Wind Turbine Research

Is The Fuselage Turbine a Better Design?

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This document summarise results of private research conducted by **BOSMIN®** into reviewing possible opportunities for improving aspects of existing Wind Turbine (WT) technology.

1 INTRODUCTION.

Research is conducted out of a personal desire to understand WT technology better. Interest was stimulated by rising public discussion and visits to King and Flinders Islands and Codrington where wind farms operate.

WT technology has experienced a dramatic growth over recent years in response to "*greenhouse*" and "*sustainable*" power generation issues. The world wide web contains a good library of technical and descriptive literature on the subject some of which is in sections 13 References and 14 Webliography.

Applications for wind power technology include;

- electricity generation
- water pumping
- compressing air

Several WT combination systems are possible including;

- power generation with battery or pump storage
- fast startup power for demand peak shaving
- supplemental supply to photovoltaic solar or hydro generating systems
- fuel saving in association with fossil fuel electricity generation.

Much R&D and commercial work is directed at capturing significant quantities of renewable energy for public or private use and is often motivated by government financial incentives and sustainable growth targets.

Published figures show a Combined Cycle Gas Turbine has a thermal efficiency of up to 50% with effective generating capital cost of $550/kW, while Pulverised Coal plant efficiency is around 36% at an effective cost of $1,100/kW. WT is about $5,000/kW, assuming a 30% utilisation factor.

WT cost figures may come down a bit with future development, but are unlikely to ever get to a point where they are commercially competitive with fossil fuels on a capital included basis.

However, some countries regard capital invested in power generation as "sunk capital" with no future value. This is an easy conclusion to reach with the cost of capital currently falling in many developed nations around the world. On a "sunk capital" basis wind generation looks more attractive because there is no fuel cost. Operating costs are therefore comparatively low, with no operating emissions offering good environmental credits.

Remaining major limitations for WT are, the availability of environmentally suitable sites, and the need for a 100% alternate power standby capacity in the absence of an effective power storage system.

There remains many viable applications for WT where periodic power capture and storage for smaller installations is appropriate such as at some rural and island communities, but these currently compete with improving efficiency of photo voltaic systems.

2 TECHNICAL BACKGROUND.

Two critical considerations include:

2.1) Existing WT operations are formulated on theory developed by German Physicist **Albert Betz** in 1919 (Betz's Law Ref:1A). "*His book "Wind-Energie" published in 1926 gives a good account of the knowledge of wind energy and wind turbines at that time. It is quite surprising that one can make such a sweeping, general statement which applies to any wind turbine with a disc-like rotor. Betz' law says that* ***you can only convert less than*** *16/27 (or* ***59%)*** ***of the kinetic energy in the wind to mechanical energy using a wind turbine****.*"

Betz' law tells us that air coming into the rotor gives up velocity and hence energy when impacting the rotor blades (Ref:1B). This causes air exiting the rotor to slow down and thereby build up back pressure behind the rotor blades. Increasing amounts of energy can progressively be extracted from the incoming stream until a limit of 59% of the available energy has been extracted. At that time the build up of back pressure behind the blades prohibits any further capture of energy from the wind stream. Other important aspects of calculating the energy available from the wind are shown at Ref:2A, Ref:2B and Ref:3

2.2) Ref:3 show the gross power extractable from a moving air stream, using a rotor, is calculated by:

$$\text{Power} = \tfrac{1}{2} \times \text{Air Density} \times \text{Rotor Area} \times (\text{Air Velocity})^3 \qquad [1]$$

3 WIND TURBINE LIMITATIONS

Existing large WT installations have several limitations including:

