POTENTIAL FOR REDUCING COST OF ENERGY BY SCALING UP A LOW-MASS WIND TURBINE DESIGN

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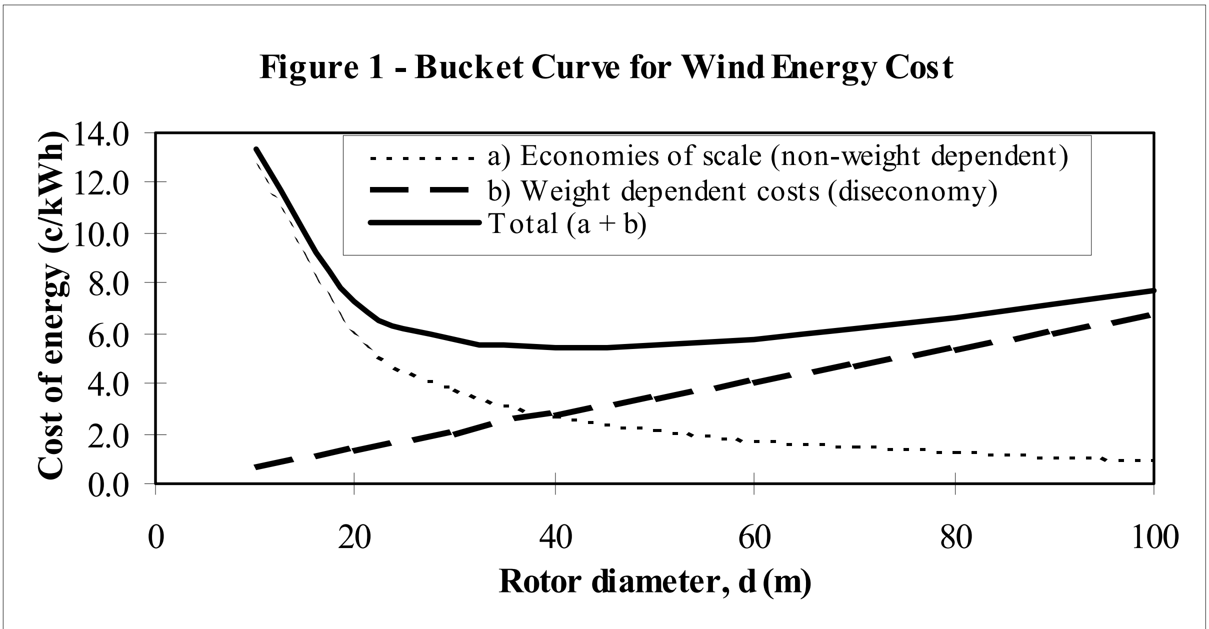
Abstract

The cost of wind energy is a function of turbine size. Economies of scale are offset by a fundamental mass-driven diseconomy, resulting in an optimum point. The diseconomy is very dependent on turbine design, while the economies of scale are relatively independent. As a result a low-mass design will reach its optimum at a larger scale than a heavier design. With heavy designs achieving cost-reductions by scaling up to around 750 kW rating and larger, a low-mass design should achieve its optimum at 1000 kW or more. This paper illustrates this potential using the example of the two-bladed Windflow 500 design. Given the lean and mean economic climate for wind energy in New Zealand, it is timely to re-examine this concept.

Introduction

The cost of wind energy is a function of turbine size, in particular rotor diameter, **d**. Wind turbine swept area, power rating and annual energy output increase with $\mathbf{d}^2$. Therefore any cost component which is independent of **d**, or increases at less than $\mathbf{d}^2$, gives rise to economies of scale. By contrast machine weight for a given design increases approximately with $\mathbf{d}^3$. Therefore any weight-dependent machine costs tend to increase with $\mathbf{d}^3$ and, per kWh of annual energy output, these costs tend to increase linearly with **d**. This is a basic "square-cube" diseconomy of scale.

For the sake of this analysis, wind energy costs are most conveniently divided into those that are weight-dependent and those that are not. The combination of these two component results in the well-known "bucket curve" for wind energy's cost of energy (COE) where there is an optimum size i.e. a size that gives minimum COE. Figure 1 illustrates this principle.



