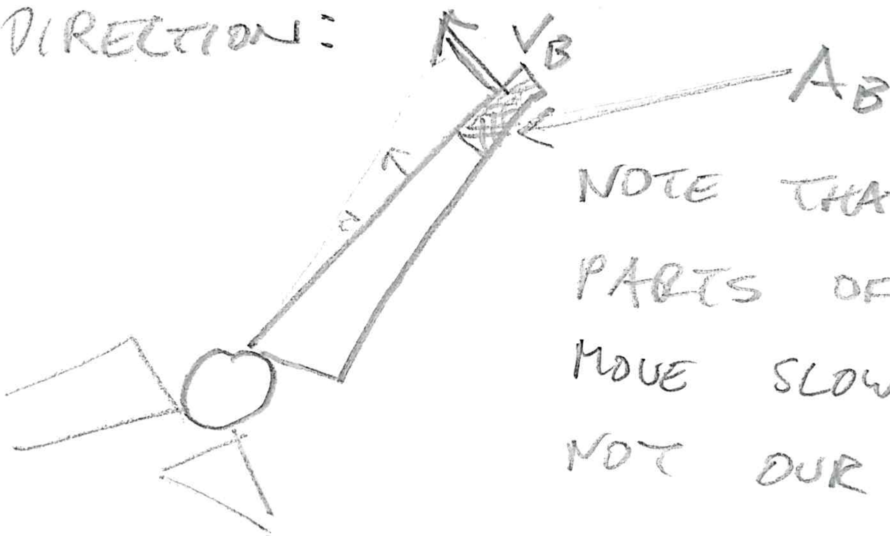
1.3 POWER DENSITY WITH RESPECT TO BLADE AREA

LET US TRY TO (ROUGHLY) ESTIMATE HOW MUCH POWER CAN BE CAPTURED BY A GIVEN BLADE AREA A_B [m^2]

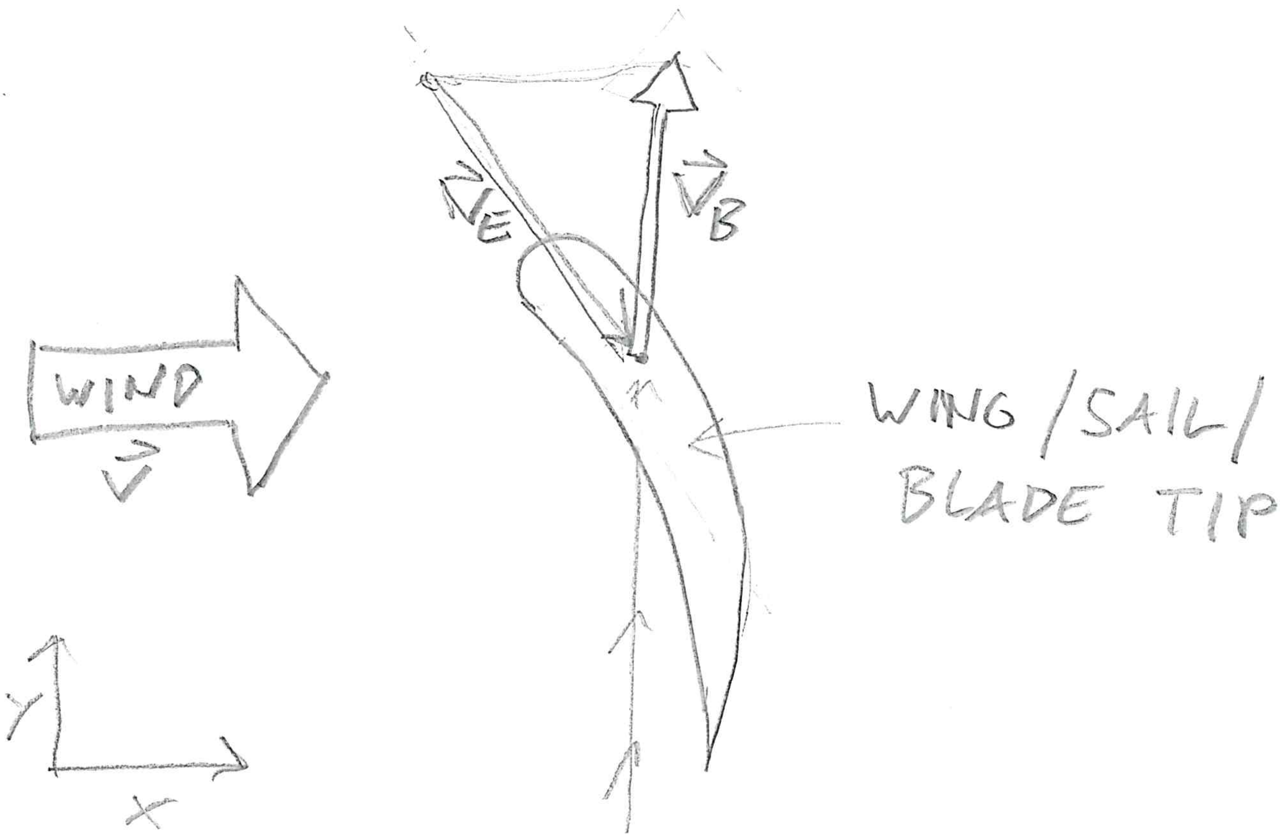
WE REGARD ONLY THE OUTER PART OF A ROTOR BLADE (CLOSE TO THE WING-TIPS) WHICH MOVES WITH A SPEED V_B IN CROSS-WIND DIRECTION:



NOTE THAT THE INNER PARTS OF THE BLADE MOVE SLOWER, BUT ARE NOT OUR FOCUS NOW.

WE SIMPLIFY FURTHER BY ASSUMING THAT THE BLADE-TIP MOVES STRAIGHT, (NOT ON A CIRCLE ...

THE MOTION OF THE BLADE-TIP CAN NOW BE COMPARED TO A SAILING BOAT MOVING "HALF-WIND" OR "CROSS-WIND" AND CAN BE DEPICTED FROM THE TOP VIEW AS FOLLOWS:



THE <u>EFFECTIVE WIND</u> $\vec{V}_E$ IS GIVEN BY $\vec{V}_E = \vec{V} - \vec{V}_B$ I.E.

$$\vec{V}_E = \begin{bmatrix} 0 \\ V \end{bmatrix} - \begin{bmatrix} V_B \\ 0 \end{bmatrix} = \begin{bmatrix} -V_B \\ V \end{bmatrix}.$$

THE MAGNITUDE OF THE EFFECTIVE WIND IS GIVEN BY

$$|\vec{V}_E| = \sqrt{V_B^2 + V^2} =: V_E$$

TO DETERMINE THE FORCES ON THE "WING" (WE USE THIS WORD NOW FOR THE BLADE-TIP OF AREA A_B) WE NEED ONE BASIC FACT FROM AERODYNAMICS: THE FORCE ON A BODY IN A MOVING FLUID IS PROPORTIONAL TO THE DYNAMIC PRESSURE $\frac{1}{2}\rho |V_E|^2$ AND THE AREA A_B. THE FORCE CAN BE DECOMPOSED INTO "LIFT" AND "DRAG", WHERE LIFT IS PERPENDICULAR TO THE VELOCITY VECTOR AND DRAG ALIGNED WITH THE VELOCITY

