Offshore wind:

Opportunities for the composites industry

Published on behalf of The Crown Estate

June 2011

BVG Associates

BVG Associates is a technical consultancy with expertise in wind and marine energy technologies. The team probably has the best independent knowledge of the supply chain and market for wind turbines in the UK. BVG Associates has over 120 man years experience in the wind industry, many of these being “hands on” with wind turbine manufacturers, leading RD&D, purchasing and production departments. BVG Associates has consistently delivered to customers in many areas of the wind energy sector, including:

- Market leaders and new entrants in wind turbine supply and UK and EU wind farm development
- Market leaders and new entrants in wind farm component design and supply
- New and established players within the wind industry of all sizes, in the UK and on most continents, and
- The Department of Energy and Climate Change (DECC), RenewableUK, The Crown Estate, the Energy Technologies Institute, the Carbon Trust, Scottish Enterprise and other enabling bodies.

The views expressed in this report are those of BVG Associates. The content of this report does not necessarily reflect the views of The Crown Estate.

Cover image courtesy of Siemens AG

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1. Introduction

1.1. UK offshore wind

The UK is the global leader in offshore wind, with more than 40 per cent (1.3GW) of the world's generating capacity in UK waters. The industry expects the UK to retain this lead for at least another 10 years. Driving this expansion is Government policy on electricity generation, which is closely linked to the UK's national interest in terms of climate change, energy security of supply and economic development.

The Government's 2009 Renewable Energy Strategy sets out a path to increase the UK's renewable energy supply to 15 per cent of consumption by 2020, which is a target enshrined in legally binding EU targets.[1] This translates to about 30 per cent of electricity generation. About half of this is likely to be offshore wind, which reflects the fact that the UK has Europe's best offshore wind resource. This political impetus has made the UK the most attractive offshore wind energy market in the world.[2]

The Crown Estate owns most of the sea bed out to the UK's 12 nautical mile territorial limit. The Energy Act 2004 also vests rights in The Crown Estate to license the generation of renewable energy on the continental shelf within the Renewable Energy Zone out to 200 nautical miles. It has sought to exploit these offshore wind assets through a series of leasing rounds, with a potential total capacity of 48GW (see Table 1.1.1). Further information is available in its 2011 Offshore Wind Report.[3]

Of the 10 Round 1 sites taken forward, nine will have been completed by the end of 2011. The first Round 2 project, Gunfleet Sands, became operational in 2009 and a further eight projects will have entered the construction phase by the end of 2012. Round 3 is by far the largest Round so far, with about 32GW of capacity. Construction of some Round 3 projects is likely to start in 2015. Developments in Scottish Territorial Waters are expected to go forward on a similar timescale to Round 3. The Crown Estate also offered extensions to Round 1 and 2 projects to enable the supply chain to continue to grow ahead of Round 3. In March 2011, an additional development round in the Northern Ireland Territorial Waters was announced.

For these developments to be economic, The Crown Estate recognises that it needs to encourage the entry of companies with relevant expertise into the offshore wind market. The UK has world-class competence in many relevant areas of the supply chain with many skills that are directly transferable to the offshore wind industry. The composites industry is one such example, founded on the UK's capability in the aerospace, automotive and marine industries.

Table 1.1.1 The Crown Estate's offshore wind leasing rounds.

Round	Year round announced	Capacity (from public announcements)
Round 1	2000	1.5GW
Round 2	2003	7.2GW
Round 3	2008	32.2GW
Scottish Territorial Waters	2008	5.3GW
Round 1 and 2 extensions	2009	1.5GW
Total		**48GW**

The UK supply of composite materials and components to the onshore wind industry has been based on the successful diversification from the marine and aerospace sectors, with companies such as Gurit, Hexcel, Exel and PPG Industries all active. The Crown Estate has commissioned this guide to help UK composites companies identify what role they can play in supporting the growth of UK offshore wind.

1.2. Composites and the wind industry

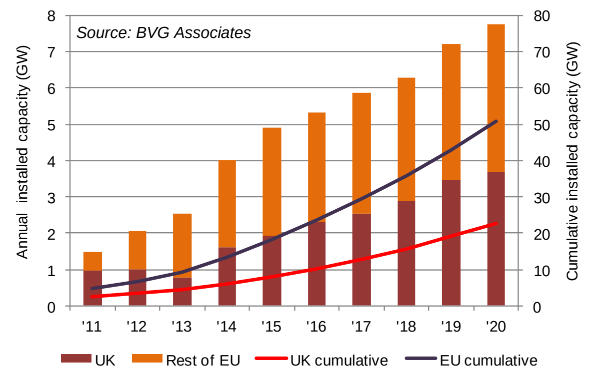
The wind industry is a major user of composites, mainly in blade manufacture. Most offshore wind turbine manufacturers, such as Siemens Wind Power and Vestas Wind Systems, produce blades in house but there are also independent manufacturers, notably LM Wind Power and Euros, which have made large blades suitable for offshore turbines. Sections 4 and 5 of this report discuss the market in further detail and the technologies employed.

Advances in blade technology will help to reduce costs over the next decade and enable the manufacture of the longer blades that will be needed for the next generation of turbines.

1.3. Market forecast

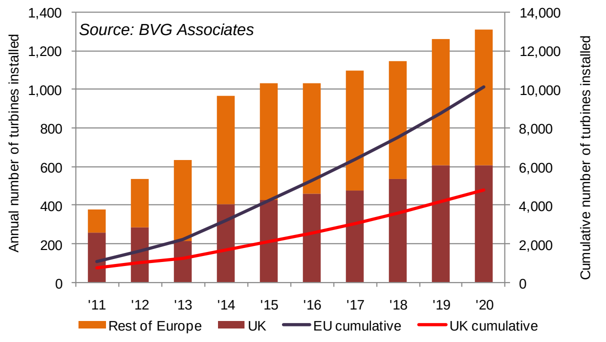
Figure 1.3.1 presents our forecast of installed offshore wind capacity for the UK and the rest of Europe, with a cumulative installed capacity of around 23GW in the UK by 2020, out of a European total of just over 50GW.[4] This equates to a capital investment in Europe of about £150 billion. Other significant active European markets include the Netherlands and Germany. The European market is expected to stabilise at between 7GW and 8GW of annual installed capacity in European waters until at least 2035, made up of new capacity and the repowering of existing wind farms.

Europe will be the dominant offshore wind market for at least the next decade. China installed its first commercial offshore wind farm in 2010 and has significant ambitions to expand this further. There is a lot of interest in the USA and its government aims to achieve 54GW installed capacity by 2030.[5] The USA's first offshore wind project, Cape Wind, was approved in 2010.



Source: BVG Associates

Figure 1.3.1 Forecast of annual and cumulative European offshore installation capacity to 2020.



Source: BVG Associates

Figure 1.3.2 Forecast of annual and cumulative European offshore turbines installed to 2020.

We forecast that the average offshore turbine size will rise from approximately 3MW in 2011 to about 6MW by 2020 and that, by the end of the decade, about 1,300 offshore turbines will be installed offshore in Europe every year (see Figure 1.3.2). These trends are discussed in further detail in a study commissioned by The Crown Estate in February 2011.[6]

Offshore wind farms currently represent around a quarter of UK installed wind capacity and, while the UK onshore market is growing, UK offshore installed capacity is expected to overtake its cumulative onshore capacity before the end of this decade. Across Europe, annual installed offshore capacity is expected to rise from around 10 per cent of total annual wind capacity in 2011 to 25 per cent in 2020.

1.4. About the wind industry

Over the last 15 years, the average annual global growth in the wind industry has been about 30 per cent. Leaders in the wind industry are used to such growth rates, which have been achieved through their presence in a range of national markets and with a confident attitude to ongoing investment and technology development. The significant growth expected in the UK offshore wind development is therefore nothing new to the industry.

Price is a sensitive factor, especially because the wind industry has been built largely with the support of economic subsidies. The industry has done much over the years to reduce costs through technical and commercial innovation. While many other industries anticipate annual price increases, the wind industry generally works for an annual price decrease that will be achieved by increasing quantities of supply or improving product design and manufacturing processes.

The wind industry uses composite technologies similar to those in other sectors, such as marine and aerospace. The key difference is that production volumes and product sizes for wind are higher, with manufacturers often needing to supply more than 200 units a year of products weighing many tonnes. The wind industry's manufacturing philosophy is therefore closer to that of the automotive sector. This means that investment and innovation in the production process is a key element of new product development.

Its development into a mainstream industry has been accompanied by the engagement of global energy and manufacturing players. The list of UK offshore wind project developers contains most of Europe's largest utilities, which see today's offshore wind farms as power stations with capacities comparable to nuclear and fossil fuel facilities.

2. Offshore wind supply chain

2.1. Overview

In the construction of an offshore wind farm, there are two main players: the developer and the turbine manufacturer. While the turbine supply contract may only be one of about eight packages offered by the developer, it is the single biggest contract. It forms about 40 per cent of the wind farm's capital expenditure and defines much of the balance of plant design. Offshore turbine supply contracts generally include a five-year warranty, making the turbine manufacturer the key player in the operations and maintenance (O&M) of an offshore wind farm.

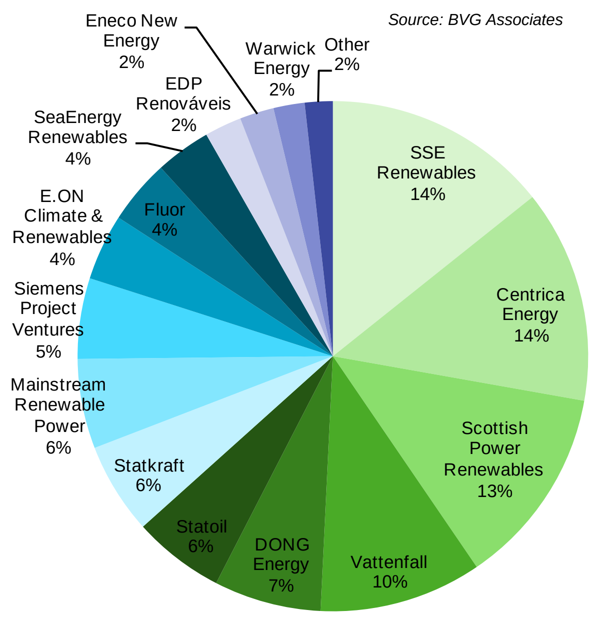
A number of offshore wind farms have used a single engineer, procure, construct (EPC) contract strategy but developers' desire to cut costs has led most of them to take on more risk, deal with the supply chain directly and adopt a multi-contract arrangement. Fewer contracts may be tendered in the future as developers seek to streamline their contracting process and major players seek to grow added value.

The offshore wind supply chain is described in detail in *A Guide to an Offshore Wind Farm*, produced on behalf of The Crown Estate in February 2010.[7]

2.2. Developers

The UK offshore market is dominated by large utilities from across Europe, such as Centrica, DONG Energy, RWE npower renewables, E.ON Climate and Renewables, and Vattenfall (see Figure 2.2.1). Early offshore wind farms were small enough to be taken forward by independent developers, which sold on the consented projects. Utility developers are now likely to take projects through to construction, although some will bring in new partners during or after completion.

In Round 3, the only independent developer is Mainstream Renewable Power.



Source: BVG Associates

Figure 2.2.1 Market share of UK offshore wind projects in development, construction and operation.

2.3. Wind turbine manufacturers

The European offshore wind turbine market has been dominated by Vestas Wind Systems and Siemens Wind Power, which together have been responsible for around 90 per cent of installed capacity to date. Both have Danish headquarters. Others with commercial-scale turbines installed offshore in Europe are the Germany-based REpower, Bard and Areva (see Figure 2.3.1).

Two years ago there were concerns about the commitment of turbine manufacturers to the offshore market but these have been allayed in the last 18 months so that now up to 30 offshore turbines are in development worldwide. Most of the top 10 manufacturers of large onshore wind turbines either have, or are in the process of developing, products for the offshore wind market, including European, Chinese and USA companies such as Gamesa, Sinovel and GE Wind.

