software Communications equipment including radio and asset tracking Safety planning and systems

O.1.3.1 Crew transfer vessels	
Function	CTVs provide access for technicians and contractors to the wind turbines from the onshore OMS base to turbine locations and substation. CTVs are the preferred access solution for projects closer to shore.
What it costs	The charter day rate for a CTV is about £2,500, depending on specification, availability and contract period.
Who supplies them (examples only)	Vessel operators: Acta Marine Wind Services, MPI Workboats, Northern Offshore Services, North Sea Logistics, Turbine Transfers and Windcat Workboats. Manufacturers: Alicat, Fjellstrand, Fred. Olsen WindCarrier, Manor Renewables, South Boats and Umoe.
Key facts	CTVs transport personnel to the wind farm on a daily basis and do not have overnight facilities. Key requirements are robust vessels that can operate in adverse weather conditions. Wind farm operators typically use aluminium catamarans up to 30m long with capacity for 12 to 16 technicians. CTVs are typically Class I passenger ships, as classified by the Maritime and Coastguard Agency, which enable them to work further than 60nm from a safe haven. These vessels can be built to carry up to 24 passengers. Vessel speeds can be up to 30kn and are designed to transfer maintenance and service team members in comfort and safety to the wind farm ready to start work. There is an oversupply of small CTVs (less than 20m), with operators typically opting for larger vessels with longer ranges and better sea keeping. There is interest in SWATH (small waterplane area, twin hull) and SWASH (small waterplane area, single hull) type vessels to increase technician comfort and lower weather downtime. CTVs may have fixed or controlled pitch propellers but operators may prefer the increased manoeuvrability of water jets. Vessels with a smaller draught (less than 2m) may be used where harbours are more challenging to operate from due to water depths. CTVs have a load capacity up to 30t for turbine components and consumables, as equipment. Fuel is not typically included in the charter cost and there is an important emphasis on fuel efficiency of vessels.
What's in it	Turbine access systems [O.1.3.3]

O.1.3.2 Service operation vessels	
Function	SOVs provide an offshore OMS base, with staff working from the vessel for periods of two to four weeks at sea. SOVs are the preferred way to maintain and service wind farms located far from shore.
What it costs	Charter costs around £25,000 per day depending on size and fit out (excluding fuel).
Who supplies them (examples only)	Vessel operators: Acta Marine, Bernard Schulte, Bibby Marine, Esvagt, Louis Drefus, Østensjø Rederi and Vroon. Manufacturers: Astilleros Gondanm Cemre, Damen, Royal IHC and Ulstein.
Key facts	SOVs offer accommodation, mess and welfare facilities for wind farm technician staff, as well as workshop and spares storage. SOVs will stay at the wind farm for up to four weeks at a time, at which point they will return to home port to restock and change crews. Access to the wind turbines is achieved either by smaller crew transfer vessel, daughter craft, by helicopter, or directly from the SOV using a turbine access system. SOVs have operational speeds of up to 15 knots. They are equipped with dynamic positions systems. Vessel manoeuvrability is a key requirement to reduce positioning time and therefore costs. For this reason, there is little use of surplus platform support vessels (PSVs) from the oil and gas industry. PSVs have a more important role in supporting installation and commissioning. SOVs can typically accommodate between a crew between 50 and 100, of which up to 50 may be wind farm workers.
What's in it	Accommodation berths Mess, welfare and leisure facilities Spares and tooling storage Workshop facilities Walk to work system

O.1.3.3 Turbine access systems	
Function	Turbine access systems provide access to the turbine from a CTV or SOV. Systems are designed to permit access to the turbines in as wide a range of sea-states as possible, in the interests of maximising possible maintenance and service time and turbine availability.
What it costs	Costs typically included in vessel costs.
Who supplies them (examples only)	Suppliers include Ampelmann, Fjellstrand, Houlder, Osbit, Uptime and Windcat.
Key facts	Many SOV based systems are based on motion compensated gangways that react in real-time to changes in the sea surface, providing a stable platform to allow personnel to walk from the vessel onto the turbine. Motion compensating gangways have been trialled on CTVs. Such systems are designed within operational limits, and will not permit access in the most severe sea-states.
What's in it	Control systems Hydraulics Steel infrastructure

