Harvesting the Wind Energy

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Introduction
How Wind is Created?

- Temperatures vary according to the amount of sun it gets.
- Uneven heating of the Earth's atmosphere and surface.
- Balance between warm and cool air is constantly changing, creating wind.
Wind Energy

• The terms "wind energy" or "wind power" describe the process by which the wind is used to generate mechanical power or electricity.

• Wind turbine rotors convert the kinetic energy in the wind into mechanical power.

• Wind power is the conversion of wind energy into a useful form of energy, such as using:
  • wind turbines to make electricity,
  • wind mills for mechanical power,
  • wind pumps for water pumping
  • etc.
Wind Turbine

- Wind turbines turn in the moving air and power an **electric generator** that supplies an electric current.
- Simply stated, a wind turbine is the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity.
- The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity.
The Evolution of Wind Turbines

1st century AD
Herón of Alexandria is credited with the invention of the windmill. He harnessed the power of the wind to power an organ. The windmill blades were attached to an axle that drove a set of pistons up and down to provide power to the organ.

9th century AD
The Persians built vertical axis windmills that were probably used to pump water or to grind corn. The vertical sails were most likely made out of reeds and wood. The sails were enclosed within a set of walls with an open door in front that would guide the wind through the machine.

10th-11th century AD
Tower mills were the earliest design in the 10th century in Western Europe. These windmills were built on large stone towers with the rotor and blades attached to a rotating cap that was mounted on the top of the tower. A wind vane was also fixed behind the blades to help guide the rotating cap towards the wind.

12th century AD
In the 12th century post windmills were being built in Europe. This type of windmill was built on a vertical post and was set on a rotating post fixture so the entire machine could rotate to face the wind. These vertical windmills were usually used for grinding grains or pumping water.

13th century AD
Tower mills were the newest design in the 13th century in Western Europe. These windmills were built on large stone towers with the rotor and blades attached to a rotating cap that was mounted on top of the tower. A wind vane was also fixed behind the blades to help guide the rotating cap towards the wind.

19th century AD
In 1887 American inventor Charles Brush built the first automatically operated wind turbine. It was called a wind mill, not a wind turbine, because it was used to generate electricity. The wind turbine weighed four tons and powered a 12 kW generator.

1922
The Savonius wind turbine is a vertical axis turbine invented by Finnish engineer Sigurd Johannes Savonius. The savonius turbine is a drag turbine meaning that its rotational energy comes from the actual push of the wind, and not from aerodynamic "lift" like most other modern wind turbines. These are low

1977
The Giromill wind turbine is a Darrieus designed vertical axis turbine. The Giromill turbine uses lift instead of drag and is usually built with two or three aerofoils that attach and rotate around a central axis tower. The giromill is a low efficiency turbine because it needs strong wind speeds to start rotating.

1941
In 1941 the Smith-Putnam wind turbine became the first megawatt-sized wind turbine to be constructed. It was a two-blade (75 ft diameter) turbine built on a 120 foot steel lattice tower. It only operated for 1100 hours until a blade failed.

20th century AD

Modern Wind Turbine
The modern wind turbine was created from years of innovation and scientific research. Today, most modern wind turbines are from the horizontal axis family and have three blades. The wind turbine blades are designed similar to airplane wings and use the "lift" from the wind to rotate. The amount of electricity that a modern wind turbine
Wind Turbine Design

Two types of turbine design: **Horizontal axis** and **Vertical axis**.

**Horizontal axis turbines:** Can reach higher altitude wind but requires a substantial tower structure. Used in most modern wind turbine designs.

**Vertical axis turbines:** No need to turn into wind (yaw), easier construction and maintenance (generator and gear box are on the ground) level, lower efficiency.
Wind Turbine Configurations

HAWT (Horizontal Axis Wind Turbine)
- Single-bladed
- Double-bladed
- Three-bladed
- Multi-bladed
- Up-wind
- Down-wind

Enfield-Andreae
Multi-rotor
Counter-rotating blades
Cross-wind
Diffuser
Concentrator

Vertical axis primarily drag-type
- Multi-bladed (plan view)
- Screen
- Screened paddlewheel type (plan view)
- Cupped (anemometer)

Primarily lift-type
- Darrieus
- H-VAWT
- V-VAWT
- 'Banki' turbine (plan view)

Combinations
- Savonius Darrieus
- Savonius (split) (plan view)
- Magnus effect rail vehicle (generator is in axle)
- Winged rail vehicle (generator is in axle)

Wind Turbine Components
Converting Kinetic Wind Energy to Mechanical Energy
Aerodynamics of wind turbines
We need wind loads to produce power!