Source: BVG Associates

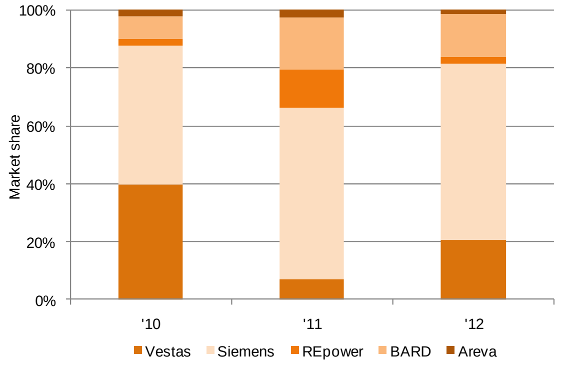


Figure 2.3.1 European offshore market share of wind turbine manufacturers from 2010 to 2012 by installed capacity (known projects).

The main components of the turbine are:

- The rotor, including the blades, the hub and pitch system
- The nacelle, housing the generator, drive train, control systems and auxiliary electrical components, and
- The tower, which is typically made up of three steel sections and includes internal access systems.

Wind turbine manufacturers are system integrators with varying degrees of in-house component manufacturing capability. Vestas Wind Systems in particular has significant manufacturing capability including nacelle components, blades and towers. To date, for the offshore market, blade manufacture has been largely undertaken in-house since the technology is more wind-specific than other large components.

2.3.1. Turbine trends

Until recently, offshore turbines were marinised versions of onshore models. There are a number of reasons why offshore and onshore technologies will diverge over the next few years, providing significant scope for innovation:

- The anticipated growth of the offshore market justifies developing specific offshore turbines.
- Offshore projects are less subject to the constraints that have shaped the onshore market, such as noise and visual impacts, and transport size limitations.
- Access to offshore turbines is more constrained and will lead to a greater emphasis on reliability.
- While larger turbines are marginally more expensive for each megawatt installed, they offer higher yields, reduced O&M costs and lower associated balance of plant costs.

Figure 2.3.2 shows the how the size of offshore turbines has increased in recent years and includes forthcoming products for which the rotor diameter has been announced.

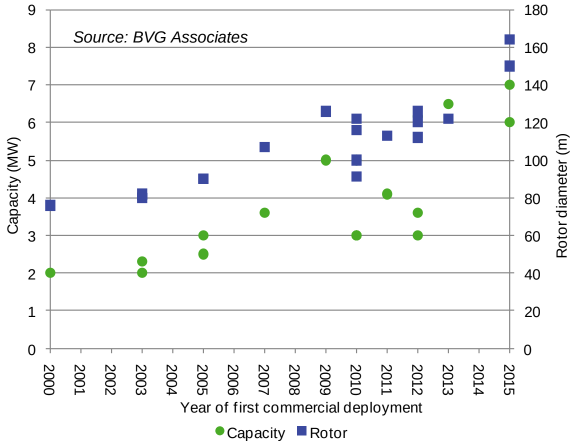


Figure 2.3.2 Trends in the size of deployed offshore turbines in Europe.

2.4. Costs

The capital expenditure (CAPEX) of an offshore wind farm varies between projects and recently has been about £3 million/MW. Component costs account for a little over half of this, with the remainder being the project costs during development, installation and commissioning. It is anticipated that like-for-like costs will fall over the next decade, although this will in part be offset by the increased cost of more challenging projects in areas with greater wind resource.

Significant additional reductions are likely in the cost of energy production through increased energy yields and savings in O&M costs. Many in the industry believe that the cost of energy will need to improve by at least 20 per cent over the next decade to give the industry a long-term, sustainable future. Developments in blade technology will play a significant part in increasing energy yields.

2.5. UK supply chain

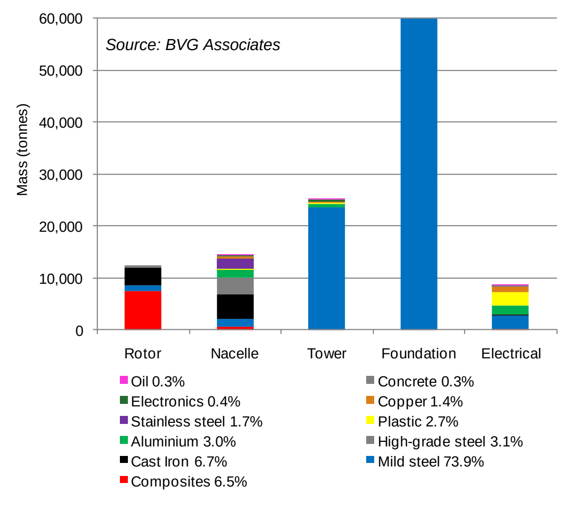
For the European wind market, the UK turbine component supply is currently limited, although there are strengths in a number of areas including composite materials. This is because supply chains grew up alongside their rapidly expanding customers in Denmark, Germany and Spain several years ago, so there are well-established suppliers that share the culture and ambitions of the turbine manufacturers.

The leadership of the UK in offshore deployment presents a fresh opportunity for UK suppliers to enter the wind market. Turbine manufacturers will need new coastal facilities to produce the increasingly large offshore turbines and Gamesa, GE Wind, Mitsubishi Heavy Industries, Siemens Wind Power and Vestas Wind Systems have announced plans for nacelle assembly in the UK, and others are exploring UK options. This does not guarantee UK supply but it enables British companies to compete with established suppliers, provided they understand and adopt the business culture of the wind industry.

Balance of plant costs are significantly higher for offshore projects, which need components such as foundations, substations and cables that are distinct from the requirements of onshore projects and which have fewer established suppliers. This means that in many cases committed UK companies have a strong chance of capturing a share of their home market.

3. Composites in an offshore wind farm

Most of the composite materials in an offshore wind farm can be found in the nacelle and the rotor blades (see Figure 3.0.1). This document focuses predominantly on these applications of composites, but it will highlight where there is potential for use in other areas.



Source: BVG Associates

Figure 3.0.1 Indicative breakdown of material usage in a 500MW offshore wind farm with 100 turbines, based on public domain Vestas Wind Systems data.

3.1. Blades

By 2015, the industry expects a typical offshore turbine to have a rated capacity of 5MW. This turbine will have blades over 60m long and 5m wide at their maximum chord (broadest point), with a mass of 15-25t each. The energy captured by a wind turbine is closely related to the swept area of the rotor so there is considerable attention being given to developing longer blades for the next generation of large offshore turbines. Figure 2.3.2 shows the trend in the blade length of offshore turbines.

For the onshore market, it is common for turbine manufacturers to make two or more models available with the same rated capacity but different rotor diameters. This is because different models are targeted at different wind regimes, with larger rotors being used at lower wind sites.

For the current portfolio of planned offshore projects, there is less variation in the average wind speed across sites and so it is not anticipated that there will be variants with different rotor diameters offered simultaneously to the market. There are, however, drivers to move to significantly larger rotors, especially when moving to deeper waters and further from shore. These may mean that we see more examples of turbines initially offered to the market with one rotor diameter and then subsequently offered with a larger rotor. For example, the Siemens 3.6MW offshore machine, widely deployed with a 107m rotor, is now available for the London Array wind farm with a 120m rotor.

Many in the industry anticipate that 10MW turbines will in time make an impact in the market. For these, the largest rotors are likely to approach 200m.

There is little consensus on how large offshore turbines will get but 10MW is unlikely to be the limit. The Azimut Project, a consortium of 11 Spanish companies, including Gamesa, Alstom, Acciona and Iberdrola Renovables, aims to develop a 15MW turbine with a view to deployment around 2020.

To date, most turbine blades have been made in a single piece and lengthwise to avoid the technical challenges of making robust joints without significant increases in weight. Sectional blades have been used successfully onshore by Enercon to overcome the limitations of transporting blades. It is expected that offshore blades will, where possible, be made at coastal facilities to avoid the need for onshore transportation and, in general, the industry will continue to manufacture blades in a single section. The UK company Blade Dynamics, based on the Isle of Wight, has plans to introduce a two-section design for assembly on site that will be able to be scaled up to more than 90m long for the offshore market.

The current generation of large turbines all have three blades. Turbines with three blades capture slightly more energy than those with two but the cost of the energy benefit is marginal at best. Designs with two blades have been deployed on land but they have an inherently higher tip speed, making them noisier, and people tend to find them more visually intrusive. These considerations are less important far from shore.

Turbines for the large wind market are almost all upwind designs (with the rotor upwind of the tower). Downwind turbines are potentially noisier because of the “thud” as the blade passes the tower. They do have advantages in that the blades can be somewhat more flexible, as under normal circumstances they flex away from the tower. Because they bend in high or turbulent wind conditions, they can reduce some of the stresses on the tower. They therefore have potential advantages offshore and on complex terrains onshore.

Offshore, noise and visual intrusion are less of a constraint and the Dutch company 2-B Energy has been an early mover towards two-bladed, downwind turbines, having a 6MW model in development. Other players are taking advantage of decreased noise constraints by adopting the more conservative approach of increasing the tip speed of the blades by allowing their conventional rotor to turn faster without making a change to the turbine concept.

While all established large wind turbine manufacturers are committed at present to horizontal axis turbines, there is some interest in developing large vertical axis turbines, especially for eventual use at 10MW or larger. One advantage of these turbines is that there is no reversing gravity load on the blades as the rotor rotates. For very large horizontal axis turbines, self weight becomes an increasing design driver for the blades. To counteract this benefit, aerodynamic loads on the blades, drive train and support structure traditionally vary much more for a vertical axis turbine as the rotor rotates, with implications on component costs. One example of a large vertical axis turbine in development is the 10MW Vertax turbine design, which aims to use 110m vertically mounted blades made in 10 sections.

3.2. Nacelle cover

Offshore nacelles need to be sealed to protect components from the marine environment. As well as providing this environmental protection, the nacelle cover supports anemometry and other auxiliary systems, and acts as a Faraday cage to protect nacelle components from lightning damage. The nacelle mass and volume vary significantly depending on the drive train configuration used by the manufacturer. The typical dimensions of a 5MW turbine nacelle are 10-15m x 4m x 4m. It does not necessarily follow that turbines approaching 10MW will have proportionately larger nacelles as developing larger turbines is associated with innovations in drive train configurations. For example, there is a trend towards direct drive (gearless) drive trains: the new direct drive Siemens 3.0MW nacelle has a mass of 73t, less than the 82t mass of its existing 2.3MW model.

The nacelle cover is usually manufactured in a number of sections from glass fibre and may have a mass of up to 20t. It is fitted as part of the nacelle assembly, either before or after the final test, and plays a valuable role in protecting nacelle components during transport to the offshore wind farm site. It is designed to withstand wind loading and allow access to lifting points on the nacelle bedplate for transport and installation.

Courtesy of Eikboom

Figure 3.2.1 The nacelle cover for the Nordex N90.

3.3. Spinner

The spinner or nose cone provides environmental protection to the hub assembly and access into the hub and blades for maintenance personnel. For a large wind turbine, the spinner may be up to 6m in diameter.

Typically, the spinner is made from glass fibre in sections and is bolted together with a galvanised steel support. Glass fibre root end collars are normally fitted around blades to provide environmental protection to the blade pitch bearings.

3.4. Other turbine components

There are potential applications of composites elsewhere in the turbine. While they offer high fatigue strength per unit mass and resistance to corrosion, the cost is generally considered to be too high to justify so composites are unlikely to be used in these areas in the short term. Some of these applications are listed below.

- **Hub.** The replacement of the cast iron hub with a composite structure to support the blades and transmit blade turning moment into the rotor and drive train could save mass, but it would need to be stiff enough to provide the necessary support to the blade pitch bearings.
- **Main shaft.** The replacement of a forged steel shaft with a composite shaft (possibly filament wound) would reduce mass.
- **Interfaces within the drive train.** Composite misalignment couplings are already used in some cases between the gearbox and generator. Opportunities arise for their increased use.
- **Generator.** The location and retention of magnets in permanent magnet generators is a structural issue and also presents challenges during assembly due to the forces (attraction and

repulsion) involved. Composites solutions may help to address these issues.

- **Bedplate.** Nacelle bedplates are usually manufactured in two parts. The heavier section is usually cast iron and supports the gearbox and transfers loads from the rotor to the tower. A lighter section supports the generator and other components at the rear of the nacelle and is normally fabricated from steel. The structures are designed by the wind turbine manufacturer but are generally manufactured by sub-suppliers. For a 5MW turbine with a conventional layout, the bedplate has a mass of about 80t with dimensions of approximately 4m x 3m x 10m.
- **Tower.** Composite towers are technically feasible and could have advantages in terms of mass and resistance to corrosion. Composite platforms have been used instead of conventional aluminium or steel systems.
- **Asset protection.** Composite blast and fire protection systems have been in use in the offshore oil and gas industry for some years. In offshore wind, transformers and safety critical power electronics and controls may use similar protection systems.
- **Tower dampers.** Tower dampers reduce vibrations and therefore fatigue. These are typically manufactured using moulded thermoplastics to hold fluids.