O.1.3.4 Helicopters	
Function	Helicopters are used to provide access for technicians and contractors to the wind turbines and offshore substation.
What it costs	Typically around £1.5 million per year (although increased flying hours or larger helicopters could increase this figure).
Who supplies them (examples only)	Operators: Babcock, Bond Air Services, Heli Service International and Northern Helicopter. Manufacturers: Airbus, Leonardo and Sikorsky.
Key facts	Helicopters allow access in otherwise inaccessible sea state conditions. Their high speeds and low carrying capacities fits well with the dispersed nature of offshore wind projects and the high frequency of low effort interventions that make up a large proportion of offshore visits. The high costs mean that helicopters are not used as primary means of technician transport. They are may be cost-effective for projects at the limit of the effective range of CTVs for which the fixed cost of SOVs is unattractive. Arrangements to use local airports need to be developed or a dedicated helicopter base set up at the operations port. This usually requires additional planning consent. It is important to locate the helicopter close to the operations base to reduce inefficiencies in journey time. Helicopters rarely land on the offshore installations, with technicians being winched down to the turbine. Helicopters are limited by weight restrictions and typically carry two to six technicians depending on the type of helicopter. The type of spare parts and tools that can be carried is limited by weight and size. Helicopters are normally contracted on a long-term basis, with either exclusive or shared access to the aircraft.
What's in it	Specialist offshore pilot training

O.1.4 Health and safety inspections	
Function	Health and safety inspections are a crucial activity to ensure the ongoing safe operation of wind farm infrastructure and systems, and to fulfil statutory obligations to inspect safety critical systems on a regular basis.
What it costs	About £400,000 per annum for a 1GW wind farm.
Who supplies them (examples only)	Suppliers include Bureau Veritas, DNV-GL, SGS and TÜV SÜD.
Key facts	Inspections of safety-critical devices and equipment including: • Fall arrest systems • Anchor points • Davit cranes • Turbine cranes • Boat landing and ladders • External gates and railings and floor gratings • External evacuation and rescue equipment • Fire fighting equipment and fire prevention equipment

	• First aid supplies & equipment • Pressure systems, and • Navigation aids and aviation lighting. Safety critical items are subject to a statutory inspection regime, where there are legal requirements including recommended inspection frequencies and method of inspection. Inspections are carried out by qualified personnel, either as part of the primary turbine maintenance works or by a team of independent inspectors. Inspection frequency will be six-monthly or annual, depending on the equipment. Drills of health and safety procedures are routine. Most owners will train their own technicians for these roles as they are frequent but require minimal time. Where there is a requirement for periodic statutory inspections and certification, such as for fall arrest systems, independent certifiers will provide these services. Owners will seek to perform inspections prior to other planned work being carried out in the summer months to minimise the likelihood of weather delays and ensure equipment remains certified for use.
What's in it	Health and safety equipment [O.1.4.1]

O.1.4.1 Health and safety equipment	
Function	Health and safety equipment provides personnel with access to vital equipment to reduce the risk of injury, and to provide equipment to assist in emergency situations.
Who supplies them (examples only)	Aspli, Trauma Resus, Viking Life Saving Equipment and WFE Safety.
Key facts	A comprehensive set of health, safety and personal protection equipment is carried in the project vessels or stored in each turbine. Running stock will be maintained at the onshore OMS logistics facilities. Turbines have basic emergency equipment to permit overnight occupation in the turbine in the event of personnel being stranded due to access restrictions. Typical health, safety and personal protection equipment includes: • First aid kits for minor injuries • Advanced medical kits • Eye-washing kits • Gloves and safety boots • Ear defenders and safety eyewear • Fuel and diesel spill kits • Fire extinguishers and suppressants • Survival suits, personal locator beacon, life-vests and floatation devices • Emergency rations and water • Emergency communications devices, and • Rescue equipment including descenders, spinal boards and stretchers, hub rescue equipment.
What's in it	Inventory tracking

O.2 Maintenance and service	
Function	Maintenance and service activities ensure the ongoing operational integrity of the wind turbines and associated balance of plant, including planned maintenance and unplanned service in response to faults, either proactive or reactive.
What it costs	About £50 million per annum for a 1GW wind farm.
Who supplies them (examples only)	Maintenance and service activities are provided by a combination of the owner’s in-house resources, wind turbine suppliers and third party service providers. These are further defined under the sub-headings below.
Key facts	There is considerable focus in the industry on optimising maintenance and service activities to reduce OPEX whilst also achieving the targeted levels of availability and reliability. This optimisation is best achieved by taking a lifetime view of the project economics, focussing on the levelised cost of energy. Operational management teams will consider the whole operational system in order to achieve this.
What's in it	Turbine maintenance and service [O.2.1] Balance of plant maintenance and service [O.2.2]

