2. Wind Turbine System
From stand-alone to wind farms

Outline

2.1 Basic principle of Wind Energy Conversion
2.2 Development in Technology
2.3 Power converters and control
2.4 Stand-alone system
2.5 Future configurations
2.1 Basic Principle of Wind Energy Conversion

Basic Energy System:

Problems to be solved

Energy storage?

Short-term solution - Long-term solution
2.1 Basic Principle of Wind Energy Conversion

**Basic power conversion:**
2.1 Basic Principle of Wind Energy Conversion

Aerodynamics of Horizontal-Axis Wind Turbine

A blade element sweeps out an annular ring
2.1 Basic Principle Wind Energy Conversion

Power curve - Aerodynamic

Power to the generator-shaft is given by:

\[ P_{tur} = \frac{1}{2} C_p \rho A_v v_{wind}^3 \]

\[ \lambda = \frac{v_{tip}}{v_{wind}} = \frac{r_{rt} \omega_{rt}}{v_{wind}} \]

= ratio between tip-speed and wind speed
2.1 Basic Principle Wind Energy Conversion

Gain in Energy production

- A given blade-design and a given rotational speed can only optimize the use of the wind at one wind speed.
- Variable speed wind turbine increases energy capture.
2.1 Basic Principle Wind Energy Conversion

Power Control

Pitch control

Stall control

Active stall control

Power curves from different wind turbines
2.1 Basic Principle Wind Energy Conversion

Basic topology for wind turbine

- Fixed speed with capacitor bank
2.1 Basic Principle Wind Energy Conversion

Variable speed

<table>
<thead>
<tr>
<th>Input</th>
<th>Mechanical Energy Source</th>
<th>Variable Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Transmission</td>
<td>Direct</td>
</tr>
<tr>
<td>Machine type</td>
<td>Multipolar Synchronous &amp; Novel Machines</td>
<td>Conventional Synchronous Machines</td>
</tr>
<tr>
<td>Rotor</td>
<td>Wound Rotor (field control)</td>
<td>Permanent Magnet</td>
</tr>
<tr>
<td>Stator</td>
<td>Wound</td>
<td>Cage Rotor M/C</td>
</tr>
<tr>
<td>Grid connection</td>
<td>Large PE converter</td>
<td>Wound Rotor or Brushless DF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Wound</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large PE converter</td>
</tr>
<tr>
<td>Output</td>
<td>Electrical Energy Source</td>
<td>Fixed Frequency or DC</td>
</tr>
</tbody>
</table>

Heat loss dump load

Power conversion

Small PE converter

Large PE converter

Large PE converter

Cage Rotor M/C

Wound Rotor or Brushless DF

Induction Machines

Conventional Synchronous Machines

Multipolar Synchronous & Novel Machines

Direct

Gearbox

Variable speed

Fixed Frequency or DC

Rotor

Stator

Grid connection

Transmission

Input
2.1 Basic Principle Wind Energy Conversion

Nacelle in wind turbine

Vestas V80-2 MW

- Example of technology
2.2 Development in Technology

Globally development

![Graph showing development in technology](image)

- Accumulated MW
- Annual MW


- MW Accumulated:
  - 1983: 0
  - 1985: 1000
  - 1987: 2000
  - 1989: 3000
  - 1991: 4000
  - 1993: 5000
  - 1995: 6000
  - 1997: 7000
  - 1999: 8000
  - 2001: 9000

- MW pr. year:
  - 1983: 0
  - 1985: 500
  - 1987: 1000
  - 1989: 2000
  - 1991: 3000
  - 1993: 4000
  - 1995: 5000
  - 1997: 6000
  - 1999: 7000
  - 2001: 8000
2.2 Development in Technology

Facts

State of the art:
- 3 MW, variable speed
- 90 m rotor-diameter
- 80 m tower-height

Key-numbers:
- Energy payback time ~3mdr.
- Efficiency ~45%
2.2 Development in Technology

