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Expression and Calculation of Betz Constant for Expanding Air Stream

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ABSTRACT

The key hypothesis of plan and activity of wind turbines is inferred in light of a first standards approach involving protection of mass and preservation of energy in a breeze stream. A point by point induction of the Betz Equation and the Betz Criterion or Betz Limit is introduced, and its nuances, bits of knowledge as well as the entanglements in its inference and application are talked about. The hypothesis that is created applies to both flat and vertical pivot wind turbines. The power coefficient of a breeze turbine is characterized and is connected with the Betz Limit. A depiction of the ideal rotor tip speed proportion of a breeze turbine is likewise introduced. This is contrasted and a depiction in light of Schmitz whirlpool proportions representing the various misfortunes and efficiencies experienced in the activity of wind energy change frameworks. The hypothetical and an amended diagram of the different breeze turbine functional systems and designs, relating the power coefficient to the rotor tip speed proportion are shown. The overall normal standards hidden breeze, hydroelectric and nuclear power transformation are talked about.

KEYWORDS: *Renewable energy, Wind power, Accelerators, Turbines, Power extraction, Betz, Free stream theory*

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INTRODUCTION

Power extraction from passive acceleration has been actively studied since the 1950's. Passive accelerators are placed in fluid flows, such as wind or hydro currents, to accelerate fluid velocity and can increase the energy density and availability of the resource. Passive accelerators operate in the unpressurized confined flow regime and constitute the primary body of research for unpressurized confined flow. The unpressurized confined flow regime presents a complex fluid mechanics problem for which there is no valid theory that accurately predicts power extraction. Power extraction from confined flows is becoming a subject of importance to the energy landscape and climate mitigation. A valid theory for power extraction from the confined flow is necessary to quantify, develop, and utilize these resources and technologies.

A wind turbine is a device that converts the wind's kinetic energy into electrical energy. Hundreds of thousands of large turbines, in installations known as wind farms, now generate over 650 gigawatts of power, with 60 GW added each year. They are an increasingly important source of intermittent renewable energy, and are used in many countries to lower energy costs and reduce reliance on fossil fuels. One study claimed that, as of 2009, wind had the "lowest relative greenhouse gas emissions, the least water consumption demands and... the most favourable social impacts" compared to photovoltaic, hydro, geothermal, coal and gas.

Fig.1 Wind Energy

Smaller wind turbines are used for applications such as battery charging for auxiliary power for boats or caravans, and to power traffic warning signs. Larger turbines can contribute to a domestic power supply while selling unused power back to the utility supplier via the electrical grid. Wind turbines are manufactured in a wide range of sizes, with either horizontal or vertical axes.

Betz's law indicates the maximum power that can be extracted from the wind, independent of the design of a wind turbine in open flow. It was published in 1919 by the German physicist Albert Betz. The law is derived from the principles of conservation of mass and momentum of the air stream flowing through an idealized "actuator disk" that extracts energy from the wind stream. According to Betz's law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. The factor 16/27 (0.593) is known as Betz's coefficient. Practical utility-scale wind turbines achieve at peak 75–80% of the Betz limit.

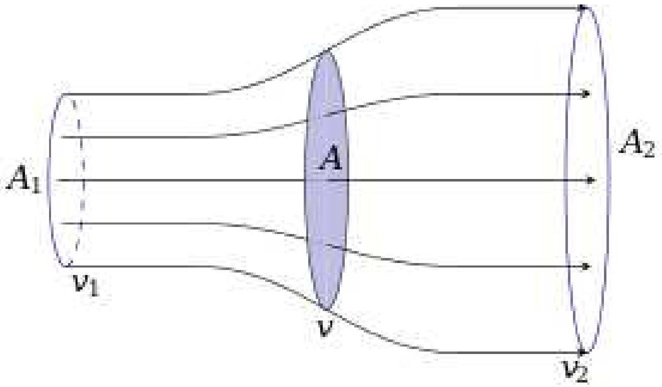

Fig.2 Indication of Maximum power

The Betz limit is based on an open-disk actuator. If a diffuser is used to collect additional wind flow and direct it through the turbine, more energy can be extracted, but the limit still applies to the cross-section of the entire structure.