O.2.1 Turbine maintenance and service	
Function	Effective turbine maintenance and service ensures the long-term productivity of the turbines.
What it costs	About £33 million per annum for a 1GW wind farm.
Who supplies them (examples only)	The wind turbine supplier, during the defect notification period (DNP) and for the duration of any agreed contract beyond the DNP. The wind farm owner may seek to bring service capability in-house or to engage an independent service provider (ISP), which involves seeking agreement with the manufacturer for the supply of spares, software systems and specialist expertise. ISPs include DWT, James Fischer Marine Services and 3Sun.
Key facts	The initial service agreement typically covers the period of the turbine defect warranty, which is usually five years. During this period, turbine technicians are typically employed by the wind turbine supplier. The service agreement may specify that on expiry technicians’ contracts are transferred to the wind farm owner. This ensures continuity of staffing and removes technicians’ disincentive to relocate to the wind farm site. Activity is divided into preventive maintenance (scheduled) and corrective service (unscheduled) works. The bulk of preventive works will typically be carried out during periods of low wind speeds to minimise the impact on production, however, in practice, this is not always achievable. Corrective service is performed in response to unscheduled outages and is often viewed as more critical, due to accruement of downtime until the fault is resolved. The primary skills required are mechanical or electrical engineering, with further turbine-maintenance training often provided by the relevant turbine provider. Typical maintenance includes inspection, checking of bolted joints, and replacement of worn parts (with design life less than the design life of the project). Unscheduled interventions are in response to events or failures. These may be proactive, before failure occurs, for example responding to inspections of from condition monitoring or reactive (after failure that

	affects generation has occurred).
What's in it	Blade inspection and repair [O.2.1.1] Nacelle component refurbishment, replacement and repair [O.2.1.2] Electrical transmission system maintenance

O.2.1.1 Blade inspection and repair	
Function	Blade inspection and repair consists of the inspection of the condition of blades and replacing or repairing blades in a timely and cost effective manner.
Who supplies them (examples only)	Service suppliers include Bladefence, Cyberhawk, Deutche Windtechnik, DNV-GL, FORCE Technology, GEV, Global Wind Service, James Fisher Marine Services, Mistras, Natural Power and 3Sun. Inspection technology suppliers include ABJ, Cornis, Scoptico, SkySpecs and TSR Wind.
Key facts	Blade maintenance and service is an area of specific focus in the offshore wind industry. Issues such as leading edge erosion have been the source of availability issues in the industry and proactive blade inspection and preventative repair is now widely pursued in response. Blade inspections are performed by drones equipped with high-resolution cameras, by rope-access technicians or by high-resolution camera equipment located on the transition piece or vessel. Where substantial repairs or blade replacement are required, this is sometimes possible using rope access teams often using a blade platform suspended from the hub. Where a blade cannot be repaired in-situ a jack-up vessel is typically required in order to deliver the swap-out, although smaller vessels than those used during turbine installation can be used. Exchange is carried out in one visit, followed by off-site or deck-based repair. Retrofit programmes are carefully planned to ensure effective vessel utilisation taking into account repair turnaround times. Blade inspection work typically requires the turbines to be stationary, therefore there is a focus on performing inspection work during the less windy periods of the year to minimise lost energy production. Specialist expertise is required to undertake damage diagnostics and repair activities. Automation of blade inspection and damage diagnostics is an active area of innovation.
What's in it	Unmanned aerial vehicle [O.2.1.1.1]

O.2.1.1.1 Unmanned aerial vehicle	
Function	Unmanned aerial vehicles (UAVs) provide low cost and safer external inspections of turbines.
Who supplies them (examples only)	Manufacturers: ASV Global, DJI and SkyFront. Operators: Esvagt, Force Technology, Perceptual Robotics and SkySpecs.
Key facts	Most UAVs for wind turbine inspection are multi-rotor copter drones. Drones are typically provided by specialist operators and are rented with qualified pilots. Drones can perform an inspection in a fraction of the time required for a traditional rope-access inspection The drone can be equipped with a digital camera, a thermographic camera or a combination, depending on the scope of the inspection task. A digital camera provides proof of the visual failures and damages to the tower, nacelle, rotor blades and bolt jointing.

