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Chapter 8

Emerging wind energy technologies

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Introduction

Since the wind industry took off in the mid-1980s, wind turbine technology has seen rapid development. This has led to impressive increases in the size of turbines: over three decades, a 100-fold increase in power output has accompanied major cost reductions due to improvements in design. If today's 6–8 MW turbines were created by simply scaling up 55 kW machines from the mid-1980s, they would weigh 10 times as much as they do now. This chapter will discuss emerging technologies that are expected to continue the development of the wind sector to embrace new markets and to become even more competitive.

Drivers for new technologies

Most emerging technologies in the wind sector address technical challenges that currently set a lower limit to the cost of electricity produced in a given environment. The cost of electricity (CoE) is proportional to the cost of the installed hardware (C) plus the cost of maintaining that hardware (M) over its lifetime, and inversely proportional to the amount of electricity (E) produced in that time:

$$\text{CoE} = \frac{C+M}{E} \quad (1)$$

Thus strategies for decreasing the CoE will focus on building cheaper hardware that needs as little maintenance as possible over its lifetime, and on harvesting as much energy as possible during that lifetime. A more general concept is the Levelized Cost of Energy (LCoE) where the interest rate of the financing and insurance is included.

Small versus large turbines

The power and hence the income generated by a wind turbine increases with the area (A) of the rotor. For a horizontal-axis turbine, $A = \pi R^2$, where R is the length of a rotor blade. Longer blades, however, also have to be thicker and wider. Thus the mass (m) of the blade will increase more or less in proportion to R^3 . Assuming that the cost of the blade is proportional to its mass, scaling up increases the cost of the blade faster than the income it generates. This relation is often called the “square-cube” law, and it applies in general for the whole turbine.

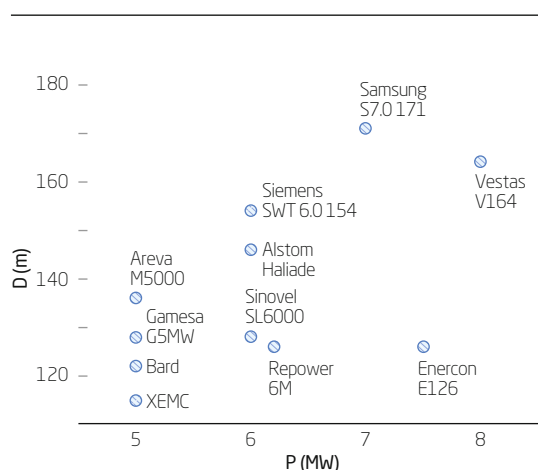
Applying the square-cube law to Equation (1) suggests that as turbines are scaled up the CoE should increase approximately in proportion to the blade length. That this has not been the case for several decades is due to technical advances and new materials and design concepts used for the blades as well as the rest of the turbine, and to engineers' growing ability to optimise their aerodynamic, structural and dynamic properties.

Figure 18 shows the rotor diameter of the 10 largest turbines as of 2014 as a function of their rated power. The typical power of onshore turbines is now 2–3 MW, whereas the largest offshore turbines range up to 8 MW and have rotor diameters up to 171 m. The rotor area of a given turbine is utilized to capture as much of the wind available for a specific site and also to increase the capacity factor to give a more constant power production. In Figure 18 the different design strategies are clearly seen since a 120–130 m rotor is used for turbines with power ratings in the range from 5–7.5 MW.

Turbine configurations

All the turbines illustrated in Figure 18 are horizontal-axis wind turbines (HAWT) with three blades. One might get the impression that this is the only configuration suitable for large-scale deployment of wind power, but in fact several other concepts have been proposed and some are under development.

Figure 18 – Rotor diameter and rated power for the 10 largest turbines.



Rotor diameter and rated power for the 10 largest turbines as of May 2014. [3]

All the turbines shown are intended for offshore operation, but the size is expected to increase even further to utilize the expensive offshore foundations.

Figure 19 - Turbine configurations.

- (a) A two-blade HAWT (Envision). [5]
- (b) Vertical-axis wind turbine (VAWT) (Deepwind small-scale demonstrator). [6]
- (c) Multi-rotor concept. [7]



We will discuss some of these emerging concepts before moving on to subsystems and components for three-bladed HAWTs.

