Basic seminar small wind energy systems with Windy Boy
Organizational Matters

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> Download areas:
  > [http://www.sma.de/handout](http://www.sma.de/handout)
Presentation topics

> Small wind turbine classification

> Grid connection

> Windy Boy Family

> Application and installation

> Planning small wind turbine systems

> Wind energy conversion

> Optimizing the system
# Small wind turbine classification

<table>
<thead>
<tr>
<th>Organization</th>
<th>Rating Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Wind Energy Association (AWEA)</td>
<td>Rated power up to 100 kW</td>
</tr>
<tr>
<td></td>
<td>Residential systems 1 kW - 10 kW</td>
</tr>
<tr>
<td></td>
<td>Commercial systems 21 kW - 100 kW</td>
</tr>
<tr>
<td>British Wind Energy Association (BWEA)</td>
<td>Rated power up to 50 kW</td>
</tr>
<tr>
<td></td>
<td>Micro wind turbines, rotor swept area less than 3.5 m²</td>
</tr>
<tr>
<td></td>
<td>Small wind turbine, rotor swept area more than 3.5 m²</td>
</tr>
<tr>
<td>German Wind Energy Association (BWE)</td>
<td>Rated power up to 100 kW</td>
</tr>
<tr>
<td></td>
<td>Residential up to 30 kW</td>
</tr>
<tr>
<td>IEC 61400 - 2</td>
<td>Rotor swept area less than 200 m²</td>
</tr>
<tr>
<td>IEC 61400 - 11</td>
<td>Rated power up to 150 kW, hub height up to 30 m</td>
</tr>
</tbody>
</table>

Source: Kühn[1]
Small wind turbine market

> Worldwide sales in 2009 42.5 MW
  (rated power up to 100 kW)

> 20,700 units (10% growth over 2008)
  > 75% were installed in Off-Grid systems
  > 25% were of a very small size
  (rated power 5 kW and less)
Small wind turbine market - Manufacturers

> More than 260 manufacturers in 26 countries worldwide

> Often cooperation in terms of production (blades, tower and inverter) and in terms of distribution and sales

<table>
<thead>
<tr>
<th>Global Distribution of Manufacturers</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
</tr>
<tr>
<td>Japan</td>
</tr>
<tr>
<td>Canada</td>
</tr>
<tr>
<td>U.K.</td>
</tr>
<tr>
<td>China</td>
</tr>
<tr>
<td>Germany</td>
</tr>
<tr>
<td>Netherlands</td>
</tr>
</tbody>
</table>

Source: AWEA [2]
Turning wind into grid compliant electricity
Turning wind into grid compliant electricity
Turning wind into grid compliant electricity

> Turbines with permanent magnet synchronous generator

> No gear box necessary = low maintenance

> Operation at variable rotation speed (fixed rotation speed with asynchronous generators) = optimized yield

> No external excitation necessary = easy installation and simple generator behaviour (rotation speed and voltage are proportional)
Wind speed to turbine power

- Connection of MPP* at all wind speeds lead to optimize load curve (best harvest by turbines)

- Programmed load curve with → operation mode: turbine

- (MPP tracking not dynamic enough)

* Maximum Power Point
Four questions to find the best match

> Minimum DC voltage of the turbine under load (at approx. 3 m/s wind speed or cut-in wind speed)?

> Maximum DC voltage of the turbine under load (at approx. 12 m/s wind speed)?

> Nominal power of the turbine?

> Maximum open circuit DC voltage of the turbine (important for over voltage protection (OVP) matching)

> See bundle list draft from SMA
Windy Boy family
Windy Boy family

> Comprehensive variety of Windy Boy inverters, starting from 1 kW up to 6 kW

> Multiplication of inverters allow combination with (nearly) all turbines

> World-wide operation due to SMA Grid Guard
Windy Boy family

> From low-voltage (20...60V) with
  Windy Boy 1100LV (1.1kW)

> Wide input voltage range (80...550V) with
  new Windy Boy 3600TL und 5000TL

> Up to high voltages (250...600V)
> and high power with
  Windy Boy 6000A (X*6kW)
Windy Boy 1100LV

