Technical and/or economic wind turbine size limits have been predicted already for decades. However, voicing such explicit size predictions is very tricky due to the many variables and uncertainties involved and perhaps grossly underestimates the power of innovation and ingeniousness.

The motherland of prototypes: Nearly all wind turbines with a power of 5 MW and above are to be found in Germany, including this Multibrid M5000, installed on a tripod at Bremerhaven in northern Germany. Rotor diameter: 116 m

Photo: Jan Oelker

Is there a limit to wind turbine size?

History shows many examples where existing technology is stretched to its limits, and is then succeeded by superior alternatives capable of again shifting boundaries in terms of size, costs, performance and reliability. Modern industrial scale wind technology covers a time span of only about thirty years and is no exception to this rule. During the past three decades the emerging global wind industry, on a largely evolutionary development path, has indeed produced many clever innovations that have resulted in new as well as upgraded technology concepts. A major part of these continuous wind technology developments have been multiple system up-scaling steps, in which the so-called bottom-up strategy has proved the most successful by far (see boxed text).

Limits

About thirty years ago the Dutch engineering journal *PT Aktueel* published an article in which the author – supported by impressive statistical evidence – argued that 500 kW was a »hard« upper wind turbine size limit. Twenty years later in a 1998 publication of the German magazine *Sonne Wind & Wärme*, an expert presented a 70 to 80 metre rotor diameter size range as an economic optimum »that will be hard to exceed«. He additionally predicted long-term competition between installations with stall-type power limitation and pitch-controlled equivalents.

Today an increasing number of suppliers offer 1.5 to 2 MW wind turbines with rotor sizes up to 92.5 m (see table 2). In the next generation, 2.5 to 3.0 MW class rotor diameters between 90 and 100 metres are common. And the upcoming 5 to 7 MW+ super class already has four suppliers, all based in Germany. At least two more contenders, US-based Clipper and GE Energy, have also announced a wind turbine in the 5 to 7 MW class. Enercon holds the size record with its E-126 prototype featuring a 127-metre rotor diameter. The power rating is 6 MW, but insiders suggest a 7 to 8 MW for the series product. The E-126 succeeds the 4.5 MW E-112 (2002; rotor diameter 114 m) that was later up-scaled to 6 MW. Repower recently announced an up-scaling of its 5 MW 5M turbine type to 6 MW, while maintaining a 126-metre rotor diameter.

A new ambitious offshore wind market entrant is Bremen-based Bard Engineering. The company recently installed a 5 MW VM prototype near the port of Emden, northern Germany, after a record-breaking combined product development and prototype completion period of only two years. Like the 5M and the E-112, the VM is considered a rather heavy turbine concept. The Top Head Mass (THM; nacelle + rotor) of both the 5M and VM is in the range of 415 to 420 tonnes, while E-112 THM is well above 500 tonnes. According to experts, the three turbine concepts above have substantial built-in (safety) design reserves. After testing and extensive monitoring these reserves can be utilised for further up-scaling in capacity and/or rotor swept area, and this is exactly what is taking place already.

Lightweight

Other companies by contrast have opted for lightweight wind turbine concepts. A good example is the 5 MW Multibrid M5000 featuring a THM of only about 320 tonnes. Other striking examples of lightweight concepts include the Vestas V90-3 MW and the Vestas V120-4.5 MW. The V90-3 MW has a THM of only 111 tonnes, making it the low-THM champion in general and in its class. The V120-4.5 MW (THM = 210 tonnes) is an upgraded former NEG Micon model envisaged to enter the wind market by 2009, but which was shelved instead.

The huge THM differences in the 4.5 to 5 MW class between especially the V120-4.5 MW and the only slightly bigger Repower 5M and Bard VM are hard to explain, according to wind experts. These last three wind turbines all feature a conventional gear-driven drive system, with pitch-controlled variable speed operation and three rotor blades.

Another question is which specific wind technology will be best equipped to become the ultimate wind turbine concept winner in terms of performance, system reliability and most importantly energy costs (€/kWh over 20 years):

- Conventional geared wind turbines featuring a multi-stage gearbox and a fast-running generator have for years dominated the world market with a share of 85 to 87 % (MW based).
- The remaining 13 to 15 % have drive systems featuring a large-diameter ring generator (no gearbox), in which the rotor and generator turn at the same speed. Enercon is market leader in this segment.
- Multibrid technology, comprising a single-stage gearbox and a slow-speed generator integrated in a highly compact cast housing, is considered the third distinct drive technology. Multibrid Entwicklungsgesellschaft of Germany and Winwind of Finland both manufacture these turbines under an Aerodyn license.

Torque

Generally, as a rule, when rotor size goes up, rotor speed has to be reduced. This is necessary because maximum blade tip speed has to remain under about 75 to 85 metres per second for reasons of noise. Aerodynamic noise as a phenomenon relates to the fifth power or higher of tip speed. Offshore a higher tip speed can be acceptable, as here noise is hardly a critical factor.