The mainstream HAWT development has an impressive track record over the last 30 years. Following early successes with this type of turbine most R&D has concentrated on HAWTs, to great effect. At a more detailed level the concept has evolved over the years. The latest development is blades designed for strength rather than stiffness, with lower than optimum induction of the rotor. This results in very long, slender, flexible blades which compared to their predecessors sweep a bigger area and so capture more energy over the year for a given generator size.

This successful evolution of the mainstream HAWT makes it difficult for radical new turbine configurations to compete, though it does set clear benchmarks for performance and cost. It is also hard to compare new designs that have not yet been built with field-proven turbine models. Advanced modelling and simulation tools are a great help here, however.

An example shows what happens when we convert a three-blade HAWT to a two-blade design with the same rotor diameter. Simulation shows that increasing the chord (width) of the blades by 50% yields a two-blade rotor with similar performance to that of the original three-blade rotor.[4] Although using two blades instead of three increases the load on each blade by 50%, the broader blade can be made from

thinner shels while still carrying the higher load. As a result, the two-blade rotor weighs only two-thirds as much as its three-blade counterpart.

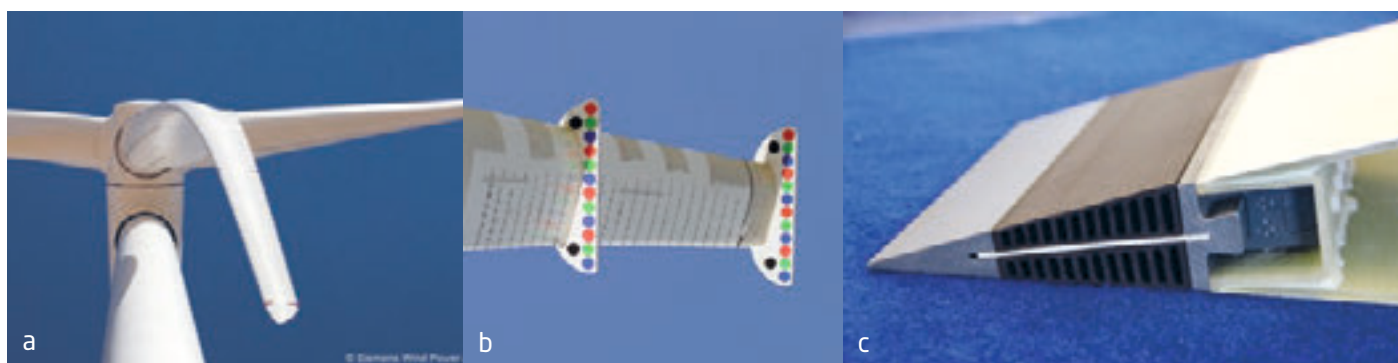
A further modification could save even more weight. Two-blade turbines have the advantage that they can be fitted with “teetering” hubs, which reduce fatigue loads by not constraining the blades to a single plane of rotation. By reducing blade loads to around the same value as for the slenderer three-blade design, the teetering hub allows the use of a rotor that weighs only half as much as the original three-blade design.

Looking at this way, the two-blade design allows the use of a larger rotor – and hence captures more energy – than a three-blade rotor made from the same amount of material.

Disadvantages of the two-blade design include a 4% increase in aerodynamic losses at the blade tips, a 15% increase in the turbulent load on the rotor, and higher fatigue loads on the tower due to turbulence. These advantages and disadvantages relative to the mainstream turbine design need to be balanced in terms of their implications for the cost of electricity. The same is true of any novel design concept, and mathematical modelling needs to be backed up with a certain degree of actual product development before a realistic comparison can be made.

Figure 19a shows a two-blade horizontal-axis turbine in which only the outer part of each blade is

Figure 20 – Blades.



fitted with pitch control. [5] Compared to a three-blade turbine this saves the weight of one blade and makes installation easier, especially offshore. This two-blade design can withstand extremely high winds, so it could be well suited to survive typhoons in Asia.

