GIGAWATT TURBINE

98% COEFFICIENT OF POWER

Revisiting Drag After a Century of Betz

By Paulo Abdala, PhD Aeronautics

The world is calling for an urgent solution to control climate change. Wind energy is one of the best possibilities not only because it is sustainable but it is the most available form of energy from the earth's atmosphere-- by longitude, latitude and altitude. This paper aims to provide new foundations regarding the use of drag-based rotors, designed by Xenecore, and to prove its **reliability, high efficiency and low cost**. This new generation of wind turbines has a very wide range of operation, from very low to extremely high wind speeds. The patented internal design, based on biomimetics principles, along with a careful selection of material provides a blade that can withstand Category 5 hurricanes, like Katrina (2005) and Camille (1969) easily.

1 – THE PROBLEM

In 2015, the United Nations (UN) adopted the Sustainable Development Goals (SDGs), also known as the Global Goals, as a **universal call to action to end poverty, protect the planet, and ensure that by 2030 all people enjoy peace and prosperity**. There are 17 SDGs in force.

Sustainable Development Goal 7 (SDG7) calls for **"affordable, reliable, sustainable and modern energy for all" by 2030**. It has core targets namely, ensuring universal access to affordable, reliable and modern energy services[1].

One of the major concerns of modern society is climate change. It refers to long-term shifts in temperatures and weather patterns, caused by natural reasons or by human activities. Since the 1800s, the accelerated use of energy in the industrial and transport sectors made human activities a main driver of climate change, primarily due to burning fossil fuels like coal, oil

[1] SDG7 targets:

- By 2030, ensure universal access to affordable, reliable and modern energy services
- By 2030, increase substantially the share of renewable energy in the global energy mix
- By 2030, double the global rate of improvement in energy efficiency
- By 2030, enhance international cooperation to facilitate access to clean energy research and technology, including renewable energy, energy efficiency and advanced and cleaner fossil-fuel technology, and promote investment in energy infrastructure and clean energy technology
- By 2030, expand infrastructure and upgrade technology for supplying modern and sustainable energy services for all in developing countries, in particular least developed countries, small island developing States, and land-locked developing countries, in accordance with their respective programs of support

and gas. Burning fossil fuels generates greenhouse gas emissions that act like a blanket wrapped around the Earth, trapping the sun's heat and raising temperatures.

In this scenario, wind energy is a key element in the UN´s policy, as it can play an important role as a clean, renewable source of energy. The wind is the most available source of energy on the planet, since its distribution is not restricted to a geographic specific area and not restricted by the altitude or land because it can be built vertically as well as horizontally It creates not only an optimal solution for the environment but also a huge market for investment.

2 – WIND ENERGY

The use of wind energy has more than 3,000 years of history. From early Persian windmills to modern wind turbines, the use of wind energy has contributed to human development. During the majority of this time, the empirical approach was used to design wind turbines, since no scientific knowledge was available. In the late 1800's to early 1900's, early advances were made to model the behavior of wind turbines and to predict their results.

For the past century, the work of Dr. Albert Betz, in his manuscript *Windmills in the Light of Modern Research* has become the premier theory in designing windmills. At that time, the use of simple models to create analytical solutions was the only possible means to achieve results. His approach lead to the oversimplified mathematical model of the behavior of the wind turbine. As a consequence, the belief that "lift" based blades were the best solution to construct wind turbines became the conventional wisdom. In his work, Dr. Betz presented two basic models: a drag device and a lift device.

The first model (drag) was described as a flat plate placed on a car, moving in the same direction of the wind figure 1. During the movement, the object was able to use the wind force to lift a weight. This device, as Betz concluded, is very inefficient because the object is moving in the same direction of the wind, therefore reducing the amount of force created by the wind. This conclusion is easy to be verified on some Vertical Axis Wind Turbine (VAWT).