- The wind mill is a large highly stressed structure with generating capacity limited by the size of blades that can be used.
- They cannot operate in high winds and are shut down. (Ref:4 Nordex 2.5MW unit operates between 4 & 25 mps, 14-90 kph). Gusty wind conditions may also cause shut down. This occurs because of asymmetric loadings on blades, and a requirement to keep blade tips operating below sonic velocities.
- Cold weather leads to icing on the blades which can be hazardous in a number of ways.
- At low wind speeds WT are 100% ineffective requiring an alternate (or stored) power supply be always on standby for power critical applications.
- Keeping the blades below sonic velocity often leads to a requirement for one or more gearbox drives, although some installations exist where customised multi-pole generators are direct coupled to a WT and operate in phase synchronisation with the reticulated grid supply.
- Large Wind Turbines have mechanical controls to ensure they always 'point' correctly. These can be problematic.
- Foundation costs (particularly at off shore installations) are high and about the same price regardless of WT size. This aspect favours a more productive unit, if available.
- A moving blade light shadow associated with WT operation is a significant consideration at some locations and has precluded the siting of other units.
- Noise levels are generally very low, but at the rural and coastal siting of many WT installations, noise is cited as having signification impact due to the incessant, throbbing, low pitched tone. This is particularly noticeable at low wind speeds when natural noise levels are not present.

This research aims to reduce or eliminate these limitations.

4 IMPLICATIONS OF BETZ' LAW

4.1) Betz' Law implies that if a device could be added to a WT which lowers back pressure, the wind mill would be able to extract more than 59% of the available wind power. Several patents are directed at introducing a form of ***DIFFUSER*** to reduce the back pressure, see Ref:5. This modification effectively encloses the wind mill inside a circular housing supporting the end of the diffuser. Enclosing the wind mill inside a casing forms a ***TURBINE*** which subtly, but importantly changes the wind mill operation and provides additional design flexibility.

4.2) Formula [1] implies that if a means is introduced which increases the effective air velocity through the blades, this will have a cubic effect on the power produced by the generator. *This means that if the wind speed doubles, the power available from the generator increases by eight times*.
The obvious intuitive way to increase the wind speed is to place a ***NOZZLE*** ahead of the turbine to concentrate the available wind into a smaller area thereby increasing its velocity. *Unfortunately introducing a nozzle also introduces energy sapping friction along the nozzle walls as well as producing an adiabatic compression of the incoming air which effectively eliminates any potential benefit.*

4.3) Formula [1] also implies that *if the effective density of the air reaching the turbine changes, the power from the turbine will alter proportionately*. Some dramatic field experience in cold climate operations with resultant air density increase is recorded at Ref:6.

5 BOSMIN® RESEARCH

Our research had four aims:

- Define the dimensions of an effective diffuser.
- Develop an energy efficient nozzle arrangement.
- Specify a suitable turbine generator combination.
- Provide an system for varying the wind density.

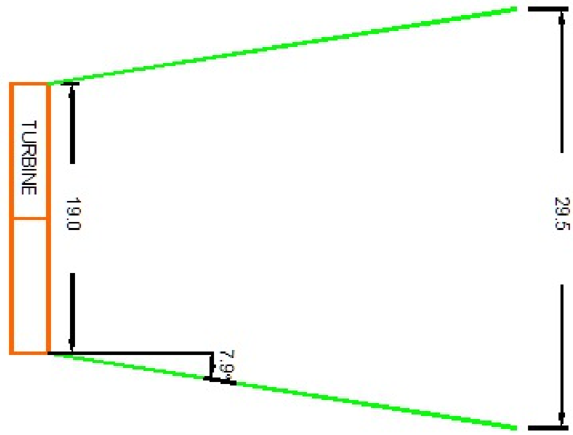
Test equipment included vane anemometers used to measure air velocity changes induced by various nozzle and diffuser designs. Air velocity passing through the anemometer was measured in a series of experiments with combinations of nozzle and diffusers fitted either side of the anemometer. "Wind" was provided by a bench mounted fan during preliminary laboratory testing of the anemometer equipment. A tripod mounted anemometer sited at an exposed windy location was used to obtain more extensive field test results.

This methodology proved time consuming and required fabrication of many combinations of diffuser and nozzle. A water resistant set of equipment was prepared to show the affects a fine water spray had on the anemometer readings.