Figure 19b is a vertical-axis wind turbine (VAWT). Compared to a HAWT this has the advantage that there is no need for a yaw system to turn the rotor into the wind. [6] VAWT blades experience cyclic aerodynamic loads and constant gravity loads, while for HAWTs this situation is reversed. VAWTs thus have the potential to become more cost-efficient at power ratings above 10 MW, where gravity loads on HAWT blades become very large.

Figure 19c shows a multi-rotor concept in which a large structural frame holds several smaller turbines (either HAWTs or VAWTs). [7] This might reduce scale-up costs by achieving large power ratings from relatively low-cost turbines manufactured in large numbers and standard sizes. Power would continue to flow even if one of the turbines failed, but on the other hand maintenance costs are likely to be higher than for a single turbine with the same output.

Components for horizontal-axis turbines

Several emerging technologies are found in specific turbine components such as blades, drive trains, towers, offshore foundations, power electronics, offshore cabling, and control systems.

Blades

Many factors have aided the move to lighter blades. In the past, the most important of these has been the development of blades that are much thicker than their predecessors, especially near the hub. This increases their load-carrying capacity at the expense of aerodynamics, so an optimum trade-off is the objective.

During the last few years there has been an important move from design for stiffness (to stop blades hitting the tower) to design for strength, which implies a more economical use of materials.

This has been made possible by angling the blades into the wind (“upwind coning” and “pre-bend”) and by tilting the whole rotor upwards. These changes allow the use of more flexible blades, and corresponding higher deflections, while still maintaining safe clearance from the tower. Greater flexibility, however, presents a challenge with respect to predicting the dynamic behaviour of the blades. Such designs are only possible thanks to advanced tools for simulating aeroelastic loads and stability – indeed; these models have even predicted improvements in stability as a result of pre-bending.

An especially elegant consequence of increased flexibility is the ability to build passive load-reduction techniques directly into the blade structure. Taking advantage of the unique attributes of composite materials, for instance, some blades are now being built in ways that couple their bending and twisting

(a) Blades with passive load reduction made by Siemens Wind Power.[8]

(b) Measuring blade deflection. (Reproduced with permission from Siemens Wind Power A/S) [9]

(c) Blade section with an active trailing edge controlled by pressurised air.[10]

deformations in order to reduce loads. Another way to reduce loads is to curve or “sweep” the blades in their plane of rotation. *Figure 20* shows such blades in operation (a), along with an experimental setup (b).

A combination of passive built-in aeroelastic tailoring of the blade characteristics with innovative systems of trailing-edge control can considerably reduce the fatigue loads on blades. Active trailing-edge control systems are being developed, though they have not yet been applied on commercial turbines (*Figure 20c*). Passive flow control devices such as vortex generators and Gurney flaps, meanwhile, are included in many new blades. They can also be retrofitted to older blades to improve flow conditions and increase power output.

The general trend in blade and rotor design is towards increased tailoring to give greater variation in aerodynamic, structural and aeroelastic characteristics along the span of the blade. Simultaneous optimisation of all these parameters produces blades with unconventional shapes that can be very far from straight in the unloaded condition. These very long blades, with a lot of pre-bend and sweep, are challenging to build, and it is tempting to manufacture them in sections that can be glued together on site. This could allow pre-bent and swept blades to be built up from nearly straight sections fixed at small angles to one other.

Drive trains

Conventional wind turbines use gears to match the slow rotation speeds of the blades and hub to the higher speeds required to drive a standard induction generator connected directly to the grid. Historically, gearboxes installed in wind turbines in some cases have turned out to have shorter lifetimes than they were designed for. This has increased the maintenance cost M as well as reduced the energy production E due to less availability of the turbine and resulted in a lower CoE than expected. The problem has been solved by developing improved gears and – in onshore turbines – procedures to replace gearboxes quickly in old turbines.

Gearbox replacement is not an attractive idea in offshore turbines, however, because access is only

available during short periods of calm weather at sea. To improve the reliability of offshore turbines, manufacturers have therefore developed a range of drive train solutions containing one, two or three gearbox stages, or with no gears at all (*Table 7*).