LIFT AND DRAG

WE HAVE

$$F_L = \frac{1}{2} C_L \cdot \rho A_B v_E^2$$

AND

$$F_D = \frac{1}{2} C_D \cdot \rho A_B v_E^2$$

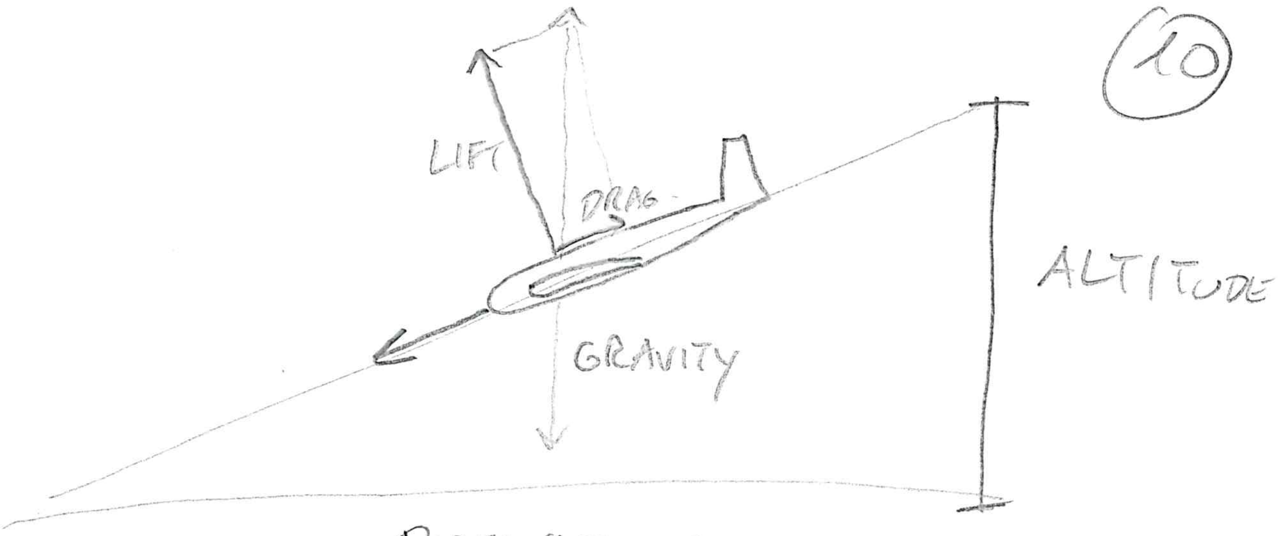
WITH LIFT-COEFFICIENT C_L

AND DRAG-COEFFICIENT C_D

(DEPENDING, AMONG OTHER, ON "ANGLE OF ATTACK" & ON THE SO-CALLED "REYNOLDS-NUMBER")

GOOD WINGS HAVE SMALL DRAG AND HIGH LIFT, E.G. $C_L = 1.5$ AND $C_D = 0.05$.

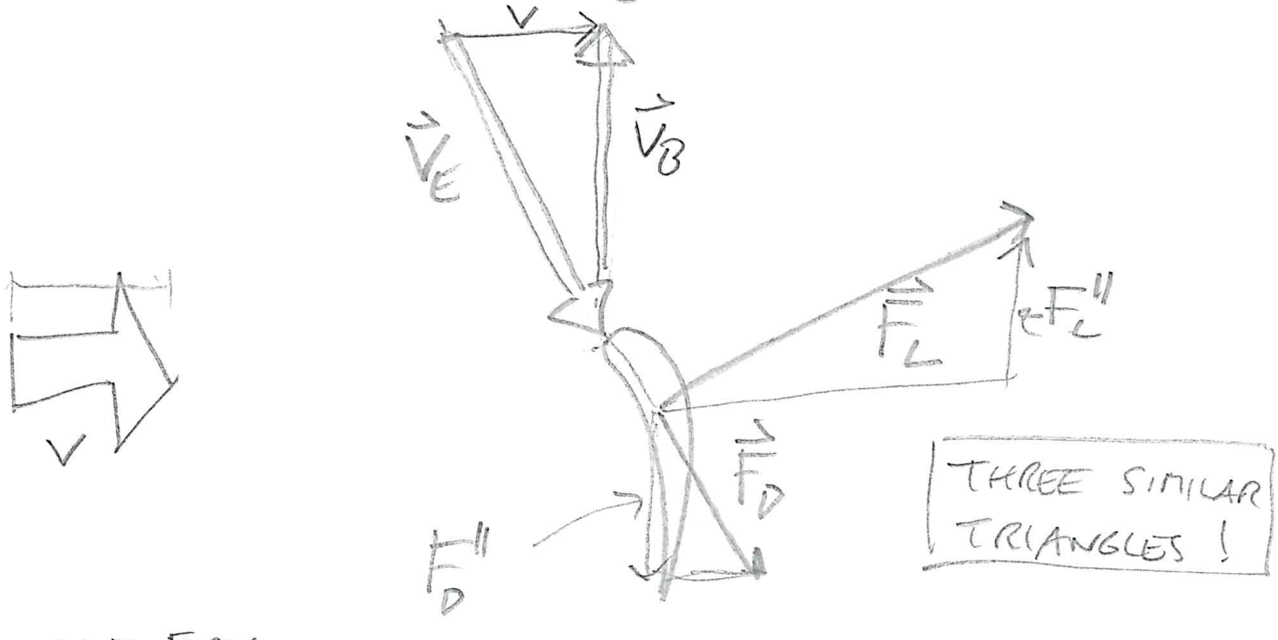
THE "LIFT-OVER-DRAG RATIO" $\frac{C_L}{C_D}$ HAS A NICE INTERPRETATION FOR SAIL-PLANES: IT DETERMINES HOW FAR A SAILPLANE CAN GO, DEPENDING ON THE INITIAL ALTITUDE. $\frac{C_L}{C_D}$ IS THEREFORE ALSO CALLED "GLIDING NUMBER"