- Max. DC power: 1240 W
- Recommended array power at 2500/5000 full load hours per year: 1000 W/900 W
- Max. DC input voltage: 60 V
- Nominal DC voltage: 25 V
- Min. open-circuit voltage for activating “Turbine Mode”: 25 V
- Voltage range in “Turbine Mode”: 21 V–60 V
Windy Boy 1200/1700

> Max. DC power:
  WB1200: 1320 W, WB1700: 1850 W

> Recommended array power at 2500/5000 full load hours per year:
  WB1200: 1050 W/1000 W, WB1700: 1400 W/1300 W

> Max. DC input voltage: 400 V

> Nominal DC voltage:
  WB1200: 120 V, WB1700: 180 V

> Min. open-circuit voltage for activating “Turbine Mode”:
  WB1200: 120 V, WB1700: 150 V

> Voltage range in „Turbine Mode“:
  WB1200: 100 V–400 V, WB1700: 139 V–400 V
Windy Boy 2500/3000

> Max. DC power:
  - WB2500: 2700 W, WB3000: 3200 W

> Recommended array power at 2500/5000 full load hours per year:
  - WB2500: 2100 W/1900 W,
  - WB3000: 2500 W/2200 W

> Max. DC input voltage: 600 V

> Nominal DC voltage:
  - WB2500: 300 V, WB3000: 350 V

> Min. open-circuit voltage for activating “Turbine Mode”:
  - WB2500: 300 V, WB3000: 330 V

> Voltage range in “Turbine Mode”:
  - WB2500: 250 V–600 V, WB3000: 290 V–600 V
Windy Boy 3300/3800

> Max. DC power:
  WB3300: 3820 W, WB3800: 4040 W
> Recommended array power at 2500/5000 full load hours per year:
  WB3300: 3100 W/2800 W, WB3800: 3600 W/3300 W
> Max. DC input voltage: 500 V
> Nominal DC voltage: 200 V
> Min. open-circuit voltage for activating "Turbine Mode":
  250 V
> Voltage range in "Turbine Mode": 200 V – 500 V
Windy Boy 5000A/6000A

> Max. DC power:
  WB5000A: 5750 W, WB6000A: 6300 W

> Recommended array power at 2500/5000 full load hours per year:
  WB5000A: 4600 W/4200 W,
  WB6000A: 5500 W/5100 W

> Max. DC input voltage: 600 V

> Nominal DC voltage: 270 V

> Min. open-circuit voltage for activating “Turbine Mode”: 300 V

> Voltage range in “Turbine Mode”: 250 V – 600 V
Windy Boy 3600TL/5000TL

> Max. DC power: WB3600TL: 3800 W, WB5000TL: 5300 W

> Recommended array power at 2500/5000 full load hours per year:
  WB3600TL: 3600 W/3600 W,
  WB5000TL: 4500 W / 4000 W

> Max. DC input voltage : 550 V

> Nominal DC voltage : 400 V

> Min. open-circuit voltage for activating “Turbine Mode”: 125 V

> Voltage range in “Turbine Mode”: 80 V – 550 V

> Cannot be connected in parallel
Windy Boy 2000HF/2500HF/3000HF (coming soon)

> Max. DC power:
  
  WB2000HF: 2100 W,
  WB2500HF: 2600 W,
  WB3000HF: 3150 W

> Max. DC input voltage: 700 V

> Nominal DC voltage: 530 V

> Min. open-circuit voltage for activating "Turbine Mode":
  220 V

> Voltage range in "Turbine Mode": 175 V – 700 V
Windy Boy family

> Integration of new technologies (e.g. Sunclix, Bluetooth™, reactive power control)

> Extend the complete Windy Boy portfolio to the US market

> Enable all Windy Boy inverters to use our new, state-of-the-art polynomial load curve (instead of three point load curve)
Application and Installation
Application and Installation

Indirect grid feed-in/Net metering
Application and Installation

Direct grid feed-in
Application and Installation

Stand-alone power supply systems (Default: OFF-Grid settings!)
Various application of Windy Boy inverters
Function of Windy Boy Protection Box