	Thermographic inspection is a non-contact and non-destructive inspection method that makes it possible to examine a large area of the blade for structural defects and weaknesses in the blade. With infrared thermography, the drone monitors variations in the surface temperature of, for example, the rotor blades. A number of specialist suppliers supply the industry with integrated drone inspection, image diagnostics and data archiving services.
What's in it	Flight planning Data storage and archiving

O.2.1.2 Main component refurbishment, replacement and repair	
Function	Main component refurbishment, replacement and repair consists of the replacement of large components such as gearboxes, blades, transformers and generators in a timely and cost effective manner.
Who supplies them (examples only)	Suppliers include James Fisher Marine Services, Seajacks, Fred. Olsen WindCarrier and Ziton.
Key facts	Design methodologies for offshore turbines to facilitate easier large component repair and replacement with less external intervention. On-board turbine service cranes can in some cases lift substantial loads. Some components on turbines however need a jack-up barge to enable replacement, although smaller vessels than those used during turbine installation can be used. Exchange is carried out in one visit, followed by off-site refurbishment. Retrofit programmes are carefully planned to ensure effective vessel utilisation taking into account repair turnaround times.
What's in it	Large component repair vessel [O.2.1.2.1]

O.2.1.2.1 Large component repair vessel	
Function	Large component repair vessels support the change-out of large nacelle and rotor components that need a stable hook height at hub height.
Who supplies them (examples only)	See turbine installation vessels [I.6.1].
Key facts	Large component repair vessels are typically self-propelled jack-ups that can install, or have previously installed turbines. Most large component repair vessels are installation vessels that are no longer able to install current turbine models or are suboptimal for the purpose. Given the large number of such vessels, day rates are competitive and owners typically seek to negotiate call-off contracts for vessel or charter them for several months for intensive maintenance or service campaigns. Older installation vessels are not necessarily well suited for maintenance and service without modification. They may not be able to work at sufficient water depths for some projects and they may be over specified in terms of crane capacity and deck space. A Site Specific Assessment must be carried out prior to commencement to ensure the vessel can safely work with the site soil conditions, weather limitations and water depths.

What's in it	Marine planning Vessel maintenance and service

O.2.2 Balance of plant maintenance and service	
Function	Balance of plant maintenance and service is focused on ensuring the operational integrity and reliability of all wind farm assets other than the wind turbines, including the substation(s), foundations, array cables, export cables, scour protection and corrosion protection systems.
What it costs	About £18 million per annum for a 1GW wind farm.
Who supplies them (examples only)	CWind, Fred. Olsen WindCarrier, James Fisher Marine Services and 3Sun.
Key facts	The balance of plant forms an integral part of the wind farm system. Proactive balance of plant maintenance is a key aspect of a reliability based preventative maintenance regime. Regular inspections of all balance of plant elements are required to ensure emerging issues are highlighted and remedial service work is planned in order to avoid loss of generation.
What's in it	Foundation inspection and repair [O.2.2.1] Cable inspection and repair [O.2.2.2] Scour monitoring and management [O.2.2.3] Substation maintenance and service [O.2.2.4]

O.2.2.1 Foundation inspection and repair	
Function	Foundation inspection and repair identifies and addresses corrosion and structural problems above and below the water line.
Who supplies them (examples only)	Suppliers include CWind, Deutsche Windtechnik, Fugro, Global Wind Service, Mistras, Offtech Wind and Strainstall.
Key facts	Maintenance consists of visual inspections, non-destructive testing (NDT) and sea bed survey work with remedial service work completed when required. Inspections focus on structural integrity, lifting, safety equipment, corrosion protection and scour protection. Inspection work is managed by the wind farm owner, although is often subcontracted to a specialist third party provider. Routine surveys are likely to be undertaken in the first two years but thereafter on a five or ten year cycle. Surveying the status of the protection installed to prevent sediment erosion, where the turbine foundation meets the sea bed (scour), can be carried out by side-scan sonar from a survey vessel or by using a ROV. Regular inspections are required on secondary steelwork such as ladders, gates, grills and platforms. On some sites, cleaning is needed to remove sea bird guano, which can be a serious health and safety hazard. Surface inspections and surveys include monopile internal inspections of the grouted or bolted connections and splash zone inspections. Activity needing subsea operations may include infrequent structural and J-tube cathodic protection inspections and weld inspections and can generally be carried

	out using ROVs. Diving is required only in exceptional circumstances and efforts are being made to maximise the use of safer, remote techniques.
What's in it	Remotely operated vehicle [O.2.2.1.1] Autonomous underwater vehicle [O.2.2.1.2]