DISTANCE TRAVELLED

$$= \frac{C_L}{C_D} \cdot \text{ALTITUDE}$$

FOR OUR ROTOR-BLADE WE GET THE FOLLOWING PICTURE



WE ARE FIRST ONLY INTERESTED IN THE FORCE COMPONENT IN THE DIRECTION OF MOTION OF THE WING, AS ITS PRODUCT WITH V_B GIVES THE MECHANICAL POWER PRODUCTION $P_B = F^{\parallel} \cdot V_B$ WITH

$$F^{\parallel} = F_L^{\parallel} + F_D^{\parallel} = F_L \cdot \frac{V}{V_E} - F_D \cdot \frac{V_B}{V_E}$$

BRINGING IT ALL TOGETHER GIVES

$$P_B = \frac{1}{2} \rho A_B V_E^2 V_B \cdot \frac{1}{V_E} \left(C_L \cdot V - C_D \cdot V_B \right)$$

TO SIMPLIFY FURTHER, WE INTRODUCE THE "TIP-SPEED-RATIO" $\lambda = \frac{V_B}{V}$

SUCH THAT $V_B = \lambda V$ AND $V_E = \sqrt{1+\lambda^2} \cdot V$

$$= \sqrt{1+\frac{1}{\lambda^2}} \, \lambda \cdot V$$

AND THE EXPRESSION FURTHER SIMPLIFIES TO

$$P_B = \frac{1}{2} \rho A_B V^3 \underbrace{\lambda^2 \sqrt{1+\frac{1}{\lambda^2}} \left(C_L - C_D \cdot \lambda \right)}_{=: \zeta}$$

POWER HARVESTING FACTOR (ZETA)

NOTE THAT FOR $\lambda = \frac{C_L}{C_D}$, NO POWER IS GENERATED ($\frac{C_L}{C_D}$ IS THE MAXIMUM POSSIBLE SPEED OF THE WINGTIPS IF THE GENERATOR IS SWITCHED OFF)

TYPICAL VALUES FOR λ ARE $\boxed{\lambda = 7}$

AND IF $C_L = 1.5$ AND $C_D = 0.05$ WE GET:

$$\varsigma = \lambda^2 \sqrt{1 + \frac{1}{\lambda^2}} \left(C_L - C_D \cdot \lambda \right) \approx 49 \cdot (1) (1.5 - 0.35)$$

$$\approx 50 \cdot 1.15 \approx 57$$

[FOR $\lambda = 20$ WE WOULD EVEN GET

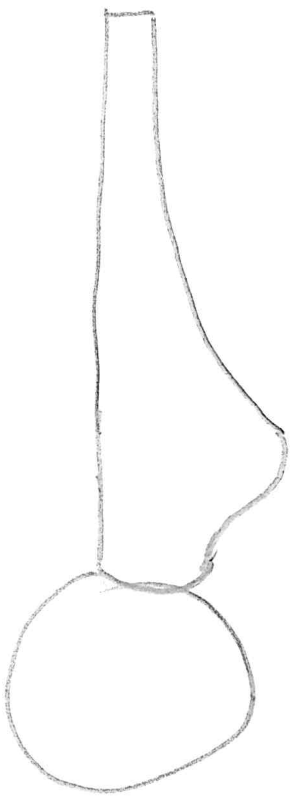
$\varsigma \approx 400 \cdot 0.5 = 200$]