- Rectifying the turbine output voltage
- Overvoltage protection through switching on load resistor in parallel in case of overvoltage
Function of Windy Boy Protection Box

Recifier

> Passive B6 bridge
> Connect “wild” AC from turbine at L1, L2 and L3
> 1- and 3-phase systems
> Bypass by direct DC-connection
Function of Windy Boy Protection Box

Overvoltage protection

- Critical DC-voltage
- Output voltage of Windy Boy Protection Box

\[ U_{DC} \]

\[ t \]
Function of Windy Boy Protection Box

Load resistor

> Continuous load up to 7000 W
> One resistor for all Protection Boxes
> Spezification:
  > Designed for up to $600 \, V_{DC}$
  > $42 \, \Omega @ 25 \, ^\circ C$ (max. $54 \, \Omega$)
  > 100 % overload for 1 min
## Function of Windy Boy Protection Box

Power uptake of load resistor:

\[ P = \frac{U^2}{R} \]

<table>
<thead>
<tr>
<th>WBP-Box Model</th>
<th>Switching voltage [V]</th>
<th>Power input [kW]</th>
<th>Can be used with:</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>350-360</td>
<td>( \approx 3 )</td>
<td>WB1200, WB1700</td>
</tr>
<tr>
<td>500</td>
<td>450-460</td>
<td>( \approx 4,8 )</td>
<td>WB3300, WB3800,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB3600TL, WB5000TL</td>
</tr>
<tr>
<td>600</td>
<td>550-560</td>
<td>( \approx 7 )</td>
<td>WB5000A, WB6000A,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>WB2500, WB3000</td>
</tr>
</tbody>
</table>
Function of Windy Boy Protection Box

Grid-tied operation of turbine

> Components 6 kW Turbine, WB 6000A, WBP-Box 600
> Grid voltage available
> Wind conditions weak up to strong
Function of Windy Boy Protection Box

Grid-tied operation of turbine

- Components: 6 kW Turbine, WB 6000A, WBP-Box 600
- Grid voltage: available
- Wind conditions: very strong, hurricane
Function of Windy Boy Protection Box

Grid-tied operation of turbine

- **Components** 6 kW Turbine, WB 6000A, WBP-Box 600
- **Grid voltage** not available/cut off
- **Wind conditions** weak up to strong
Function of Windy Boy Protection Box

Sunny Island grid with small wind turbine

> Components  6 kW Turbine, WB 6000A, WBP-Box 600
> Grid voltage  Sunny Island
> Wind conditions  strong wind/high consumption
**Function of Windy Boy Protection Box**

Sunny Island grid with small wind turbine

> Components 6 kW Turbine, WB 6000A, WBP-Box 600

> Grid voltage Sunny Island

> Wind conditions strong wind/low consumption, reduced power
Use of Windy Boy Protection Box

Connection of 1 x WBP-Box 1-phase

Small WES up to 7 kW
Use of Windy Boy Protection Box

Connection of 1 x WBP-Box 3-phase

Small WES up to 7 kW
Use of Windy Boy Protection Box

Connection of 3 x WBP-Box 3-phase

Small WES up to 18 kW
Windy Boy Protection Box with Load Resistor
Planning small wind turbine systems
### Planning small wind turbine systems – Key tasks

<table>
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<tr>
<th>Task</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resource assessment</td>
<td>Average wind speed, main wind direction, turbulence</td>
</tr>
<tr>
<td>Siting</td>
<td>Positioning of tower, effects of obstacles, terrain type</td>
</tr>
<tr>
<td>Turbine technology</td>
<td>Rotor design, type of generator, inverter</td>
</tr>
<tr>
<td>Operation</td>
<td>Noise, maintenance and repair (accessibility), safety risks</td>
</tr>
<tr>
<td>Identification of local regulations</td>
<td>Planning and building laws</td>
</tr>
</tbody>
</table>
Planning small wind turbine systems – Resource assessment - Siting

> Preliminary Assessment: Evaluation of selected site for adequate wind speed based on available sources (e.g. Wind Atlases, NASA [5])

