THE ADVANTAGES OF COMPOSITE MATERIALS IN NEW DESIGN CONCEPTS FOR WIND TURBINES

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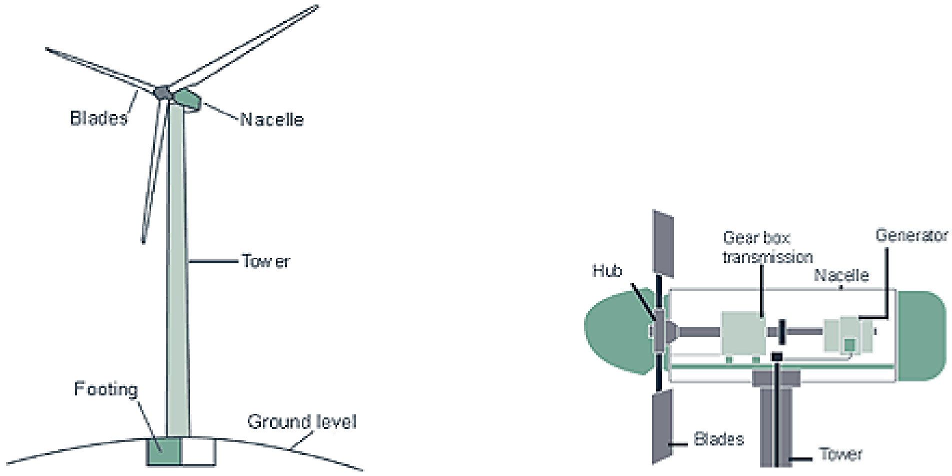
THE CURRENT STATE OF THE ART IN WIND TURBINE DESIGN.

The current accepted design configuration of wind turbines across the output scale is for a horizontal axis, three bladed propeller systems, mounted on a large tower, with a housing that encompasses the gear train and power transmission components. The blades are typically aerodynamically profiled and the pitch may be adjusted in service to accommodate variable wind speeds and feathered to provide minimum wind resistance id the wind speed exceeds a critical threshold value. The entire turbine blade assembly can be rotated in order to face into the wind and optimise the efficiency of the unit, figure 1.



a) b)

Figure 1: A general configuration of horizontal axis wind turbine b) transmission and generator mechanisms contained in nacelle (source: Australian Dept of Energy Utilities and Sustainability)

The construction of most modern turbines follows a similar format. The towers are typically steel, the nacelles are composite structures or steel and the blades themselves are a composite structure made variously from wood, glass or carbon fibre reinforced plastics, with the materials of choice varying according to the size of the structure (1).

The structure of the blade conforms to conventional design approaches for this form of rotating cantilever structure. The majority of the blade is hollow or filled with a lightweight core such as balsa wood, to minimise weight and maximise stiffness with a spar supporting skins shaped to provide an optimum aerodynamic profile, figure 2.

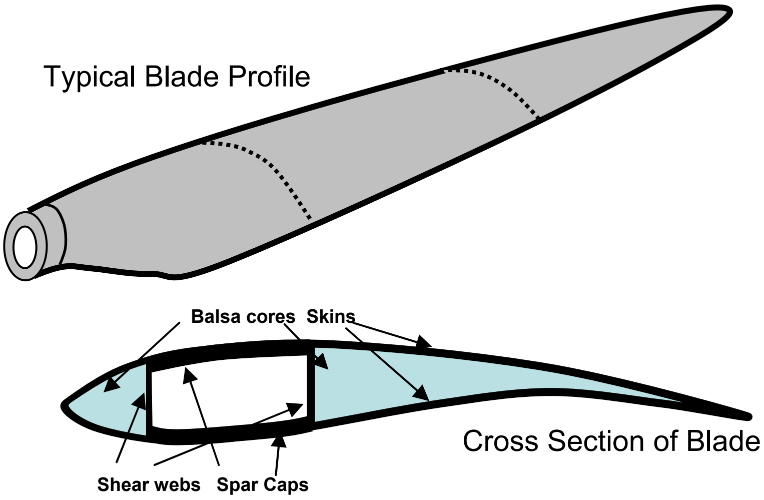


Figure 2. A typical blade profile with aerodynamic cross-section

The structure progressively thickens towards the root to meet the increasing stresses in the region. The primary stresses acting on a blade during operation are shown in figure 3. In terms of critical design limiting factors the existence of fatigue loads has become paramount. The blades are subject to a complex mix of fatigue loading with some flexural fatigue regimes introduce by wind variations and other significant loads arising from self weight effects during rotation.