Table 1 shows the relationship between rated capacity, rotor speed and drive train torque. Based on rounded figures, the table shows a 36-fold drive train torque increase when a given wind turbine is scaled up from 500 kW to 4,500 kW. Increased torque requires thicker drive shafts, larger bearings, stronger and heavier machine castings, et cetera.

Wind turbine up-scaling is a highly complex process for many reasons and one of the inherent difficulties is dealing with »negative« effects of the so-called scaling or Square Cube Law (SQL). Think of a cube with all sides having a length of »1«. If you double all

New generation of 2004: Based on Bonus technology Siemens installed its prototype with a 3.6 MW turbine in Høvsøre, Denmark (on the top). The prototype of Repower 5M with a 5 MW turbine was built up in Brunsbüttel, northern Germany (in the middle).

Photos (3): Eize de Vries

A further development from 2006: The Enercon E-82 has a rotor diameter of 82 m.

the lengths, the volume (and therefore mass) of the object increases eight-fold ($1^3 = 1$ versus $2^3 = 8$). Without proper SQL counter-measures, wind turbine up-scaling processes can add excessive mass to the system. As a consequence the new larger turbine can become uneconomical to manufacture, as each additional kilogramme of steel or copper has to be paid for. In addition, extra nacelle mass is known to increase dynamic loads within the entire system. Wind turbine designers therefore try to use hollow structures and other weight-saving elements within the mechanical

Rated capacity (kW)	500	1,500	4,500
Relative rated capacity	1	3	9
Rotor speed (rpm)[1]	40	20	10
Relative rotor speed	1	0.5	0.25
Relative rotor torque	1	6	36

[1] Rounded rotor speed figures in the example indicate the range, but do not necessarily reflect actual product figures.

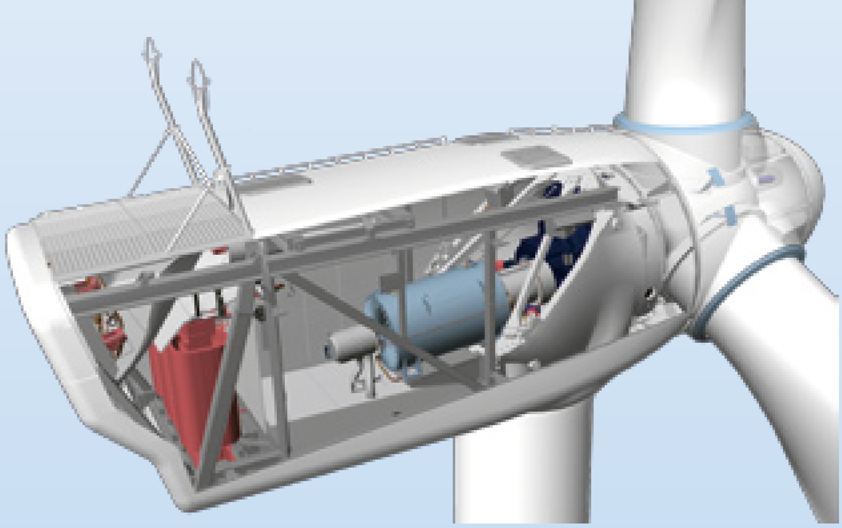
Table 1: Some implications of wind turbine up-scaling

structures. This is typically combined with the use of high-strength steel, superior computer design tools, and the introduction of load reducing (control) measures. Direct drive type wind turbines are at a SQL disadvantage compared to conventional gear driven wind turbines as they feature a large and therefore heavy ring generator. However, a favourable weight value is only one key wind turbine design variable and there are many factors to consider when comparing wind turbine concepts.

Finally, each time when a new leap forward is being made in wind technology and wind turbine capacity, there are a number of challenges to tackle. Among them is the manufacture of heavy and bulky cast components. Today's 5 to 6 MW class turbines, for example, feature 30 to 40-tonne rotor hubs, and mainframes with masses up to 70 tonnes. Only a few specialised foundries are today capable of casting such complex pieces, which require controlled cooling-down periods of up to six weeks. Other key challenges are in the manufacture, machining and (heat) treatment of large bearings and other heavy components. Another issue is the manufacture and handling of huge rotor blades with lengths of 60 metres and beyond. And while LM of Denmark ships the 61.5 m long rotor blades for the Repower 5M by road if necessary, Enercon has chosen to shift boundaries by manufacturing the E-126 blades in two sections. So far, in other words, each time when there has been a problem, a solution has been found. That has been the pattern in past decades and that is what we can expect for the future too.

Eize de Vries

Eize de Vries is an experienced journalist based in the Netherlands and specialised in wind energy.



A third-generation wind turbine: diagram of a Vestas V90-3 MW nacelle *Figure: Vestas*

Thirty years of evolutionary development

In the years following the first energy crisis (1973) a number of Danish manufacturing firms typically with roots in the agricultural sector started developing their first wind turbine models. These generally uncomplicated fixed-speed stall type installations made by small companies were in the 10 to 25 kW class. The low-tech »learning by doing bottom-up« approach of these pioneering firms is often referred to as a key example of successful product and industrial development. It contrasts positively when compared to high-tech multi-megawatt class prestige projects that took place during the same period in industrialised nations like the U.S., the UK, Sweden and Germany. Typically, the participating partners were large established industries, many with roots in aerospace. However, the bulk of prototypes they developed never made it into series products.