To extract power from kinetic energy

\[ P = \frac{1}{2} m (v_1^2 - v_2^2) \]

Tangential load to harness the available energy as useful power.
1-D Momentum theory for ideal rotor (no losses)

Conservation of mass, energy and momentum in flow direction:

\[ T = \rho v' A (v_1 - v_2) = \dot{m} (v_1 - v_2) \]  \hspace{1cm} \text{Thrust}  \\
\[ P = \frac{1}{2} \rho v' A (v_1^2 - v_2^2) = \frac{1}{2} \dot{m} (v_1^2 - v_2^2) \]  \hspace{1cm} \text{Power}  \\
\[ v' = \frac{v_1 + v_2}{2} \]  \hspace{1cm} \text{Wind speed at rotor plane}
Ideal Extractor Derivation

Due to Albert Betz

Continuity, energy balance, and force balance across rotor area

Main assumptions

• Ideal rotor
  – No hub
  – Infinite number of blades
  – Blades without drag

• Pure axial flow

• Incompressible flow

• Uniform thrust over the rotor

• Equal far-field pressures
Ideal Extractor Derivation (2)

Due to Albert Betz

*Continuity and force balance across rotor area*

Mass conservation: \[ \dot{m} = \rho v_1 A_1 = \rho v' A = \rho v_2 A_2 \]

Forces on the rotor: \[ F = ma = \dot{m} \frac{dv}{dt} = \dot{m} \Delta v = \rho v' A (v_1 - v_2) \]
Ideal Extractor Derivation (3)

**Power computed based on force balance**

Power (rate of work):

\[ P = \frac{dE}{dt} = F \frac{dx}{dt} = Fv \]

Forces on the rotor:

\[ F = ma = m \frac{dv}{dt} = \dot{m}\Delta v = \rho v' A (v_1 - v_2) \]

Extracted power (1):

\[ P_1 = \rho A (v')^2 (v_1 - v_2) \]
Ideal Extractor Derivation (4)

*Power computed based on energy balance across rotor area*

Kinetic energy:

\[ E = \frac{1}{2} m v^2 \]

Power (rate of energy):

\[ P = \frac{dE}{dt} = \frac{\Delta E}{\Delta t} = \frac{1}{2} \dot{m}(v_1^2 - v_2^2) \]

Extracted power (2):

\[ P_2 = \frac{1}{2} \rho A v'(v_1^2 - v_2^2) \]
Ideal Extractor Derivation (5)

"Power = Power"

\[ P_1 = P_2 \]

\[ \rho A (v')^2 (v_1 - v_2) = \frac{1}{2} \rho A v' (v_1^2 - v_2^2) \]

\[ = \frac{1}{2} \rho A v' (v_1 - v_2)(v_1 + v_2) \]

Rotor speed:

\[ v' = \frac{1}{2} (v_1 + v_2) \]
We have found that:

\[ v' = \frac{v_1 + v_2}{2} \]

\[ P_0 = \frac{1}{2} \rho v_1^3 A \]

\[ P = \frac{1}{4} \rho A (v_1 + v_2) (v_1^2 - v_2^2) \]
Ideal Extractor Derivation (7)

\[ C_p = \frac{P}{P_0} = \frac{1}{2} \left( 1 + \frac{v_2}{v_1} \right) \left( 1 - \left( \frac{v_2}{v_1} \right)^2 \right) \]

\[ C_{p_{\text{max}}} \approx \frac{16}{27} = 0.593 \]

- Irrotational system
- No boundary layer or compression flow
- Creeping flow (Re \( \ll 1 \))
- Uniform power extraction
- No geometry boundary conditions
- Never true!
More Rigor: Deviation from Betz Limit

\[ \lambda_A \equiv \frac{\omega R}{v_1} \]
Blade Pitch: Trade-offs

Since most designs use twisted blades, power quality is never ideal across the entire rotor blade.
“Why you should choose three blades”
Rotor Speed Control

Active Stall Control

Advantages: Dynamic, reduces train complexity
Disadvantages: Costly

Passive Stall Control

Advantages: Simple, self-regulating
Disadvantages: Requires strength in high winds, hard to start-up, complex brake systems
Induction factor \((a)\)

By definition (axial induction factor) \(v' = (1 - a)v_1\)

\[ v' = \frac{v_1 + v_2}{2} \]

then gives

\[ v_2 = (1 - 2a)v_1 \]