3.5. Other wind farm components

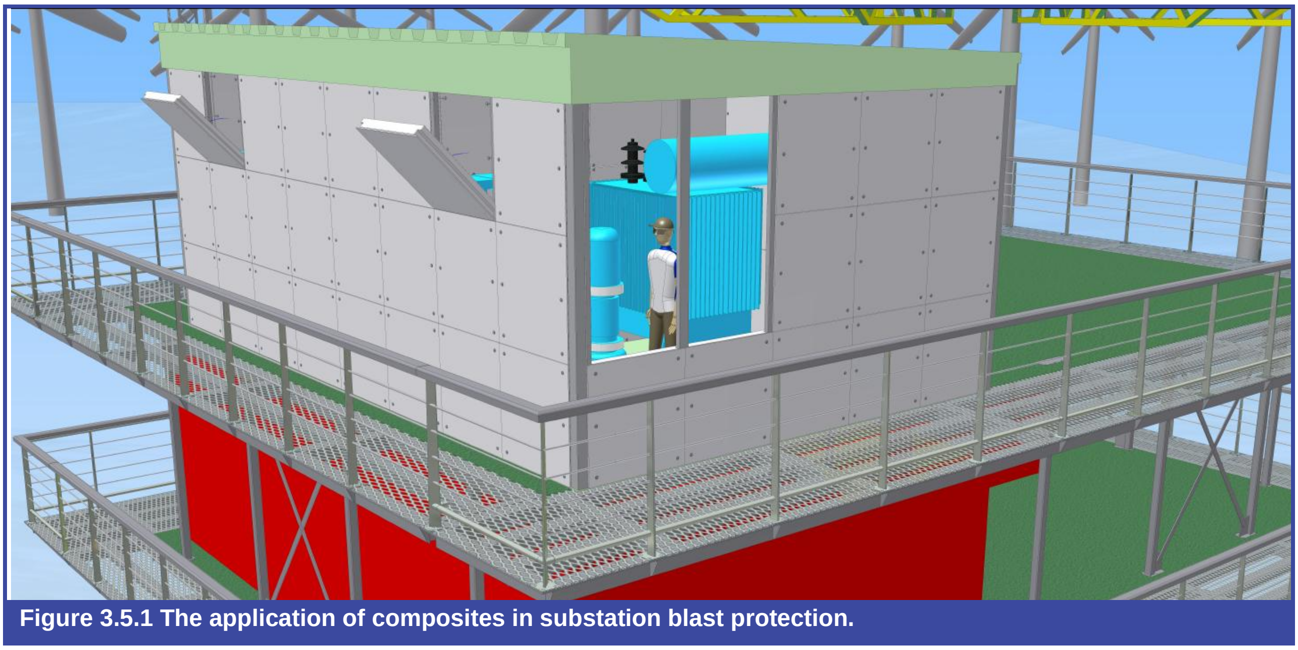
3.5.1. Offshore substations

Fire and blast-resistant enclosures may protect critical control systems or to enclose the “at risk” components such as high voltage electrical equipment operating at high temperatures (see Figure 3.5.1).

Composite walkways are used in the offshore oil and gas sector and there may be applications in areas of the substation where insulation or mass are critical. They may offer benefits in terms of reduced maintenance.

3.5.2. Vessels

There is a demand for fast crew vessels up to 20m in length, particularly for near-shore wind farms. A 500MW wind farm may operate up to 10 such vessels. Aluminium is currently preferred despite being more expensive than composites as it provides greater resistance to impact damage, which is a significant risk during crew transfer to the turbine. Composites could be a cost-effective alternative in designs that are capable of matching the ruggedness of designs using aluminium.



Courtesy of Solent Composite Systems

Figure 3.5.1 The application of composites in substation blast protection.

4. Blade technologies

Although the choice of blade technology varies between manufacturers and turbine models, composites are used as the basis of all blades. Consideration of blade technology is covered by the following headings:

- Materials
- Design and certification
- Manufacturing, and
- Additional blade function.

4.1. Materials

4.1.1. Technology drivers

The primary technology drivers for material use are:

- **Cost**. Materials make up more than 50 per cent of the cost of the blade, so price has a significant impact on the commercial and technology decisions being made for blades. Labour and consumables account for about 30 per cent of blade costs and tooling and factory depreciation costs are usually 20 per cent.
- **Fatigue resistance**. Blades are exposed to a high, cyclical and variable load regime under which the materials must last for 20 years in an offshore environment with minimal or no maintenance.
- **Mass**. As turbines get larger, mass becomes a significant driver for material choice. This is because self weight is a design driver for large blades and mass reduction in blades can lead to reduced costs in the rest of the turbine and foundations.
- **Ultimate tensile strength.** Blades need to withstand a range of operational and storm conditions. Materials that are stronger enable the design of lighter blades.
- **Stiffness**. The potential for the blade to strike the tower is an issue which drives the need for stiffer structures as the length of blades increases. In addition, keeping natural frequencies away from driving frequencies is critical.
- **Consistency**. In order to optimise blade design, material properties must be well understood. There is therefore benefit in avoiding materials with variations in their properties.

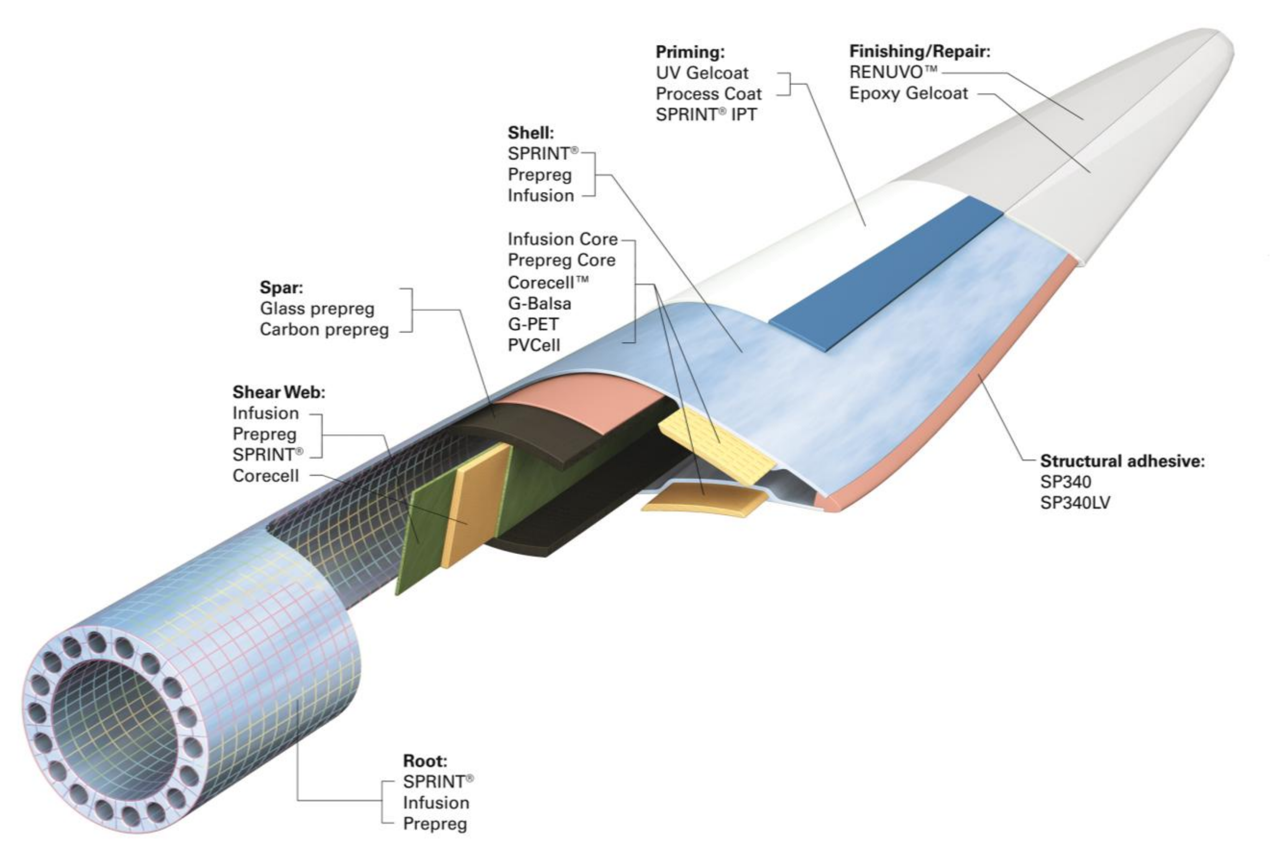


Figure 4.1.1 An example of composite materials in a turbine blade.

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4.1.2. Composite materials

Composite materials are formed from two major components, the structural material and the matrix material. The structural material is often a fibre and provides the key mechanical properties. The matrix material is a resin which supports and holds in place the structural materials. Different properties are achieved by altering the combination of structural and matrix materials. Some examples of the different elements of the blade are shown in Figure 4.1.1. Additional materials used within the composite structure of the blade include:

- Sandwich core materials, used to stabilise the structural layers and carry the shear loading on the structure
- Surface finish coatings, which are needed to protect the composite from erosion and UV light, and
- Adhesives, used to bond together the composite subcomponents.

4.1.3. Structural materials

The most commonly used structural material in wind turbine blades is glass fibre (see Figure 8.3.1). Carbon fibre is also used in approximately one quarter of wind turbine blades being installed worldwide and, where it is used, carbon fibre forms about 15 per cent of blade mass.

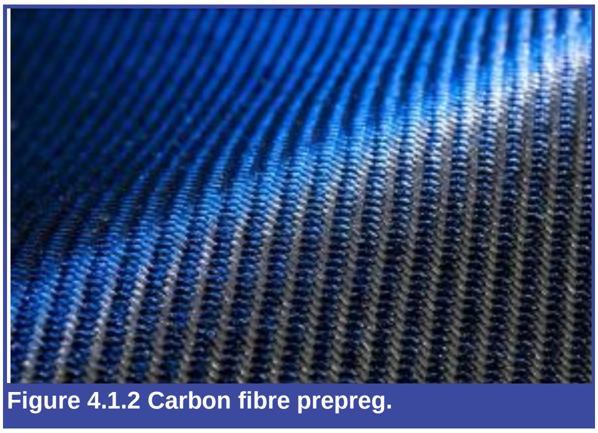

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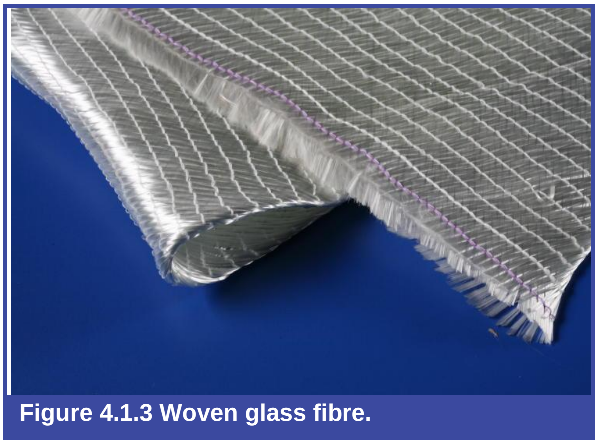
Figure 4.1.2 Carbon fibre prepreg.

A range of glass fibre grades are available. E glass is extensively used and each glass fabric-resin combination has to be tested and qualified before it is specified in a blade design. As wind blades grow in length, higher demands are placed on the reinforcements. A new generation of glass fibres is entering the market and is being evaluated by blade manufacturers. These materials provide a higher modulus (stiffness) and are moving to fill the gap in performance between carbon and E glass. They may provide a more cost-effective alternative to carbon in developing blades over 70m long. Two options are R glass and S glass. While the properties of S glass are superior to R glass, it is more expensive and requires significant investment on the part of manufacturers. R glass may therefore prove to be the favoured material for the next generation of offshore blades.

Table 4.1.1 Types of blade material.