The main weight-dependent cost is the capital cost of the ex-factory windmill, which includes the raw material and processed material costs, both of which are strongly weight-dependent. Other weight-dependent costs include the transport costs to site, foundation costs and some of the erection costs (craneage etc).

The two major costs which are not weight-dependent are as follows:

a) "balance of plant" costs, which are partly a linear function of power rating, or $\mathbf{d}^2$, (transformer and cabling components), partly a linear function of machine diameter, **d**, (trenching and road works) and partly independent of size (site establishment, remote monitoring and control systems, etc). Thus the overall effect is that the balance of plant component tends to increase with size at less than $\mathbf{d}^2$, giving an economy of scale;

b) "operating and maintenance (O&M) costs", which are basically independent of size, although the cost of some consumables (e.g. lubricants, brake pads) and some other costs (e.g. insurance) increase with size.

Evolution of the Bucket Curve

Piepers' (Ref. 1) showed in 1985 how the bucket curve was evolving and projected to evolve further. As shown in Figure 2, the "Big is Beautiful" philosophy had been abandoned and the optimum size was expected to increase as the years go by, due to improvements in the technology.

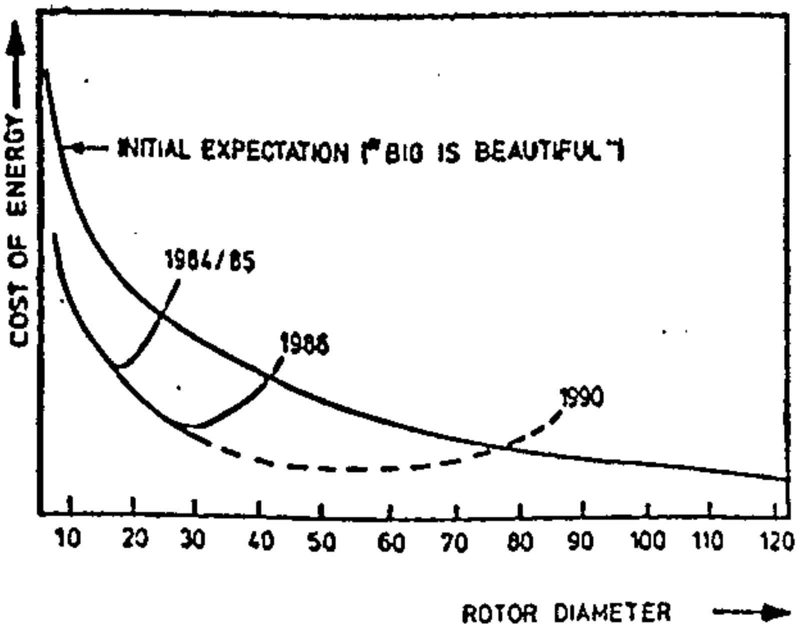
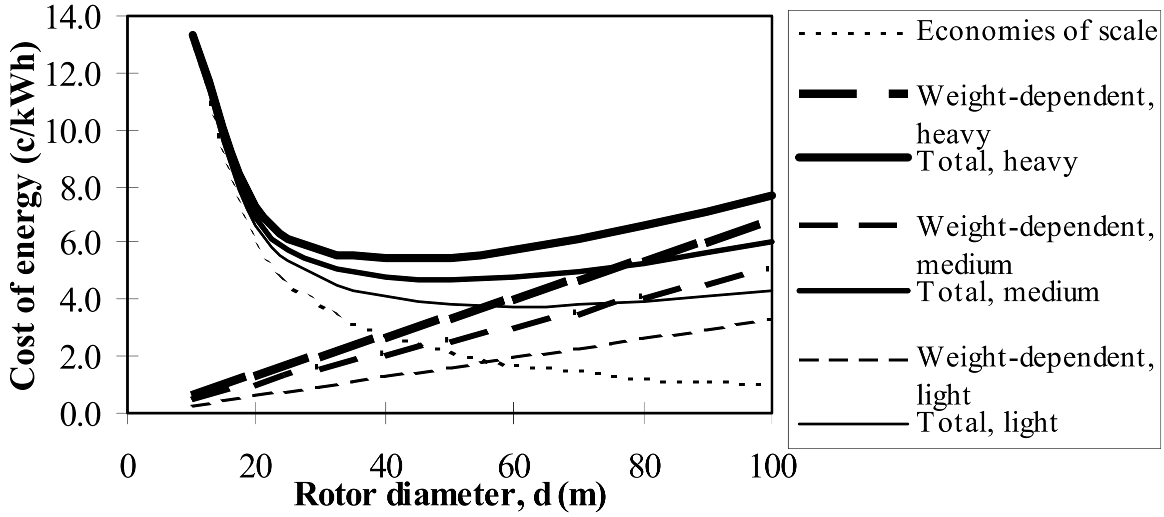