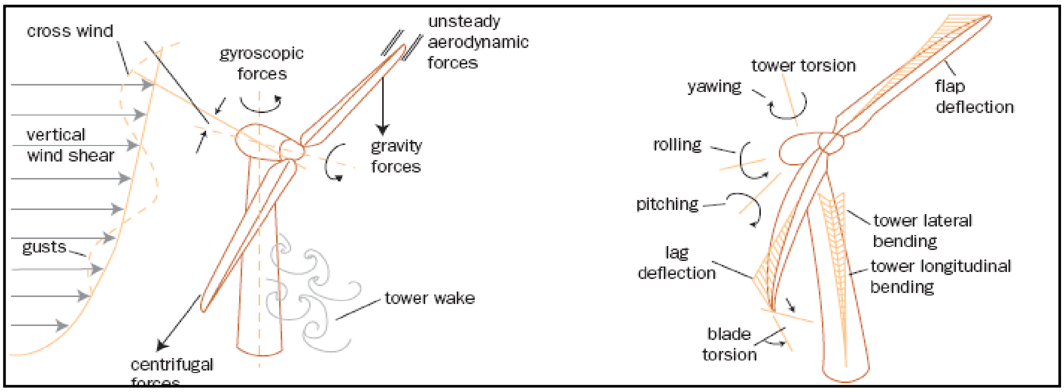


Figure 3. Schematic diagram illustrating the loading that may be experienced by a wind turbine (source DFVLR-FB 84-10, 1984).

The impetus for wind turbine design is for ever larger turbines to provide more cost effective generation and less environmental intrusion. Many studies have shown that the intrusive effects of wind turbines do not scale with their size, whereas the power generating capacity increases significantly (2). Figures 4 illustrates the importance of rotor diameter on power output, and shows how a similar area can be populated with fewer large turbines but yield considerable more power output.