O.2.2.1.1 Remotely operated vehicle

Function	ROVs are used to inspect wind farm underwater structures.
Who supplies them (examples only)	Manufacturers: ECA Hytec, Saab Seaeye and Seatronics. Operators: Fugro, James Fisher Marine Services and ROVCO.
Key facts	Inspection class ROVs are used to inspect the foundation below the water line and the cable route, particularly in areas at risk of scour or other sea bed movements, and at other high risk locations, such as crossings with other cables. Inspection ROVs typically have a speed of 3-5kn, weigh 8-12kg and have dimensions 1m x 0.7m x 0.5m. They are equipped with propulsion systems, lighting and a range of imaging equipment. ROVs are launched form a DP2 vessel equipped with an A frame or moon pool. The communication between the operator and the vehicle is controlled by an umbilical or tether cable, transmit electrical power, optical signals and mechanical payloads. It strengthened, usually with steel wire, to support the mechanical loads of the ROV underwater. The development and use of unmanned subsea inspection vessels is an area of innovation.
What's in it	Propulsion system Control system Remote camera Lighting system Power supply Manipulator arm

O.2.2.1.2 Autonomous underwater vehicle

Function	Provide low cost means of surveying below water, focussing on balance of plant assets such as cables and foundations.
Who supplies them (examples only)	Manufactures: Bluefin Robotics, ECA Hytec, Teledyne Gavia and Woods Hole Oceanographic Institution. Operators: Fugro, Modus and UTEC.
Key facts	Autonomous underwater vehicles (AUV) have the potential to replace vessel-based surveys. They are launched offshore from parent vessels. AUVs can be launched from a CTV and therefore avoid the need for a larger vessel with the lifting capacity needed to launch and recover an ROV.
What's in it	Vehicle maintenance and service

O.2.2.2 Cable inspection and repair	
Function	Identify faults and replace whole or sections of cable.
Who supplies them (examples only)	Offshore works: Boskalis, Briggs Marine, CWind, Offshore Marine Management and Pharos Offshore. Electrical works: Boskalis, Power Cable Services.
Key facts	The frequency of inspections depends on sea bed mobility and results of the initial surveys. Surface surveys can be used to detect substantial cable exposure, but ROV surveys will be required for more accurate burial depth data. Insufficient burial or cable exposure is typically resolved by remedial measures including protective mattressing and rock dumping, normally using a dynamically positioned fall pipe vessel, or occasionally side-dumping vessels. Cable damage may come from the mechanical loads of wave and tidal action if the cable is exposed, from anchors or fishing gear, or as a result of handling during transport or installation that exceeds the cable's specification. Although cables typically come with a two-year warranty, none of the main causes of damage is covered by the warranty The owner is therefore responsible for monitoring and surveying the cable and repairing it when required. The survey work and remedial work is likely to be subcontracted to a specialist provider. For array cables and export cables before the transfer of transmission assets to the OFTO (UK only, up to 18 months after works completion date), the wind farm owner is responsible. For the export cable the transmission operator or OFTO (UK only) is responsible, although the wind farm owner has a strong interest in ensuring that export cable faults are rapidly fixed to reduce and reduction in transmission capacity. Some offshore wind farms have redundant export cables so a fault on one cable will not necessarily lead to loss of wind farm output. Cable repair will normally require a full cable laying spread consisting of a cable laying barge with cable plough or jetting equipment, with a quadrant to ensure that the minimum bend radius is not exceeded. On deck, the cable is cut and a new section inserted with cable joints linking the new and old sections. Unlike in subsea telecoms, where cables are largely standardised, subsea power cables may differ substantially. In the past, bespoke joints have been used but there is high interest by transmission operators in developing universal joints. For array cables, shorter cable lengths and challenges in joining shorter cables mean that replacement of the cable may be more cost effective than repair. If so, the cable will be cut at the bases of the foundations, the internal section of cable removed, and a new cable laid using the same process as installation.
What's in it	Maintenance and service record management

