Physics and engineering of wind power systems

Hermann-Josef Wagner

Institute for Energy Systems and Energy Economy
Ruhr-University Bochum, Germany

lee@lee.rub.de
Structure of my presentation

- Present status of wind energy use
- Physical and meteorological basics
- Techniques of wind converters
- Off shore windparks
- Wind use in Europe
Wind energy use – a good idea since a lot of years
# Worldwide wind use – present status

**Wind energy use worldwide**  
(values rounded)

<table>
<thead>
<tr>
<th></th>
<th>Rated Capacity [GW]</th>
<th>Share worldwide [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>the end of 2017</td>
<td>worldwide 2017</td>
<td></td>
</tr>
<tr>
<td>China</td>
<td>188</td>
<td>35</td>
</tr>
<tr>
<td>USA</td>
<td>89</td>
<td>16</td>
</tr>
<tr>
<td>Germany</td>
<td>56</td>
<td>10</td>
</tr>
<tr>
<td>India</td>
<td>32</td>
<td>6</td>
</tr>
<tr>
<td>Spain</td>
<td>23</td>
<td>4</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>19</td>
<td>4</td>
</tr>
<tr>
<td>France</td>
<td>14</td>
<td>3</td>
</tr>
<tr>
<td>Canada</td>
<td>13</td>
<td>2</td>
</tr>
<tr>
<td>Brazil</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Italy</td>
<td>9</td>
<td>2</td>
</tr>
<tr>
<td>Remaining countries</td>
<td>85</td>
<td>16</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>540</strong></td>
<td><strong>100</strong></td>
</tr>
</tbody>
</table>

Germany at beginning of 2017 about 56 GW, 51 Onshore and 5 Offshore *.  
For comparison:  
At the end of 2003: world about 40 GW, Germany about 15 GW  

Source: [http://www.gwec.net/global-figures/graphs/](http://www.gwec.net/global-figures/graphs/)  
* [http://www.windbranche.de/windenergie-ausbau/deutschland](http://www.windbranche.de/windenergie-ausbau/deutschland)
Shares of the suppliers in the world market in 2015

New erected capacity 2015:
56,000 MW

Source: http://www.ingenieur.de/Fachbereiche/Windenergie/Das-9-groessten-Windradhersteller-Welt
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Structure of my presentation
Energy and power density of wind

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 $\Delta m$

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

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

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

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

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

Efficiency

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

For Germany

Yearly average approx. 200 W/m²

Max. hourly average

Max. ten minute average

100 year high
Bird’s eye view of horizontally positioned rotor blades

Bird’s eye view of vertically positioned rotor blades

Velocity triangle at the rotor blade

For the pitch angle applies:

\( \alpha_A \) should be optimal, besides use \( b \) as a set variable in accordance to \( v_0 \) and \( u \) (revolution)

\[ \alpha_A = f(\beta, v_0, u) = \arctan\left(\frac{v_0}{u}\right) - b \]
The velocities and forces acting on a blade

\[\alpha_A = \text{Angle of attack}\]
\[\beta = \text{Pitch Angle}\]
\[u = \text{Average circumferential velocity}\]
\[v_n = \text{Wind velocity in the rotor plane}\]
\[w = \text{Relative approach velocity}\]
\[F_R = \text{Drag force}\]
\[F_A = \text{Lift force}\]
\[F_{RS} = \text{Resulant force}\]
\[F_T = \text{Tangential component}\]
\[F_S = \text{Axial component}\]
Percent of total capacity (28 MW)

July – September 1997

Percent of total capacity (28 MW)

January - March 1997


Load distribution – Measurement 250 MW program
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Structure of my presentation
Different types of realised wind energy converters (Solar chimney only 1 prototype)
Warm air flows up into the tower, at the top of the tower water is sprayed into the air. The water evaporates and cools the air. By the ensuing convection the air sinks toward the ground and drives a vertical axis turbine. Subsequently, the cold air flows back into the environment.

Suitable locations are hot and dry areas with nearby large water supplies. The independent time of day electricity production is advantageous.