If this is used in the equations for power and thrust

\[ P = 2 \rho A a (1 - a)^2 v_1^3 \quad T = 2 \rho A a (1 - a)v_1^2 \]
Induction factor \((a)\) (continued)

Definition of power and thrust coefficients

\[
C_p = \frac{P}{\frac{1}{2} \rho V_o^3 A} \quad C_T = \frac{T}{\frac{1}{2} \rho V_o^2 A}
\]

\[
C_p = 4a(1-a)^2 \quad C_T = 4a(1-a)
\]

Betz limit

\[
C_{p,\text{max}} = \frac{16}{27} \approx 0.59 \quad \text{for} \quad C_T = \frac{8}{9} \quad \text{at} \quad a = \frac{1}{3}
\]
Relation between $\frac{v_2}{v_1}, C_p, C_T$
The wanted loads is created by the lift and drag from the local flow past the blade:

\[ p_N = L \cos \phi + D \sin \phi \]

\[ p_T = L \sin \phi - D \cos \phi \]

\( L \) and \( D \) depends on:
- Angle of attack
- Airfoil geometry
- Reynold number
\[ V_{\text{rel}} = V_o + W - V_{\text{blade}} \]

In \( V_{\text{blade}} \) is included elastic velocities, translations and stiff body rotation

\[ \alpha = \phi - \theta \]
Several options, as e.g.

- Full CFD
- Vortex methods (unsteady panel methods, lifting line etc.)
- BEM

But since we are solving in the time domain with $\Delta t$ small a fast model is needed and BEM is almost always used.

The more advanced models are mostly used to check the various submodels in the BEM method.
BEM
Blade Element Moment Method

\[ \frac{1}{N_b} \text{ annulus} \]
BEM method gives the equilibrium of the aerodynamic loads and the induced velocity $W$

Knowing, $W$, the flowangle and thus the angle of attack, $\alpha$, is known and new loads can be found from table look up in airfoil data, $C_l(\alpha)$ and $C_d(\alpha)$

$$L = \frac{1}{2} \rho V_{rel}^2 c C_l(\alpha)$$

$$D = \frac{1}{2} \rho V_{rel}^2 c C_d(\alpha)$$
For zero yaw the conservation of linear and angular momentum in a streamtube intersecting the rotor plane at radial position, r, yields

\[ W_n = \frac{-BL \cos \phi}{4\pi \rho r F (V_o - W_n)} \]

\[ W_t = \frac{-BL \sin \phi}{4\pi \rho r F (V_o - W_n)} \]

These equations can be rewritten to \((W_n = aV_o \text{ and } W_t = a'\omega r)\)

\[ a = \frac{1}{\frac{4F \sin^2 \phi}{\sigma C_n} + 1} \]

\[ a' = \frac{1}{\frac{4F \sin \phi \cos \phi}{\sigma C_t} - 1} \]
Prandtl’s tip loss factor

In the BEM method we assume no azimuthal variation of $W$ corresponding to infinitely many blades.

For a finite number of blades the flow is different, especially near the tip, as shown using a simple vortex model with constant circulation and using Biot-Savart.
With the use of the BEM code the theoretical optimal rotor can be computed for various number of blades

\[ C_p = \frac{P}{\frac{1}{2} \rho A V_o^3} \]

\[ \lambda = \frac{\omega R}{V_o} \]
"Glauert" correction for high values of

\[ C_T = \frac{T}{\frac{1}{2} \rho A V_o^2} \]

Mostly for low wind speed
For large values of $C_T$ the momentum equations are replaced by empirical relationships

\[
C_T = \begin{cases} 
4a(1-a)F & a \leq \frac{1}{3} \\
4a(1-\frac{1}{4}(5-3a)a)F & a > \frac{1}{3}
\end{cases}
\]

\[
C_T = \begin{cases} 
4a(1-a)F & a \leq a_c \\
4(a_c^2 + (1-2a_c)a)F & a > a_c
\end{cases}
\]
HAWT vs VAWT
Advantages
• Omnidirectional
  – Accepts wind from any angle
• Components can be mounted at ground level
  – Ease of service
  – Lighter weight towers
• Can theoretically use less materials to capture the same amount of wind

Disadvantages
• Rotors generally near ground where wind poorer
• Centrifugal force stresses blades
• Poor self-starting capabilities
• Requires support at top of turbine rotor
• Requires entire rotor to be removed to replace bearings
• Overall poor performance and reliability
• Have never been commercially successful
Horizontal Axis
Wind Turbine