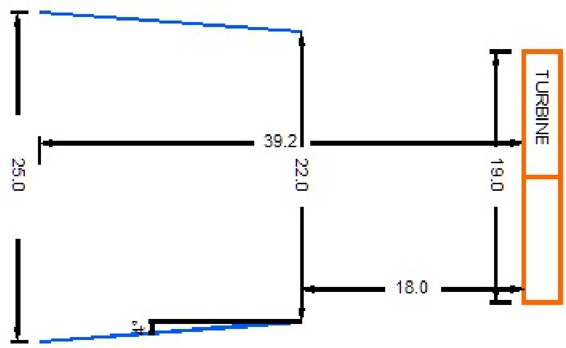
Consistent test results were obtained showing promise for improving wind power operation through modifications to existing WT designs.

Fuselage Turbine Test Equipment

6 EXPERIMENT RESULTS

<table>
<tr>
<td>The most effective DIFFUSER design was found to increase wind velocity passing through the anemometer by 22.8%. The diffuser diagram illustrates the preferred cone angle and scale ratios.</td>
<td>

Diffuser X-section</td>
</tr>
<tr>
<td>Introducing a NOZZLE to the anemometer inlet usually reduced velocity through the apparatus to less than 22.8% previously gained. However, one of the nozzle designs, when placed in combination with the diffuser, improved the raw wind velocity by an average of 33.6%.

This nozzle has an air space between the nozzle and turbine housing and effectively worked like a wind lens. The nozzle diagram illustrates the preferred cone angle, clearances, and scale ratios.</td>
<td>

Nozzle X-section</td>
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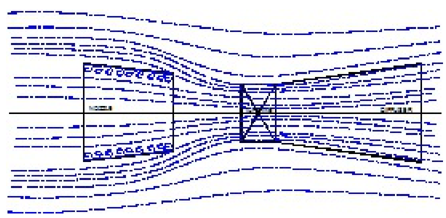
<tr>
<td>Cotton trace indicators showed paths of the wind stream passing the nozzle inside and outside surfaces.</td>
<td></td>
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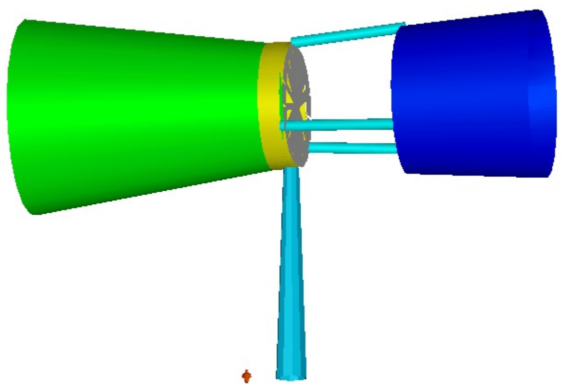
<tr>
<td>A combined nozzle, turbine and diffuser assembly is called a Fuselage Turbine (FT), as illustrated.

The human scale comparison is for an FT capable of generating up to 1.25MW in 8.9 mps (17 knot) winds.</td>
<td>
Fuselage Turbine</td>
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</table>

Using a nozzle ahead of the turbine provides a useful opportunity to inject a fine spray of water into the incoming air stream. The nozzle can be made from light weight sail cloth mounted on a pipework supporting frame which also pipes spray water. This effectively preconditions the air flow, and increases turbine air density by a variable amount depending on ambient moisture content.

Field tests showed a fine spray of water increased wind velocity through the anemometer by a further 6.1% to a maximum of 39.7% improvement for the whole FT combination. Spray water benefit is ambient condition dependant.

7 TURBINE GEARBOXES

Eliminating the common gearbox interfaced between the turbine and generator removes a costly and cumbersome component associated with many WT operations.

Step up gearboxes are required to match a slowly rotating wind mill with a rapidly rotating generator. This develops an alternating current frequency synchronised with common power supply systems.

WT supplier ENERCON (Ref:7) has developed a large custom generator which directly couples to their open wind mill, providing supply frequency alternating current.

8 GENERATORS

An important historical note at Ref:8A tells why asynchronous generators are the preferred alternative for wind turbines connecting to a power grid.

Increasing the number of poles reduces generator synchronous speed and does not appear to present major problems with existing generator designs as discussed under Ref:8B - *provided not too many poles are required.*

The example given shows 200 poles (400 rotor slots) are required for a 30 rpm synchronous generator. These are purpose built generators and may be expected to be difficult to repair and expensive to build.