Figure 2 - Evolution of the Bucket Curve (Piepers, Ref. 1)

Ref. 1 was published in 1985, and the projection for 1990 proved rather optimistic. Technological progress was not as rapid as Piepers envisaged but by now (the late 1990's) machines in the 30-70 m size range dominate the market and Piepers' general concept has been validated. In particular reliable machines are becoming lighter and the width of the bucket is increasing with time. In the 30-70 m range there is some controversy as to what is the optimum size, which tends to vindicate the idea that the differences in COE are small. For the conventional three-bladed European design the general expectation is that 60-70 m machines will normally give a higher COE than 40-50 m machines. However land use and offshore maintenance considerations (which are somewhat peculiar to Europe) are driving developers to the larger machines.

The representation of technological progress is expanded and updated in Figure 3. Technological progress in the wind business generally involves some kind of jump or gradual change whereby weight can be taken out of the machine without compromising reliability so that the importance of the "square-cube effect" described above is diminished relative to the other cost components. Referring back to Figure 1, technological progress lowers the slope of the weight-dependent cost line. Thus the starting point in weight/m^2 for a given size is reduced and the optimum size can be increased.

Figure 3 - Bucket Curves as Weight Reduces



If the top curve (same as Figure 1) represents the status quo using three-bladed technology ("heavy"), the bottom curves indicate the effect of weight reductions of 30% ("medium") and 50% ("light"). The present optimum size using three-bladed technology is around 40-50 m diameter or 500-750 kW rating. Three-bladed designs around 60-70 m diameter (1000-1500 kW rating) are now available but, as noted above, these are expected to give a higher COE except for offshore applications or where land for small wind farms is at a premium. (Note: the effect of such factors is to increase the non-weight dependent costs, thus raising the left-hand end of the bucket curve. This shifts the curve upwards and the minimum to the right.)

For onshore, large wind farm applications (as required in New Zealand for economic viability), the situation portrayed in Figure 3 is expected to apply. This indicates that lighter designs are necessary to push the COE down. To some extent this is already happening within the three-bladed architecture, where the Vestas V47 uses more flexible, relatively lighter blades than the V39. And the V39 used a planetary gearbox and a torque-limiting generator to achieve a relatively lighter design than the V27.

Thus the evolution of larger windmill designs and the achievement of lower COE comes about through technology developments which enable relatively lighter machines, provided of course that reliability is not compromised in the process. If there is a reliable design with lower mass than the present three-bladed concept, this process would be expected to continue.

The Windflow Design

The Windflow design combines two new technologies, the patented torque limiting gearbox (TLG) system of power control and the pitch regulated two-bladed teetering rotor. It has been described in other papers (Refs. 2 and 3) so only a brief description of these two technologies will be given here:

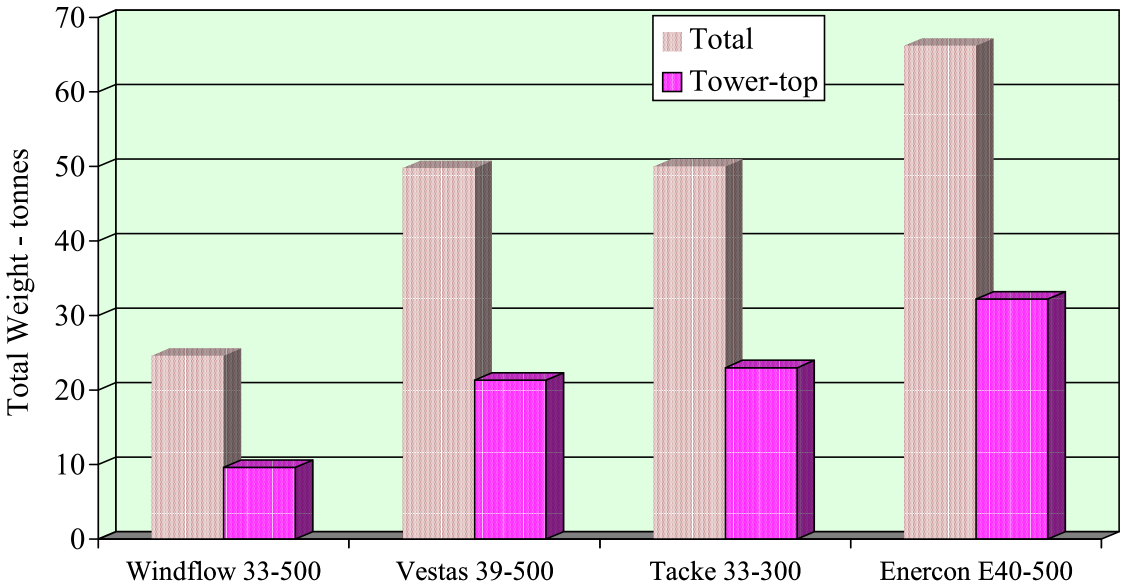
The TLG system is a hydraulic variable speed (VS) system. Like other VS systems it allows rotor speed to vary and as a result keep torque constant at rated power. This gives major savings in gearbox weight and cost. Unlike other VS systems:

- rotor speed varies independently of the fixed generator speed, enabling the use of a light-weight, low-cost synchronous generator directly on line. This provides superior electrical output characteristics as well as cost savings
- the hydraulic torque limitation enables the rating (and hence weight and cost) of the torque limiting hardware to be minimised. It also eliminates problems with fault-condition transient torques which affect electrical VS systems.

In the two-bladed teetering design, the rotor is mounted on a hinge, allowing it to teeter back and forth as it rotates. Fixed-hub three-bladed turbines experience large overturning moments caused by asymmetrical rotor loading. These overturning moments are a major source of fatigue loads on the entire windmill structure. Teetering greatly reduces these fatigue loads allowing a significantly lighter design. A "pitch-teeter coupling" feature ensures the advantage of teetering is not undermined by dynamic problems associated with other teetered rotor designs.

The combination of the TLG system and the two bladed teetering rotor results in weight reductions of more than 50% relative to comparable three-bladed designs as indicated by Figure 4, which shows the results of detailed design work for the Windflow at 500 kW scale. The right-hand bars show tower-top weight, i.e. nacelle plus rotor, but excluding the tower.

Figure 4 - Weight Advantage of the Windflow 500 Design



Both technologies have been proven in service. The TLG system was prototyped in 1990 in a 200 kW three-bladed windmill and ran very reliably for about six years before the unit was decommissioned. It is based on simple hydraulic components with a long track-record in general industrial applications. The two-bladed teetering rotor was used by a major British manufacturer for about 80 units of 33 m rotor diameter in UK wind farms since 1988. These units, which are about 30-40% lighter than comparable three-bladed units, are achieving wind farm availabilities in excess of 98%.

Until recently it seemed likely that windmills of 30-40 m diameter (500 kW rating) would be the optimum. For this reason the Windflow design, which was developed for New Zealand manufacture and optimised for New Zealand wind conditions, was set at 33 m, 500 kW. Costing studies and a detailed business plan showed that a profitable manufacturing business could be established based on this design, provided that long-term power purchase contracts could be obtained in the 5-6 c/kWh range.

Recent developments in the electricity industry, which have followed years of uncertainty, have reduced, rather than increased, the likelihood of such power purchase contracts becoming available. Therefore it is timely to explore whether a scaled-up version of this design may be more cost-effective and thus closer to viability in New Zealand's economic settings. Based on rotor sizes coming out of Europe, a 47 m, 1000 kW or a 66 m, 2000 kW unit may be appropriate. The fundamental trends shown in Figure 3 would indicate that significant cost reductions may be available to the Windflow design, whereas they would not be available for conventional European three-bladed designs.