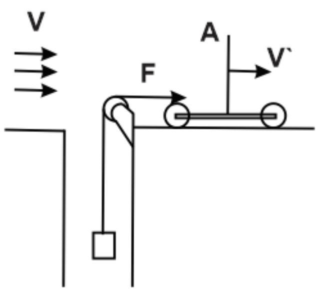


Figure 1 - Drag device (from *Windmills in the Light of Modern Research*)

The second device (lift based), figure 2, based on an airplane wing was presented as the optimum solution for wind turbines, since it lifts the weight more efficiently. In his model, the drag force was considered as an "energy loss" and for this reason it should be minimized. From that time to now, the lift-based wind turbines fast became the industry standard.

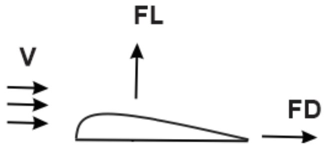


Figure 2 - Lift device (from *Windmills in the Light of Modern Research*)

Fortunately, the fast growth of computer science and the use of numerical solutions approach, such as Computer Fluid Dynamics (CFD), has surpassed the limitation of simplified analytical models, thus opening many doors for new technological improvement. New research has shown that the intelligent use of drag forces can generate a huge amount of energy, even going beyond what is known as Betz´s limit of 59,3% of efficiency. This is the case of Diffuser Augmented Wind Turbine Technologies and the Xenecore Fanturbine.

3 – BASIC SOLUTION - Industry standard

The monumental contribution by Dr. Albert Betz created the foundation for the new industry standard. To operate a large wind turbine, the solutions provided by Betz and other pioneers has led to very complex and expensive wind turbines, making the cost of energy very high.

Some problems are listed below:

3.1 - Material used to make wind turbines

In the past, wind turbines were made from many different materials such as wood, aluminum, steel or any other available material. Today the prevalent material is fiberglass reinforced plastic (FRP). The choice of FRP is not only due to its mechanical properties, good durability but mainly due to its low cost. It is important to note that the FRP gives only the outer external shape of the blade (skin).

The web is the part responsible for providing structural strength for the blade. This arrangement is a box-like structure in the inner part of the blade, and it acts like an I-beam, carrying the main load of the blade.

The process of construction is composed of two negative moulds parts (top and bottom). Many layers of FPR are deposited on each part of the moulds. After, the blade is assembled.

3.3 – Prandtl´s tip and root losses

Wind turbine blades are not capable of producing power over its entire length. In fact, the blades cannot generate power in regions very close to the tip and root. The so called Prandtl´s tip and root losses can be seen in figure 3.

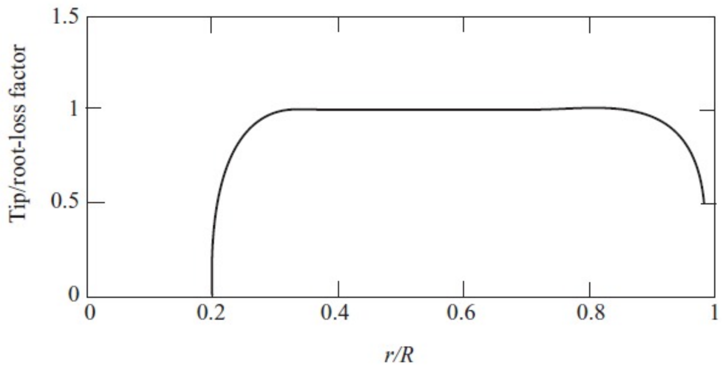


Figure 3 – Span-wise variation of combined tip/root-losses for a three-blade turbine optimized for a tip speed ratio of 6 and with a blade toot at 20% span (wind energy handbook).

3.4 – Complex shape calculated is simplified for industry.

To achieve the most efficiency, the aerodynamics principles are incorporated during the process of blade design. The result of this process is a blade design with a very good performance but complicated to build and very costly.

In order to reduce costs, commercial wind turbines are equipped with blades with a simplified shape. As a consequence, wind turbines in operation today produce less power.

3.5 - Efficiency

The efficiency of a conventional wind turbine, in optimum conditions is around 40%.