However, using a nozzle, we can adopt a smaller diameter turbine with a design speed of 375 rpm, or 188 rpm as per **Table 1**, while keeping blade tips below sonic velocity.

The typical synchronous motor stator picture shown in Ref:8B has 64 such slots and could be made up as an 18 pole stator (375 rpm) of 36 slots suitable for FT#1 (Table 1), or 32 poles (188 rpm) and 64 slots for FT#2.

'File:FuseTurb1/Generators.123		TABLE 1		
20/09/04				
		Option	FT#1	FT#2
Inputs				
	Hz	cps	50	50
	Poles	##	16	32
	Gearbox Ratio	##	1	1
	Mid Blade Cu:Cv Ratio	##	1.15	1.15
	Max Blade Diameter Ratio - A1	##	24.3	24.4
Outputs				
	Min Blade Diameter Ratio - A2	##	0.04	0.04
	Turbine Wind Velocity	mps	11.9	11.9
	Max Mid Blade Speed Mu	mps	13.7	13.7
	Synchronous Speed	rpm	375	188
	Max Turbine Diameter @ A1xMu	m	16.9	34.0
	Min Turbine Diameter @ A2xMu	m	2.00	2.00
	Blade Tip Speed	mps	332	334
	Mach Number	##	0.98	0.98

At the end of Ref:8B there is mention of difficulties associated with high torque leading to heavy, expensive rotors. This problem is worse with a large overhanging wind mill attached directly to the generator, inducing significant bending moments and a need for very large generator bearings.

FT employs a universal joined connecting shaft between the turbine and generator supplying less than 1,500kW capacity. This will not induce particularly high shaft stress and results in a more conservative generator design.

WT requires the front end bearing be overhung, whereas FT turbine blades may be supported at both ends of the power shaft, and separately supported to the directly coupled generator. The FT generator is positioned within the diffuser and is easily accessible for maintenance or replacement - a feature not present in the ENERCON arrangement.

9 WIND TURBINES

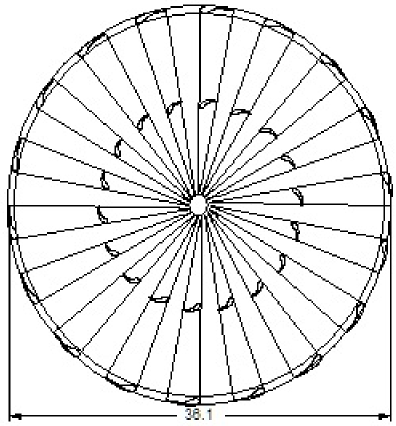
Increasing pole numbers is critical to keeping blade tips below Mach 1 speed. Mach 0.98 is applied in **Table 1** calculations, because asynchronous generators only slow about 1% at full load having no ability to speed up when operating within their design envelope.

FT power calculations (**Table 2**) are compared with WT operations discussed at Ref:1C.