O.2.2.3 Scour monitoring and management	
Function	Mitigates the risk of undermining sea bed movements on subsea structures.
Who supplies them (examples only)	Inspection: CodaOctopus, DHI. Management: HR Wallingford, Norfolk Marine and Subsea Protection Systems.
Key facts	The presence of scour (erosion of the sea bed surface) around marine structures including offshore wind

	farm foundations is common. Larger diameter structures are particularly prone to scour because of the deflection of water movement around the structure. Monopile foundations are at a higher risk of scour. Jackets may still suffer from scour but design features can mitigate the risk. Scour is generally managed through rock (or grout, sand or gravel) dumping around the base of the foundation. Mats are generally laced on top and these stabilise the infill material and prevent secondary scour. Frond mats, tyre-filled sacks and tyre-based mats have also been used. Concrete mattresses may also be used, potentially with protective mats, where cables have become exposed.
What's in it	Sea bed inspection

O.2.2.4 Substation maintenance and service	
Function	Ensures there is no interruption to transmission from electrical failures or structural problems with the offshore platform.
Who supplies them (examples only)	High voltage electrical contractors such as ABB, Alstom, GE, Schneider and Siemens. Offshore contractors such as Deutsche Windtechnik, Petrofac.
Key facts	Maintenance and service of the offshore substation primarily consists of non-intrusive inspections of topside switchgear and transformers, sampling of transformer oil, foundation and topside structural inspection and resulting infrequent service interventions. The owner carries out paint repairs and secondary steelwork repairs (for example to railings, gratings, gates, stairs and ladders). Serious repair operations, such as replacing transformers, require heavy lift vessels. Rapid turnover parts and consumables are stored in a large warehouse at the onshore base. Back-up diesel generators require periodic maintenance and refuelling. Access to the substation may be by vessel or helicopter but since few failures require urgent attention, the weather downtime of vessels may not be an important consideration, as it is for turbines. During planned power outages to support detailed inspection and service operations, careful planning is required to ensure weather windows are used to avoid excessive wind farm downtime if work cannot be completed and assets re-energised. Onshore substation maintenance comprises non-intrusive inspections of switchgear, transformers and any reactive power compensation equipment. Infrequent service in response may be required. Unlike many of the systems of an offshore wind farm, the onshore substation is almost entirely non-offshore wind specific – consisting of standard high-voltage electrical equipment.
What's in it	Inspection Maintenance and service record management

6. Decommissioning

D Decommissioning	
Function	Removal or making safe of offshore infrastructure at the end of its useful life, plus disposal of equipment.
What it costs	The decommissioning of a 1GW offshore wind farm will cost around £300 million (gross, excluding any resale value of equipment removed).
Who supplies them (examples only)	Contractors will be similar to those used for installation. Likely also other offshore operators will enter the space, including players with offshore oil and gas decommissioning experience who will not get involved with new product installation.
Key facts	At the end of the nominal design life of an offshore wind farm, there are a number of options: • Extend the operational life of existing assets through a programme of risk assessments, inspections, addressing regulatory aspects, and some component replacement. • Repower the site with new (larger) turbines, likely meaning decommissioning of existing turbines, foundations and array cables, with the possibility to extend the life of electrical transmission assets. The MW rating of the wind farm and transmission system may be unchanged as the area of the wind farm and density of turbines (MW installed per square km) are likely to be unchanged. • Fully decommission the site. Properly financed decommissioning plans typically are required as part of gaining planning approval to construct the wind farm. In practice, permission is likely to be sought to deviate from decommissioning plans as the sector matures decommissioning techniques. UK Government acts as decommissioner of last resort so is ultimately responsible. As a result, it takes security for decommissioning. Turbine decommissioning will require complete removal of the structure. For nacelle and tower components, the potential for recycling is considerable. There is no current process for recycling composite materials such as those used in the blades and nacelle cover, but is likely that methods will emerge by the time a large volume of offshore wind turbine commissioning is required. The process for foundation decommissioning will depend on the technology adopted and its sea bed connection. Decommissioning has only been carried out on a number of small, early offshore wind farms overseas. Environmental surveys are typically required before and after decommissioning, along with post-decommissioning management of the site in line with the Energy Act 2004.
What's in it	Turbine decommissioning [D.1] Foundation decommissioning [D.2] Cable decommissioning [D.3] Substation decommissioning [D.4] Decommissioning port [D.5] Reuse, recycling or disposal [D.6] Environmental surveys