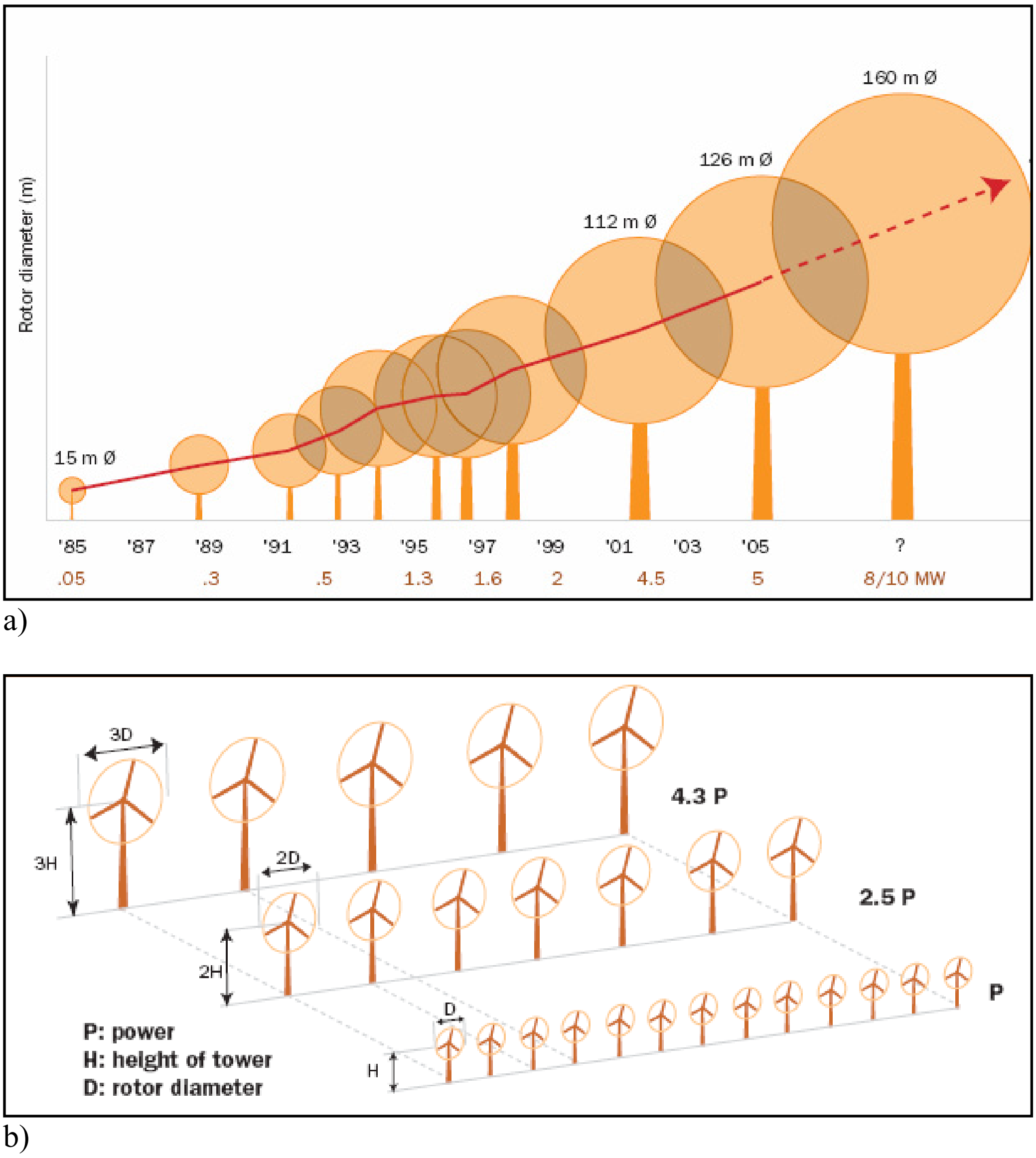


Figure 4. a) Illustration of the increasing size of turbines since 1985. The scales at the bottom refer to both the year of introduction of the turbines and the output that they can produce. b) illustration of how an array of larger turbines (height 3H) can produce more power (4.3P) than an array of small turbines (height H) which produce P.
(Source : Jos Beurskens, ECN)

An increase in the size of a wind turbine can result in a number of significant problems as well as benefits. The balance between the various items on manufacturing balance sheet changes. A recent study emanating from the Sandia Labs in the USA looked in detail at the estimated costs associated with manufacturing and installing turbines with blades at three scales (3). These were a 30m, 50m and 70m blade of similar but scaled plan-forms, as shown in figure 5.