File:FuseTurb1.123	TABLE 2			
20-Sep-04	Fuselage Turbines			
Inputs		**Units**	**FT#1**	**FT#2**
V1	Nozzle Entrance Wind Velocity	kph	32.1	32.1
AusIMM-FGMp278	Air Density	kg/m^3	1.225	1.225
	Model Raw Inlet Velocity - v1	mps	3.13	3.13
	Model Accelerated Inlet Velocity - v2	mps	4.17	4.17
Ref. 6	Turbine Efficiency	%	100%	100%
	Generator Efficiency	%	100%	100%
	Gearbox Efficiency	%	100%	100%
	Nozzle D1 to Turbine Diameter Ratio	factor	1.373	1.373
	Nozzle d1 to Turbine Diameter Ratio	factor	1.144	1.144
	Nozzle Sail Length to Turbine Diamete	factor	1.146	1.146
	Diffuser d2 to Turbine Diameter Ratio	factor	1.481	1.481
	Diffuser Length to Turbine Diameter Ra	factor	1.954	1.954
	Nozzle Length to CL Turbine Diameter	factor	2.197	2.197
	Diffuser Length to CL Turbine Diameter	factor	1.739	1.739
Outputs	Wet Assist ? Y=1	##	1	1
	Model Accelerated Inlet Velocity - v3	mps	4.42	4.42
	Nozzle-Diffuser Velocity Scaling Facto	factor	1.41	1.41
V1	Nozzle Entrance Wind Velocity	mps	8.923	8.923
V2/V3	Turbine Intake Velocity	mps	12.6	12.6
	Generator Poles	##	16	32
	Synchronous Speed	RPM	375	188
	Gearbox Ratio	##	1	1
	Max Turbine Diameter	**m**	**18.0**	**36.1**
	Min Turbine Diameter	m	2.0	2.0
	Turbine Annulus Area	m^2	250	1018
	System Efficiency	%	100%	100%
	Nozzle Inlet Area	m^2	477	1924
	Nozzle Inlet Diameter	m	24.6	49
	Combined Nozzle Inlet Diameter	**m**	**24.6**	**49.5**
	Nozzle Outlet Area	m^2	331	1336
	Unit Nozzle Outlet Diameter	m	20.5	41
	Unit Nozzle Sail Length	m	20.6	41
	Unit Diffuser Length	m	35.1	70
	Diffuser Outlet Area	m^2	555	2240
	Unit Diffuser Outlet Diameter	m	26.6	53
	Unit Nozzle Length	m	39.4	79
	Unit Diffuser Length	m	31.2	63
	Unit Overall Length	m	70.7	142
	Combined Overall Length	m	70.7	142
	Multiple Turbine-Generator Units	##	1	
	Fuselage Diameter Fill Factor	##		
	Unit Power Factor	W/m^2	1,229	1,229
Power Generated	0.5 x Rho x V^3 x A x Eff / 1000	kW	307	1,251

The nozzle entrance wind speed Table 2, is set equal to the velocity used in medium size (54m) WT rotors at Ref:1C. The "wet lens" or water spray injection, should be an easy adaptation at off shore locations, or where fresh water is readily available.

Selecting a C_u:C_v ratio of 1.15, where C_u is mid blade rotor speed and C_v is rated wind velocity, allows us to reach a maximum turbine diameter of 18 m driving an 16 pole asynchronous generator at 375 rpm or a 36.1 m turbine (*Turbine Blades*) driving a 32 pole asynchronous generator at 188 rpm .



Turbine Blades

The hub size does not significantly affect turbine output. A 2m hub is shown in *Turbine Blades* with supporting low profile peripheral ring, tying the ends of the blades together. This eliminates the need for larger blade attachment structure at the hub. It should also improve the fan operating efficiency and reduce noise by acting as a "winglet" addition to the blade ends. A further design features will include blade pitch adjustment to correlate with changing wind speeds and to enable a complete shut down of the turbine when required.

Unit Power Density for a wet operation, is 1,229 kW/m^2 and the FT#1 machine yields a rated capacity of 307 kW and 1.25 MW for FT#2.

We can compare this calculation with Ref:1C where a 33m diameter WT is rated at 300 kW against the 16.9m FT#1 at 228kW (dry) and 307kW (wet). The 34m FT#2 at 1,256kW (wet) compares closest with 54m diameter WT at only 1,000kW. However, as might be expected, the FT nozzle and diffuser diameters are similar to their respective WT machines indicating they collect equal wind power from a similar area of space.

The advantage the FT design has is that it collects much of the energy with fixed large nozzle and diffuser structures whereas WT machines rely on problematic large blade sweeps to cover the same area.

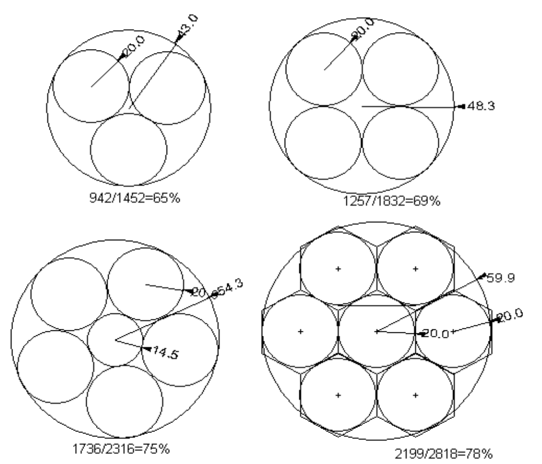
10 DISCUSSION

Comparing the FT design against the limitations cited for the WT under Section 3 where we noted:

10.1) *The wind mill is a large highly stressed structure with generating capacity limited by the size of blades that can be used.*

- FT fan blades operate in a housing which ensures the air flow is always travelling axially to the blades. This removes one of the major loading affects noted with WT which occurs when gusts of wind catch the blades at an angle before the mechanical pointing system can react to the changed wind direction.
- FT blades can be attached at the hub as well as at a peripheral low profile ring tying the ends of the blades together. Turbine blades have a different shape aspect being flatter and more plate shaped, which is a stronger shape than the typically long slender WT blades.
- FT units can be scaled up in size more than WT units because several turbines can be nested in the same nozzle and diffuser structures. This is achieved by mounting the turbines in a circular or honey comb shaped housing as shown in the attached sketches. A nest of seven turbines fits neatly into a circular housing 3 times the diameter of each turbine, and uses 78% of the circular area. The seven unit arrangement provides generation capacity from 1.5 to 7 MW with machines conveniently located on three horizontal (or vertical) bearers.

Nested turbines permit some generators to be feathered down during low wind periods, or for maintenance, thereby ensuring that some generating capacity is available from the remaining turbines. Proportionally large nozzles and diffusers are required for a nested installations.



Nested Turbines

The structural support for the large diffuser and nozzle is a concern but "do able". The nozzle and diffuser provide balanced weights either end of the turbine cowling. This lends itself to a single main gas filled carry structure (similar to some dragline booms). An alternate and simpler boom support structure may be formed by installing a post tensioned rod inside a pipe. A minimum of three such columns are required to support the nozzle. The nozzle and diffuser are covered with membrane technology sails on the inside to form the perforated nozzle where the pressure will be higher, and on the outside to form the diffuser where the higher pressure will come from the outer surface. Two side benefits of this structure are that it can be made self pointing into the wind, with the aid of a wind vane, as well as providing an opportunity to precondition the wind - thereby altering the density of the incoming air stream. The wind vane may be replaced by forming the nozzle inlet into a horizontal elliptical shape while forming the diffuser outlet into a vertical elliptical shape.

A limiting design factor used with WT units keeps the maximum blade tip velocity to less than 45 fps (13.7 mps). This ensures the necessary safety factors are included to protect against excessive noise and to reduce blade and turbine stresses. A much higher tip limit velocity should be obtainable in the FT design, because the fan operates within the housing where noise is contained and wind conditions are predictable.

10.2) *WT cannot operate in high winds and are shut down. (**Ref:4** Nordex 2.5MW unit operates between 4 & 25 mps). This occurs because of asymmetric loadings on blades, and a requirement to keep blade tips operating below sonic velocities.*

Asynchronous generators have little slip (1% see Ref:8A). Higher wind speeds generate more torque on the generator delivering more power. Thus a generator can also operate as a turbine over-speed limiter. This handy control feature is not generally available at WT installations, because of an interspersed gearbox. A step-up gearbox easily goes into overload when the generator starts acting as a brake to the wind mill.

An FT installation avoids introducing a gearbox which means the unit is more self controlling and can operate in higher wind speeds. These units also operate at lower wind speeds as discussed previously. The FT unit therefore has a larger operating envelope than the WT design.

10.3) *Cold weather leads to icing on the blades which may be hazardous in a number of ways.*

Cold weather icing problems are detailed at Ref:6 and will affect both wind power systems.

However, FT is largely enclosed and the “missile” aspect of ice shedding from the blades is contained. The more structured design of the FT blades could also prove amenable to introducing mechanical ice shedding adaptation to the blades. Similarly, the water spray facility may prove useful in delivering anti freeze agent into the wind stream ahead of the turbine. However, FT large surface area could result in hazardous quantities of fixed ice forming on nozzle and diffuser structures which would require special consideration.

A wind vane attachment as discussed in 10.6, avoids many control problems associated with anemometer freezing, and the automatic pointing aspect of FT eliminates yaw drive control problems.