Cost pr. kWh

- Power scaling important
2.2 Development in Technology

- Low Cost of Energy
  - Deregulated market
- High Reliability
  - Availability above 98%
- Good Grid Integration
- 1 US$ ~ 7 DKK
2.2 Development in Technology

Development Trends

• Generic Development
  – Improved aerodynamics
  – Flexible and Controllable
  – Extended monitoring
  – Improved grid integration
  – Concurrent design of aerodynamics, structure, electrical system and controls
  – Site specific optimisation and operation

• Application Specific Development
  – Wind climate
  – Off-shore
  – Weak grids
### 2.2 Development in Technology

#### The Global Market

<table>
<thead>
<tr>
<th>Category</th>
<th>Size</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Micro wind turbines</td>
<td>3 kW</td>
<td>Stand alone</td>
</tr>
<tr>
<td>Smaller wind turbines</td>
<td>10 - 100 kW</td>
<td>Hybrid-systems</td>
</tr>
<tr>
<td>Big wind turbines</td>
<td>500 - 1500 kW</td>
<td>Grid connected</td>
</tr>
<tr>
<td>Offshore wind turbines</td>
<td>&gt; 2000 kW</td>
<td>Wind power stations</td>
</tr>
</tbody>
</table>
2.3 Power Converters and Control

Two-generator principle (exists in many systems): (System II)

Shift between number of poles
- “Variable speed with 1 bit resolution”
- No reduction in mechanical load
- No reduction in power pulsations to the grid.

<table>
<thead>
<tr>
<th>Poles</th>
<th>50 Hz grid (rpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3000</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
</tr>
<tr>
<td>8</td>
<td>750</td>
</tr>
<tr>
<td>10</td>
<td>600</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
</tr>
</tbody>
</table>
2.3 Power Converters and Control

Rotor resistance control (System IV):

- Higher speed range
- Lower mechanical stress
- Less grid pulsations
- Still reactive power compensation
- Use basically slip-rings.
- Improvement in Optislip (no rings)
- Speed range still limited to 5-10% of nominal speed (above synchronous speed)
- Higher power losses in the rotor
2.3 Power Converters and Control

Rotor resistance control (System IV):

Example: A 2 MW wind turbine based on rotor resistance control (Optislip):

A slip of 5% will result in a rotor power of 95 kW (losses)

The main problem is cooling!!

\[ P_r = s \cdot P_s \]
\[ P_{tur} = P_r + P_s \]
\[ P_r = \frac{s \cdot P_{tur}}{1 + s} \]

\[ s = \frac{\omega_r - \omega_s}{\omega_s} \]
2.3 Power Converters and Control

Doubly-fed induction generator - wounded rotor (System V)

- Limited speed range (-20% to +20%, typical)
- Small-scale power converter (Less power losses, price)
- Complete control of active $P_{\text{ref}}$ and reactive power $Q_{\text{ref}}$
- Need for slip-rings
- Need for gear
2.3 Power Converters and Control

Induction generator - Squirrel cage rotor (System VI)

- Full speed range
- No brushes on the generator
- Complete control of active and reactive power
- Proven technology
- Full-scale power converter
- Need for a gear

![Diagram of Induction generator - Squirrel cage rotor (System VI)]
2.3 Power Converters and Control

Synchronous generator - External magnetized (System VII)

- Full speed range
- Possible to avoid gear (multi-pole generator)
- Complete control of active and reactive power
- Small converter for field
- Need of slip-rings
- Full scale power converter
- Multi-pole generator may be big and heavy

Diagram:

- Synchronous Generator
- Gear
- DC/AC converter
- Grid

Variables:
- \( P_{\text{ref}} \)
- \( Q_{\text{ref}} \)
2.3 Power Converters and Control

Synchronous generator - Permanent magnets (System IX)

