Physics and engineering of wind power systems

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Structure of my presentation

• Present status of wind energy use

• Physical and meteorological basics

• Techniques of wind converters

• Market introduction and problems
Wind energy use – a good idea since a lot of years
In 2021 4 GW of offshore wind power will be added across Europe – in Germany only 3.1 GW by 2025.

Germany detailed: ~ 53 GW & Onshore ~ 8 GW Offshore (2019)

Compared to Germany in 2003: only 14.6 GW Onshore

Sources: https://www.volker-quaschning.de/datserv/windinst/index.php
Shares of the suppliers in the world market in 2019

New erected capacity 2019:
63 GW

Source: https://gwec.net/wind-turbine-sizes-keep-growing-as-industry-consolidation-continues/
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Derivative of the equation with steady velocity of wind \( v \)

\[
\Delta V = A \cdot \Delta l
\]

\[
v = \frac{\Delta l}{\Delta t}
\]

\[
\Delta V = A \cdot v \cdot \Delta t
\]

Kinetic energy \( E \) of a mass element \( \Delta m \)

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

\[
\Delta m = \Delta V \cdot \rho_L
\]

\[
\Delta E = \frac{1}{2} \cdot A \cdot \rho_L \cdot v^3 \Delta t
\]

\[
E = \frac{1}{2} \cdot A \cdot \rho_L \cdot v^3 \cdot t
\]

Power of Density of Wind [kW/m²]

Efficiency

\[
\eta = \frac{P_{el}}{\frac{1}{2} \cdot \rho_L \cdot A \cdot v^3}
\]

Energy and power density of wind
Bird’s eye view of horizontally positioned rotor blades

- $a_A$ = angle of attack (angle between profile chord and relative approach velocity)
- $\beta$ = pitch angle
- $\alpha$ = angle between wind velocity and approach velocity
- $u$ = circumferential velocity
- $v_0$ = wind velocity in the rotor axis
- $w$ = relative approach velocity

Bird’s eye view of vertically positioned rotor blades

for the pitch angle applies:
- $a_A$ should be optimal,
  besides use $b$ as a set variable in accordance to $v_0$ and $u$ (revolution)
- $a_A = f (\beta, v_0, u) = \arctan (v_0/u) - b$

Velocity triangle at the rotor blade
The velocities and forces acting on a blade

\[ \alpha_A = \text{Angle of attack} \]
\[ \beta = \text{Pitch Angle} \]
\[ u = \text{Average circumferential velocity} \]
\[ v_n = \text{Wind velocity in the rotor plane} \]
\[ w = \text{Relative approach velocity} \]
\[ F_R = \text{Drag force} \]
\[ F_A = \text{Lift force} \]
\[ F_{RS} = \text{Resulant force} \]
\[ F_T = \text{Tangential component} \]
\[ F_S = \text{Axial component} \]
Pitch angle $\beta$ of a blade section
Load distribution – Measurement 250 MW program on land in Germany

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Different types of realised wind energy converters  (Solar chimney only 1 prototype)
• Electrical power: 4 MW
• Height: 96 m
• Rotor diameter: 10 - 65 m

Source: www.reuk.co.uk

Vertical axis of “Darrieus” wind turbine
Definition of the rotor power

\[ P = 0.5 \cdot c_p \cdot \rho \cdot A \cdot v^3 \]

- \( v \) = wind velocity
- \( A \) = rotor circular area = \( \pi \cdot l^2 \) with \( l \) = rotor length
- \( \rho \) = air density
- \( c_p \) = power coefficient

The theoretical maximal power coefficient is 0.593 (Betz-number)

Dependence of the power coefficient \( c_p \)

\( c_p \) interdepends with three factors:

1. Blade design, i.e. ratio of buoyancy factor to friction factor = glide ratio.
   The glide ratio affects the tip speed ratio strongly.

2. Ratio blade tip velocity to wind velocity = tip speed ratio \( \lambda \)
   Dutchmen windmills: \( \lambda = 2 - 4 \)
   Modern 3-blade conversion systems: \( \lambda = 3 - 12 \)
   Limitation of the tip speed ratio in practice due to sound emissions (blade tip velocity contributes to sound emissions with the power of six)

3. Ratio of the sum of all blade areas to the rotor circular area \( A = \) solidity ratio.
   which is simplified the number of rotor blades.

„Cooking recipes“ for dimensioning of wind energy conversion systems

1. High glide ratios lead to high tip speed ratios and therefore to a large power coefficient \( c_p \)
   \( \rightarrow \) Modern converters with good aerodynamic profiles rotate quickly.