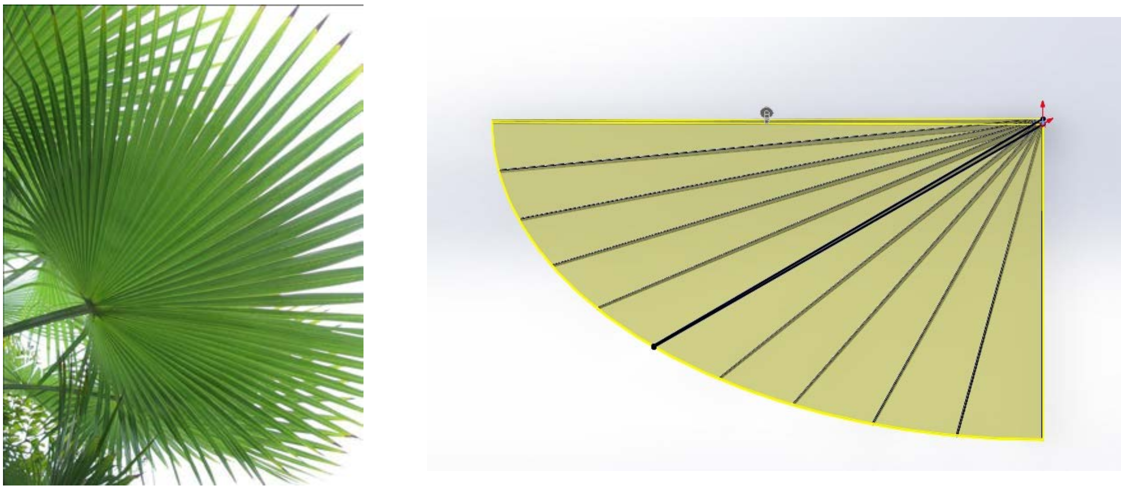
4 – NEW SOLUTION - FANTURBINE

In order to develop a new generation of wind turbines, the engineers of Xenecore challenged all the limits imposed by conventional wisdom, really "*thinking outside the box*". The understanding on how to convert the turbulence provided by drag force into energy production was the main goal in the development phase and simulations.

During the process, many commercial analysis programs based on blade element momentum theory were used to predict the performance. Det Norske Veritas and Germanischer Lloyd, DNV-GL's Bladed, FAST (by National Renewable Energy Laboratory, NREL), QBlade (by TU-Berlin), HAWC2 (by Technical University of Denmark (DTU), and ASHES (by SIMIS) are some examples of some of the software. However, these simulation tools, that only support lift-type wind turbines, cannot be used in the analysis of the drag-base wind turbines. Therefore, a numerical approach through a computational flow dynamics program was used. The simulation tool used for analysis was Ansys Fluent.

4.1 - New design

The blades were designed using biomimetics principles. The goal of biomimetics is the emulation of the models and systems of nature aiming at solving complex problems. The task faced by Xenecore engineers was to design a blade that can withstand the tremendous wind load yet be light enough to capture all of the wind even at low speeds. The solution found was a proprietary system of "ribs" or "I-beams". These structures make the blade very light and strong at the same time (figure 4) and have an orthogonal structure, the strongest geometry on Earth per weight.



(a) (b)

Figure 4 – Biomimetics principles applied. (a) Nature design, (b) Fanturbine ribs system.

The new design is also unique due to the intelligent use of the drag force. This force Betz considered as an energy “loss” for lift concepts, are now being used to generate power. The high turbulence created by the high solidity makes the pressure behind the rotor drop drastically. The increased difference of pressure induces higher wind speed, thus contributing to power generation.

4.2 - New material

The new design proposed by Xenecore requires a careful selection of materials. The use of a very high modulus carbon fiber and a filler material (the patented microgel by Xenecore) provides extraordinary strength and stability for the blades. The ability to resist high wind loads force was proven by simulations and real models. Section 5.1 provides more information regarding blade strength.

The use of carbon fiber associated with microgel not only provides unmatchable strength but also the best strength-to-weight ratio of the market.

4.3 – The construction method

The new design also requires a special technique for its production. The blades are made of a single piece of high modulus carbon fiber. Inside there are several chambers limited by the patented structural ribs systems. The chambers are filled with special microgel that contributes to the overall strength.

The single piece design, called unibody, allows the blade to have more stability, reliability and durability.