Complicating Factors

This paper is putting a very simple argument about the impact of weight reductions on the cost of wind energy and the shape of the overall cost curve. It is not a new argument in the wind business or in other industries. However it is worth restating in the New Zealand context because:

- the wind business is likely to be undercut by gas-fired power for several years
- the economy here is free from subsidies which have supported heavy designs elsewhere
- high materials use has an environmental impact which, to be consistent with wind power's green image, should be minimised
- regardless of the above factors, all credible avenues for cost-reduction should be explored.

At the same time it is acknowledged that there are several complicating factors omitted from this argument. Some of these affect the argument, whereas some affect the cost of wind energy in general, but not necessarily the validity of the argument.

The main example of the first type of factor is the trade-off between weight and complexity. If weight is saved by using exotic materials or by adding complexity, any cost-savings may be completely undermined. But this is not the case with the Windflow design, which uses conventional materials throughout. The TLG system uses a planetary gearbox and a hydraulic sub-system, both of which are standard in modern windmills. There are additional complexities in each sub-system, but these are small, especially compared to electrical VS windmills which introduce whole new sub-systems (e.g. power electronics) into the design. Similarly the rotor design uses full-span pitch control but this is standard in modern windmills. The teetering hub introduces some complexity but this is offset by the fact that there are only two blades to be

pitched. Overall the complexities introduced by the Windflow design are minor, relative to the 50% weight saving.

Optimisation for high wind sites is a factor which affects the magnitude of the weight saving. The Windflow design is optimised for 9-11 m/s sites whereas European designs are optimised for 6-7 m/s sites. This makes the comparison of weight-saving somewhat more complicated but does not affect the basic argument. In Figure 4 the "comparable" machines either have larger rotors or a smaller power rating. A "Windflow 39-500" would have a tower-top mass of about 13 tonnes, which is "only" a 40% reduction relative to the Vestas 39-500 (but 60% relative to the Enercon E-40!). Perhaps the easiest way to address this is to think of the high wind optimisation as another weight-saving technology for a New Zealand designed and manufactured product. When this is included, the claim of at least 50% weight saving becomes easily defensible.

There are two other factors which affect the COE but not necessarily the argument about weight saving. In fact they bear more on the question of establishing New Zealand manufacturing, rather than the choice of technology.

Quantity production has an even greater effect on windmill cost than weight. This creates a barrier to the adoption of a new low-mass design such as the Windflow, especially when the target market (New Zealand) is not mature enough to support quantity production. To date the author has not found a way around this barrier. However it should be noted that this does not undermine the validity of the basic weight argument. It simply raises the question of whether the design should be first developed overseas rather than in a start-up New Zealand venture.

Secondly manufacturing subsidies can distort the weight argument considerably. In this context the author would question whether the heavy subsidies on German coal and steel have underpinned the competitiveness of heavy European three-bladers to date. If this is so the point needs to be made that it is not particularly responsible from an environmental resource viewpoint. It is to be hoped that progress on GATT will see such subsidies diminish, and the economic signals strengthened for low-mass designs.

Conclusion

Machine weight remains a major determinant of the cost of wind energy, and a limiting factor for the economic scaling up of turbine designs. This follows from the fundamental square-cube law of turbine scaling - that output increases with the square of rotor diameter whereas weight increases approximately with the cube.

Therefore a design which gives a significant weight-saving (without compromising reliability) should, all else being equal:

a) give an absolute cost advantage at any size
b) give a relatively higher cost advantage as size increases
c) reach its optimum COE at a larger size than established designs.

The Windflow is such a design. Based on two low-mass technologies which have been proven overseas, it has been developed to an advanced stage at 33 m, 500 kW scale for New Zealand manufacturing and New Zealand's high wind conditions. The economic climate in New Zealand has not so far been conducive to the establishment of such a manufacturing enterprise

because there has been too much uncertainty about the future of wholesale electricity prices. Furthermore the current situation is likely to maintain downward pressure on those prices.

For these reasons it is timely to assess the prospects for scaling up the Windflow design so as to maximise its chances of achieving economic viability. Based on fundamental engineering-economic considerations, the prospects appear good. The $64 question remains, when will there be a stable market for wind power in New Zealand?

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