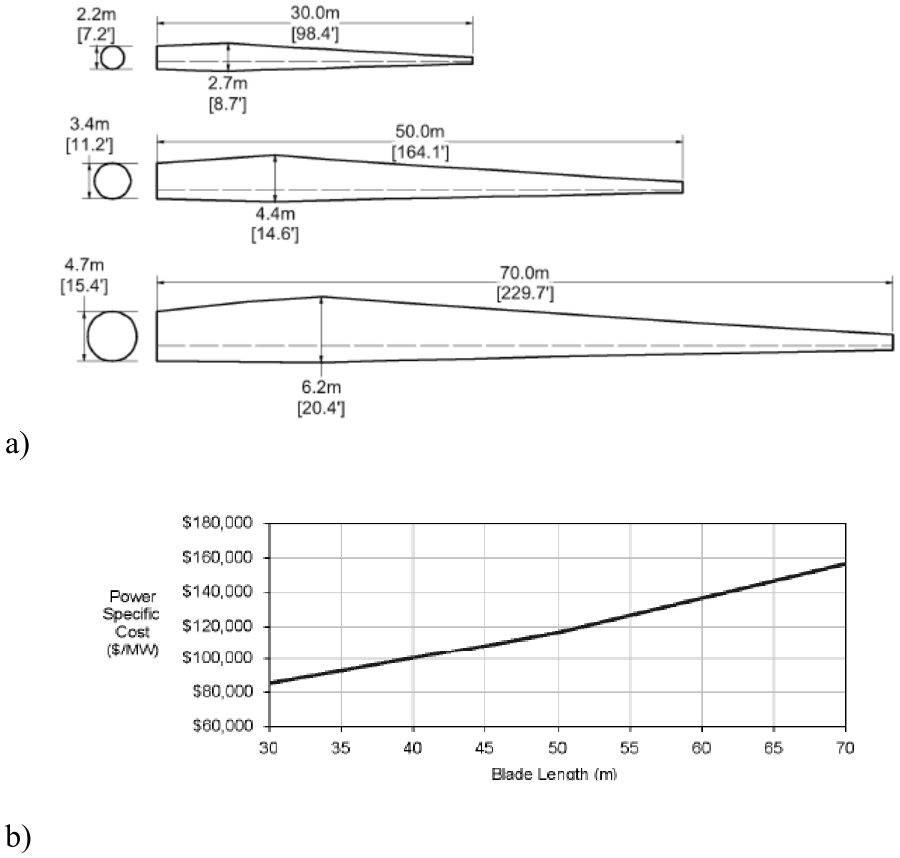


Figure 5 : a) Platform drawings for three blades used as the basis for a cost survey by TPI (3) b) the results of the study showing how the specific cost of power is linked to blade size.

At higher sizes, material cost becomes a larger percentage of the total cost of an installed turbine whereas the labour element in manufacture decreases. The survey included the costs of delivering the blades to an on-shore site and indirect manufacturing overheads. The study found that the specific cost of power production actually increased with an increase in blades size. The increased size of the components can be a significant factor in the total installation costs. Transport becomes difficult and erection becomes costly. Large cranes are required which become extremely expensive both on and off-shore.

In terms of using new and alternative materials, the increasing size of turbine blades results in a drive to reduce weight to minimise the effects of self weight induced fatigue which could become a show stopper for very large turbines. This has already meant a considerable interest in the use of carbon fibre reinforcements for blades, alongside the glass fibres currently used. A number of parametric studies have been conducted to investigate the cost implications of using carbon fibres as a part replacement for glass. Ong and Tsai from Stanford University (4) have evaluated the costs and performance benefits of progressively replacing glass fibre with carbon in a nominal 8 m blade. Full replacement of glass by carbon could result in weight savings approaching 80% but increase costs by a factor of 150%, whereas a 30% replacement of glass by carbon could reduce weight by half but increase costs by 90% if only materials costs are considered. If the bigger picture is taken into account allowing for manufacturing costs then the likely cost penalties from switching to carbon decrease to about 40% of the overall cost, even for a fully carbon fibre blade. This survey was conducted in 2000 and the methodology assumed certain price ratios for glass and carbon and included assumptions that the price of carbon was likely to fall. Since that time the increased usage of carbon fibre by the aerospace industry has resulted in a big global shortage of carbon fibres and hardening of prices. This may make the introduction of carbon less attractive for smaller blades, but the other trend is that blade sizes have increased and the need for carbon to offset the increased weight has become more significant. The Stanford study assumed carbon to replace glass to a uniform degree over the entire blade. Other studies assume that carbon may partially replace glass over the overall structure, but the use of the carbon reinforcement will be concentred at the root end of the blade, which requires new thinking of the integration and transition from carbon to glass reinforcements in the spar caps. An initial concept of a suitable carbon-glass transition from Sandia labs (1) is shown below, figure 6.

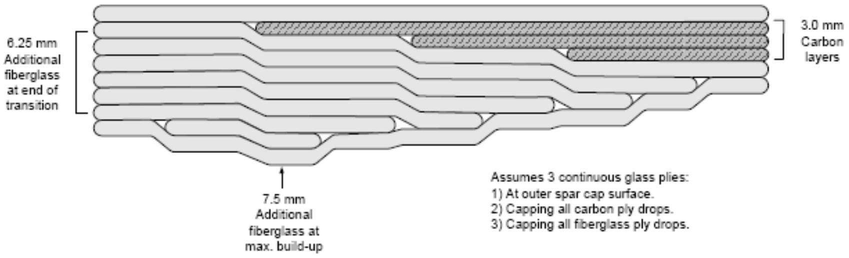


Figure 6. Transition form carbon to glass plies in a hybrid spar cap. Source Griffin and Ashwell X)

An additional factor which has to be taken into account when size is considered is the need for a tower, the average wind power at different altitudes and the problems associated with assembling the tower. Towers obviously add to the cost of installation by virtue of their weight which impacts on foundations and by the need to transport and assemble the towers. The material of choice at the moment for towers is steel, although concrete towers have been used in some instances. Steel towers can be produced in sections for ease of transport, but have to be assembled on site. Welding steel sections for the largest towers is now becoming a problem due to the thickness required of the tower where the ability to produce a quality weld is approaching the limits of welding technology. At the same time, high towers provide a benefit as the power of the available wind increases with the altitude (5) as shown in figure 7.