4.4 – Performance advantages

The performance of the Xenecore new design rotor is higher than the best wind turbines provided by any manufacture. The main differences are:

a) The largest chord of the blade is very close to the tip, therefore generating unparalleled torque production.
b) The superlight strength of the orthogonal ribs or I-beams inside the blade allows the rotor rotation when the wind speed is very low yet withstanding hurricanes.
c) The coefficient of power (Cp) is well above the average standard design wind turbine. More information of the Cp can be found in section 5.2.
d) The high solidity and the higher number of blades substantially reduces the Prandtl´s tip and root losses. This fact contributes to the increase value of torque generation.
e) The high efficiency of the design provides the possibility of a more compact design.
f) The biomimetics principles used in the design of the internal structure (orthogonal ribs) associated with the high modulus carbon fiber and microgel can make the rotor easily withstand category 5 hurricanes. (See section 5.1).
g) The simplicity and elegancy of the design results in a cost reduction compared with the cost of complex shaped blades, without sacrificing the performance as the conventional lift-based blades.
h) The concept of unibody construction blades, in contrast with traditional two pieces glued blades, provides more stability, reliability and durability. This also impacts on the reduction of the costs associated with maintenance.
i) The huge amount of drag force, neglected in the design of modern wind turbines, is being used to create low pressure behind the rotor. This lower pressure induces more wind speed through the blade, and therefore generating power. This is also the case of some Diffuser Augmented Wind Turbine Technologies which surrounds the blade with a flange device to create the turbulence. The new breakthrough of Xenecore rotor is to design a rotor that creates the same effect by itself.
j) The rotor has an extraordinary range of operation. It is able to withstand the tremendous wind load yet being light enough to capture all of the wind even at low speeds.

5 - EXAMPLE OF 100M WIND TURBINE BLADE

The force (wind load) and power produced by the wind in a cross-section can be expressed as follows:

$$F_{wind} = \frac{1}{2} .Cd .\rho A. V^2 \quad (1)$$

$$P_{wind} = \frac{1}{2} . \rho A. V^3 \quad (2)$$

Where:

Cd is the coefficient of drag

ρ is the density of air (1.225 kg/m^3)

V is the wind speed.

A is the cross-section area.

The power output, P, that can be generated by a wind turbine is given by the well-known expression:

$$P = \frac{1}{2}.C_p.\ \rho.\ A.\ V^3 \qquad (2)$$

Where:

C_p is the power coefficient

Since the wind turbines have a defined cross-section swept area, the amount of power generated will depend on the Cp, and mainly on the wind speed.

The following example shows the performance the new technology blade by Xenecore.

5.1 – Strength Resistance of the blade

In order to assess the amount of stress that the blades can withstand until it reaches its maximum resistance, simulations were conducted using the softwares Solidworks and Ansys Fluent.

The wind load (N), per blade, can be calculated using the expression (1). The results are expressed in figure 5.

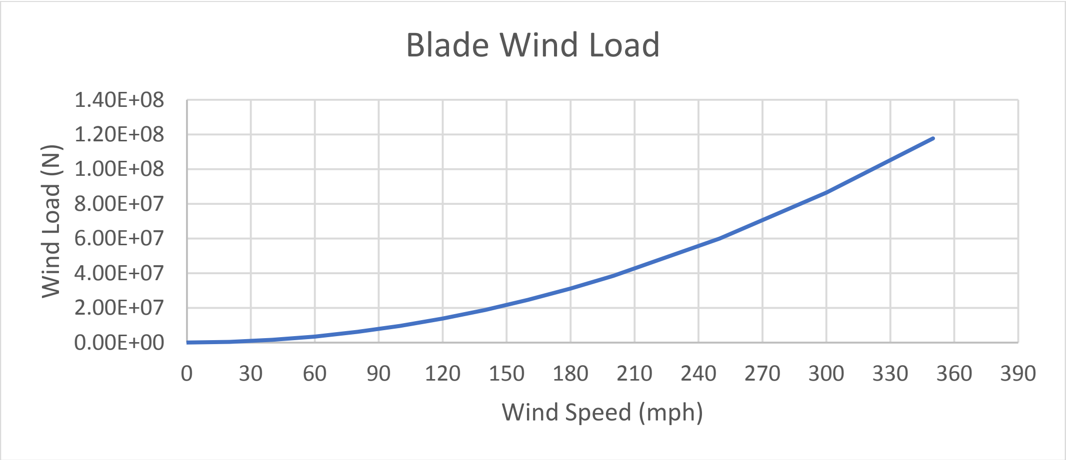


Figure 5– Wind load as a function of the wind speed in a 100m rotor.