Betz's law applies to all Newtonian fluids, including wind. If all of the energy coming from wind movement through a turbine were extracted as useful energy, the wind speed afterward would drop to zero. If the wind stopped moving at the exit of the turbine, then no more fresh wind could get in; it would be blocked. In order to keep the wind moving through the turbine, there has to be some wind movement, however small, on the other side with some wind speed greater than zero. Betz's law shows that as air flows through a certain area, and as wind speed slows from losing energy to extraction from a turbine, the airflow must distribute to a wider area. As a result, geometry limits any turbine efficiency to a maximum of 59.3%.

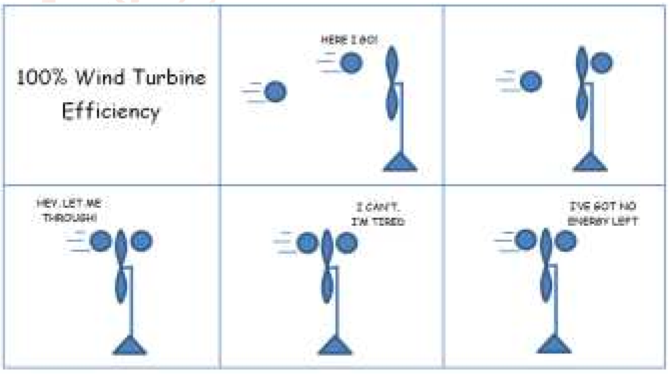

Fig.3 Turbine Efficiency

Assumptions

1. The rotor does not possess a hub and is ideal, with an infinite number of blades, which have no drag. Any resulting drag would only lower this idealized value.
2. The flow into and out of the rotor is axial. This is a control-volume analysis, and to construct a solution, the control volume must contain all flow going in and out, failure to account for that flow would violate the conservation equations.

3. The flow is non-compressible. Density remains constant, and there is no heat transfer.
4. Uniform thrust is exerted on the disc or rotor.

Application of conservation of mass (continuity equation)

Applying conservation of mass to this control volume, the mass flow rate (the mass of fluid flowing per unit time) is given by

$$\dot{m} = \rho A_1 v_1 = \rho S v = \rho A_2 v_2,$$

Where v_1 is the speed in the front of the rotor, v_2 is the speed downstream of the rotor, v is the speed at the fluid power device, ρ is the fluid density, the area of the turbine is given by S are the areas of the fluid before and after reaching the turbine.

So the density times the area and speed should be equal in each of the three regions: before, while going through the turbine and afterward.

The force exerted on the wind by the rotor is the mass of air multiplied by its acceleration. In terms of the density, surface area and velocities, this can be written as

$$\begin{aligned} F &= ma \\ &= m\frac{dv}{dt} \\ &= \dot{m}\,\Delta v \\ &= \rho S v (v_1 - v_2). \end{aligned}$$

Betz equation and criterion, performance coefficient Cp:

The Betz Equation is analogous to the Carnot cycle efficiency in thermodynamics suggesting that a heat engine cannot extract all the energy from a given source of energy and must reject part of its heat input back to the environment. Whereas the Carnot cycle efficiency can be expressed in terms of the Kelvin isothermal heat input temperature T1 and the Kelvin isothermal heat rejection temperature T2:

$$\eta_{Carnot} = \frac{T_1 - T_2}{T_1} = 1 - \frac{T_2}{T_1},$$

the Betz Equation deals with the wind speed upstream of the turbine V1 and the downstream wind speed V2.