Advantages
• Blades are to the side of the turbines center of gravity, helping stability
• Ability to pitch the rotor blades in a storm to minimize damage
• Tall tower allows access to stronger wind in sites with wind shear
• Tall tower allows placement on uneven land or in offshore locations
• Can be sited in forest above tree-line
• Most are self-starting

Disadvantages
• Difficulty operating in near ground winds
• Difficult to transport (20% of equipment costs)
• Difficult to install(require tall cranes and skilled operators)
• Effect radar in proximity
• Local opposition to aesthetics
• Difficult maintenance
HAWT vs. VAWT

HAWT complexity and inaccessible drivetrain increase O&M costs

VAWT insensitivity to wind direction allows for large rotors

HAWT sensitivity to wind direction change with height limits rotor size

VAWT simplicity and accessible drivetrain reduce O&M costs

High HAWT C.G. increases substructure costs

Lower VAWT C.G. decreases substructure costs

HAWT Components
1. Blade Pitch System
2. Yaw System
3. Gearbox
4. Generator

VAWT Components
1. Gearbox
2. Generator
Type of Wind Turbine Design

Wind turbines are designed based on either aerodynamic Drag or Lift force.

- **Drag designs**
  - Savonius

- **Lift designs**
  - VAWT Darrieus
  - Most HAWT designs
Lift design

- Blade is essentially an airfoil (like wings of airplanes).
- When air flows past the blade, a wind speed and pressure differential is created between the upper and lower blade surfaces. The pressure at the lower surface is greater and thus acts to "lift" the blade.
- The lift force is translated into rotational motion.
- Lift design generally has higher efficiency and is used in most modern turbines.
Drag design

- The wind literally pushes the blades out of the way.
- Slower rotational speeds and high torque capabilities. Useful for providing mechanical work (water pumping).
Converting Mechanical Energy to Electrical Energy
Electromagnetic induction

Maxwell-Faraday

\[ \nabla \times E = -\frac{\partial B}{\partial t} \]

Faraday's law

\[ e = -N \frac{\partial \phi}{\partial t} \]

E – electric field strength
B – flux density
e – Induced Voltage
N – number of turns
\( \phi \) – total magnetic flux

"Relative motion"
A simple generator

- Armateur: A conductor in the stationary portion, i.e. "stator"
- Rotor: Permanent magnet in the moving part
- Need mechanical force to move the magnetic field!

Mechanical Input  →  Electrical Output
AC Generation

How fast should the rotor turn?
Rotation rate

If we want to generate 60 Hz frequency:

\[
\text{shaft rotation rate} = \frac{1 \text{ revolution}}{\text{cycle}} \times \frac{60 \text{ cycles}}{\text{sec}} \times \frac{60 \text{ sec}}{\text{min}} = 3600 \text{ rpm}
\]

When a rotor has more poles:

\[
\text{shaft rotation rate (rpm)} = \frac{1 \text{ revolution}}{(p/2) \text{ cycles}} \times \frac{f \text{ cycles}}{s} \times \frac{60 \text{ s}}{\text{min}}
\]
How to create magnetic field

• Use permanent magnet for small generator
• Use DC current passing through a coil
Self induced magnetic field

Create *rotating* magnetic field in stator
- Coils imbedded in a 3-phase generator
- Need *AC-voltage*
Major types of generators

Synchronous generator
- Operate at constant rational speed to create constant voltage
- Need magnetic field
  - Permanent magnet rotor for small machine
  - Almost all WT creates magnetic field by DC current

Asynchronous generator
- Induction generator
- Do not operate at fixed speed
- Magnetic field is induced from AC voltage
Synchronous generator

To increase rotational speed in order to produce 50/60 Hz voltage frequency

To supply DC current for field winding
Induction machine

- Require rotating magnetic field, supplied by AC voltage
- Use (squirrel) cage rotor made from a number of aluminium bars shorted together at their ends, forming a cage
- Rotor have to spin with a slower speed than synchronous speed
Typical Wind Turbine Operation

0 ~ 5 m/s --- Wind speed is too low for generating power. Turbine is not operational. Rotor is locked.

5 ~ 15 m/s ---- 5 m/s is the minimum operational speed. It is called “Cut-in speed”. In 10 ~ 25 mps wind, generated power increases with the wind speed.

15 ~ 25 m/s ---- Typical wind turbines reach the rated power (maximum operating power) at wind speed of 15 m/s (called Rated wind speed). Further increase in wind speed will not result in substantially higher generated power by design. This is accomplished by, for example, pitching the blade angle to reduce the turbine efficiency.