Progressive loads were applied on a computer model to estimate the strength of the blade, when an orthogonal force is used, therefore simulating a static test, figure 6. The results can be found in figure 7.

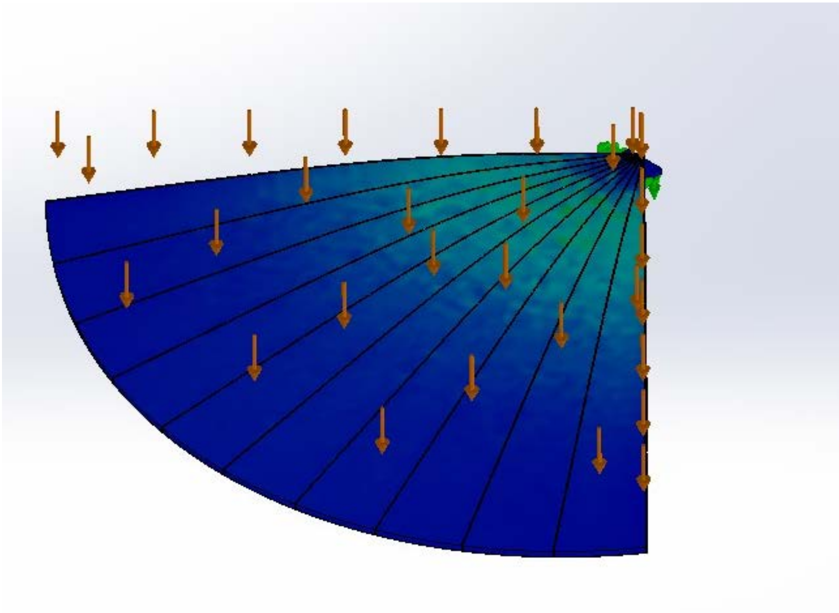


Figure 6 – Simulation of static test using Solidworks.

The maximum blade stress can also be obtained from figure 7. Considering that the limit of the material used to make the blade (2,86 GN/m^2), the maximum wind speed that the blade can withstand is 376 mph.
As a comparison, the wind speed registered by hurricane Katrina was 175 mph, which is well below the maximum wind speed that the blade can withstand.