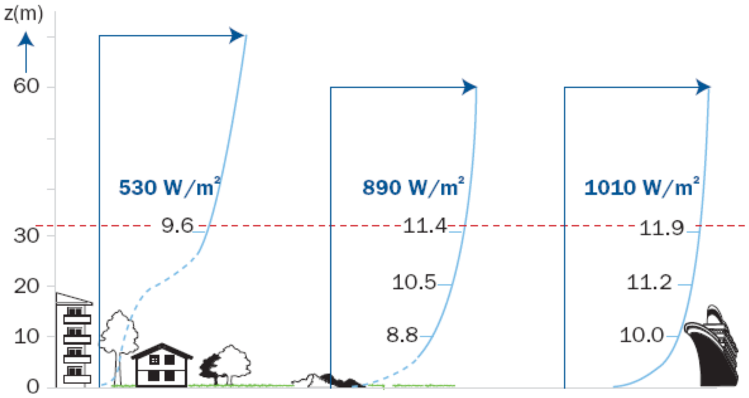


Figure 7. The vertical wind gradient for different terrain. The wind power at 30 m is compared for the three terrains examined. (Source EWEA, 5)

The drive for bigger machines, particularly for off-shore installation is accompanied by a general desire within the industry to reduce costs on existing machines, both by using cheaper materials and using lower cost manufacturing processes.

The trend for the industry in general is therefore to make more use of low cost manufacturing processes such as vacuum infusion and to utilise high performance materials forms such as non-crimp fabrics as opposed to woven materials (6). Improved reliability is important for operators and increasing use of condition monitoring is likely via the use of embedded sensors within the composite structure of the blade. Continuous improvements are also expected in the design of blades to facilitate adaptive structures and to accommodate improve aerodynamic features. The incorporation of composites with improved fatigue characteristics would inevitably result in significant improvements in blade life and hence the cost of wind power.

ALTERNATIVE DESIGN STRATEGIES

It is evident that wind energy has resulted in a viable industry with mature products and an established design philosophy. It is however also true that wind energy at present is more expensive than conventional fossil fuel derived energy and is at least partly dependent on public policy, legislation and national commitments to clean energy for its survival.

Some of the problems facing the industry are caused by the basic design philosophy of horizontal axis configuration for the turbines themselves. Whatever manufacturing cost reductions may be achieved using alternative materials and processes, the classic wind turbine blade is a complex profiled structure that has to be manufactured as a one-off assembly. The blades are not amenable to manufacturing in sections with on-site assembly and hence they introduce significant problems and therefore costs during the transport and assembly phase of the turbine. The largest wind turbines currently utilise blades of approximately 64m which generate in the region of 5MW of power. These blades are extremely expensive to make and transport. They also seem to represent a practical limit to the size of turbines. The weight of blades now makes it unlikely that turbines could grow to say 10MW output. A blade of at least 80m would be required, probably supported by a tower of 150m in height which would be impossible to transport on land, impractical to assemble and so heavy that the blades would fatigue very rapidly. Radar interference problems would be extreme as would the probable effect on birdlife.

The standard turbine configuration also is constrained in that the turbine has to be capable of changing its orientation to hunt the wind, and if that wind exceeds a critical value, then the blades have to be feathered to avoid damage to the gearbox and drive mechanisms by excessive rotation speeds.

There are of course alternative to the classic horizontal axis configuration. Vertical axis wind turbines have been designed and built for many years with varying degrees of success. The most famous design of vertical axis wind turbines has been the egg whisk configuration which was originally proposed back in 1924 by French engineer Darrieus. The advantages of this design include the elimination of a lower tower and the elimination of the need to point the turbine into the wind. It is always at the right orientation. However the structure is relatively complex to produce, figure 8. The concept was investigated in great detail in the USA where the use of a composite construction was explored, notably by Sandia National Labs (7). For a time a number of wind farms operated using these turbines, usually of aluminium construction, in California but all manufacturing of the egg whisk configuration has now ceased.