Technology	Resin infusion	Prepreg	Integral blade vacuum infusion
Fibre	Glass or carbon	Glass or carbon	Glass or carbon
Resin	Polyester or epoxy	Epoxy (pre-impregnated into fibre)	Epoxy
Sandwich core	Balsa or polymer foam	Balsa or polymer foam	Balsa or polymer foam
Surface finish	In mould gelcoat when polyester is used; paint when epoxy is used	Sprayed on polyurethane paint	Sprayed on polyurethane paint
Assembling of blade shells and web	Bonding with structural adhesive	Bonding with structural adhesive	No bonding zones
Company example	LM Wind Power, Areva, REpower	Vestas Wind Systems, Gamesa	Siemens Wind Power



Courtesy of PPG Industries

Figure 4.1.3 Woven glass fibre.

Carbon fibres are produced by either the polyacrylnitrile (PAN) or pitch methods. In the first, a chain of carbon atoms is separated from PAN through heating and oxidation. The pitch method pulls out graphite threads through a nozzle from hot fluid pitch. Fibres are combined into tows, with the aerospace industry typically focusing on small tow products (1,000-12,000 filaments per tow) and industrial applications, such as wind, where productivity is the key driver, focusing on large tow products (above 12,000). Vestas Wind Systems and Gamesa are the dominant users of carbon fibre in wind turbine blades. Although it is significantly more expensive, carbon fibre composites can be a financially viable alternative to glass fibre composites as they have higher strength and stiffness, so less material is required for a given application and blades are lighter.

Carbon fibre composites have typically been used by pre-impregnating them with an epoxy resin. The fabric can either be completely impregnated with resin (called prepreg) or have a layer of resin on one side (semipreg). In both of these forms, the resin and hardener of the epoxy resin are premixed, which means the material must be stored in a freezer to prevent curing taking place.

4.1.4. Matrix materials

Epoxy resin

The majority of blade manufacturers, with the significant exception of LM Wind Power, use epoxy resin and it is anticipated that this technology will account for most offshore blades up to 2020. Epoxy is a thermosetting polymer with better mechanical properties and environmental resistance than polyester, although it is more expensive. Epoxy resin is produced by mixing two parts, the resin and the hardener, which undergo a cross-linking process causing the material to cure or set. The final properties of the resin are defined by the mixture ratio of resin and hardener and by controlling the curing process. Some formulations require heating during the cure process, whereas others simply require time at ambient temperature. Epoxy, like most thermosetting resins, cures exothermically. Care must therefore be taken during the curing process when applying heat or in making thick parts to avoid charring or even ignition. The fibre:epoxy resin ratio is generally 60:40.

Polyester resin

Polyester has been used extensively in smaller blades up to 25m long and by LM Wind Power on blades up to 61.5m. Polyester is an unsaturated, thermosetting polymer which is cheaper than epoxy resin but has inferior mechanical and environmental properties. It is commonly used in the marine vessel industry. Polyester resins need a catalyst rather than a hardener to initiate cure, which makes the mixing process less critical. Polyester resin can also include many additives such as pigments, UV stabilisers, fillers, and fire or chemical resistant substances. Styrene is added to reduce the viscosity of the resin, making it flow better. Styrene plays a vital role in the curing process of the product but does create environmental issues during processing as well as significant shrinkage of parts on cure. Polyester does not need to be heated to activate the process and achieve its full strength, so mould tooling tends to be simpler and cheaper and energy costs of production are lower. It is typically used in a 50:50 fibre: resin ratio.

Table 4.1.2 Combinations of structural materials used in large wind turbine blades.

	Polyester resin	Epoxy resin
Glass fibre	• Traditionally used in boat manufacture • Cost-effective and proven • Less strong than the glass and epoxy combination • Most commonly moulded using infusion	• The most widely used structural material combination for blades • Many players see the epoxy and glass combination as the best compromise on performance, cost and weight as it avoids the high costs associated with carbon fibre • Infusion is the most common moulding technique
Carbon and glass fibre	• Carbon fibre is usually not used with polyester resin due to its lower strength and because it is difficult to wet the fibre during infusion	• Used to optimise strength, stiffness and weight • Carbon is most commonly used in prepreg or semipreg fabric form for an internal spar or spar cap which is pre-manufactured and cured before moulding into the blade structure

4.1.5. Material combinations

A number of matrix material and structural material combinations are used in the manufacture of wind turbines blades (see Table 4.1.2).

4.1.6. Core materials

The foam core consists of structural cross-linked PVC. It is used in sandwich construction and sometimes as an infusion medium. The use of balsa requires good temperature and humidity control and has some natural variation in properties. All blade manufacturers use structural foam or balsa in their designs, and sometimes both. By volume, balsa makes up approximately 40 per cent of the core material used in blade manufacture, with PVC foam (40 per cent) and styrene acrylonitrile (SAN), polyethylene terephthalate (PET) and polyurethane foams (20 per cent) making up the balance.

Structural foam is globally available. Balsa core is currently all sourced from Ecuador and is environmentally friendly if sourced from sustainable forestry.

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Figure 4.1.4 Structural foam materials.

4.1.7. Coatings

Surface coatings are designed to provide environmental and erosion resistance, and must be able to repel dirt and be chemically stable. The choice of surface coating is determined by the resin used in the structure of the blade because of the need for strong chemical adhesion. Polyester, polyurethane and epoxy coatings are commonplace on blades.

4.1.8. Adhesive

Structural adhesives join the moulded parts of the blade and are formed by mixing resin constituents with a filler material. Epoxy adhesives are used to join epoxy-based parts and polyester adhesives for polyester-based parts. Adhesives used in blade construction must have strong fatigue properties, similar to those of the main blade structure.

4.1.9. Future developments

RD&D of materials for wind turbine blades is focused on better understanding and modelling of the materials and the way in which they are used in blades as well as on developing new materials with a balance of properties even better suited to large wind turbine blades. Manufacturers then choose the design and manufacturing route that gives the optimal lifetime cost of energy for the wind farm using the new blades.

Research is addressing the use of different ratios of mixed fibres (usually glass and carbon) in a variety of formats, including uni-directional, woven (2D and 3D), non-crimp and non-woven formats to improve mechanical properties and the speed of manufacture. The addition of stitching or tufting through the thickness and interfacial veils or layers can help prevent crack propagation and delamination. This is important for an application where the maintenance requirements mean

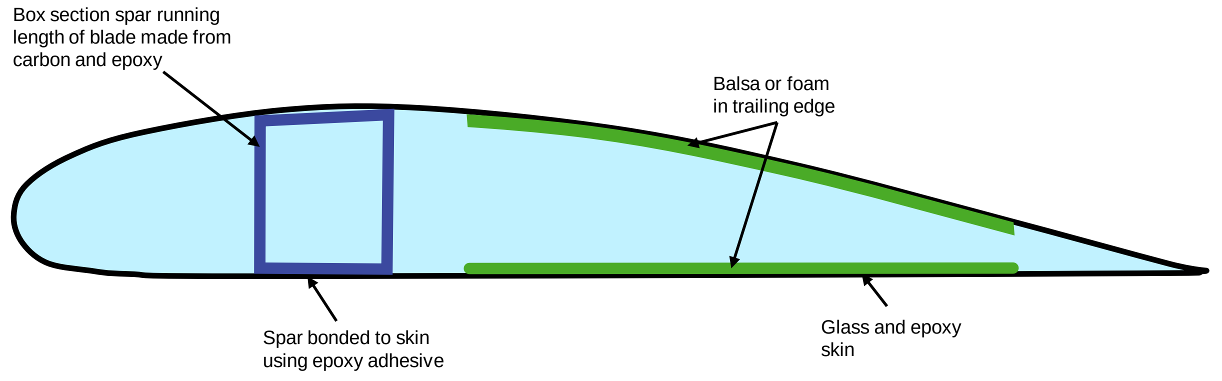

Figure 4.2.1 The spar concept.

that damage initiation and propagation are not tolerated.

Work is also being carried out on resin additives that can be used in the composite material or even the blade coatings, either to improve the mechanical properties or to introduce additional functionality. One example is the addition of electrically conductive materials to provide lightning protection or self-sensing capability.

A number of suppliers and manufacturers are looking at more sustainable materials for use in wind turbine blades. This includes natural resins and fibres and the use of thermoplastic composites which are potentially more easily recycled.

4.2. Design and certification

4.2.1. Technology drivers

Blade designers seek to optimise energy capture, cost, weight, turbine loads and reliability. The choice of turbine design concept will often determine characteristics such as the stiffness and blade length for a given turbine size.

4.2.2. Structure

In all blade designs, the challenge is to create the lightest structure that will only flex within given limits (to avoid tower strike and meet natural frequency requirements) and can withstand both fatigue and extreme loading.

All blades consist of three main components:

- **Shell**. This provides the aerodynamic shape of the blade.
- **Load bearing beam**. In structural terms, a blade is a hollow, cantilevered, taper beam. Different design concepts use a spar, shear webs, and spar caps or a monocoque approach to create the load-bearing beam in conjunction with the external aerofoil shape.
- **Root end.** This is part of the blade that attaches the blade to the blade pitch bearing. Some blades use a separately moulded (or wound) root end section, joined to the shells and the spar later in the manufacturing process. This avoids thick laminate layers in the mould which can cause an exothermic reaction in the infusion process. The root end is then either mechanically fixed or positioned with the rest of the blade materials in the mould.

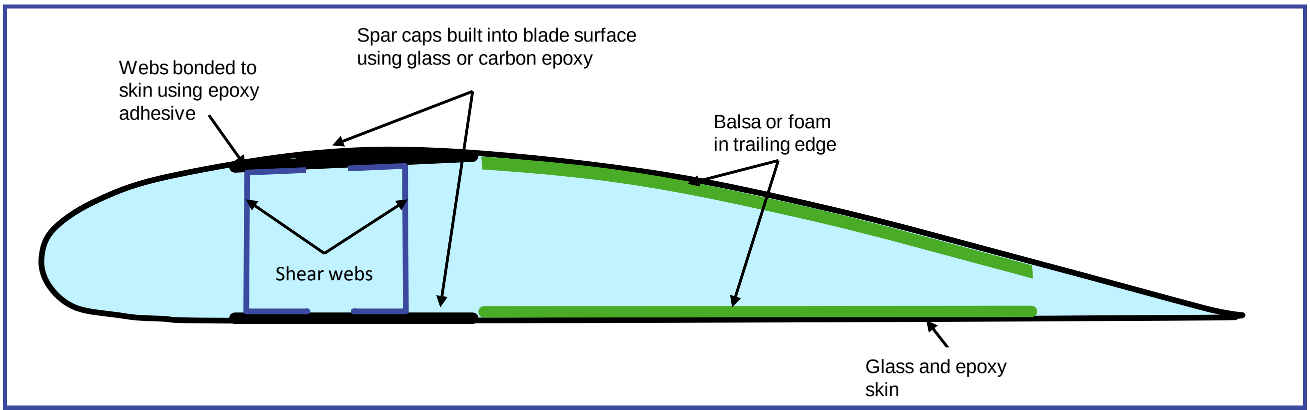

Figure 4.2.2 The spar cap concept.

The two most widely used structural concepts in blade design can be classified by the method used to create the load bearing beam.

A spar-based design is used by Vestas Wind Systems and Gamesa and incorporates a separately manufactured spar made of epoxy, glass and carbon (see Figure 4.2.1). This is assembled and glued into the two shells at the point of mould closure. The blade skin is typically thinner than for blades using the spar cap concept as it is not carrying the main loads.

The spar cap concept incorporates spar caps (see Figure 4.2.2) that generally are made separately and then assembled into each shell. Longitudinal shear webs are used to stiffen the blade and hold spar caps apart. Additional shear webs may be used in the trailing edge section near the widest chord.

4.2.3. Design process

For a large offshore blade developed in-house by a wind turbine manufacturer, the design team will generally follow a stage-gate process, an example of which is provided in Figure 4.2.3.

For a blade, the time needed to progress from an idea proposal through to prototype approval will be not significantly different from the rest of the turbine, due mainly to the significant time needed to manufacture the plug and mould.

At gate reviews, the following areas will be covered:

- Project purpose
- Financial evaluation (development budget and product costing)
- Product specification
- Competitor comparison
- Resource and responsibility plan
- Time plan
- Risk analysis
- Test and certification plans, and
- Supplier plan.

Key elements of the development process are outlined below.

Idea proposal and concept design

A significant number of load simulations are carried out based on preliminary blade designs, often derived from rules of thumb coupled with latest materials test results and process changes. Initial checks on the overall blade structural strength, stiffness and natural frequency are completed, resulting in a reasonable derivation of material and production cost. Blade root interface dimensions are fixed in cooperation with the hub team, again based mainly on previous experience, scaling-type calculations and preliminary hub and blade pitch bearing designs.