- Full speed range
- Possible to avoid gear (multi-pole generator)
- Complete control of active and reactive power
- Brushless (reduced maintenance)
- No power converter for field (higher efficiency)
- Full scale power converter
- Multi-pole generator big and heavy
- Permanent magnets needed
### 2.3 Power Converters and Control

Comparison of systems

<table>
<thead>
<tr>
<th>System</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
<th>V</th>
<th>VI</th>
<th>VII</th>
<th>VIII</th>
<th>IX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variable speed</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Control active power</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Control reactive power</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Short circuit (fault-active)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Short circuit power</td>
<td>contribute</td>
<td>contribute</td>
<td>contribute</td>
<td>contribute</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Control band width</td>
<td>1-10 s</td>
<td>1-10 s</td>
<td>1-10 s</td>
<td>100 ms</td>
<td>1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
<td>0.5-1 ms</td>
</tr>
<tr>
<td>Standby function</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes+</td>
<td>Yes+</td>
<td>Yes+</td>
<td>Yes+</td>
<td>Yes+</td>
</tr>
<tr>
<td>Flicker (sensitive)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Softstarter needed</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Rolling capacity on grid</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Reactive compensation (C)</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Investment</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Maintenance</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>
2.3 Power Converters and Control

Control of induction generator:

- Controllers (internal)
- Modulation
- Overall system control
2.3 Power Converters and Control

Control of doubly-fed induction generator system

\[ P_{mea} \quad Q_{mea} \]
2.3 Power Converters and Control

Control of permanent magnet synchronous generator system

- Can also be used with ordinary SG
2.4 Stand-alone System

Why?

- Small efficient wind turbines can be successfully used in remote locations without access to the grid.
- Adjustable-speed wind generators provide higher efficiency, eliminate the capacitor bank but they require power converters and flexible control.

Main goals

- Develop control strategy for a grid converter capable of working in both stand-alone and grid-connected modes.
2.4 Stand-alone System

a) Diode bridge rectifier + VSC
- suitable for fixed-speed wind turbines
- requires capacitor bank for IG magnetizing
- simple and low-cost

b) Back-to-back VSC
- bi-directional power conversion
- capacitor decoupling → separate control
- dc-link capacitor is bulky and exhibits relative reduced lifetime
- high cost and complexity

Back-to-back VSC allows the use of the proven standard frequency inverter technology!

c) Matrix VSC
- bi-directional power conversion
- all-silicon without dc-link capacitors → longer lifetime
- not mature technology yet (bi-directional switches required!)
- high cost and complexity
2.4 Stand-alone System

Basic configuration

- In case of overproduction ($R_{\text{damp}}$)
- Full-scale converter
2.4 Stand-alone System

- A 15kW induction motor controlled by a commercial frequency inverter is used to emulate the wind turbine.
- The 11kW induction generator is controlled by a commercial flux vector controlled inverter controlling the speed and providing magnetization.
- The grid converter uses the power-stage of a 11kW frequency inverter with the control implemented using a dSPACE controller.
- An LCL filter is introduced between the grid and the grid converter.
2.4 Stand-alone system

Grid connected

- All the available power that can be extracted from the wind turbine is transferred to the grid.
- Additionally, the static reactive power compensation is possible by adjusting the reactive current iq reference
- Standard decoupled dq PI control of the currents is used together with voltage feed-forward
- PI DC-voltage controller provides d-axis current reference

- A PLL is used for grid synchronization
2.4 Stand-alone System

Stand-alone

- The consumed power is decided by the load. Speed adjustment is used to balance the power to some extent. Eventual exceeding power will be quickly damped in the damping resistor by starting the chopper.

- The output voltage controller is aiming to control the output voltage with minimal influence of the shape of the non-linear load currents or load transients.

- Standard PI DC-voltage controller and current limiter are also part of the control.