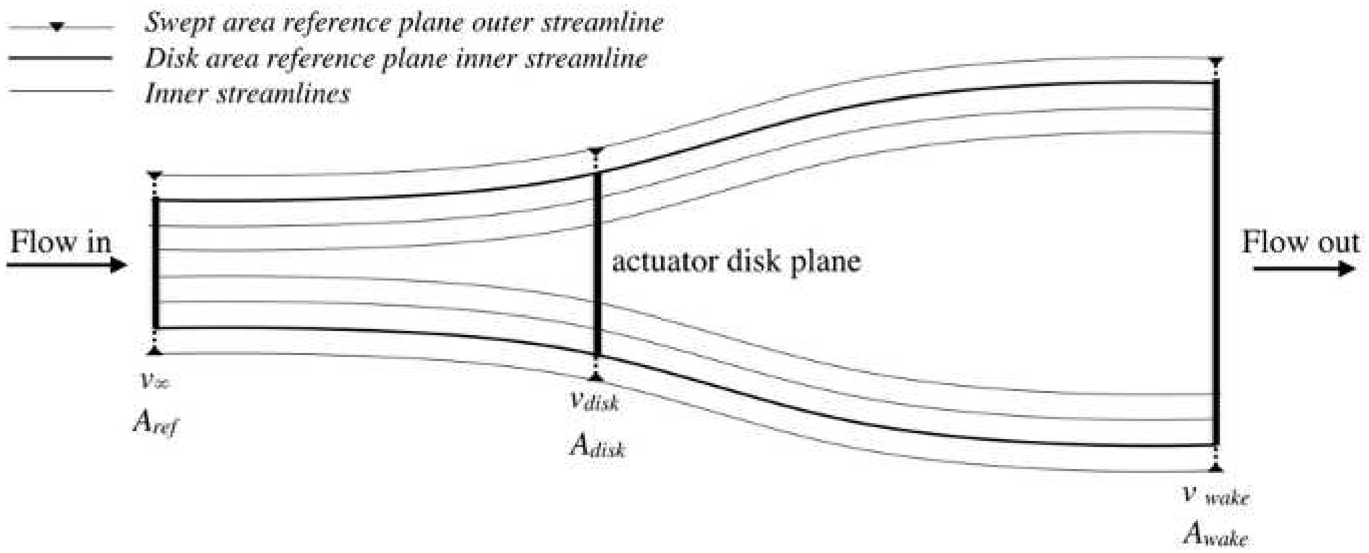

Figure 4. Betz streamlines.

The Continuous Energy and Momentum

Unlike the Betz model, the scheme shown in Figure allows a continuously variable wind velocity within the harvester. We also extend the harvester's abstract actuator region to cover the expansion regions of the wind, making the inlet and outlet pressure ambient, and therefore the inlet and outlet velocity are the initial and final wind speeds. (Section will later relax that requirement as well.) In order for the velocity of an incompressible flow to vary within the confines of a fixed cross-section, the harvester must shed mass flow out of its cross-section. In Figure , we show this as extruded wind outside the harvester aperture where it no longer can interact with the energy extraction mechanism within.