Detailed design

The lead time for a new blade design is determined by the timescales for prototype manufacture. Parallel activity is necessary in order to minimise development

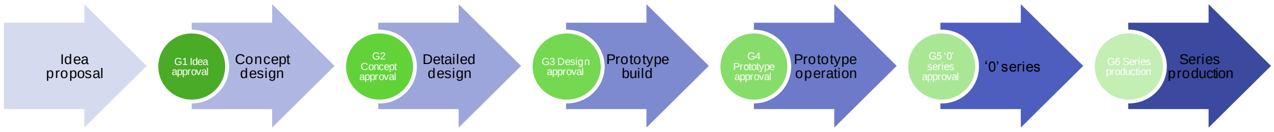

Figure 4.2.3 Wind turbine blade development process.

time. In order to start manufacture of the plug (the pattern used for manufacturing mould halves), the geometric shape must be fixed. Changes to the geometry after this point may be expensive and time consuming.

The structural design will be developed to fit inside the geometric profile and modelled to demonstrate that it provides sufficient strength and stiffness for the aerodynamic shape required. Iterations on shape, loads and structure will be carried out, considering both the aerodynamically critical outer part of the blade and the structurally critical inner part.

Prototype build

The design process continues with completing the overall structural design and implementing the design details, such as root end, webs or spars and the incorporation of lifting points, lightning protection, load sensing and other auxiliary systems. Some details may only be fixed just before the manufacture of the first blade, due to the practical nature of working with composites in large, curved structures.

As the plug is manufactured, the mould skin, mould frame and auxiliary systems are designed. The highest value commitment to be made during the blade development process is the mould itself. A complex modern mould may take up to six months to manufacture, with various risk-points during that time (such as removal of the mould skin from each half of the plug). Other production tooling, for example for the spar or webs, may also take a significant time to complete.

The manufacture of the first blade is likely to take several weeks to enable detailed checks to be carried out and to incorporate any necessary changes to the process. It is important when the resin is drawn through the structure during infusion that there are as few voids (air pockets) as possible. The webs or spar are manufactured separately from the aerodynamic shells, and it is likely that a trial fit of the separate blade components will be required in order to ensure that the gaps are within the range necessary for the acceptable performance of the adhesives used.

Once fully assembled, the prototype blade is removed from the mould and finished. Checks are made on the mass, the centre of gravity and the quality of manufacturing processes before the blade is tested on a dedicated test rig.

Prototype operation

Prototype operational tests relating to blades consist of the following: system identification (frequency scan) tests to confirm the expected headline dynamic behaviour; tuning of the turbine controller; and power curve, noise and loads measurements, resulting in the verification of loads prediction software. After the site tests, the usual approach is to complete the type certification process although, in some cases, further optimisation is carried out in advance of this.

0 series

Prototype blades are typically made according to preliminary instructions and with significant input from design engineers. A purpose of 0 series manufacture is to productionise manufacture and rationalise manufacturing documentation, both for purchasing (including bills of materials and specifications for key bought-in components) and for production (including process and quality documentation).

Significant hands-on training is required for teams involved with 0 series manufacture of new blades. During this stage, close checking of completed blades before and during operation may identify any design changes that are required. Such changes are generally implemented in batches in order to maximise the continuity in production. New certification is only required if changes are considered significant by the certificating body.

4.2.4. Design tools

A range of design tools are used in blade development. These can be broadly categorised as:

- Structural design tools, such as finite element analysis (FEA)

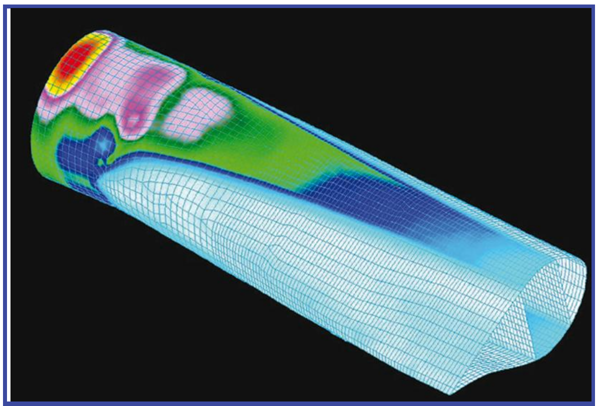

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Figure 4.2.4 Finite element analysis used in blade design.

- Aerodynamic design tools, such as computational fluid dynamics (CFD), and
- Quality tools, such as Six Sigma and failure mode effects analysis (FMEA).

A number of testing processes are used in the blade design process:

- **Material testing.** Extensive load and fatigue testing is carried out on all new materials being considered for use in blades, including materials from a new supplier. This activity is often initially handled by the material supplier with oversight from the blade manufacturers or in conjunction with them (see Figure 4.2.5).
- **Component testing.** Sections or components of blades are load and fatigue tested in order to verify the laminate arrangements and design details.
- **Blade load testing.** Before prototypes are certified and released to the field, new blade designs are tested for fatigue and load on specially constructed test rigs. Three types of tests are undertaken:
    - Static mode, to verify the survival of the extreme load case, flatwise and edgewise, and
    - Fatigue mode, both edgewise and flatwise, cycling to simulate full life fatigue loading.

  There are currently two test rigs capable of full blade tests in the UK. These are the Vestas Wind Systems facilities on the Isle of Wight and the open-access Narec facilities in Blyth (see Figure 4.2.7), for which £15 million of public funding was announced in 2009 to enable it to test the next generation of 100m long offshore blades.

  Tests are normally witnessed or certificated by an external design authority, such as Germanischer Lloyd or Det Norske Veritas (DNV), as part of a design evaluation, which is the precursor to eventual type approval.
- **Lightning testing**. Lightning protection systems within turbine blades are tested at specialised high voltage and high current test facilities, such as those operated by Cobham and Narec in the UK and Testinglab Denmark (see Figure 4.2.8).
- **Prototype testing**. The full turbine prototypes are installed and operated before commercialisation. Certification may be granted on a phased basis for prototype and limited production before full serial production manufacture begins, enabling modifications to the design to be made.

Figure 4.2.5 Material fatigue testing.

Courtesy of PPG Industries

Figure 4.2.6 Wind tunnel testing on a wind turbine blade section.

Courtesy of LM Wind Power

Figure 4.2.7 The blade testing facility at Narec.

Courtesy of Narec

Figure 4.2.8 Lightning testing on a wind turbine blade.

Courtesy of LM Wind Power

4.2.5. Future developments

The two main challenges facing blade designs are to make larger blades for offshore turbines and to gain greater energy capture from the same rotor size. Manufacturers are looking at getting better performance from existing designs and developing new concepts.

4.2.6. Certification

Wind turbine designs are certified against IEC 61400 series or Germanischer Lloyd standards by independent bodies.[8] Full type approval will include the following verification and testing processes:

- Design review against design allowable stresses and safety factors
- Material sample testing in both static and fatigue modes
- Static testing of completed blades, and
- Fatigue testing to simulate full life cycles.

It is also normal for a sample blade to be static tested to failure to understand the failure modes. Any changes to the design or materials must be notified to the certifying authority. For this reason, design stability is maintained with changes being grouped together for approval.

4.3. Manufacturing

4.3.1. Technology drivers

Capital costs. A typical offshore wind blade factory is likely to produce approximately 500 blades a year and will cover up to 30,000m^2. Factory set-up costs, particularly for tooling and infrastructure development depend on the technology selected, as mould tool life, process controls and space requirements are all affected.

Manufacturing cost. Manufacturers constantly work to drive down material, labour and overhead costs. Lean manufacturing concepts and Six Sigma tools are applied to drive year on year improvements and reduce waste.

Speed. The time taken to manufacture blades is a strong focus for innovation in manufacturing processes. The process lead time directly determines the floor area and number of moulds required to manufacture products. The moulding process from an empty mould to removing the blade will be up to 48 hours for large offshore blades.

Quality. Reliability and cost improvement drive increases in the quality of manufacturing processes in all turbine components.

Size. As blades and nacelle covers increase in size, the scale of manufacturing challenges grows.

4.3.2. Key processes

The shells and the shear webs or spar are usually made separately and then bonded together. These components are mostly manufactured using prepreg moulding or resin infusion methods, depending on the manufacturer.

Prepreg moulding

Prepreg moulding involves the laying up of structural (glass and carbon fibre) materials that are pre-impregnated with resin. These materials are laid in a mould and a vacuum is applied. The mould is then heated to allow the resin to flow between the fibres. The prepreg is then left to cure. Unlike aerospace prepreg processes, autoclaves are not generally used, although heat management in the mould is critical.

Prepreg tooling

The main tooling component of prepreg moulding is the mould. This is by far the most expensive tool used in the process as it must have good temperature control systems. The moulds are more expensive than those used for the resin infusion process. A mould is commonly made of the same material as the blade and is supported in a steel frame.

Some manufactures have automated parts of the lay-up process.

Resin infusion moulding

During resin infusion, dry materials are laid into the mould. A vacuum bag is sealed in place over the mould and a vacuum is applied. This causes the resin to be drawn from a reservoir in the mould and distributed through the dry materials. The mould is heated to start the curing process.

A wide range of manufacturers and market entrants use infusion. The most commonly used system involves infusing two blade halves separately, joining the halves by closing the mould and then gluing the halves together along with internal structural components. Some manufacturers use elements of wet lay-up although the main blade skins are normally infused.

Resin infusion tooling

Most manufacturers use moulds with integrated heating systems. Moulds are commonly made of glass fibre and epoxy and are supported in a steel frame. Where the blade joining is carried out in moulds, the moulds are hinged either with self-powered hydraulic hinges or mechanical hinges that use overhead lifting capability.

Figure 4.3.1 Wind turbine blade mould.

Courtesy of Solent Composites Systems

Other processes

Other processes carried out during the manufacture of blade include:

- Painting or gel-coating
- Non-destructive testing
- Composite repair, and
- Blade trailing and leading edge finishing (see Figure 4.3.2).

Figure 4.3.2 Wind turbine blade finishing.

Courtesy of Vestas Wind Systems

4.3.3. Future developments

Blade manufacturers are increasing the level of automation in their manufacturing processes. There is attention being given to automated lay-up processes to improve both the speed and quality of the placement of materials in the mould. This automation is looking at both the placement of preimpregnated fibres in tape form (automated tape laying) and the placement of dry fabrics to produce a preform for subsequent infusion. In this area of development, there are significant synergies between the requirements of the wind and aerospace industries.

Some manufacturers are developing blades shells in multiple parts that are later assembled at the factory or even at the wind farm site. These allow different processes and materials to be used for different sections of the blade and reduce blade transport challenges.

Additional blade function

4.3.4. Technology drivers

- **O&M costs.** Additional condition monitoring can both increase the reliability of blades and allow better understanding of the operating environment of the blade. This allows optimisation of O&M strategies.
- **Availability of sites.** Some sites are either uneconomical or cannot be developed due to environmental features such as radar interaction, or a high risk of lightning strike or ice build-up. Technology can be applied to turbine blades to make these sites viable.

4.3.5. Available technologies

In addition to the key structural and aerodynamic features of the blade, most manufacturers offer additional functionality that improves the blade's performance.

Lightning protection

Damage from a lightning strike is usually a result of the explosive expansion of air within the blade as a result of rapid heating from the lightning. Lightning protection is therefore essential for all large blades. Protection systems may employ aluminium mesh, stainless receptors, copper strips or solid aluminium blade tips. No lightning protection system can avoid damage from the most severe combination of current and voltage. Some manufacturers record lightning strikes using memory cards integrated into the lightning protection systems.

Load sensing and strain measurement

Load sensing is used routinely in the blade both during testing and prototyping. A few manufacturers also integrate load sensing into the series-manufactured blade; this provides input to the control systems to enable optimised load control. It is likely that such strategies will be adopted by more players in the future, especially as larger blades are used.

Condition monitoring

Condition monitoring systems are increasingly used in wind turbine blades. These can detect damage to the blade and the propagation of the damage can be tracked, allowing the operation and repair strategy of the turbine to be altered to prolong life and reduce maintenance costs. Condition monitoring systems in use or under development incorporate acoustic emissions sensors, fibre optic strain gauges and crack detectors.

Radar mitigation

Reduced radar signature or "stealth turbines" are expected to come onto the market in the next two years. These turbines integrate radar absorbent material into the composite structure of the blade and nacelle cover.

Figure 4.5.1 Stealth blade technology is being developed through a joint project between Vestas Wind Systems and QinetiQ.