THIS IS A REMARKABLY HIGH NUMBER: ς SHOWS HOW MUCH POWER THE WING (BLADE-TIP) HARVESTS, COMPARED TO THE ENERGY DENSITY IN THE AIR

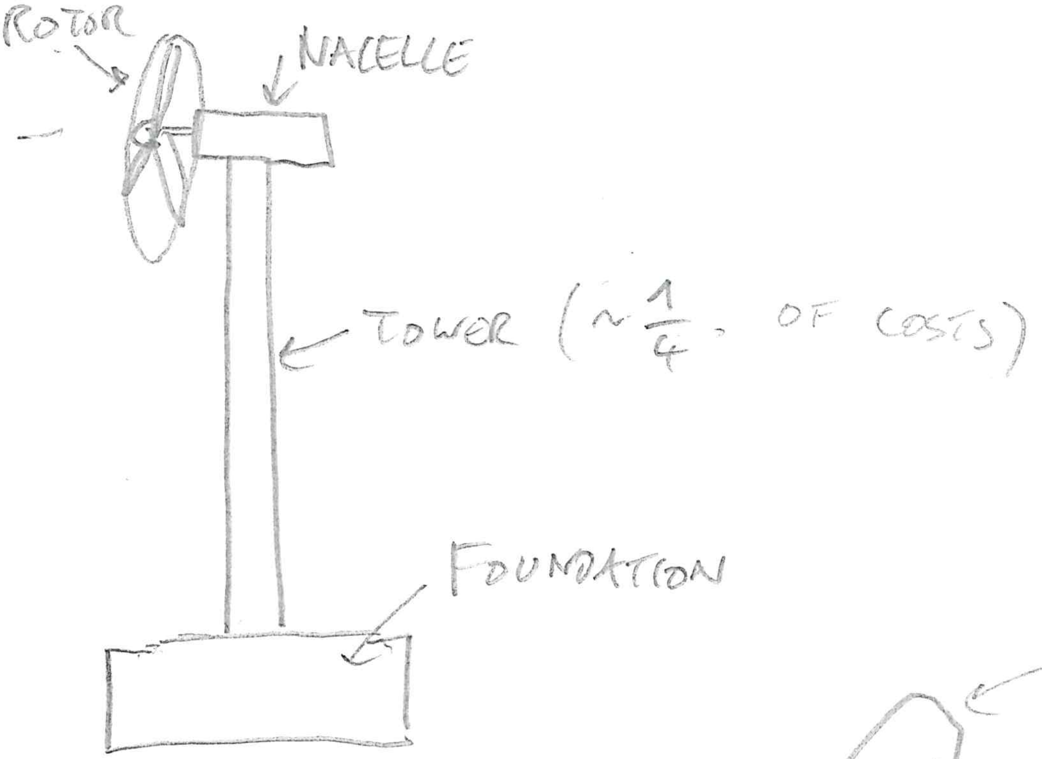
FOR $\varsigma = 50$ AND $v = 10 \frac{m}{s}$ WE THUS GET A POWER DENSITY OF