D.1 Turbine decommissioning	
Function	Complete removal and shipment to shore of turbine rotor, nacelle and tower.
What it costs	Around £40 million for a 1GW offshore wind farm.
Who supplies them (examples only)	Turbine installation contractors such as A2Sea/GeoSea (DEME Group), Seajacks and Van Oord Offshore Wind can provide turbine decommissioning. Likely also other offshore operators will enter the space, including players with offshore oil and gas decommissioning experience.
Key facts	The process will be a reverse of the installation process, such as individual blades being removed, then hub and nacelle then finally tower. In some cases where it is determined that the remaining life if sufficient, there will be a market for reuse of second-hand components, either as spares for other operating wind farms or possibly for re-installation elsewhere. Similar lifting frames and arrangements will be used at installation to enable work in the largest envelope of weather conditions. For complex lifting operations, the same level of planning and health and safety management as at installation is required, with the added assessments and method statements to deal with the risks of damaged components or seized interfaces. In general, the removal process may be quicker than for installation because minor damage to components will be less critical. If components are to be recycled rather than reused, then in some cases less care needs to be taken to preserve the delicate aerodynamic surfaces and the condition of other components, potentially enabling the use of different equipment or enabling operations in a wider operating environment.
What's in it	See [I.6]

D.2 Foundation decommissioning

Function	Removal and shipment to shore or cut-off at sea bed level and making safe.
What it costs	Around £70 million for a 1GW offshore wind farm.
Who supplies them (examples only)	Foundation installation contractors such as Boskalis, Geosea (DEME Group) and Jan de Nul can provide foundation decommissioning. Likely also other offshore operators will enter the space, including players with offshore oil and gas decommissioning experience.
Key facts	Decommissioning plans may define specific requirements for removal of components below the mud line which in turn may drive the choice or design of foundations and installation methods. It is possible that in some circumstances, structures could be left in position where they support ecosystems that in the opinion of the regulator must be safeguarded. For monopiles or jackets, all elements above the sea bed will probably need to be removed with piles cut off at an agreed height (typically 1m below the top of the sea bed). Initially, the process is likely to draw heavily on the oil and gas industry's experience of removing subsea structures and then be optimised for the offshore wind industry. Removal of foundations is likely to involve the use of a work-class ROV fitted with a range of cutting and drilling tools including guillotine saws, hydraulic hole cutting tools (for making lifting holes) and abrasive waterjet cutting. Gravity base manufacturers stress the ease of decommissioning as the structures can be de-ballasted and lifted/floated off to be broken down or used as breakwaters, the basis for artificial reefs or similar. The use of suction caissons has been put forward as a means of reducing fabrication and installation costs. Decommissioning could also be straightforward, using the suction system in reverse to raise the foundation from the sea bed. Early trials have shown positive results, but removal after many years of fatigue loading has not been tried yet in wind.
What's in it	See [I.1]

D.3 Cable decommissioning	
Function	Removal and shipment to shore.
What it costs	Around £140 million for a 1GW offshore wind farm.
Who supplies them (examples only)	Cable installation contractors such as Boskalis, Global Marine and Subsea 7 can provide cable decommissioning. In addition, companies such as CRS Holland, Pharos Offshore and Subsea Environmental Services can carry out subsea cable recovery.
Key facts	The value, especially of the main conductor material in array and export cables, is such that it is likely to remain worth removing the cable, rather than leaving it buried. Cables will be disconnected each end then pulled from the sea bed and wound on to drums or chopped into short sections for storage on the decommissioning vessel. The method of gripping and pulling the cable will depend on the ground conditions and burial depth. For sandy conditions the approach is likely to involve fluidising the sea bed while the cable is pulled. The industry is likely to develop new tools for the process. Particular care will be needed at cable crossings (power or telecommunications) to avoid damage to functioning assets.
What's in it	See [I.5]