- Standard decoupled voltage PI control in synchronous dq frame is used.
2.5 Future Configurations

Windfarms

Converter controlled wind turbine system (Windfarm solutions):

- Major concentration of wind turbines makes it economical attractive with common control.
- Higher power quality demands to the wind turbines in normal operation and fault situations.
- Development of power semiconductors makes it possible to control large power.
2.5 Future Configurations

Windfarm – Common AC-grid

- Performance seen from grid controlled by a common converter.
- Less complex.
- Two non-redundant converters
- All wind turbines have same speed.
2.5 Future Configurations

Windfarm - Individual connection to DC-bus (could be HVDC)

- Individual speed control
- Grid-side controlled by a common converter.
- Only 1 critical converter
- Higher complexity.
- Only SG
2.5 Future Configurations

- Centralised var-control
2.5 Future Configurations

160 MW Windfarm (in operation)

- Doubly-fed induction generator system
- Horns Rev, Denmark
2.5 Future Configurations

160 MW Windfarm (being installed)

- Two-speed wind turbine system
- Rødsand, Denmark
### 2.5 Future Configurations

<table>
<thead>
<tr>
<th>Design Concept</th>
<th>World-Market Share</th>
<th>Market Share Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Fixed speed</em> (Stall or active stall regulation, fixed speed operation, gearbox, pole-switchable asynchronous)</td>
<td>23%</td>
<td>22%</td>
</tr>
<tr>
<td><em>Dynamic slip control</em> (Limited variable speed, pitch regulation, gearbox, pole-switchable asynchronous generators with variable slip)</td>
<td>11%</td>
<td>0%</td>
</tr>
<tr>
<td><em>Doubly-fed generator</em> (Variable speed operation, pitch control, gearbox, double-fed generator utilizing power electronics in the inverter)</td>
<td>50%</td>
<td>49%</td>
</tr>
<tr>
<td>Direct-driven variable speed synchronous (generators with large-diameter synchronous ring generator, including pitch control, but no gearbox, utilizing power electronics in the inverter)</td>
<td>16%</td>
<td>29%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>100%</strong></td>
<td><strong>100%</strong></td>
</tr>
</tbody>
</table>
## 2.5 Future Configurations

<table>
<thead>
<tr>
<th>MANUFACTURER</th>
<th>WIND TURBINE</th>
<th>CONCEPT</th>
<th>POWER AND SPEED CONTROL FEATURES</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>VESTAS (DK)</strong></td>
<td>V80 - 2.0 MW</td>
<td>Type C1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (DFIG concept)</td>
</tr>
<tr>
<td></td>
<td>V80 - 1.8 MW</td>
<td>Type B1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (GpSlip concept)</td>
</tr>
<tr>
<td><strong>ENERCON (GE)</strong></td>
<td>E112 - 4.0 MW</td>
<td>Type D1</td>
<td>Pitch Full variable speed</td>
<td>Gearless WRSG</td>
</tr>
<tr>
<td></td>
<td>E66 - 2.0 MW</td>
<td>Type D1</td>
<td>Pitch Full variable speed</td>
<td>Gearless WRSG</td>
</tr>
<tr>
<td><strong>WEK MCHGM (DK)</strong></td>
<td>NM80/2.75 MW</td>
<td>Type C1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (DFIG concept)</td>
</tr>
<tr>
<td></td>
<td>NM70/2 MW</td>
<td>Type A2</td>
<td>Active stall Fixed speed</td>
<td>ECIG</td>
</tr>
<tr>
<td><strong>CAMESA (ES)</strong></td>
<td>G83 - 2.0 MW</td>
<td>Type C1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (DFIG concept)</td>
</tr>
<tr>
<td></td>
<td>G60 - 1.8 MW</td>
<td>Type B1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (OptSlip concept)</td>
</tr>
<tr>
<td><strong>GE WIND (US)</strong></td>
<td>3.2 MW</td>
<td>Type C1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (DFIG concept)</td>
</tr>
<tr>
<td></td>
<td>1.5 MW</td>
<td>Type C1</td>
<td>Pitch Limited variable speed</td>
<td>WRIG (DFIG concept)</td>
</tr>
</tbody>
</table>