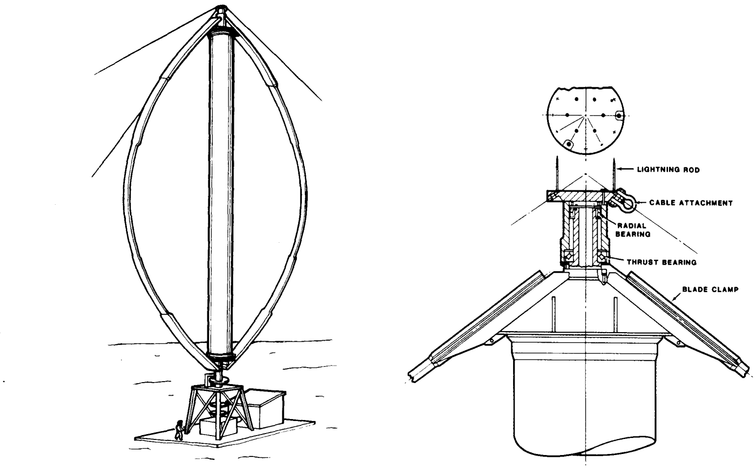


Figure 8. Schematic of the Darriues style vertical axis turbines investigated by Sandia national Labs with detail of the top bearing assembly (7).

A simpler configuration of vertical axis wind turbine has also been investigated, with some significant resources devoted to the idea by the UK government in the 1970s. The “Carmarthen Bay” wind turbine utilised a relatively straightforward H-conjuration. This project was a technical failure due to complexities in the design which introduced variable configuration blades, and an inherently fatigue prone bearing arrangement (8).

Figure 9. The Carmarthen Bay vertical axis wind turbine VAWT 850 (500kW) from the late 1970’s.

The concept of large VAWT turbines disappeared for a number if year but is now being revived (8). Eurowind, a small UK based company has developed the VAWT concept initially from the premise of utilising existing chimney structures around which a turbine could be mounted, figure 10.

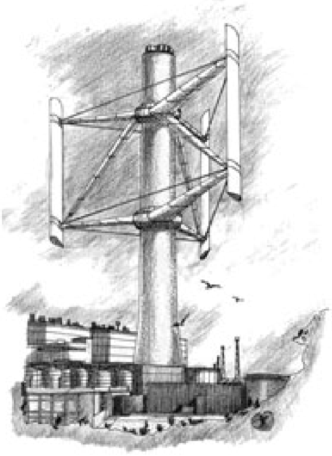


Figure 10. Eurowind concept of utilising existing industrial towers for the support of vertical axis turbines.

This has evolved into considerations of both large and small turbines with purpose built housings and towers. The advantages of the VAWT concept are numerous but the economics will depend on the cost of building and installing the turbines and this in turn depends on a materials / manufacturing concept that keeps cost to minimum. The advantages of the VAWT system are primarily the elimination of self weight imposed fatigue, the elimination of the need to originate the turbine in the direction of the wind, the ability of the turbines to tolerate greater wind speeds without the need for feathering, and the ability to consider sectional manufacture and assembly. The problems associated with VAWT were, in the past, the need to start the turbine, the problems with fatigue in the bearing and support structures and a general reduction in the efficiency of conversion of wind energy to electricity.

Refinements in the design of blade aerofoil sections and the change from two to three bladed assemblies has removed the self starting problem and VAWT will now rotate automatically at low wind speeds. The bearing problems have been potentially overcome by the repositioning of the bearings with a twin bearing arrangement mounted encircling the tower. The fatigue problems of the support structure will be reduced by using lighter weight materials for the blade and the support structures themselves. Previous poor experience in this respect was achieved with aluminium structures.

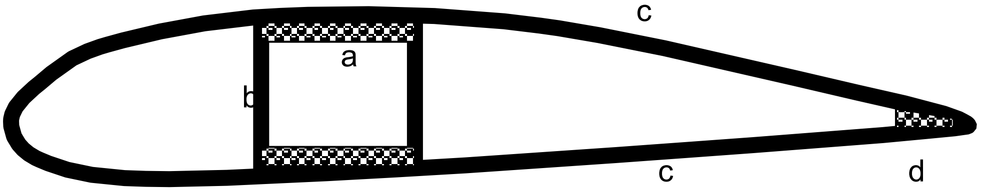
Figure 11 Artist's impression of Eurowind's advanced VAWT designs operating off-shore.

OPPORTUNITIES FOR LOW COST MANUFACTURING WITH COMPOSITES.