D.4 Substation decommissioning	
Function	Decommissioning plans typically are required as part of gaining approval to construct. These may define specific requirements for removal of components below the mud line which in turn may drive the choice or design of substation foundations and installation methods.
What it costs	Around £50 million for a 1GW offshore wind farm.
Who supplies them (examples only)	Substation installation contractors such as Boskalis, Saipem and Seaway Heavy Lifting (Subsea 7) can provide substation decommissioning.
Key facts	The process is likely to be a reverse of the installation process, although it may prove cheaper to cut the substation into sections for removal to enable a series of smaller lifts that can be undertaken by a lower cost vessel. In some cases, there will be a market for reuse of second-hand electrical components, after refurbishment, as spares or for other applications. If the remaining life of the substation structure and equipment, after refurbishment, is sufficient, the substation could be left in-situ and reused for a repowered wind farm of the same capacity.
What's in it	See [I.2]

D.5 Decommissioning port	
Function	Port where equipment removed is offloaded and marshalled for next stage of processing.
What it costs	Included in decommissioning contract for each of the components.
Who supplies them (examples only)	Similar to installation ports, but also including facilities with less stringent requirements and locations dedicated to decommissioning. Examples in the UK include Belfast, Great Yarmouth and Hull and specialist decommissioning facilities at Seaton. Non-UK ports include Eemshaven, Esbjerg and Vlissingen. Ideally, decommissioning ports will have salvage and processing facilities on site and some ports may develop expertise in handling certain types of materials. In some cases, some specialisations developed as part of oil and gas decommissioning may be valuable, even if this involves additional transit time from the wind farm site.
Key facts	Facilities similar to those used for installation will be required. Large structures that will be broken up are likely to be transported to facilities dedicated to such activity.
What's in it	See [I.7]

D.6 Reuse, recycling or disposal	
Function	Once equipment is onshore, there is a motivation to extract maximum value via reuse, recycling or disposal.
What it costs	Overall, net positive value.
Who supplies them (examples only)	Contractors that provide salving/recycling include Delta Marine, DUC Marine Group and Scaldis Salvage & Marine.
Key facts	Currently, different parts of decommissioned onshore wind turbines are reused, recycled or disposed of, depending on age, condition and material content. There is an established second-hand market for onshore turbines known to be robust and reliable and determined to have sufficient fatigue life remaining. In this case, the turbines are refurbished and installed on new foundations for operation up to 50% beyond the design life period. Offshore costs and financing are such that it is unlikely that offshore turbines will be decommissioned with sufficient fatigue life remaining and so be re-installed offshore, Turbines are typically disassembled for recyclable scrap, with relatively low proportion of nacelle and tower mass having no residual value and requiring safe disposal. There is typically a high content of a range of known steel grades and cast iron; also valuable amounts of copper, aluminium and in future, permanent magnet materials. Today, the wind turbine component that cannot be cost-effectively recycled are the composite blades and nacelle cover, but is likely that methods will emerge by the time substantial offshore wind turbine decommissioning is required, as there are a range of projects underway in this area. Blades are typically made from a combination of glass- and carbon-fibre in epoxy- or polyester-based resin matrices, along with polyethylene terephthalate (PET) or balsa foam. At the root end, there are steel inserts to provide bolted connection to the blade bearing. Other than this, there is typically a copper-based lightning protection system. So far, blades have been cut up and either sent for burning (in waste to energy or district heating plant) or to landfill. Most foundations and substation topsides typically have high steel content, so can be broken down and recycled as input to the manufacture of new steel components. Some substation components may be reused; others can be recycled as for turbines, again with relatively low proportion requiring having no residual value and requiring safe disposal. The cable conductor can be readily processed and reused in a range of sectors, XLPE may be cleaned, dried and ground and recycled as filler for new power cables or as insulation in lower voltage cables or accessories.

7. Further assistance and information

Information on the role of The Crown Estate is available at www.thecrownestate.co.uk.

The Offshore Renewable Energy Catapult is playing a leading role in stimulating innovation in offshore wind. ore.catapult.org.uk

RenewableUK is the leading trade association representing offshore wind energy companies. Among its wide-ranging activities is its work on helping the industry meet its requirements for a skilled workforce. www.renewableuk.com

The Department for Business, Energy and Industry Strategy is the leading UK Government Department facilitating the deployment of offshore wind. www.gov.uk/government/organisations/department-for-business-energy-and-industrial-strategy

InnoEnergy provides reports on innovation and future cost reduction, including in offshore wind. http://www.innoenergy.com/news-list/tag/offshore-wind/

The UK's devolved administrations and a range of national and regional bodies are also active in stimulating the growth of the offshore wind industry.

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