Using a gearbox allows the generator to be kept relatively small because the power of the generator is proportional to its speed:

$$P_{gen} \sim B_g A_s V_g \omega_g \quad (2)$$

where P_{gen} is the generator power, B_g is the magnetic field strength in the air gap, A_s is the current loading of the stator windings, V_g is the volume of the generator, and ω_g is the rotation speed. Thus if we reduce the rotation speed by reducing the gear ratio, we have to increase the volume of the generator to get the same power output. [11]

From *Table 7* it is evident that many – and very different – drive train concepts are now appearing in offshore turbines. It remains to be seen whether any of them will become widely accepted as the offshore wind sector grows. We can say, however, that the current trend is to remove as many stages of the gearbox as possible, in order to improve reliability, and to use medium-speed multi-pole permanent magnet generators. [11]

Permanent magnet generators use powerful magnets made from neodymium or other metals of the type known as rare earths elements. Compared to generators that rely on current-carrying coils for their magnetic fields, permanent magnet generators have fewer moving parts and might be more reliable. Since commercial sources of rare earths element magnets are concentrated in Asia, there is concern that supplies may not be able to meet demand for the large magnets used in wind turbine generators. Other types of magnets can be used, but since these are weaker they would require larger generators.

The frequency of low- or medium-speed permanent magnet generators does not match the frequency of the grid, so all the power produced has to go through an electronic converter. This increases costs, but at the

Table 7 - Drive train details for the 10 largest turbines as of May 2014.