5. Other turbine applications

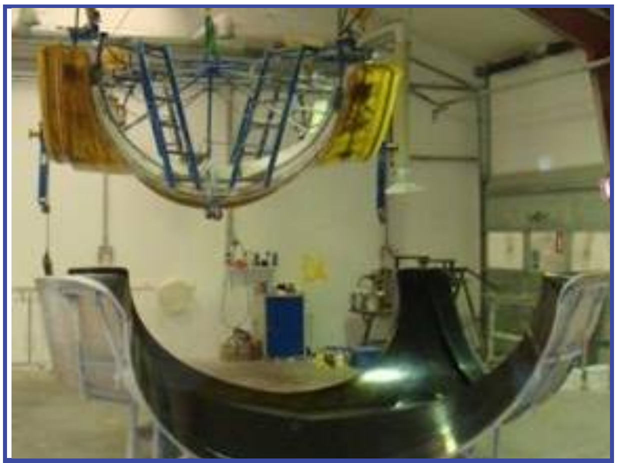
Composites are also used in the manufacture of the nacelle cover and the spinner or nose cone.

5.1. Materials

Nacelle covers and spinners are usually made in sections. The most common material combination used is glass fibre and polyester resin with a polyester gelcoat. Depending on its structural role, glass fabrics may be woven or chopped strand mat. Foam may also be used.

5.2. Processes

Resin infusion moulding and resin transfer moulding are commonly used for these components. Both processes use a vacuum to draw resin into the mould. In the case of infusion, the mould is single-sided and a polythene vacuum bag seals the surface. In transfer moulding, a two-part fixed mould is used with a male and female closing to form the finished surfaces. Resin transfer moulding (see Figures 5.2.1 and 5.2.2) is a low-pressure, closed-moulding process, in which a mixed resin and catalyst are injected into a closed mould containing a fibre pack or preform. After the resin has cured, the mould can be opened and the finished component removed. In exceptional circumstances, wet lay-up is used for prototype or product modifications.



Courtesy of EM-Fiberglas

Figure 5.2.1 Resin transfer mould tooling for a spinner.

Gelcoat is applied to the mould under extraction to contain fumes and minimise airborne styrene content. Pre-cut fabric and foam are then laid in the mould. After curing, the component is removed from the mould, trimmed and assembled with fittings.

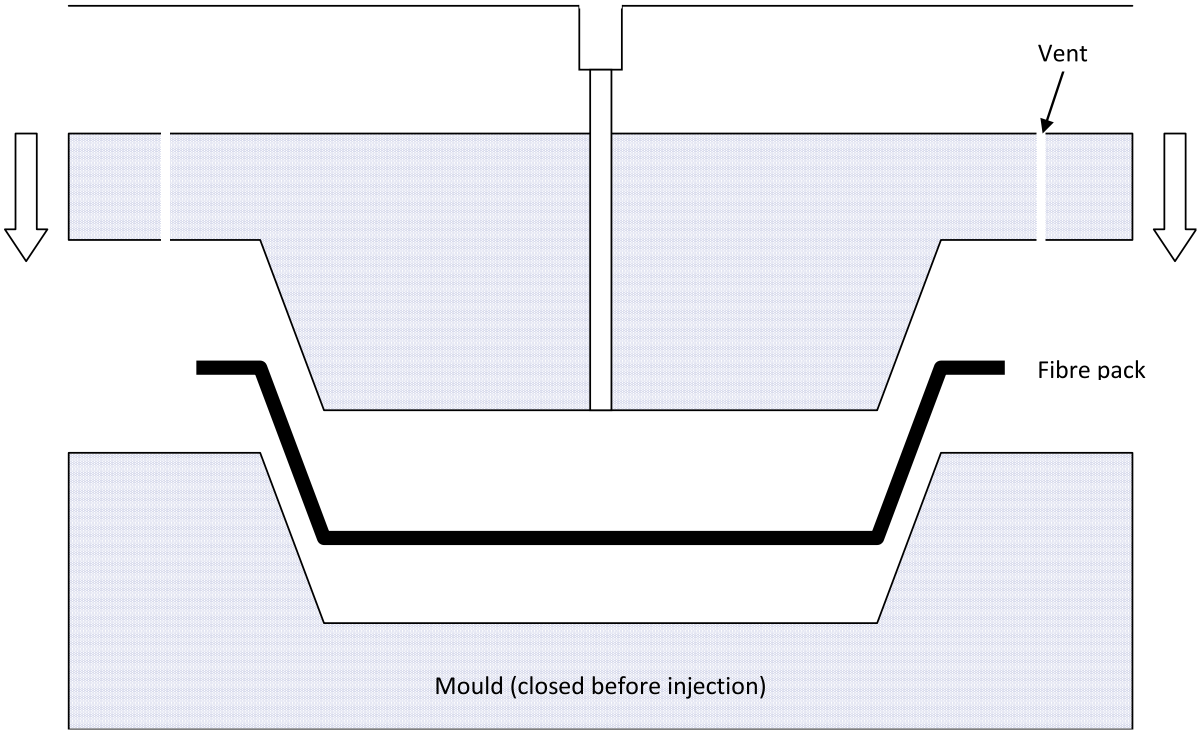


Figure 5.2.2 The resin transfer moulding process.

6. Research and development landscape

6.1. Composites RD&D for the wind industry

Approximately £50-70 million was spent in the last two years in the UK on RD&D in composites for the wind industry. Funding for these activities is primarily from commercial sources such as blade manufacturers and their supply chain. There has also been investment in RD&D from EU and UK government sources such as the Technology Strategy Board (TSB), Engineering and Physical Sciences Research Council (EPSRC), Energy Technologies Institute (ETI), the English regional development agencies, the devolved administrations, the Department of Energy and Climate Change's (DECC) Environmental Transformation Fund, the Carbon Trust and EU Framework Programmes. In May 2011, ETI announced that it intends to invest around £10 million in a project to develop the next generation of wind turbine blades, stating: "Along with improved system reliability, the impact of larger blades is a crucial factor in helping to bring down the costs of generating electricity by offshore wind which is why we are now seeking partners to develop and demonstrate these large-scale high performance blades."[9]

Table 6.1.1 Centres with a significant expertise in development of composites for wind turbine blades.

Universities	Bristol, Cambridge, Cranfield, Imperial College, Manchester, Nottingham, Plymouth, Southampton
University consortia	The EPSRC's Centre for Innovative Manufacturing, SuperGen Wind
Collaborative/open facilities	The Advanced Manufacturing Research Centre (AMRC) the Composites Centre, the National Composites Centre, Narec (the National Renewable Energy Centre), the Northern Ireland Advanced Composites and Engineering Centre, the Northwest Composites Centre, The Welding Institute Non-Destructive Testing Validation Centre
Commercial blade development facilities	Blade Dynamics, Clipper Wind Power, Solent Composite Systems, Vestas Technology

The main centres working on composites for wind turbine blades are listed in Table 6.1.1 above. Some examples of composites RD&D in the UK are described below.

Vestas Wind Systems and University of Bristol wind turbine blade development

The Advanced Composites Centre for Innovation and Science at the University of Bristol has partnered with Vestas Wind Systems to develop wind power technology using composite materials. Projects have been initiated in three areas: manufacturing of blades, smart materials and lightweight structures. This work is primarily funded by Vestas Wind Systems.

SuperGen Wind

SuperGen Wind is an EPSRC-funded programme that started in 2006 and is currently in its second phase. It is a consortium of seven universities and a number of supporting industrial partners. It carries out research into the challenges relating to offshore wind farms. As part of this programme, the University of Manchester is leading a project on wind turbine blade material development. The aim of the research is to reduce overall manufacturing costs by 20 per cent while retaining state of the art performance through improved material use and process improvements.

Clipper Wind Power's Britannia programme

Clipper Wind Power was awarded a £4.4 million grant from DECC's Environmental Transformation Fund in 2010 to develop the technology and manufacturing site for its 10MW offshore Britannia wind turbine blade in Newcastle.

Aerogenerator X turbine

The initial phase of the "NOVA" project was supported by ETI. Aerogenerator X is a multi-megawatt vertical axis wind turbine design. The design and structural analysis of composite rotor structures is being carried out by Cranfield University's Offshore Engineering and Naval Architecture Group. The project also includes researchers from the Aircraft Design Group within the School of Engineering and the Composites Centre at the School of Applied Sciences.

There are number of other organisations that support the UK composites industry as well as the wind turbine sector. These include:

- **Composites UK**. The trade association for composites in the UK. It provides support to companies within, and trying to get into, the composite sector and promotes the UK composites industry.
- **British Composites Society**. One of the technical divisions of the Institute of Materials, Minerals and

Mining. It supports individuals working in the composites sector by providing information and career, qualification and networking opportunities.

- **Materials Knowledge Transfer Network Composites Group**. This network facilitates knowledge transfer, holds events and advises on government policy and funding. It is jointly funded by the government, industry and academia.

6.2. RD&D challenges

There are a number of challenges that are being faced by blade manufacturers. These areas provide opportunities for RD&D in the material, component and technology supply chain. Areas of potential composites RD&D beyond blade development are presented in Section 3.4

6.2.1. Structural design of large blades

As the blade length needed for offshore turbines increases, the technical challenges grow. This is due to increasing demands being put on both the materials and the structure in order to maintain sufficient stiffness. In large composite structures carbon fibre is often used to increase stiffness but this drives up the cost of blades and so alternative solutions are being sought.

6.2.2. Manufacture of large blades

Manufacturing of any large, one-piece composite structure presents challenges. It is difficult to prevent voids developing and to ensure even curing. Material and final product handling and logistics also present challenges.

6.2.3. Faster production cycle time

In order both to reduce costs and increase the utilisation of factories, most manufacturers are working to reduce the time needed to manufacture a blade. Currently, the industry standard is around one to two days moulding with up to three days finishing. This can be reduced by improving curing times and material lay-down rates, and by increasing automation.

6.2.4. Speed to market

In order to bring forward the next generation of offshore wind turbines, the time taken from turbine concept to commercially available product needs to be reduced. This can be achieved through improvements to, and adoption of, rapid prototyping technologies, improved design tools, improved material understanding and performance models, and optimised testing and prototyping.

6.2.5. Reducing blade costs

The economic margins for offshore wind are tight, more so than some other industries that use composites such as luxury cars, motorsport and aerospace. Within the wind sector there is a constant need to drive down costs through improved performance from materials and structures, and optimised design and manufacturing processes.

6.2.6. Reducing O&M costs

O&M constitutes about 25 per cent of the lifetime cost of an offshore wind farm. The average cost of hiring a crane vessel to repair a blade offshore is in the order of £100,000 a day, so there are strong drivers to build robust blades. The risk of blade failure can be reduced by improving structural and fatigue models for the blades and materials, enhancing manufacturing processes, and using condition monitoring and technologies such as self-healing composites.

A significant cause of damage in wind turbine blades is lightning strike. Most blades are currently installed with lightning protection systems but there are opportunities for improvements in this area.

O&M costs can also be lowered by reducing the levels of routine maintenance required. This could be achieved through improvements to blade coatings and leading edge protection.

Avoiding the erosion of the surface (especially near the tip of the blade) is another consideration that will grow in importance as tip speeds are increased in future designs. Today, the leading edge of the outer part of a blade spends a significant fraction of its 20 year design life cutting through the air at over 150 miles per hour. In successive future generations, the tip speed could approach 250 miles per hour.

6.2.7. Increasing energy capture

A key driver for wind turbine manufacturers is to increase the amount of energy captured. This can be addressed by improving the aerofoil design or through improved aerodynamic control. Today, the pitch angle of each blade can be adjusted almost constantly by the turbine controller in order to balance turbine loading with energy capture as conditions change. On some turbine types, this process is carried out independently on each blade; on most, all three blades are moved in step with each other. The adjustment of pitch angle is a relatively coarse and slow response to different wind speeds along a long blade. It is likely that, in time, more advanced measurement of incoming wind conditions and control responses including aerodynamic devices mounted built into the blades will be developed.

6.2.8. Reduced radar visibility

Up to half of the UK’s wind farms face objections from civil or military radar operators. Solutions to mitigate this issue are under development, but treating the turbine to reduce the radar signature of the blades and nacelle cover is a viable partial or complete solution at some sites.

6.2.9. End of life

Although the recycling of blades from offshore wind farms has not yet been a concern, it is likely to become a pressing issue in 15-20 years when the current generation of turbines reaches the end of their design life. Recycling composites presents some significant challenges as the fibres and matrix must be separated if they are going to be reused for any significant-value purpose. Research is ongoing to find an economic way of achieving this.