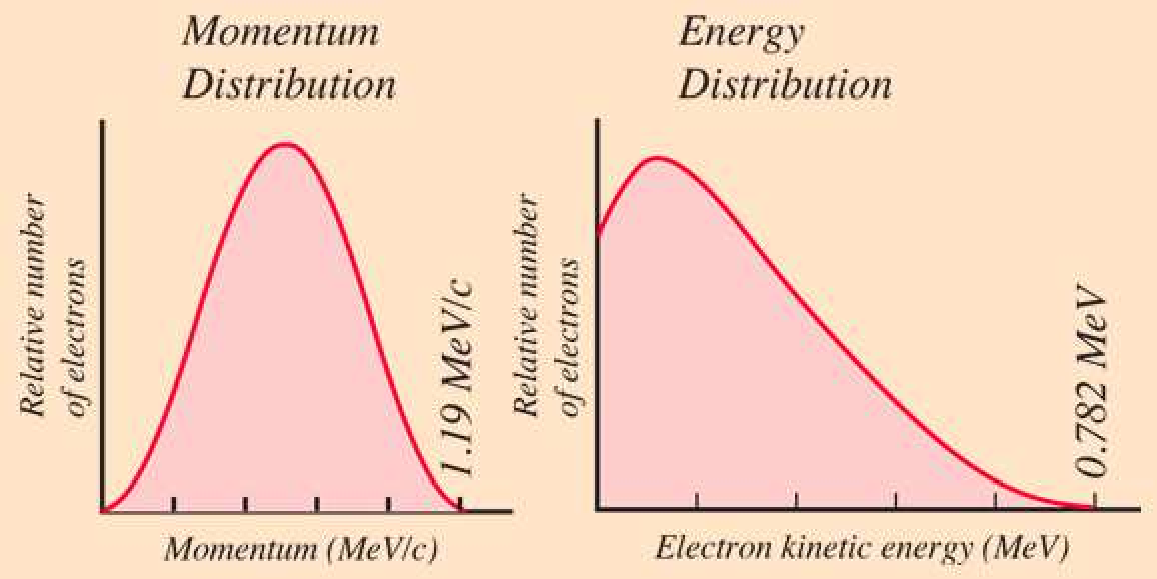

Fig.5 Energy and Momentum

Force and Power:

The momentum of a mass flow changes only when force is applied, and by equal and opposite reaction we can extract work by slowing the flow. We can thus upper bound the power extraction of any possible machine simply by the amount of power needed to slow the wind to a given value, in a way consistent with flux conservation. In conserved incompressible flow without a force, there is no change in velocity. By Euler's theorem, the infinitesimal velocity change from an infinitessimal force is:

$dF = mdv$

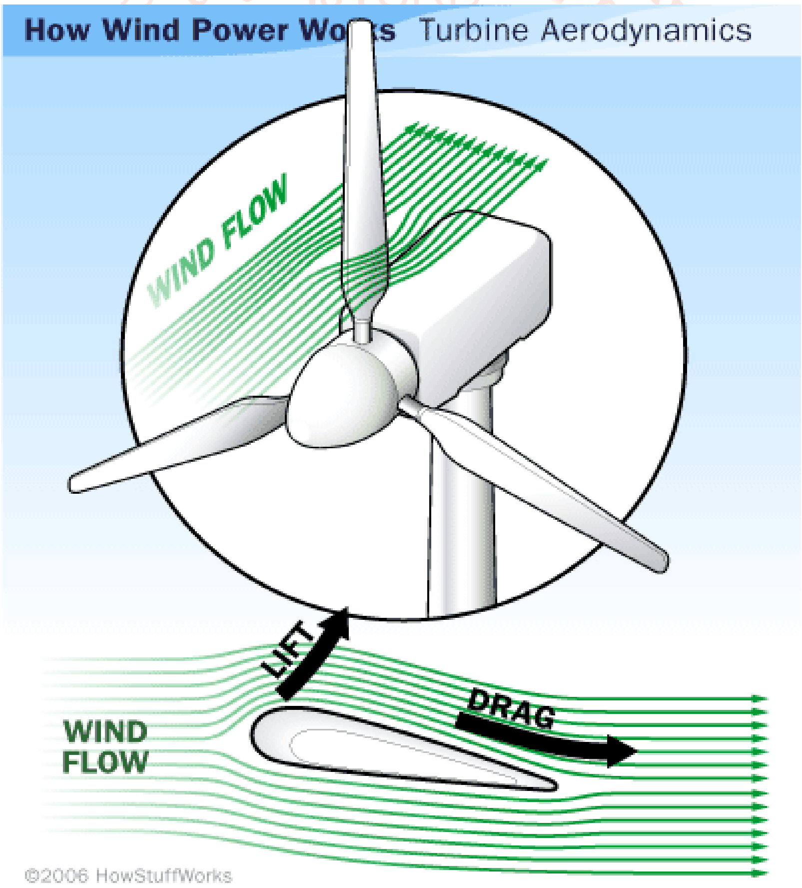

Fig.6 Force and Power

Minimizing interference between nearby windmills:

Harvesters emit an expanded low velocity wind-field. In a compact wind farm, windmills will interfere not just because of turbulence but the depletion of kinetic energy. For a given plot of land or ocean barge, this may limit how many windmills we can array without interference. Or looking at it another way, one large wind machine across the entire plot of land can use all of the wind efficiently but it steals the neighbor's access to the full wind speed. Here the CEMS has an advantage. We note that the negative pressure zone of the Betz model is external to harvester itself, and thus the expansion is not controlled and will expand in all directions. With the CEMS the expansion happens in the control region, and so we can select where it is deposited. For example, a U-shaped partial cowling could extruded the depleted air out the top of each windmill in the wind farm where it wont intersect other windmill inlets. In that case the depletion zone impacting other windmills only depends on the outlet pressure; if it is ambient, then the depletion zone is simply S itself not a larger expansion zone as in the Betz harvester.