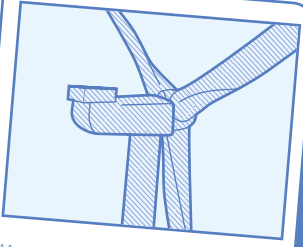
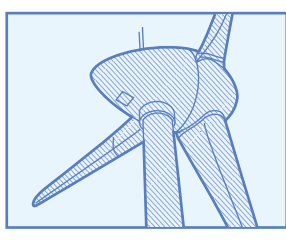
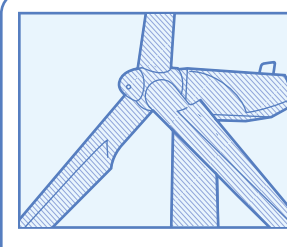
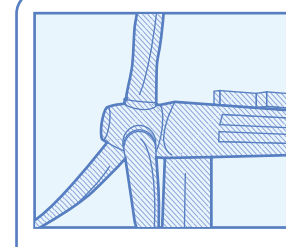
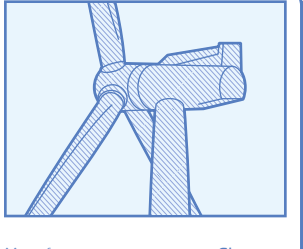
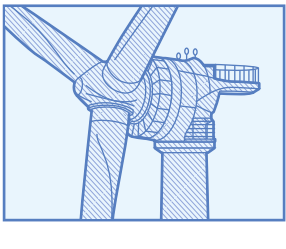
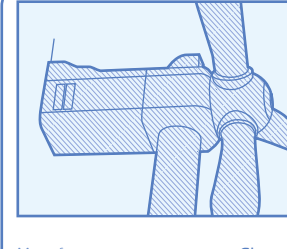
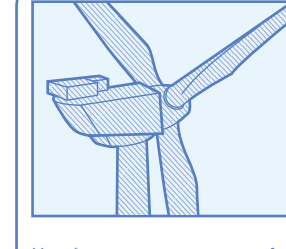
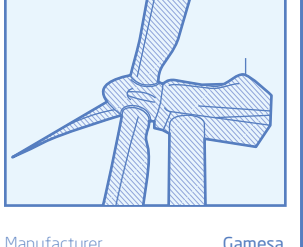
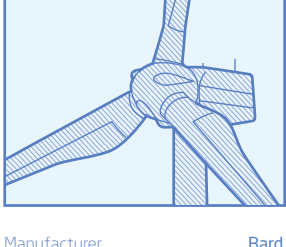
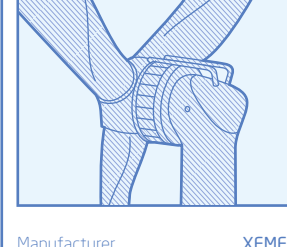
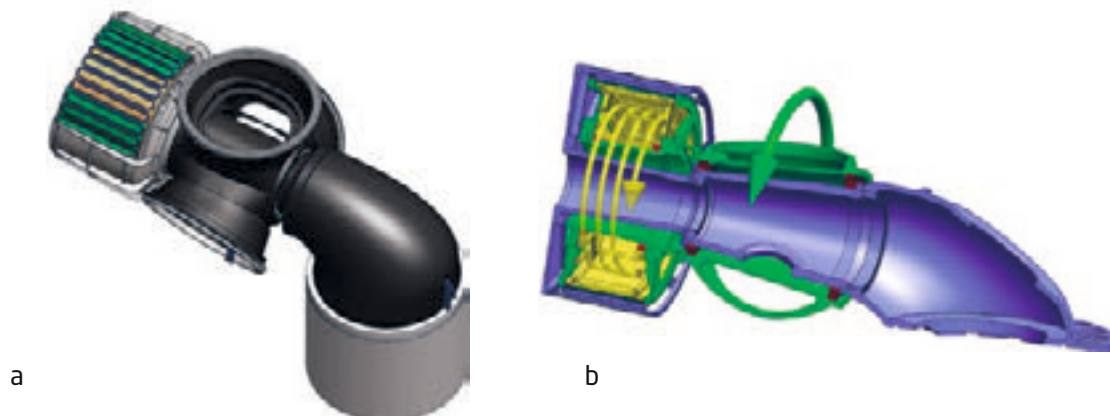
 Manufacturer Vestas Model V164 Power (MW) 8.0 Rotor diameter (m) 164 Drive train 1-stage gear, PM, full converter	 Manufacturer Enercon Model E126 Power (MW) 7.5 Rotor diameter (m) 126 Drive train DD, Wound Cu, full converter	 Manufacturer Samsung Model S7.0-171 Power (MW) 7.0 Rotor diameter (m) 171 Drive train 1-stage gear, PM, full converter	 Manufacturer Senvion Model 6M Power (MW) 6.2 Rotor diameter (m) 126 Drive train 3-stage gear, DFIG, partial converter
 Manufacturer Siemens Model SWT6.0-155 Power (MW) 6.0 Rotor diameter (m) 154 Drive train DD, PM, full converter	 Manufacturer Alstom Model Haliade Power (MW) 6.0 Rotor diameter (m) 146 Drive train DD, PM, full converter	 Manufacturer Sinovel Model SL6000 Power (MW) 6.0 Rotor diameter (m) 128 Drive train 3-stage gear, DFIG, partial converter	 Manufacturer Areva Model M5000 Power (MW) 5.0 Rotor diameter (m) 136 Drive train 1-stage gear, PM, full converter
 Manufacturer Gamesa Model G5MW Power (MW) 5.0 Rotor diameter (m) 128 Drive train 2-stage gear, PM, full converter	 Manufacturer Bard Model Bard 5.0 Power (MW) 5.0 Rotor diameter (m) 122 Drive train 3-stage gear, DFIG, partial converter	 Manufacturer XEMEC Model XD115-5MW Power (MW) 5.0 Rotor diameter (m) 115 Drive train DD, PM, full converter	Drive train details for the 10 largest turbines as of May 2014. [3,12] The turbines are ranked by rated power and then by rotor diameter. Key: DD = direct drive, PM = permanent magnet generator, DFIG = doubly fed induction generator, wound Cu = generator using only electro magnets, full converter = all power goes through the electronics, partial converter = only generator rotor power goes through the electronics.

Figure 21 - Drive trains.

- (a) Superconducting direct drive generator front-mounted in the “kingpin nacelle” configuration (INNWind.EU). [13]
- (b) Pseudo magnetic direct drive integrating a magnetic gearbox and a multi-pole generator (Magnomatics/DNV-GL). [14]



same time decouples the generator from the grid and so improves the “ride through” of grid faults.

Several other drive train concepts exist that are radically different from those found in the “top 10” list. Superconducting coils, for instance, could provide magnetic fields even stronger than those of permanent magnet generators. *Figure 21a* shows how this might yield a direct drive generator that is compact enough to be mounted on the turbine hub, eliminating the need for a conventional nacelle [13]. The challenge is to integrate the cryogenic system needed to cool the superconducting coils.