The support structure that is required to attached the blades to the bearing/hub units of a VAWT could be conceived as being simple composite tube structures, either pultruded using multiaxial fabrics or filament wound with a fibre orientation selected to instil adequate bending stiffness and longitudinal strength. A long term creep problem would need to be addressed in the design stage along with some fatigue loading. The support structure is an additional cost that is not present in the HAWT turbine configuration and hence presents additional cost. Attachments and joints linking the support structure to both the tower and the blades themselves would also need to be considered carefully but structures could be conceived either of metallic or composite origin. Metallic cast bearings have been proposed by Eurowind that would allow simple power generation as well as harness the blade structure.

The major cost benefit from the VAWT configuration lies in the design and manufacture of the blades themselves. The blades are a major element in cost for the HAWT turbines and as has already been discussed do not lend themselves to sectional manufacture and on-site assembly. The vertical axis blade is very different in shape. Unlike the HAWT which requires an aerodynamic shape of varying cross section, tapering to a root with a transition from hollow to solid structures, the VAWT blade has a constant cross section along its length. The velocity of the blade with respect to the wind is constant at all positions along the blade. A relatively simple aerofoil shape is required to provide the rotational forces, but that does not need to change at any position. The use of two attachment points would mean that the blade does not flex in the same way as a HAWT turbine and this will reduce tension-tension fatigue. The absence of any rotation in the horizontal plane eliminates self-weight fatigue (although it will also introduce self weight creep).

If the blade has a constant cross section then it is amenable to manufacture by pultrusion which is the lowest cost manufacturing process available for volume production. Most current approaches to HAWT blade manufacturing involve the simultaneous manufacture of the spar with the rest of the blade structure during a simultaneous curing or infusion/curing process. In some instances the spars are produced separately and incorporated into the blade during the final consolidation as cured parts. With a constant cross-section blade for a VAWT it is conceivable that the entire blade could be produced as a single pultruded profile or that multiple pultrusions could be assembled in a separate consolidation step, figure 11.



a) Integral spar with 0° fibres on spar caps
b) Shear wall with +/- 45° fibres
c) Skins with +/- 45° fibres
d) Trailing edge spline with 0° fibres

Figure 11. Proposed cross section of a blade produced from a single Pultrusion incorporating an integral spar within a hollow structure

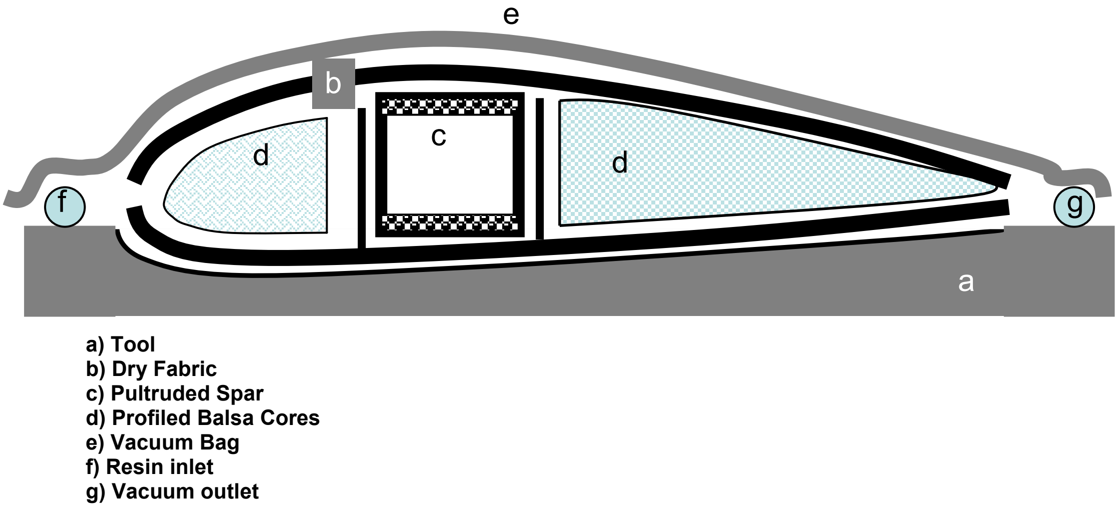


Figure 12.An alternative approach whereby individual elements such the pultruded spar, c, and profiled balsa cores, d, are consolidated into a single blade via an infusion process. The skins and connection layer, b, would be dry glass fabrics.