*Status April 2003*
### 2.5 Future Configurations

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Active stall</th>
<th>SCG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fixed speed</td>
<td>Gen. voltage 650V</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two gen. speeds: 1000 / 1500 rpm</td>
<td>Two gen. speeds: 1000 / 1500 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two rotor speeds: 11 / 17 rpm</td>
<td>Two rotor speeds: 11 / 17 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 700 - 1300 rpm</td>
<td>Rotor speed range: 10.5 - 19.1 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. speed range: 1000 - 1600 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rotor speed range: 9.0 - 17.2 rpm</td>
<td>Rotor speed range: 9.0 - 17.2 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Active stall</th>
<th>SCG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fixed speed</td>
<td>Gen. voltage 650V</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two gen. speeds: 1000 / 1500 rpm</td>
<td>Two gen. speeds: 1000 / 1500 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two rotor speeds: 11 / 17 rpm</td>
<td>Two rotor speeds: 11 / 17 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 747 - 1445 rpm</td>
<td>Rotor speed range: 7.4 - 14.8 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. speed range: 1000 / 1512 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rotor speed range: 12.5 / 18.8 rpm</td>
<td>Rotor speed range: 12.5 / 18.8 rpm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Type</th>
<th>Active stall</th>
<th>SCG</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fixed speed</td>
<td>Gen. voltage 650V</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two gen. speeds: 1010 / 1519 rpm</td>
<td>Two gen. speeds: 1010 / 1519 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Two rotor speeds: 12.5 / 18.8 rpm</td>
<td>Two rotor speeds: 12.5 / 18.8 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 900 - 1800 rpm</td>
<td>Rotor speed range: 10 - 20 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. speed range: 1000 - 1800 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rotor speed range: 5.6 - 17.3 rpm</td>
<td>Rotor speed range: 5.6 - 17.3 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 900 - 1800 rpm</td>
<td>Rotor speed range: 10 - 19 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 1000 - 1800 rpm</td>
<td>Rotor speed range: 10 - 19 rpm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WRG (DFIG concept)</td>
<td>Gen. voltage 650V</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Gen. speed range: 1000 - 1800 rpm</td>
<td>Rotor speed range: 10 - 19 rpm</td>
</tr>
</tbody>
</table>

**Status April 2003**
2.5 Future Configurations

Growth of WTG's

- 1985: 15 m, 30 kW
- 1989: 30 m, 300 kW
- 1992: 37 m, 500 kW
- 1993: 46 m, 600 kW
- 1996: 70 m, 1.500 kW
- 2003: 112 m, 4.500 kW

The diagram illustrates the growth in wind turbine generators (WTG's) over the years, showing an increase in size and power output.
2.5 Future Configurations

Expected market

<table>
<thead>
<tr>
<th>Country</th>
<th>Windpower 1 2001 MW</th>
<th>Goal in 2010 MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>8.700</td>
<td>22.000</td>
</tr>
<tr>
<td>Netherlands</td>
<td>520</td>
<td>2.500</td>
</tr>
<tr>
<td>Italy</td>
<td>400</td>
<td>2.500</td>
</tr>
<tr>
<td>Spain</td>
<td>3.500</td>
<td>9.000</td>
</tr>
<tr>
<td>Norway</td>
<td>17</td>
<td>1.000</td>
</tr>
<tr>
<td>UK</td>
<td>520</td>
<td>6.000</td>
</tr>
<tr>
<td>France</td>
<td>110</td>
<td>5.000</td>
</tr>
<tr>
<td>Denmark</td>
<td>2500</td>
<td>???</td>
</tr>
</tbody>
</table>

Kilde: BTM-consult
2.5 Future Configurations

Installed capacity: 2002 32 GW
Windforce 10: 2010 180 GW
2020 1200 GW
2.5 Future Configurations

Horns-Rev Wind Farm