$$\frac{P}{A_B} = 50 \cdot 600 \frac{W}{m^2} = 30 \frac{kW}{m^2}$$

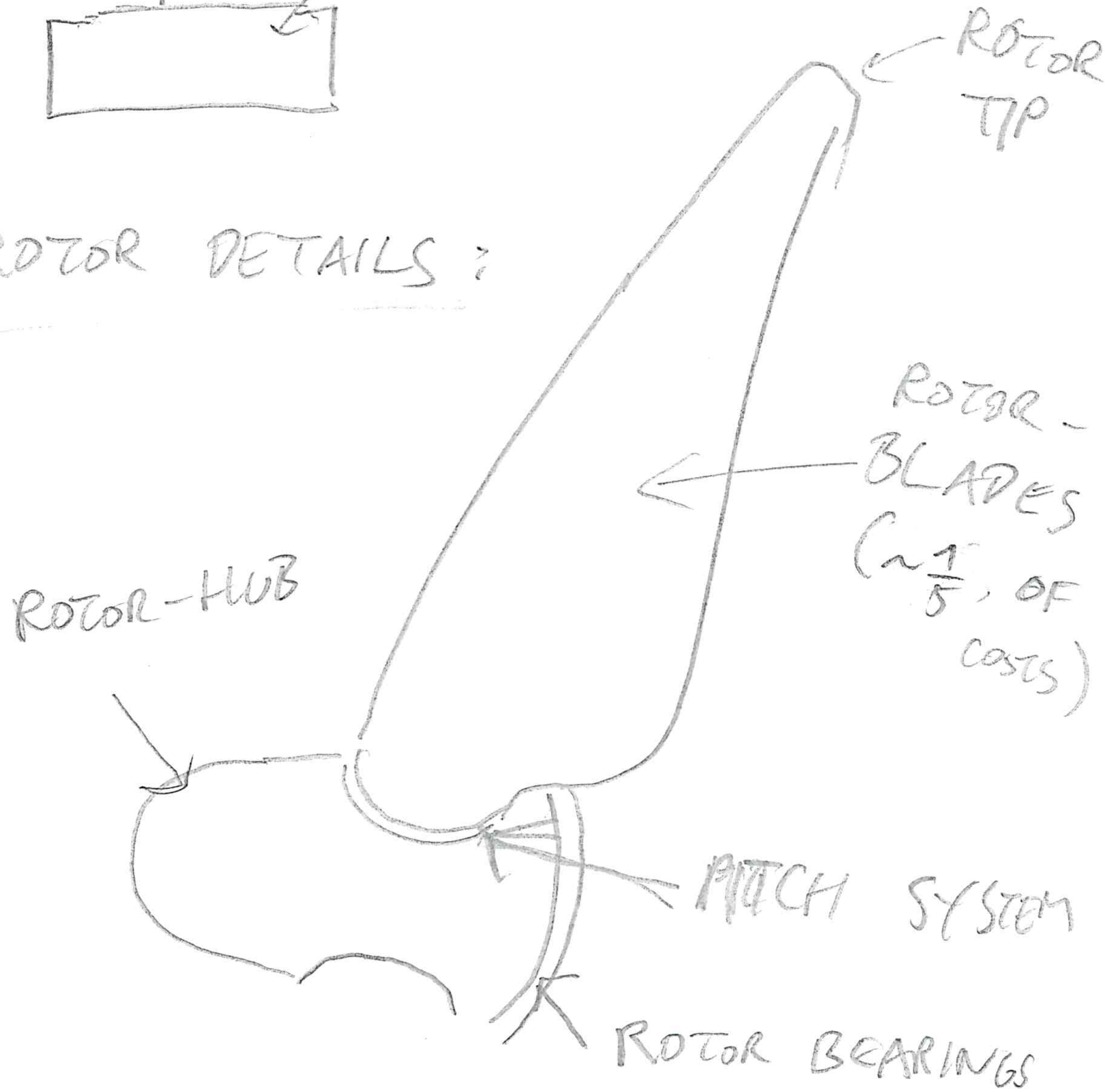
AS THE INNER PARTS OF THE BLADE MOVE SLOWER, THEIR λ IS SMALLER AND THEREFORE ALSO THEIR HARVESTING FACTORS. THIS IS ONE MAJOR REASON WHY THE BLADES BECOME THICKER TOWARDS THE CENTER :