Source: (Information and graphic): http://www.solarwindenergytower.com/the-tower.html

Planned Energy Tower (solar - wind hybrid power plant) in Arizona, USA
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 = \( \pi l^2 \) 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 of 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
Assembling of a wind converter by Nordex AG
Constructional type of the WEC Enercon-66
Wind energy converter without gear box

Source: ENERCON GmbH
Installation of the generator by a wind mill without gearboxes
### The technical figures of two different multi-megawatt wind turbines for onshore

<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>
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**
New devices need testing: Problems with gear boxes
Grid connection for synchronous generators (SG) without gear box

Grid connection of asynchronous generators (ASG) Double excited asynchronous generator

\[ n = 0.5 \text{ to } 1.2 \ (f/p) \ \text{(controllable)} \]
Inductive reactive load
Controllable reactive power

\[ n = (1+s) \ f/p, \ s = 0 \text{ to } 0.3 \ \text{(controllable)} \]
Controllable reactive power

\[ n= \text{ rotation number [1/min]} \]
\[ f= \text{ frequency [1/s]} \]
\[ p= \text{ number of polepairs} \]
\[ s= \text{ slip between the mechanical and magnetical rotation} \]

Safety - Burned off wind power station in Lahr/ Germany
| 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? |
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Structure of my presentation
Offshore wind energy in Germany in 2018

Source: offshore-stiftung.de/sites/offshorelin.de/files/mediaimages/uebersichtoffshorewindparks
Offshore-wind projects in Great Britain
Possible foundations of offshore wind converters

**Monopile**
- until 20 m deep of water
- Steel- or concrete construction

**Gravity foundation**
- until 10 m deep of water
- Steel- or concrete construction

**Tripod, Jacket**
- more than 20 m deep of water
- Steel construction
Repair of corrosion protection

Photo: Helmut Müller; Sonne, Wind und Wärme 4/2012
Fundaments for windmills for the windward Alpha Ventus
Offshore windpark, transformer station and entrance
Montage of a rotor blade

Source: http://www.siemens.com/press/pool/de/pressebilder/2012/photonews/300dpi/PN201209/PN201209-01_300dpi.jpg
Size of rotor blades of a 6 MW wind turbine
Floating offshore windparks

TLP = Tension-leg-platform
Semi-Sub = Semi-submersible platform

Source: Deep Water The next step for offshore wind energy, EWEA
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Structure of my presentation
Costs of a 2 MW onshore wind power station in Germany

### Investment plan

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

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

### Operating costs: 5,1 ct/kWh

(Average over 20 years operating time)

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</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>

**Average operating costs: 5,1 ct/kWh**
Different conveying systems for electricity (renewable energies) in the EU

FiT = Feed-in tariffs  
FiP = Feed-in premium  
TGCs = Tradable green certificates  
CfD = Contract for Difference

Source: 2014 JRC wind status report
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 (2018)

Source: http://www.netzausbau.de/SharedDocs/Bilder/DE/Karten/MonitoringGesamt.jpg?__blob=normal
Thank you for attention
Discussion
Total: 29,0 €-ct/kWh\(^1\), of which 56% are federal demand

For comparison: The electricity price was at the beginning of the year 2010 about 21,3 ct/kWh

![Diagram showing the breakdown of electricity costs]

- **Value-added tax**
  - 4,6 ct/kWh

- **Electricity tax (former “green tax”)**
  - 2,1 ct/kWh

- **Concession levy for communities**
  - 1,8 ct/kWh

- **Act on Combined Heat and Power Generation**
  - 0,4 ct/kWh

- **Renewable energy law**
  - (support of photovoltaics, wind and biomass)
  - 6,8 ct/kWh

- **Network access**
  - 7,2 ct/kWh

- **Generation/acquisition**
  - 4,1 ct/kWh

- **Basic price**
  - 2,0 ct/kWh

- **At consumption of 4,000 kWh/a**
  - 80,- €/year (gross)

**Energy-price:** 22,0 ct/kWh

**Basic price:** (for measuring, accounting, amortization)

Source: Basic price, generation, network access by using of tariffs of the Stadtwerke Velbert, Dezember 2018

Concession levy is an average: It is depending from the population in the city, Status 2017

Average structure of the electricity rate in Germany:
Household with a consumption of 4,000 kWh/a

\(^1\) 1,00 € = 1,14 USD – 17th January 2019
1,00 € = 42,89 ARS – 17th January 2019
12 Wind energy converter, each 5 MW

(6 of Multibrid (AREVA) and 6 of REpower (Senvion) company)

Operation time 20 years

Lifetime foundation 20 years

Capacity Factor 45% (load duration 3900 h/a):

incl. maintenance- and failure times, power consumption of WEC and transmission platform inside wind park

Maintenance and services:

Change of 1/2 gearbox per station and operation time

Change of 1,25 rotor blades per station and operation time

120 helicopter transports per year for the wind park

180 ship transports per year for the wind park

Life Cycle Assessment wind park alpha ventus - Reference system
Classification of the results - Comparison with German Power Mix (uniform ranking)