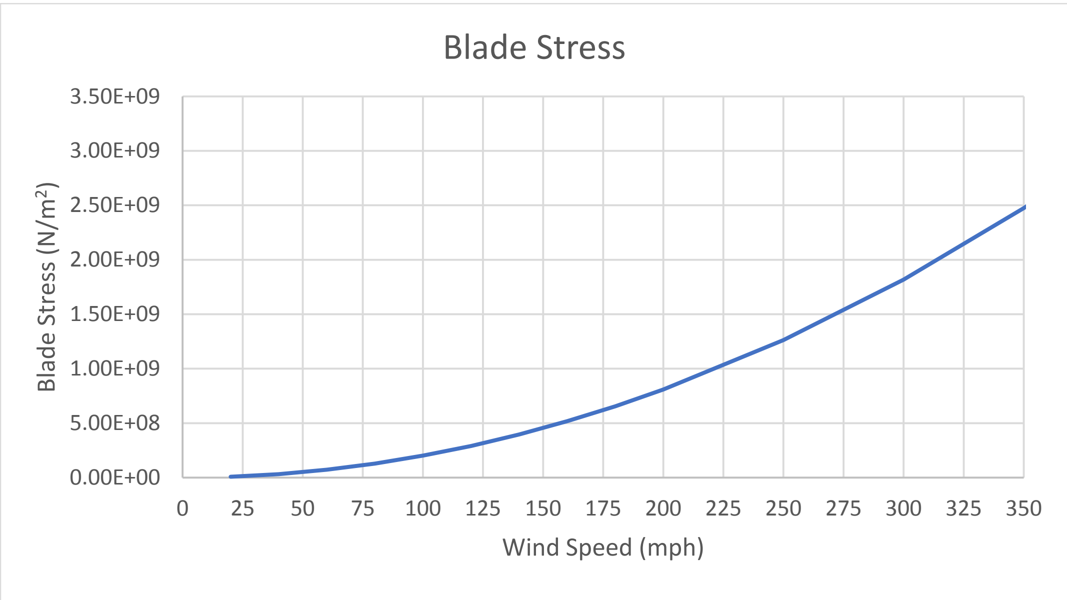


Figure 7 – Blade stress as a function of the wind speed in a 100m rotor.

5.2 – Wind turbine power.

The survival speed of commercial wind turbines ranges from 40 m/s (144 km/h, 89 mph) to 72 m/s (259 km/h, 161 mph), typically around 60 m/s (216 km/h, 134 mph). Some turbines can survive 80 meters per second (290 km/h; 180 mph).

Considering a wind speed of 125 mph (55,88 m/s) and a swept cross-section radius of 100m, and according to expression (1), the maximum power available from the wind is 3,44 GW.

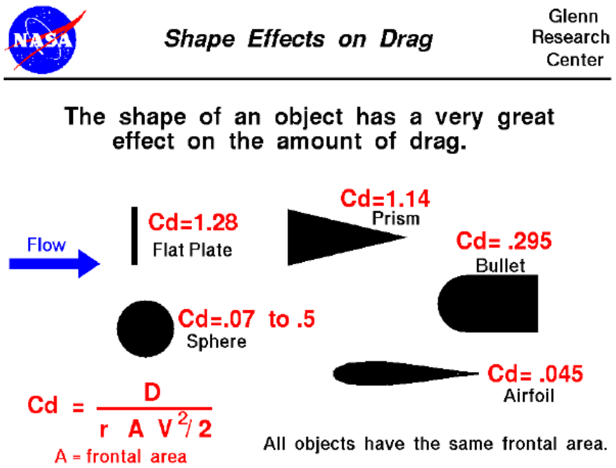
Assuming absolute rigidity of the tower and blades and nominal moment of inertia, the maximum theoretical coefficient of power for a wind cross-section is Cp 98%.

The maximum power produced by wind turbine under the above condition, according to expression (1) is:

$$P = \frac{1}{2} . 0,98. 1,225. 31415. 55.88^3$$

P = 3.77 GW (or 0.842 GW per blade in a 4 blades rotor).

The above results proves that fan turbine can produce a large amount of energy using drag-based blades, as opposed to what the common sense believed. The surface power is the cross section wind surface bended 10º.



INPUT		
Wind Speed	38	m/s
Rotor Radius	100	m
Coefficient of Drag	1.28	Flat Surface Drag Coefficient
Angle (degrees)	10	º
OUTPUT		
Wind Available Force (0º)	35,565,844.8	N
Surface Force	35,025,519.7	N
Percentual	98.48%	

Wind Available Power (0º)	1,055.9	MW
Surface Power	1,039.8	MW
Percentage	98.48%	

6 – CONCLUSION

The world is desperate for an immediate solution to reduce the emissions of greenhouse gases and, in consequence, to control climate change. In this scenario, wind energy may be the best clean, renewable source of energy.

The industry of wind turbines evolved based on Dr. Albert Betz ideas thus limiting the potential of using drag-based rotors. Fortunately, the fast growth of computer science and the use of a numerical solutions approach, such as Computer Fluid Dynamics (CFD), has broken the limitation of simplified analytical models, thus opening many doors for new technological developments.

The intelligent use of drag-based rotors, along with new materials and manufacture processes, is a proven way to generate power, and represents a new approach to wind turbines. The results from Xenecore Fanturbine shows that this new approach is technically feasible, cost effective and environmentally beneficial.