Magnetic gears are a new type of power transmission device originally developed at Sheffield University in the UK. A magnetic gearbox uses two sets of magnets rotating on rings placed close together so that their magnetic fields interact. With more magnets on one side than the other, the device acts like a conventional gearbox – and with claimed similar efficiency – in converting both shaft speed and torque.

Figure 21b shows a magnetic gearbox integrated with a multi-pole generator, again mounted directly on the hub. [14] This arrangement is claimed to be more compact than either a direct-drive generator or a mechanical gearbox with a conventional wound generator. It contains more moving parts than a direct-drive power train, however, and also requires a relatively large quantity of permanent magnets.

A direct drive concept based on the weaker types of magnets that could be used if rare earth magnets were in short supply. The lower magnetic field strength requires a large-diameter generator which is supported like a bicycle wheel in the Sway concept, where the generator diameter is about 30 meters [11].

Towers

As the turbine diameter increases, the tower on which it is mounted must become not only taller but also wider, and made from thicker material, so that it can carry the increased load from the nacelle and rotor down to the foundation. This will clearly cost more.

Tower performance and cost depend on the material used. Currently most towers are made from steel plates up to 150 mm thick, which are rolled into tube sections that are welded together. These sections are then lifted on top of one another and bolted together to form the complete tower. Bending and welding such thick plates is challenging, so designers are now looking into other materials such as concrete and even wood [15]. One idea is to cast concrete sections on site and then assemble these to create a tower.

Offshore foundations

The installed cost of a turbine includes the cost of the foundation, which for offshore wind farms can exceed the capital cost of the turbine itself. As with towers, the size of the foundation scales

with the square of the rotor diameter (times the tower height). For a given set of wind and wave conditions, it also scales linearly with water depth.

Expensive as offshore foundations are, it turns out that their costs scale relatively slowly with increasing turbine size, compared to the other contributors to the total installed cost. As a result, the economics of foundation design favour the use of turbines much larger than the typical 2–3 MW onshore turbine. This is clearly reflected in *Figure 18*, where almost all the turbines above 5 MW are aimed at offshore applications.

For water depths of 10–30 m the preferred foundation is a monopile (*Figure 22a*). This consists of a large-diameter steel tube hammered into the seabed, on top of which is a “transition piece” connected to the tower. A more innovative foundation is the jacket suction bucket (*Figure 22b*), which is sucked into the seabed by introducing a vacuum in the bucket part. In water 30–50 m deep a jacket

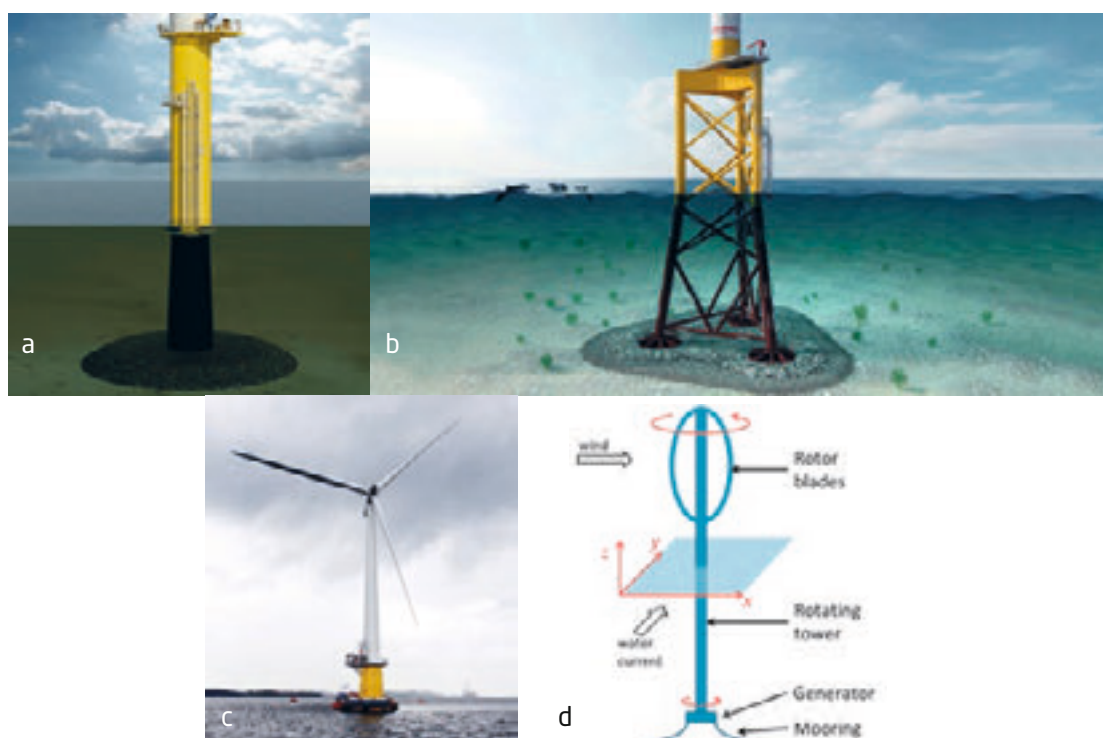
foundation is considered to be the most economic. For water deeper than 50 m a floating foundation (*Figure 22c and d*) is probably preferred.