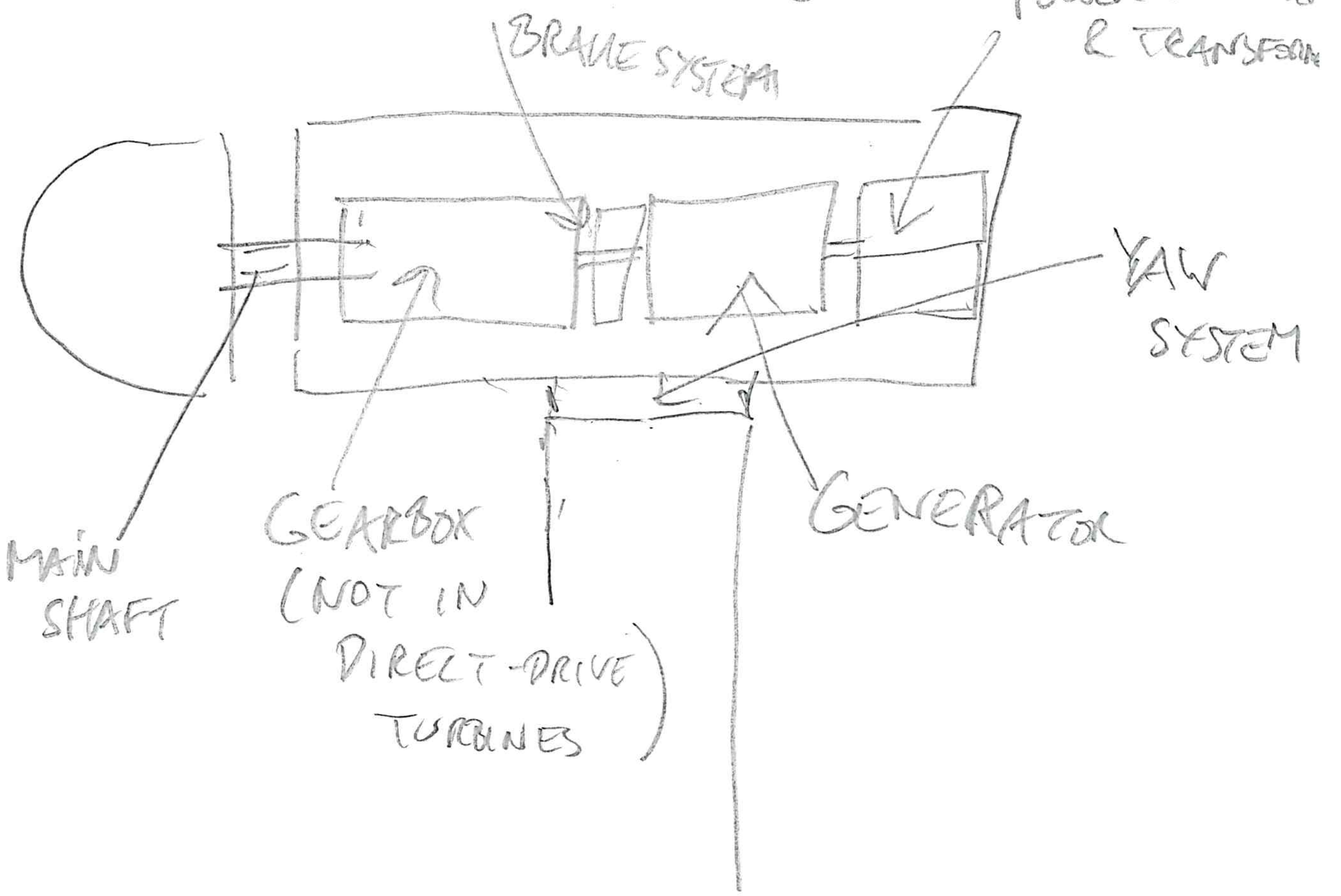
1.4 COMPONENTS OF A MODERN WIND TURBINE



ROTOR DETAILS:



NACELLE DETAILS



ROTOR DIAMETER

HUB HEIGHT

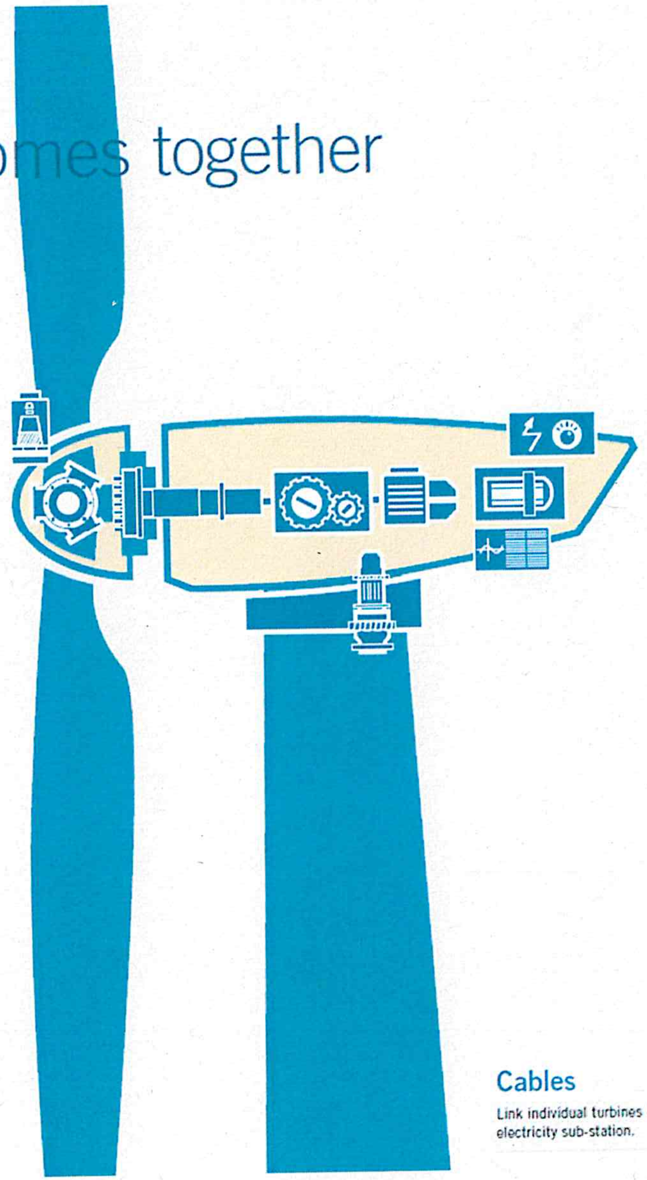
TIP SPEED RATIO

WITH ITS FIVE JOINTS (YAW, ROTOR, 3× PITCH)

A WIND TURBINE CAN BE REGARDED A GIGANTIC ROBOT-ARM COMPARABLE TO THE SIX JOINT ROBOT ARMS IN CAR MANUFACTURING. HOWEVER, IT IS A "ENERGY-HARVESTING ROBOT"

How a wind turbine comes together

A typical wind turbine will contain up to 8,000 different components. This guide shows the main parts and their contribution in percentage terms to the overall cost. Figures are based on a REpower MM92 turbine with 45.3 metre length blades and a 100 metre tower.



Tower 26.3%
Range in height from 40 metres up to more than 100 m. Usually manufactured in sections from rolled steel; a lattice structure or concrete are cheaper options.

Rotor blades 22.2%
Varying in length up to more than 60 metres, blades are manufactured in specially designed moulds from composite materials, usually a combination of glass fibre and epoxy resin. Options include polyester instead of epoxy and the addition of carbon fibre to add strength and stiffness.

Rotor hub 1.37%
Made from cast iron, the hub holds the blades in position as they turn.

Rotor bearings 1.22%
Some of the many different bearings in a turbine, these have to withstand the varying forces and loads generated by the wind.

Main shaft 1.91%
Transfers the rotational force of the rotor to the gearbox.

Main frame 2.80%
Made from steel, must be strong enough to support the entire turbine drive train, but not too heavy.

Gearbox 12.91%
Gears increase the low rotational speed of the rotor shaft in several stages to the high speed needed to drive the generator

Generator 3.44%
Converts mechanical energy into electrical energy. Both synchronous and asynchronous generators are used.

Yaw system 1.25%
Mechanism that rotates the nacelle to face the changing wind direction.

Pitch system 2.66%
Adjusts the angle of the blades to make best use of the prevailing wind

Power converter 5.01%
Converts direct current from the generator into alternating current to be exported to the grid network.

Transformer 3.59%
Converts the electricity from the turbine to higher voltage required by the grid.

Brake system 1.32%
Disc brakes bring the turbine to a halt when required.

Nacelle housing 1.35%
Lightweight glass fibre box covers the turbine's drive train.

Cables 0.96%
Link individual turbines in a wind farm to an electricity sub-station.

Screws 1.04%
Hold the main components in place, must be designed for extreme loads.

Source: EWEA