7. Skills

7.1. Industry requirement

It is expected that the UK wind industry workforce will increase 10-fold in the next decade. The UK Composites Strategy, published in November 2009, highlights the opportunities for composites within this skills sector.[10] These occur in the design, manufacturing and maintenance of wind turbine blades and nacelle components (see Figure 7.1.1).

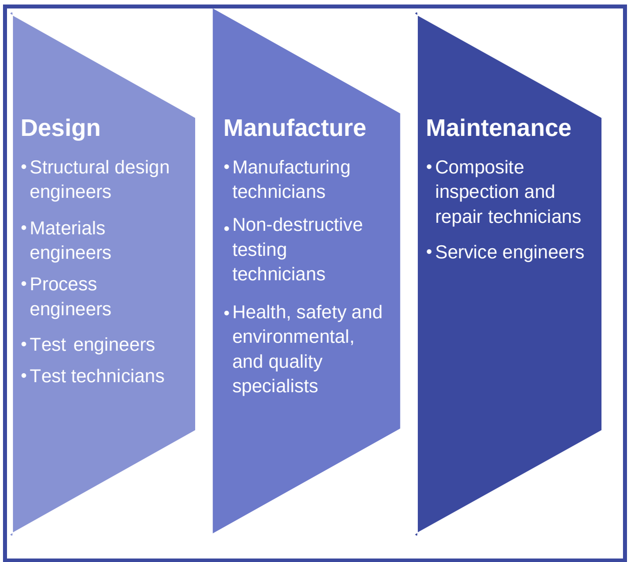


Figure 7.1.1 Composites skill requirements in the wind industry.

7.1.1. RD&D

Within the RD&D departments of blade manufacturers and their supply chain, the greatest need is for graduate or postgraduate engineers with composites expertise. They require a combination of structural, mechanical, material, process, and test and verification engineers. Specific role-related skills are also required, including the use of design tools and the Six Sigma quality improvement process and formal project management skills. Increasingly, RD&D activity may include manufacturing specialists working with modelling and simulation tools.

7.1.2. Manufacture

The majority of the workforce carrying out the manufacturing of wind turbine blades and nacelle covers will be made up of skilled technicians. These technicians must have basic numeracy and literacy skills and will need to be trained in the relevant composite manufacturing process, depending on the type of facility, and in health and safety, quality processes, blade finishing and non-destructive testing techniques. Technicians will need a clear understanding of the process and materials used and there may be value in greater emphasis on level 3/4 training rather than the level 2/3 training that has been the practice so far.

In addition, manufacturing facilities require supporting competences including in process engineering, health, safety and environmental regulations and quality tools, and process optimisation tools such as “lean” and Six Sigma.

7.1.3. Maintenance

The primary skill required for carrying out maintenance on wind turbine blades is polyester and epoxy field repair capability. Working at height, offshore survival and rope access skills and qualifications will be needed.

7.2. Provision

There are four main forms of composite skills development in the UK.

- **In-house training** is provided by most blade or turbine manufacturers to ensure their specific needs are required. Currently, there is little external provision for specific training on composites in wind turbines.
- **Higher education institutions** such as universities provide training in composites, typically through undergraduate, masters and doctorate degrees, or as multi-day short courses aimed at professional technical development. About 15 universities in the UK provide stand-alone composite degree or postgraduate courses but, more commonly, composites will form part of a more generic course such as aerospace or marine engineering.
- **Further education institutions** generally provide technician level training in composite manufacture and repair. A number of qualifications are available in composites including Business and Technology Education Council qualifications (BTECs), Higher National Diplomas (HNDs), National Vocational Qualifications (NVQs) and FdScs (two year foundation degree courses). At present there is no qualification available related directly to blade manufacture or the use of composites in the wind industry but this is currently being considered by the National Skills Academy for Composites and Biotechnology.
- **Private training companies** can provide short courses on specific areas of composites skills such as an introduction to composites, design in composites, manufacturing with composites, composite lifecycle analysis and training in specific process such as infusion or tools.

In some cases, partnerships have been formed between further education colleges and private training organisations to develop and provide courses.

A comprehensive list of composites skills providers is available on the Composites UK website.[11]

7.3. Supporting organisations

7.3.1. Composite Skills Strategy Group

The Sector Skills Council for Science, Engineering and Manufacturing Technologies (Semta) and Cogent have together formed the Composite Skills Strategy Group (CSSG). It provides strategic leadership from the industry on issues relating to composite skills, which are then delivered through the National Skills Academy for Composites and Biotechnology. In line with industry requirements, the CSSG has three main work streams:

- Workforce development and apprenticeships
- Higher education, and
- Continuing professional development.

7.3.2. National Skills Academy for Composites and Biotechnology

The creation of a National Skills Academy for Composites was announced in 2010. It will partner the National Skills Academy for Process Industries and will receive £2 million over three years. The skills academy will be run by Cogent and will work with the composites user and supply community, including the wind industry, to determine skills needs, set training standards and develop skills provision. This includes developing and implementing a new apprenticeship framework. It will be based at the National Composites Centre in Bristol.

7.3.3. Cross-sectorial skills transfer

There are opportunities for skills transfer from other industries. Both the aerospace and marine sectors have skill sets in composites that are directly applicable or can be adapted for wind turbine blade and nacelle cover manufacture. These include structural and material design and testing, manufacture, and composite repair. Other industries, such as the defence, construction and transport sectors, also have some transferable skills.

7.4. Challenges

A strong skills base and training infrastructure in composites will help attract investment in UK composites manufacturing for the wind industry. There are concerns that there is a gap between future wind industry requirements for skilled composite engineers and technicians and their likely availability. This is due to number of factors:

- The speed of growth of the wind industry
- The increasing use of composites in the UK across a range of sectors such as aerospace
- A lack of composite training infrastructure, and
- A limited experienced skill base that can provide training and support for new entrants.

8. Opportunities for the composites industry

There are a number of opportunities for new suppliers and service providers to enter the offshore wind market in composites or expand their offering to the wind industry. These opportunities primarily exist in five areas:

- Component manufacture and supply
- Tooling supply and manufacturing support
- Material and subcomponent supply
- RD&D of processes and materials, and
- Blade inspection and repair.

8.1. Component manufacture and supply

8.1.1. Blade supply

The size of offshore wind turbine blades and the forecast growth in the sector means that new blade manufacturing facilities will be needed. In doing so, most manufacturers will size their facilities to meet the demand for the whole European market. Figure 8.1.1 shows our forecast for the number of blades required to 2020. A typical offshore blade manufacturing facility is likely to have an annual capacity equivalent to about 1GW. To supply components for a 5MW turbine, it would therefore produce 200 sets of blades a year. The size of these components and the volume required means that, wherever possible, manufacturers will look to establish coastal facilities. It is anticipated that the total European offshore market will grow to support about six average-sized blade facilities.

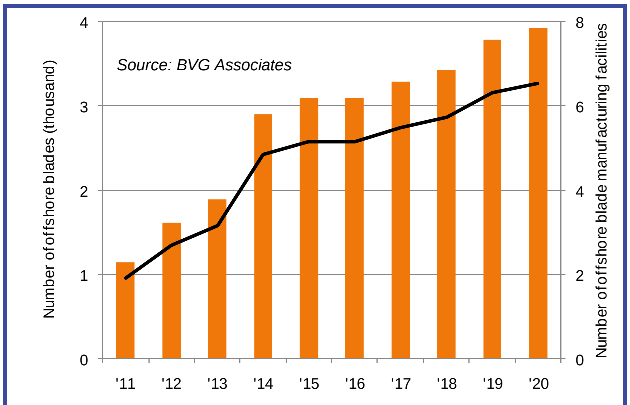


Figure 8.1.1 Forecast demand for offshore turbine blades and manufacturing facilities in Europe to 2020.

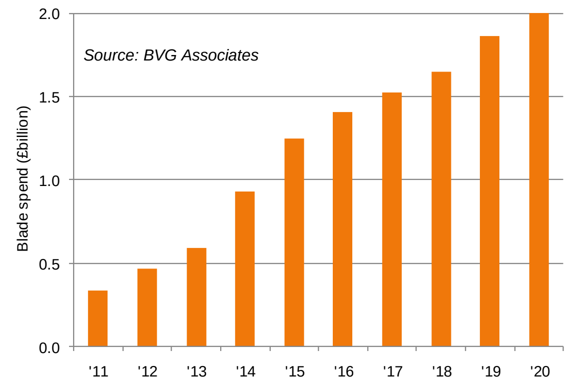


Figure 8.1.2 Forecast spend on offshore wind turbine blades in Europe to 2020.

With the UK expected to lead the European offshore wind market for some time, most offshore turbine manufacturers have committed to UK manufacture or are currently examining sites. In the first instance, manufacturers are likely to focus on nacelle assembly but blade manufacture is likely to be a next step for most companies. Independent blade manufacturers are also considering UK manufacture.

As Table 8.1.1 shows, most wind turbine manufacturers make blades in-house or through a subsidiary or joint venture. Table 8.1.2 lists some significant independent manufacturers, of which LM Wind Power is by far the largest. Although some turbine manufacturers may consider dual sources of blades, there is a limited opportunity for new independent blade manufacturers to enter the market as volumes are not that high, entry costs are significant and much emphasis is put on track record. The design is typically owned by the turbine manufacturer (with the exception of LM Wind Power).

Table 8.1.1 Blade suppliers to the leading offshore wind turbine manufacturers.

Wind turbine manufacturer	Blade supplier
Siemens Wind Power	Siemens Wind Power
Vestas Wind Systems	Vestas Wind Systems
REpower	PowerBlades (REpower joint venture with SGL Rotec); LM Wind Power
Bard	SGL Rotec
Areva	PN Rotor (wholly-owned subsidiary of Areva)

Table 8.1.2 Principal independent blade manufacturers.

Blade manufacturer	Significant offshore customers
LM Wind Power	REpower
SGL Rotec	Bard
Sinoi	WinWind
Euros	WinWind, Areva
Lianyungang Zhongfu	Sinovel
HT Blade	Sinovel

8.1.2. Blade component supply

Blade manufacturers will often subcontract the supply of components used in the blade. These may include shear webs, root end sections, root end platforms and covers, root end fixings, lightning protection systems, load sensors and balancing weights.

8.1.3. Nacelle covers and spinners

Most wind turbine manufacturers subcontract the supply of these components so there is a greater opportunity for companies to enter the market than for blades. The intellectual property (IP) associated with nacelle covers and spinners is also less contentious, lifetime risks are lower and tooling is cheaper. Existing suppliers include Jupiter, EM-Fiberglas, Bach Composites and Eikboom.

8.2. Tooling supply and manufacturing support

There are a number of opportunities for companies to support manufacturing activity both during set-up and operation. These include the supply of tooling and consumables and the provision of services such as training and testing.

8.2.1. Tooling

An offshore blade manufacturing facility will usually have between two and four moulds in series production mode. Each mould will be capable of 300-1,000 mould cycles, depending on the tooling technology and process design, and is limited by the longevity of the mould surface.

Blade mould manufacture is highly specialised and may include technologies relating to composites, heating and cooling, steel frames, hydraulic systems, electrical and compressed air services, insulation, hinge systems and process controls. Most blade manufacturers in offshore wind will manufacture their own moulds, although specialist subcontractors do exist.

Infusion and mixing equipment

Equipment for handling resin and adhesives includes resin pumps, mixing systems, vacuum pumps and dispensing equipment. Most are provided by specialist manufacturers.

Glass cutting, fibre placement and other automated equipment

Automated equipment is often used for cutting and preparing glass and carbon fibre fabrics. Increasing use is being made of automated guidance and placement systems for the positioning of lay-up materials within the mould, aimed at achieving consistency and tight process control. Some blade manufacturers have developed their own systems for resin impregnation into fabrics.

Blade handling and support frames

Blade handling systems include forklifts, telescopic handlers, cranes and specially designed tools. Blades are typically stored and transported using purpose-built blade steel frames, which also allow the blade to be fixed on board an installation vessel.

8.2.2. Consumables

Blade and nacelle factories require large amounts of consumables such as health and safety equipment, vacuum bags and infusion mesh. The amount and type required varies depending on the blade manufacturing process. but typical spend for a facility producing 500 blades a year on consumables would be about £300,000 for an infusion facility and about £1 million for prepreg facility.