Power electronics

As *Table 7* shows, most modern turbines use a full power electronic converter to allow variable-speed operation of the generator at frequencies different from that of the grid. This conversion usually begins with a set of semiconductor switches to rectify the AC power from the generator. The resulting DC current is fed to a capacitor bank, which is connected in turn to another set of semiconductor switches that chop up the DC to create an AC current at a frequency matching the electrical grid. This basic configuration can be realised in many topologies and with different numbers of semiconductor switches [20].

Although semiconductor switches are developing rapidly in terms of power ratings and reliability, they are still only used in small numbers and their cost is high [21]. Packaging is a key area of expertise:

Figure 22 – Offshore foundations.



Top: Bottom-mounted offshore foundations.

(a) Monopile foundations are used in most European offshore wind farms with typical water depths of 10–30 m (Reproduced with permission from Rambøll) [16]

(b) Suction bucket foundation for water depths of around 30–50 m (Reproduced with permission from DONG ENERGY) [17].

Bottom: Floating offshore foundations.

(c) The Hywind concept, here supporting a HAWT (Hild Bjelland Vik – Statoil ASA). [18]

(d) Deepwind concept supporting a VAWT. [19]

it is challenging to make reliable electrical connections to the semiconducting wafers themselves, and thermal cycling can create fatigue which shortens the life of the devices. In the future, silicon (Si) semiconductor material might be replaced by silicon carbide (SiC), which can sustain higher operating temperatures.

A second central question for power electronics concerns the generator voltage. Most turbines have 690 V generators because that is the standard for general power electronics used in industry. As turbines continue to increase in size, however, this relatively low voltage will require the use of unrealistically large currents.

Several commercial turbines, in fact, already use medium-voltage power converters. The problem with using voltages above 1 kV inside turbines is that this requires more stringent standards for design, construction and maintenance, and the associated switchgear and other equipment costs more.

One way to simplify the design of turbines – though not necessarily of complete wind farms – would be to export DC power to the collection grid (see next section). This would eliminate the need for the DC-to-AC stage of the power converter [22, 23].

Control of turbines, wind farms and grids

Central to the successful implementation of wind power is not just the hardware, but also the control of that hardware. Since turbines operate in turbulent wind conditions, they experience loads that fluctuate greatly and are occasionally very high. Both extreme and fatigue loads reduce the lifetime of the machines.

The systems that control turbines have the primary job of trying to keep the power output to the grid as steady as possible. At the same time, however, suitably designed controllers could also mitigate mechanical load peaks by changing the pitch of individual blades, varying the generator speed, or damping oscillations in the drive train.

Any turbine control system needs an input signal that is linked to the behaviour of the system it is

trying to control. At present the main such signal is the wind speed at the turbine, as measured by an anemometer mounted on the nacelle.