2. Simple profiles with a smaller glide ratio have smaller tip speed ratios. Therefore is a large solidity ratio required to achieve an increase of the power coefficient.
   \( \rightarrow \) Slow rotating converters have poor aerodynamic profiles and a high number of blades

3. Glide ratio and tip speed ratio have a larger influence on the power coefficient than the solidity ratio.
   \( \rightarrow \) Number of blades for fast rotating converters has a secondary relevance (in practice mostly 2-3).
Constructional type of a WECS with „classical“ power train
Nacelle of a 2 MW wind turbine with gearbox (by Repower Systems)
Assembling of a wind converter by Nordex AG with gearbox
Wind energy converter without gear box

Source: ENERCON GmbH
Sectional view of a wind turbine without gearbox (by ENERCON)
Constructional type of the WEC Enercon-66 without gearbox
Installation of the generator by a wind mill without gearboxes
Both designs (gearbox and multipole generator / without gearbox) have one disadvantage each:

- The design with gearbox has the disadvantage of losses during transmission of power and high speed drive required for connecting the generator

- The design without a gearbox has the disadvantage of increased weight of the nacelle due to an increased number of poles

- Possible solution -> combination between a special gearbox and a multipole generator
<table>
<thead>
<tr>
<th>Design</th>
<th>Enercon E-182 E3</th>
<th>REpower 3,2 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub height</td>
<td>80 - 130 m (onshore)</td>
<td>100 - 130 m (onshore)</td>
</tr>
<tr>
<td>No. of blades</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>6-18 rpm</td>
<td>6.7 -12 rpm</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>82 m</td>
<td>114 m</td>
</tr>
<tr>
<td>Material of blade</td>
<td>Fibreglass (reinforced epoxy)</td>
<td>Fibreglass (reinforced epoxy)</td>
</tr>
<tr>
<td>Blade regulation</td>
<td>Pitch</td>
<td>Pitch</td>
</tr>
<tr>
<td>Rated power</td>
<td>3 MW</td>
<td>3.2 MW</td>
</tr>
<tr>
<td>Transmission ratio of gearbox</td>
<td>None</td>
<td>approx. 99</td>
</tr>
<tr>
<td>Generator</td>
<td>Multi-pole</td>
<td>Asynchronous, few poles</td>
</tr>
<tr>
<td>Grid connection</td>
<td>Via frequency converters</td>
<td>Via frequency converters</td>
</tr>
</tbody>
</table>

The technical figures of two different multi-megawatt wind turbines for onshore
Adjusting of the revolutions and the line frequency with:

- controllable gearing or
- changeable number of pole pairs (electrical gearing) or
- asynchronous generator with extended slip or
- intermediate direct currency link

**Curve family of a fast rotating rotor development of wind velocity**
Example of the relationship between the power coefficient and the tip-speed ratio
Grid connection of converter systems with synchronous and asynchronous generators

<table>
<thead>
<tr>
<th>Systems with asynchronous generators</th>
<th>Systems with synchronous generators and permanent magnetes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wandlersysteme mit Asynchrongeneratoren</strong></td>
<td><strong>Wandlersysteme mit Synchrongeneratoren</strong></td>
</tr>
<tr>
<td><strong>a)</strong> Direkte Netzkopplung (übliche Anlage für Netzbetrieb)</td>
<td><strong>d)</strong> Netzkopplung über Gleichstromzwischenkreis mit Thyristorwechselrichter</td>
</tr>
<tr>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
</tr>
<tr>
<td>( n = (1 - s) \frac{n}{p} ) ( s = 0 \ldots 0.08 ) (leistungsabhängig), Induktiver Blindleistungsverbraucher</td>
<td>( n = 0.5 \ldots 1.2 \frac{n}{p} ) (regelbar)</td>
</tr>
<tr>
<td><strong>b)</strong> Dynamische Schlipfregelung</td>
<td><strong>e)</strong> Netzkopplung über Gleichstromzwischenkreis mit Pulswechselrichter</td>
</tr>
<tr>
<td><img src="image3" alt="Diagram" /></td>
<td><img src="image4" alt="Diagram" /></td>
</tr>
<tr>
<td>( n = (1 - s) \frac{n}{p} ) ( s = 0 \ldots 0.1 \ldots 0.3 ) (leistungsabhängig, dynamisch), Induktiver Blindleistungsverbraucher</td>
<td>( n = 0.5 \ldots 1.2 \frac{n}{p} ) (regelbar)</td>
</tr>
<tr>
<td><strong>c)</strong> Doppeltgepfeister Asynchrongenerator</td>
<td><strong>f)</strong> Netzkopplung über Gleichstromzwischenkreis mit Pulswechselrichter</td>
</tr>
<tr>
<td><img src="image5" alt="Diagram" /></td>
<td><img src="image6" alt="Diagram" /></td>
</tr>
<tr>
<td>( n = 0.8 \ldots 1.2 \frac{n}{p} ) (regelbar), Regellbare Blindleistungsabgabe</td>
<td>( n = 0.6 \ldots 1.2 \frac{n}{p} ) (regelbar)</td>
</tr>
</tbody>
</table>