> 25 m/s ----- Turbine is shut down when wind speed is higher than 25m/s (called “Cut-out” speed) to prevent structure failure.
Size and Applications

Small (10 kW)
- Homes
- Farms
- Remote Application

Intermediate (10-250 kW)
- Village Power
- Hybrid Systems
- Distributed Power

Large (660 kW - 2+MW)
- Central Station Wind Farms
- Distributed Power
- Community Wind
Offshore wind turbines
What is an Offshore Wind Turbine?

A wind turbine shall be considered as an *offshore wind turbine* if the support structure is subject to hydrodynamic loading.
Potential of North Sea

More energy than from the Middle East!
Potential

Wind energy annual installation
2000-2020 (GW)

Source: EWEA/GWEC
Bottom Fixed Offshore Wind Turbine

- Includes:
  - Rotor/nacelle assembly (RNA)
  - Support structure
    - Tower
    - Substructure
    - Foundation
Floating Offshore Wind Turbine

- Includes:
  - Rotor/nacelle assembly (RNA)
  - Support structure
    - Tower
    - Floating substructure
    - Mooring system
Foundations Design with Changing Depth

- Shallow Water
  0 – 30 M

- Transitional Depths
  30 M – 50 M

- Deep Water
  50 M – 200 M
Common Types of Fixed Bottom Support Structures
Common Types of Fixed Bottom Support Structures

- Monopiles
- Tripods
- Jackets
- Gravity based

http://www.theengineer.co.uk/in-depth/the-big-story/wind-energy-gets-serial/1012449.article
Equipment Needed: Onshore to Offshore

- Wind turbines and foundation structures
- Underwater high voltage cables
- Offshore substations and operations

- Onshore substations
- Onshore high voltage transmission
External Conditions

“Metocean” Conditions

- Wind conditions
- Marine conditions
  Waves, sea currents, water level, sea ice, marine growth, seabed movement and scour
- Other environmental conditions
- Soil properties at the site
  Including time variation due to seabed movement, scour and other elements of seabed instability
Assessment of **Metocean** External Conditions for Offshore Wind Turbines

- Wind speeds and directions
- Significant wave heights, wave periods and directions
- Correlation of wind and wave statistics
- Current speeds and directions
- Water levels
- Occurrence and properties of sea ice
- Occurrence of icing
- Other parameters: air, water temperatures, densities; water salinity; bathymetry, marine growth, etc
Offshore Turbines: Energy Integration

1. Offshore wind turbine plants generate medium-voltage AC power.
2. Wind energy generated by the wind farm turbines transformed to higher AC power at the substation platform.
3. HVDC platform converts the alternating current from several substation platforms to direct current for transmission.
4. Subsea cables, some more than 100 km in length, transport the low-loss direct current onto land.
5. A converter station on land transforms the direct current back into alternating current for feeding into the high-voltage grid and for further transmission.
Things to Consider While Designing Offshore Wind Turbines

- Wave models
- Hurricanes/cyclones
- Wind shear as affected by waves
- Floating ice
- Boat (service vessel) impact
- Soil characterization
- Vortex induced vibrations
Active Area of Research in Offshore Technology Development

- Aerodynamic design-FSI (blades/structure)
- Foundation design (soil/structure interaction)
- Material properties
- Offshore data collection
- Environmental impact
Technology Trend for Wind Turbines

- Rotor diameter (m):
  - 1985: 0.05
  - 1987: 0.3
  - 1989: 0.5
  - 1991: 1.3
  - 1993: 1.6
  - 1995: 2
  - 1997: 4.5
  - 1999: 5
  - 2001: 8/10 MW
  - 2003: 160 m Ø
  - 2005: 126 m Ø

- Airbus A380 wing span: 80 m

- First year of operation installed power: ?
Consequences of Up-Scaling

Transport & Installation
Consequences of Up-Scaling Installation Methods

Marine Transport

Required Port Facilities

Heavy Machinery

Floating hotel during construction of offshore wind farm
Consequences of Up-Scaling
Consequences of Upscaling
Consequences of Upscaling

Assessment of Soil Conditions

- Geological survey of the site
- Bathymetric survey of the sea floor including registration of boulders, sand waves or obstructions on the sea floor
How Loud Is A Wind Turbine?

- **105 dB(A)** lawnmower
- **90 dB(A)** blender
- **80 dB(A)** vacuum cleaner
- **50 dB(A)** mid-size window ac
- **40 dB(A)** refrigerator

Wind turbines, in residential areas, are placed no closer than 300 meters from the nearest house.