An emerging alternative uses the principle of “light detection and ranging” (LIDAR) to measure wind speed some distance upwind of the turbine. LIDAR is an analogue of radar, using laser light instead of radio waves; particles or droplets in the path of the beam create reflections from which the air velocity can be calculated. Measuring the speed of a gust several seconds before it hits the turbine improves control by allowing the control system to take pre-emptive action.

Further into the future, the ability to measure wind speeds across the whole rotor diameter (*Figure 23*) and in front of the blades might eventually be used to control the individual sections of “smart blades”. This could allow the turbine to respond more efficiently to off-centre gusts and turbulence. [24]

LIDAR is also a useful tool for measuring the wind conditions at a site before a wind turbine or wind farm is installed. On new projects it might replace the use of tall meteorological masts.

The control aspects of wind power relate not only to individual turbines, but also to an increasing extent to a wind farm’s collective response to the wind and its interaction with the grid. This calls for a wind farm controller that can take into account the responses of individual turbines to, for example, wake effects caused by their neighbours. Controlled shutdown of a wind farm in the face of an advancing storm is another important job of the main controller.

Learning from other industries

This chapter has shown that the biggest technology changes are taking place in the offshore sector, yet turbines for onshore use still make up by far the biggest fraction of the installed wind power base.

Even though onshore and offshore technologies are developing differently, there is still considerable transfer of emerging offshore turbine technologies to the onshore sector. An example of this is the ability to build longer rotor blades, which are used

Figure 23 – LIDAR.



(a) LIDAR could improve control by warning of gusts before they arrive at the turbine, and in future could even measure wind speeds across the whole rotor diameter.

(b) ZephIR LIDAR installed in the spinner of a NM80 2.3 MW wind turbine. [24]

for onshore turbines targeted at low wind speeds in the 2–3 MW class. Other examples are the option of direct drive and permanent magnet generators for most of the Siemens turbines, and growing use of full-scale converters in onshore turbines.

The challenge remains, however, to make wind more competitive with other power sources by continuing to introduce emerging technologies and new production methods into mainstream products. This calls for coordination between the medium- to long-term research performed by academia and the short- to medium-term R&D done by industry. Another important factor is the role of governments, which can promote wind power by drawing up steady development tracks for the energy system as a whole and specify clear targets for wind energy. Our recommendations for academia, industry and government to foster the development of emerging wind energy technologies are:

Academia

- Academic research should strive to expand the technical limits of specific wind power technologies, since these limits often determine the cost of wind energy.
- New technologies will always be expensive compared to mainstream technology, so we

need methodologies for assessing how emerging wind technologies could affect the cost of energy.

- Incremental innovations generally have the fastest impact on LCoE, while the effect of long-term research targets might be more dramatic. What should be the balance between these approaches?

Industry

- As the wind industry matures it is moving towards mass production. Manufacturers can learn from other sectors, such as the automotive industry, how to do that in cost-competitive ways. Can shared technology platforms for the wind industry be developed, produced, maintained and decommissioned?
- The largest expansion of the wind sector is expected to be offshore. Lowering LCoE for offshore wind power may require larger companies with the ability to develop, produce and deploy entire offshore wind farms by themselves.

Governments and industry associations

- Clear formulations of future requirements for energy systems will allow emerging wind technologies to be developed appropriately.

- Consistent support is required for long-term wind power research carried out by academia.
- Support for the industrial development of the wind sector may also be needed.

Conclusions

Emerging wind technologies often come about as a result of the need to enter new markets, such as offshore (shallow or deep water) and sites with low wind speeds. Their take-up is driven by the potential to lower LCoE in these new markets, but they often move into more traditional markets once the technology matures.

We have shown above that the three-blade horizontal-axis turbine is the dominant design around which most current component development is based. The

most remarkable achievement of the last few years has been the increase in rotor size. This trend is expected to continue with the introduction of even more advanced blades, and perhaps also smarter blades with active control.

The drive trains of offshore turbines show a lot of variation, and it will be interesting to see whether geared or direct-drive designs come to dominate the offshore market. Finally, foundations and offshore cabling call for rapid development, since they are essential in driving down LCoE for offshore wind power and making wind competitive with other energy sources.