The ideal manufacturing configuration will depend on both the size of the blades to be produced and the complexity of the reinforcement required locally. The spars caps would remain an overall triaxial reinforcement pattern with a predominance of fibres in the spar direction. A likely manufacturing strategy would be to configure the entire spar cross section with a biaxial +/- 45 fabric with additional tows or uniaxial fabrics interspersed at the spar cap surfaces. The incorporation of the spar into a single pultrusion would be feasible for relatively small blades where the skins would be produced using a biaxial fabric and the interior of the blade could remain hollow. It is conceivable that this interior space would be filled with foam during or after the pultrusion operation when the blades are cut to length. It is however probable that for MW-scale blades the pulling force required would require a very substantial machine and the economics would favour the pultrusion of the individual components, spars and skins, independently. A solid core such as balsa could also be added at this stage in a final assembly process which would allow thinner skins to be produced.

Assembly of a large blade from components would require some jigging structure to ensure that all components are correctly aligned during a bonding cycle. If some pressure is required then it might be appropriate to utilise matched tooling, but this would not need to be expensive precision tooling as the external profile of the blade would have already been determined by the pultruded skins.

Various hybrid process routes involving pultruded components such as spas and possibly end caps could also be envisaged with a liquid moulding process to infuse the skins and bond the assembly, figure 12. In an infusion process of this sort the outer tool would need to be semi-rigid in order to introduce an accurate and smooth surface for the blade. A detailed analysis of the various costs would be required on a case by case basis to identify the best strategy for any particular blade design.

A further advantage offered by the VAWT configuration is that it may be possible to achieved cost reductions by producing blades for different output turbines simply by varying the length of the blades without changing the construction. While this could not be taken to extremes, it should be possible to adopt a compromise construction with a spar design that can work for a range of lengths. This would reduce the number of pultrusion dies and jigging tools for any manufacturer wishing to offer a range of products.

CONCLUSIONS

The continued need for an increase in the percentage of energy generation that can be attributed to renewable sources will drive an expansion of wind power while a need to reduce energy costs will simultaneously drive innovation in wind turbine design.

The introduction of new materials including improved glass fibre and increasing quantities of carbon fibres will extend the performance range of large horizontal axis triunes, but due to weight and transport restrictions this is not an unlimited process.
It is likely that horizontal axis wind turbines are very close to the limits of their growth, despite now reaching unprecedented levels of operating efficiency.

Vertical axis machines offer a route to continuing to increase turbine output levels whilst retaining some control on turbine size and installation and manufacturing costs. The very significant problem of self-weight fatigue is dramatically reduced, along with issues such as susceptibility to wind direction and the ability to operate over a large range of wind speeds.

If low cost manufacturing processes can be harnessed effectively, then it should be possible to develop a new generation of wind turbines in the 10MW range whilst maintaining or even reducing the existing price band of wind energy.

The viability of vertical axis wind turbines will depend on the exact manufacturing strategy adopted and a number of possible processing/assembly options must be considered. It is clear that some form of composite structure coupled with a low cost process route, at least in part involving pultrusion is an attractive prospect for these machines.

REFERENCES

1. D A Griffin and T D Ashwill, " Alternative Composite Materials for Megawatt-Scale Wind Turbine Blades: Design considerations and Recommended Testing, AIAA-2003-0696

1. 2.Energy Research Centre of the Netherlands, http//www.ecn.nl

2. 3."Cost Study for lsarge Wind Trubnie baldes" TPI Composites Inc, Sand2003-1428 report for Sandia National Laboratories. Available from http://www.sandia.gov/wind/topical.htm#MATERIALS

3. 4 C H Ong and S W Tsai " The Use of Carbon Fibers in Wind Trubine Blade Design", Sand2000-0478. Available from http://www.sandia.gov/wind/topical.htm#MATERIALS

4. “ Prioritising Wind energy Research”, European Wind Energy Association, 2005,
5. http://www.ewea.org

6. D A Griffin“ Evaluation of Design Concepts for Adaptive Wind Trbuine Blades, Sand2002-2424, Available from http://www.sandia.gov/wind/topical.htm#MATERIALS

7. D Berg “ Structual Design of the Sandia 34-Meter Vertical Axis Wind turbine, Sandia Report Sand84-127, 1985

8. S Peace, “Wind alternatives: Why not vertical axis?, ReFocus, May/June, p30-33. , 2003