**Direct grid connection**

**Dynamic slip control**

**Double excited asynchronous generator**

**Synchronous generator with gear box**

**Synchronous generator without gear box**

**Synchronous generator with permanent magnetes**

Graphic source: Forschungsverband Sonnenenergie 96/97 & Prof. Wagner
New devices need testing: Problems with gear boxes in previous years
Safety - Burned off wind power station in Lahr/ Germany
10 Millionen Lastwechsel und ihre Folgen

Source: Jörg Sarbach; SonneWind&Wärme, ISSN 1861-2741 H 2607, Stand 04/2017

Fallen concrete fundament of wind turbine after 10 Mio load changes
95 m high wind turbine twisted by a storm at the wind park „Sitten/Bockelwitz“ (Germany, 29th of December 2016)
| Generators                     | - Copper? Permanent Magnet?  
|                               | - Rare earths?             
|                               | - Superconductors?         |
| Rotor Blades                  | - Cost reduction?          
|                               | - Utilization?             
|                               | - Legal situation?         
|                               | - Active control elements in rotor blades? |
| Operations Monitoring         | - Drive train monitoring (CMS) for onshore plants?  
|                               | - Tower- and foundations vibrations — Number of Sensors, also Onshore?  
|                               | - Periodic Inspections- Scope, Number? |
| Technical Uncertainties       | - Handling of new developments? |
| Offshore Foundations technologies | - Steel? Concrete?         
|                               | - Gravity Foundations?     
|                               | - Environment, under water noise protection during the piling for the foundation? |
Montage of a rotor blade

Source: http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201209/PN201209-01_300dpi.jpg
Windpark „Trianel II“ at Borkum – with financial support of the „Stadtwerke Bochum“. The ship is able to change height and connect the blades to the tower.

A construction ship with rotor blades
Size of rotor blades of a 6 MW wind turbine

Source: http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201204/PN201204-06e_300dpi.jpg
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Structure of my presentation
## Investment plan Costs [€/kW]

<table>
<thead>
<tr>
<th></th>
<th>&lt; 120 m</th>
<th>&gt; 120 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hub height</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind power station, transport, installation</td>
<td>1150</td>
<td>1340</td>
</tr>
<tr>
<td>Foundation</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Grid connection</td>
<td>70</td>
<td></td>
</tr>
<tr>
<td>Site development (lanes)</td>
<td>40</td>
<td></td>
</tr>
<tr>
<td>Planning, environmental measures, concession, others</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>1520</strong></td>
<td><strong>1710</strong></td>
</tr>
</tbody>
</table>

## Operating costs: 5,1 ct/kWh

(Average over 20 years operating time)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Service, reparation, others</td>
<td>50 %</td>
</tr>
<tr>
<td>Rent</td>
<td>20 %</td>
</tr>
<tr>
<td>Management (technical and business)</td>
<td>20 %</td>
</tr>
<tr>
<td>Reserve for unforeseen events</td>
<td>5 %</td>
</tr>
<tr>
<td>Insurance</td>
<td>5 %</td>
</tr>
</tbody>
</table>

Source: Deutsche WindGuard GmbH; Kostensituation der Windenergie an Land in Deutschland, Stand 2013

**Costs of a 2 MW onshore wind power station in Germany**
Remuneration rates for electricity from onshore wind in Germany

Graphic source: Fachagentur Windenergie an Land – Loccumer Finanztage (online) Mai 2020
Objective power station capacities in Germany 2024

2012
Statistical value (175 GW)

2024
Objective of government (225 GW)
(Scenario B)
Renewables and liberalisation require the grid extension europeanwide
Network development plan for the german electricity system (2020)

Source: https://www.netzausbau.de/leitungsvorhaben/de.html
Most common reasons for complaints against onshore wind turbines
Species protection may be the clearly dominant cause of complaint; however, a remarkably high proportion is also attributable to formal and procedural errors.

Most complaints include more than one reason.
Top 3 reasons people complaining about wind power: species protection (especially birds), process and manufacturing defects, noise level

Source: Fachagentur Windenergie an Land, Umfrage, „Hemmnisse beim Ausbau der Windenergie in Deutschland, Juli 2019

Pleas against wind power in Germany
Upward lightning strikes on rotor blades of wind turbines
Thank you for your attention