Eliminating gearboxes avoids problems associated with low temperature operation of this component.

10.4) *At low wind speeds WT are 100% ineffective requiring an alternate power supply be always on standby for power critical applications.*
FT can operate at lower wind speeds than WT due to the nozzle lens effect in boosting wind speed. Similarly nested turbines can be shut off to direct limited wind supplies to fewer units remaining in operation, thereby avoiding a complete system shut down.

10.5) *Keeping the blades below sonic velocity often leads to a requirement for one or more gearbox drives, although some installations exist where customised multi-pole generators are direct coupled to a WT and operate in phase synchronisation with the reticulated grid supply.*
FT are also direct coupled to the generator, but the design allows for a standard generator installation with the possibility that more high speed wind events can be tolerated, and because the turbine cowling ensures wind gusts always enter the blades in an axial direction. This will lead to increasing the operating envelope for FT units.

10.6) *Large Wind Turbines have mechanical controls to ensure they always 'point' correctly. These can be problematic.*
A wind vane can be mounted with the diffuser to effectively keep the unit pointing into the wind. An adjustable vane may be required to point away from the wind during FT shutdown, although a similar effect is obtained if the blades are feathered to a shut position.

10.7) *Foundation costs (particularly at off shore installations) are high and about the same price regardless of WT size. This aspect favours a more productive unit, if available.*
A large nested FT unit at an offshore location appears to offer several benefits including lower capital cost, bigger capacity more flexible operation and possibly lower maintenance requirement.

10.8) *A moving blade light shadow associated with WT operation is a significant consideration at some locations and has precluded the siting of other units.*
Enclosed turbine blades eliminate moving shadow patterns. Moving blades are also cited as visually distracting at exposed vista sites. These impacts are eliminated with enclosed blades, and reduced by using of camouflage designs on the FT structure.

The FT nested structure also implies the unit may be mounted closer to ground level. This could prove more cost effective and less of an environmental impact by having a larger FT positioned in the lower wind speed location rather than on a tall tower. This option is not available to WT where exposed blades are featured.

10.9) *Noise levels are generally very low, but at the rural and coastal siting of many WT installations, noise is cited as having signification impact due to incessant, throbbing, low pitched tone. This is particularly noticeable at low wind speeds when natural noise levels are not present.*

FT will also emit noise which is more likely to be directional and low pitched hum in nature. This may prove more acceptable than a throbbing sound. However, the FT noise should be reduced by the peripheral ring which eliminates exposed blade tip turbulence, and the opportunity to provide sound deadening features in the fuselage.

In the final analysis if the rotor proves too noisy it can be reduced in diameter thereby reducing the tip speed, or a higher number of poles can be used in the asynchronous generator. The FT design may also be "nested" as discussed previously. This allows for several smaller diameter, and slower rotating mills, to be housed in the one nozzle/diffuser structure thereby increasing the power generated at lower blade speeds.

11 CONCLUSIONS

11.1) No operating installation of this FT design has been tested and the conclusions must be regarded as preliminary.
11.2) Potential benefits suggest that an operating FT unit should be designed and tested at a suitable location.
11.3) Building a small scale (FT#3) unit provides a comparatively low cost way of testing many of the claims for this technology.
11.4) Large FT installations sited in remote high wind locations such as the Bass Strait islands have the potential to provide a useful energy supply when interconnected to a large generating system.
11.5) Low cost power generated in Bass Strait may offer opportunity for new local industry.
11.6) Wind turbines are used to compress air for farm dam pumps in particular. This may provide a backup store of useful energy and should be further investigated together with the use of pump storages.

I look forward to any comments or suggestions this report may stimulate.

Bob Beatty BE FausIMM(CP)
Principal, BOSMIN

12 REFERENCES.

Note. Some of these references have been removed from the internet. An extract from the reference is available at the BOSMIN web site at the Ref hyperlink.

12.1) Original references:http://www.windpower.org/en/tour/wres/tube.htm
Ref:1A
Ref:1B
Ref:1C
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12.8) Original refrences:http://www.newenergy.org.cn/english/guide/async.htm
Ref:8A
Ref:8B

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