Fig.7 Minimizing interference

Power coefficient and tip speed ratio of different wind converters designs:

The theoretical maximum efficiency of a wind turbine is given by the Betz Limit, and is around 59 percent. Practically, wind turbines operate below the Betz Limit. In Fig. for a two-bladed turbine, if it is operated at the optimal tip speed ratio of 6, its power coefficient would be around 0.45. At the cut-in wind speed, the power coefficient is just 0.10, and at the cut-out wind speed it is 0.22. This suggests that for maximum power extraction a wind turbine should be operated around its optimal wind tip ratio. Modern horizontal axis wind turbine rotors consist of two or three thin blades and are designated as low solidity rotors. This implies a low fraction of the area swept by the rotors being solid. Its configuration results in an optimum match to the frequency requirements of modern electricity generators and also minimizes the size and weight of the gearbox or transmission required, as well as increases efficiency. Such an arrangement results in a relatively high tip speed ratio in comparison with rotors with a high number of blades such as the highly successful American wind mill used for water pumping in the American West and all over the world. The latter required a high starting torque.

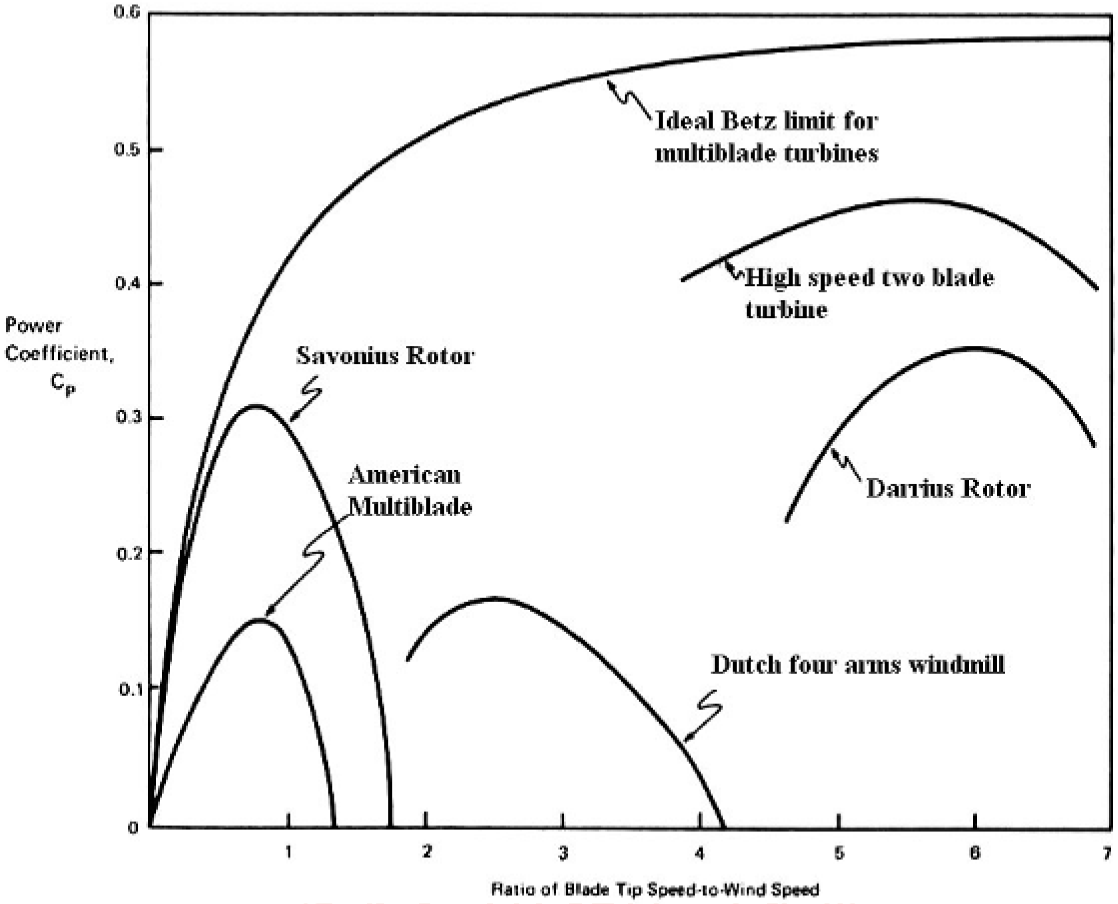

Fig.8 Power coefficient

Modern Development:

The expression for turbine efficiency, when the angular component of velocity is taken into account, by applying an energy balance across the rotor plane. Due to the Glauert model, efficiency is below the Betz limit, and asymptotically approaches this limit when the tip speed ratio goes to infinity.

An exactly solvable model (GGS), that considers non-uniform pressure distribution and curvilinear flow across the turbine plane (issues not included in the Betz approach). They utilized and modified the Kirchhoff model, which describes the turbulent wake behind the actuator as the "degenerated" flow and uses the Euler equation outside the degenerate area. The GGS model predicts that peak efficiency is achieved when the flow through the turbine is approximately 61% of the total flow which is very similar to the Betz result of 2/3 for a flow resulting in peak efficiency, but the GGS predicted that the peak efficiency itself is much smaller: 30.1%.

In viscous computations based on computational fluid dynamics (CFD) were applied to wind turbine modeling and demonstrated satisfactory agreement with experiment. Computed optimal efficiency is, typically, between the Betz limit and the GGS solution.

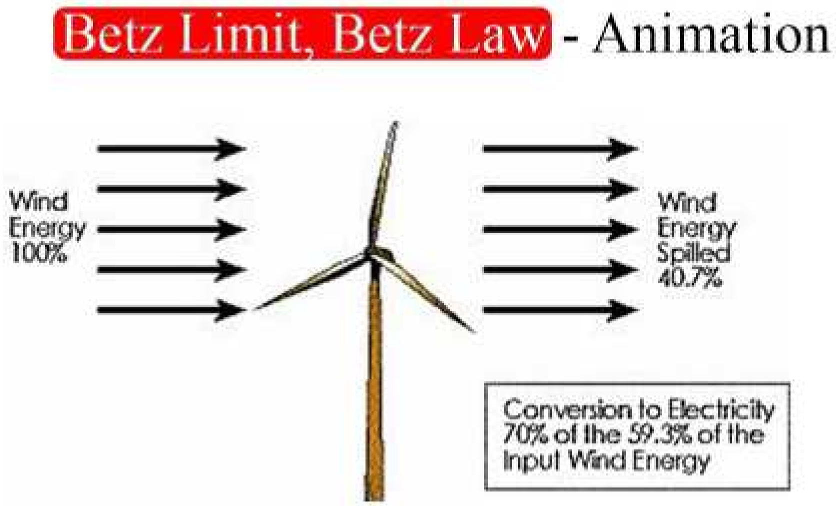

Fig.9 Betz limit

CONCLUSION-

Our objective here is to observe the proportion of force removed from a breeze field to the power in an undisturbed breeze field a similar cross-area as the reaper. One may speculate that by eliminating the imperatives of Betz model that maybe the response will decline to the trifling, for example, having a complicated reliance on the now factor inward speed. Or then again one may expect that the new ideal reaper will have infeasible properties like boundless extension of the breeze at its best working point, or require limitless length in the collector. Truth be told we will see there is a higher however limited cutoff, there is no necessary length, and that the limited development is definitely not exactly the Betz gatherer requires, and, shockingly, it is autonomous of the inward speed direction. Besides since the gatherer is substantial for a vastly meager reaper also, it overrides Betz law in that system too. In this way one ought not consider Betz law the cutoff case for a restricted edge windmill. Rather Betz is a cutoff on wind machines uniquely developed to not permit air to evade during section: for instance a windmill with a cowling or passage. The most extreme 2/3 change of the collector is right for all windmills inside its supposition of uniform cross over inward wind speeds, no matter what the thickness of the windmill.

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