Several first-hour »bottom-up« pioneers disappeared, but others survived and their ranks were reinforced by a number of entrants from countries like the US, Germany, and the Netherlands. As a parallel development, the wind turbines they manufactured gradually increased in capacity. Initially, scaling up steps with increments of 20 to 50 kW were rather modest, but later 50 to 150 kW steps were made. By 1993/94 many suppliers had a 450 to 600 kW wind turbine in their product portfolio.

A huge leap in wind turbine up-scaling was made during 1995/96, when two Danish and two German pioneers with European Commission support each introduced a new 1.5 MW class concept (see table 2). The manufacturers involved were Nordtank (now Vestas), Vestas, Tacke (now GE Energy) and Enercon. All four had to take their previously largest 500 to 600 kW model as a technology development starting point. Nordtank, in line with company tradition, developed a fixed-speed turbine with »classic stall« power limitation. Vestas again relied on pitch-controlled optislip technology that enables limited variable speed operation. Tacke, by contrast, switched from fixed-speed stall to a variable speed pitch-controlled system based on a doubly-fed induction generator. And Enercon further built on experiences with its smaller variable speed pitch-controlled 500 kW direct drive E-40 turbine (1992). Rotor diameters of these four 1.5 MW turbines varied from 60 to 66 metres, which was at that time about the largest size that could be manufactured in series.

Ten years later the combination of »fixed-speed and classic stall« had lost its one-time dominance and nearly vanished from the wind market. More advanced »active stall« (pitch-enabled blades) technology also suffered the same fate, and faster than many expected, due to both noise issues and new electric power quality legislation. By contrast, the power conversion concept introduced by Tacke in April 1996 proved highly successful. The doubly-feed technology in fact turned into a semi-standard solution that has been widely adopted by many of the world's leading geared wind turbine suppliers. U.S. giant GE Energy became the third and current owner of what used to be Tacke in 2002. At the end of 2008 GE plans to pass the 10,000 installed turbine milestone for its 1.5 MW turbine series.

Optislip is today used only in the Vestas V80-1.8 MW for the North American market. Vestas made a switch in 2000 to variable speed operation based on employing doubly-fed generator technology. Finally, Enercon further developed the 1.5 MW E-66 in steps into the latest 2 MW E-82. For this model the German market leader claims a 70 % increase in energy yield, whereas the THM has only increased by 16 %. A distinct feature of the E-82 and all sister models, including the E-126, is the application of a new rotor blade design. Enercon claims 12 to 15 % extra yield for a similar swept area compared to »conventional« rotor blades.

	Capacity [MW]	Rotor diameter	Year of first erection
Prototypes with 1,5 MW			
Nordtank NTK 1500	1.5	60	1995
Vestas V63	1.5	63	1995
Enercon E-66	1.5	66	1995
Tacke TW 1.5	1.5	65	1996
Further development (selection)			
GE 1.5s/sl [1]	1.5	70.5/77	2000
GE 1.5xle [1]	1.5	82.5	2005
Vestas V66	1.65	66	1998
Vestas V80	2.0	80	2000
Enercon E-70	2.3	71	2003
Prototypes with 2 up to 3 MW (selection)			
Repower MM70	2.0	70	2002
Nordex N80	2.5	80	2000
Gamesa G80	2.0	80	2000
Nordex N90	2.3	90	2002
GE 2.5	2.5	88	2004
Vestas V90	3.0	90	2002
Bonus 2.0 MW [2]	2.0	70	1999
WinWinD WWD-3	3.0	90	2004
Clipper Liberty C-93	2.5	93	2005
Fuhrländer FL2500	2.5	90	2006
Further development (selection)			
GE 2.5xl	2.5	100	2007
Nordex N100	2.5	100	2007
Gamesa G90	3.0	90	2005
Repower MM92	2.0	92.5	2005
Enercon E-82	2.0	82	2006
Bonus 2.3 MW [2]	2.3	82.4	2002
Prototypes with more than 3 MW			
GE 3.6	3.6	100	2002
NEG Micon NM 110/4200	4.2	110	2003
Siemens SWT-3.6-107	3.6	107	2004
Enercon E-112	4.5	112	2002
Multibrid M5000	5.0	116	2004
Repower 5M	5.0	126	2004
Bard VM	5.0	122	2007
Enercon E-126	6.0+	127	2007

[1] former Tacke TW1.5s/sl
[2] later Siemens 2.0 MW / 2.3 MW

Table 2: Wind turbine development: Since the large European Union research support programme of 1995/1996, which brought about the 1.5 MW class, wind turbine technology has continued to develop in leaps and bounds. The newest generation has rotors twice the size and has three times the power.

Source: own research