8.2.3. Manufacturing training

Due to the specialist nature of blade manufacture and the different manufacturing processes used across the sector, most blade manufacturers give in-house training to new recruits. Numeracy and literacy skills are essential and knowledge of composites materials and infusion technology is desirable. Experience in hand-laminating fibreglass is unlikely to be relevant. Training for manufacturing personnel will generally include:

- Health and safety in the manufacturing environment, including safe working practices and the use of specialised equipment and hand tools
- The use of personal protective equipment, including clothing, masks, breathing equipment and ear protection
- Classroom training in the use of work instructions, safe working practices, process procedures and quality systems
- Classroom training in composite materials and manufacturing techniques such as resin infusion
- Classroom training in process tools, such as Six Sigma and “lean”
- Workshop training in generic equipment such as power tools and mixing equipment
- Training in processes specific to the individual facility, including fabric lay-up, infusion, spray painting and finishing
- Workshop training in processes, and
- Introduction to the factory floor.

For specific roles, additional training will be required in:

- First aid
- Lifting equipment and cranes
- Fork lift truck driving
- Equipment maintenance and cleaning
- Working at heights
- Quality assurance, and
- Team leadership.

8.2.4. Manufacturing development services

Most composite manufacturing facilities use consultancy services to support their activities. Opportunities exist to provide services in the following areas:

- Logistics
- Health and safety support
- Lean manufacturing tools
- Factory design and flow modelling, and
- Supply chain support.


Courtesy of Consuta Training

Figure 8.2.1 Blade manufacturing training.

8.3. Material and subcomponent supply

There are some opportunities in supplying materials for nacelle cover and spinner manufacturing. Assuming a combined nacelle cover and spinner mass of 20t, of which 15t is composite, the annual European demand in 2020 will be about 23,000t.

Bigger opportunities exist in the supply to blade manufacturing plants. The breakdown of materials shown in Figure 8.3.1 assumes that innovations in blade technology will be incremental and that the proportions and types of materials used across the industry remain largely constant. Within these material types, there will be innovations, for example in glass fibre. Based on the current relationship between blade length and mass, the demand for composite materials for blade manufacture by European offshore wind will be about 78,000t in 2020.

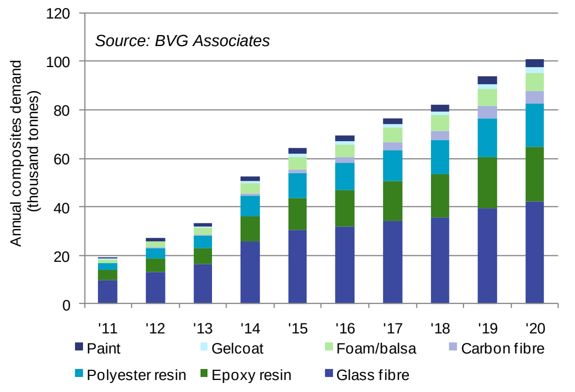


Figure 8.3.1 Forecast composite material demand in Europe from offshore wind farms to 2020.

Most of these materials are likely to be sourced from within Europe and most large manufacturers looking to build blade factories in Europe will expand their European supply chain. Some significant material suppliers are shown in Table 8.3.1. They include among them a number of UK companies.

8.4. RD&D of processes and materials

8.4.1. Opportunities to enter the technology supply chain

There are opportunities for the supply and licensing of technology to the offshore wind blade manufacturers and their supply chain. The key areas of opportunity are listed in Section 6.2.

If technology developers and research organisations that own IP relevant to the wind industry lack the capability to commercialise or manufacture their technology, opportunities exist to license their IP to blade manufacturers or their supply chain, or to form a joint venture.

Collaborative projects offer a strong platform for engagement between technology developers and research organisations, and blade manufacturers and their supply chain. These allow co-development and steering from the eventual customers.

8.4.2. Opportunities to provide support to RD&D activities

There are opportunities to support composites RD&D activities within the wind industry. These opportunities tend to be clustered around RD&D centres and can be roughly split into two categories:

- Design and testing services, and
- Composite design training.

Design and testing services

Design tool supply and support

The design and development of composite components for wind turbines require the use of a number of design tools such as FEA and computer-aided design (see Section 4.2). Opportunities exist to supply and provide ongoing support to design engineers within blade and composite development centres.

External design services

Consultants and design houses are engaged in developing new blade designs or concepts. The level and type of engagement varies significantly depending on the manufacturer or project. In an extreme case, whole blade designs are outsourced but more typical tasks that are subcontracted are:

- Sub-component design, such as the lightning protection system
- FEA on blade or components
- Project management, and
- Independent design review.

Table 8.3.1 Material and component suppliers (examples only).

Material	Main suppliers
Glass fibre	Hengshi, Jushi, Owens Corning, PPG Industries
Carbon fibre	Hexcel, SGL, Toho Tenax, Toray, Zoltek
Textiles	Formax, Gurit, Hexcel, PRF Composite Materials, Saertex, St Gobain
Epoxy resin	Cray Valley, Dow, Gurit, Hexion, Hunstman, Leuna Harze, Scott Bader
Polyester resin	DSM, Gurit,
Epoxy prepreg	Gurit, Hexcel, Saertex
Gelcoat	3M, Blade Dynamics, Cray Valley, Gurit, Dow, Scott Bader
Balsa	3A Composites, DIAB,
Polymer foam	3A Composites, DIAB, Gurit,
Spar	Gurit, Hexcel

Test sample manufacturing services
Small numbers of coupons, panels, components and moulds need to be tested. Some RD&D centres have facilities in-house to do this but other will outsource testing.

External testing services
These are required by all blade or composite development facilities. While most blade development facilities have some testing facilities, they draw on external testing facilities for specialist tests or when they cannot meet capacity. Facilities required may include:

- Material coupon testing (biaxial, multi-axial, fatigue and load testing)
- Subcomponent structural testing (fatigue and load testing)
- Lightning testing (high voltage and current), and
- Environmental testing.

There is some requirement for whole blade testing, although much blade testing is carried out in-house by the blade manufacturers. Narec is the only open-access blade test facility in the UK.

8.4.3. Composite design training

Blade development centres need both professional training and high-quality qualified staff. There are opportunities to provide short courses in composite design-related subjects and to provide longer-term courses such as degree programmes (see Section 7).

8.5. Blade inspection and repair

Turbine operators carry out regular inspection of their blades. Damaged blades can significantly reduce the overall power output of the turbine. Regular inspection of the blades can pick up minor damage before it propagates, reducing the risk of catastrophic failure.

There is an opportunity to provide these services to wind turbine owners. Technicians carrying out this work are usually qualified composite repair specialists competent in both polyester- and epoxy-based repairs as well as in rope access and working from height. Most of these inspections and repairs are carried out while the blade remains on the turbine. The main services required by the turbine owners are:

- Internal and external blade inspection
- Paint and gel coat repairs
- Composite damage repairs, and
- Lightning protection systems inspection and repair.

8.6. Parallel sectors

Composites are used extensively by a number of sectors with technologies relevant to the wind industry. Their characteristics and the technologies they employ mean that their opportunities in wind and the obstacles are distinct.

8.6.1. Aerospace and defence

Opportunities

There are a number of opportunities for technology transfer between aerospace and blade manufacture. These mainly focus around manufacturing, design and testing. There is some overlap in the supply chain.

The aerospace industry has previously favoured autoclave processing of carbon fibre epoxy prepreg to achieve the highest possible mechanical properties. Drivers to reduce costs and production time are now leading the industry towards developing out-of-autoclave processing and automated production techniques wherever possible. This means there are significant synergies between the composite production technology requirements of the aerospace and wind industries, as demonstrated by the technology collaboration announced in 2009 between Vestas Wind Systems and Boeing.[12]

There is potential for skills transfer from the aerospace sector to the wind industry, particularly in design, testing and process development. The application of aerospace and defence composite design and material technology could improve the performance of blades through improved material use or by introducing additional functions. Examples of technology that have been transferred include radar mitigation, lightning protection and erosion resistance.

Challenges

The rate of production is much higher in the wind industry than in aerospace and defence. A large manufacturer of offshore blades will produce more than 500 blades a year. Unlike the wind industry, the predominant composite technology used in aerospace and defence is prepreg with a large percentage of carbon. Although these technologies are used in the wind industry, their use is not widespread due to the cost, which is a significantly greater driver in the wind industry than in aerospace or defence.

8.6.2. Marine

Opportunities

The processes and materials boat construction are similar to those used in manufacturing blades, nacelle covers and spinners. As with composite manufacture for wind turbines, glass and epoxy or glass and polyester resin infusion is widely used in boat building with a few manufacturers using prepreg and/or carbon.

There are significant opportunities in offshore wind for companies in the marine composites sector, in terms of skills, materials, tooling, and manufacturing support supply chain and technology transfer.

Challenges

The use of composites in the marine industry mainly revolves around the military and leisure markets, where manufacturing rates of production are generally lower.

8.6.3. Automotive

Opportunities

While the automotive industry has significant experience in the mass production of parts and the lean, cost reduction and process flow approach to manufacture, it has traditionally had limited experience of making composite parts in large volumes because their cost has been considered prohibitive. Environmental considerations and the need to reduce weight mean this attitude is changing and there is now interest from composite providers and automotive manufacturers in producing composite parts in high volumes. There may be some scope for technology transfer between the wind and automotive sectors as both explore these new manufacturing routes; however, it should be recognised that most developments in composite manufacture for mass automotive manufacture are taking place outside the UK.

Challenges

The UK does have expertise in the use of composites in the high-end automotive industry, but there are few parallels with the wind industry. The materials and processes that have been developed have different drivers from those found in the wind industry. As a result, costs are too high and the size and volume too small for significant technology transfer.

8.6.4. Motorsport

The opportunities for technology and skills transfer between motorsports and the wind industry are mostly in design skills and tools, and rapid prototyping. The challenges are similar to those for the aerospace and defence and automotive sectors with smaller components produced in lower volumes.

8.6.5. Oil and gas

Composites have been used for some time in the oil and gas industry. Knowledge of environmental resistance can be transferred across to the similar environment for offshore wind. For example, the use of ladders and gratings for offshore platforms could be directly transferred to wind turbine and offshore substation platforms. Cost may be an obstacle.

9. Further information

9.1. Wind industry

9.1.1. RenewableUK

RenewableUK (formerly British Wind Energy Association) is the principal trade association for the large scale UK wind and marine renewables industries.

RenewableUK
Greencoat House
Francis Street
London, SW1P 1DH, UK
Telephone: 020 7901 3000
Email: info@renewable-uk.com
Web: www.renewable-uk.com

9.1.2. The Crown Estate

The Crown Estate owns virtually the entire seabed out to the 12 nautical mile territorial limit. It has rights to issue leases for the generation of renewable energy on the continental shelf within the Renewable Energy Zone out to 200 nautical miles.

The Crown Estate
16 New Burlington Place
London W1S 2HX
Telephone: 020 7851 5000
Email: enquiries@thecrownestate.co.uk
Web: www.thecrownestate.co.uk

9.2. Skills

9.2.1. National Skills Academy for Process Industries

National Skills Academy for Process Industries is an employer-led centre that addresses the skills and training needs of the chemical, polymer, and pharmaceutical sectors.

National Skills Academy for Process Industries
5 Pioneer Court
Morton Palms Business Park
Darlington DL1 4WD
Telephone: 01325 740900
Email: enquiries@process.nsacademy.co.uk
Web: www.process.nsacademy.co.uk

9.3. Composites industry

9.3.1. National Composites Centre

The National Composites Centre is an open-access national centre that supports innovation in the design and rapid manufacture of composites.

The National Composites Centre
Queen's Building
University Walk
Bristol BS8 1TR
Telephone: 0117 928 8173
Email: enquiries@nationalcompositescentre.co.uk
Web: www.nationalcompositescentre.co.uk

9.3.2. National Composites Network

The National Composites Network is a Knowledge Transfer Network jointly funded by government and industry that embraces the entire UK composites industry and its supply chain.

National Composites Network
Granta Park
Great Abington
Cambridge CB1 6AL
Telephone: 01223 894 662
Email: info@ncn-uk.co.uk
Web: www.ncn-uk.co.uk

9.3.3. Composites UK

Composites UK is the representative body of the UK composites industry.

Composites UK
4A Broom Business Park
Bridge Way
Chesterfield S41 9QG, UK
Telephone: 01246 266245
Email: info@compositesuk.co.uk
Web: www.compositesuk.co.uk

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