Welcome to www.windatlas.dk

At present, the wind atlas methodology – in the form of the Wind program – has been employed in about 110 countries and territories around the world. In the map below, these countries are shown in blue and red. National wind atlases exist for more than 50 countries (marked in red); many of these atlases contain wind data and wind statistics on disk. A list of the red wind atlas countries with references is given here. A list of other wind investigations and data bases is given here.
Planning small wind turbine systems – Resource assessment - Siting

- Frequency distribution of wind speeds. Mathematical approximation possible (Weibull function)
- The wind speed for the hub height (largely determined by the roughness of the site’s surface, defined by the roughness length $z_0$)

<table>
<thead>
<tr>
<th>Types of terrain surfaces</th>
<th>$z_0$ [m]</th>
<th>Roughness class</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water surfaces</td>
<td>0.0001</td>
<td>0</td>
</tr>
<tr>
<td>Sand surfaces</td>
<td>0.0003</td>
<td>0.1</td>
</tr>
<tr>
<td>Snow surfaces</td>
<td>0.004</td>
<td>0.2</td>
</tr>
<tr>
<td>Bare earth</td>
<td>0.005</td>
<td>0.4</td>
</tr>
<tr>
<td>Meadow</td>
<td>0.008</td>
<td>0.7</td>
</tr>
<tr>
<td>Airports, runway</td>
<td>0.01</td>
<td>0.8</td>
</tr>
<tr>
<td>Airports with building and trees</td>
<td>0.02</td>
<td>1</td>
</tr>
<tr>
<td>Agricultural terrain with very few buildings, trees</td>
<td>0.03</td>
<td>1</td>
</tr>
<tr>
<td>Agricultural terrain with an open appearance</td>
<td>0.05</td>
<td>1.5</td>
</tr>
<tr>
<td>Agricultural terrain with a closed appearance</td>
<td>0.1</td>
<td>2</td>
</tr>
<tr>
<td>Many trees and/or bushes</td>
<td>0.2</td>
<td>2.5</td>
</tr>
<tr>
<td>Built-up terrain</td>
<td>0.3</td>
<td>3</td>
</tr>
<tr>
<td>Suburbs</td>
<td>0.5</td>
<td>3</td>
</tr>
<tr>
<td>Forest</td>
<td>0.8</td>
<td>&gt;3</td>
</tr>
<tr>
<td>City</td>
<td>1</td>
<td>&gt;3</td>
</tr>
</tbody>
</table>

Source: Hau [3]
Planning small wind turbine systems – Resource assessment - Siting

> Wind measurement campaign on-site (time period of at least one year)
> Data output is organised in bins, e.g. two-dimensional binning of wind speed and wind direction

| Bin Mean | Start | End | Sum  | N     | NNE  | EN | ENE  | E    | ESE  | SSE  | S    | SSW  | WSW  | W    | WNW  | NNW  |
|----------|-------|-----|------|-------|------|----|------|------|------|------|------|------|------|------|------|
|          |       |     | 7.05 | 6.44  | 5.67 | 4.81| 5.01 | 5.53 | 6.78 | 7.5 | 6.86 | 6.55 | 7.5 | 8.29 | 9.34 |
| 0        | 0.49  | 912 | 311  | 149   | 18   | 154 | 64   | 17   | 136  | 20  | 12   | 10   | 11   | 10   |
| 1        | 0.5   | 1.49| 611  | 82    | 48   | 48  | 44   | 50   | 56   | 56  | 43   | 40   | 54   | 45   | 50   |
| 2        | 1.5   | 2.49| 1336 | 155   | 123  | 135 | 120  | 112  | 128  | 116 | 96   | 103  | 57   | 92   | 99   |
| 3        | 2.5   | 3.49| 2208 | 224   | 238  | 208 | 209  | 208  | 198  | 177 | 150  | 121  | 114  | 152  |
| 4        | 3.5   | 4.49| 3152 | 308   | 292  | 262 | 345  | 281  | 306  | 291 | 247  | 193  | 184  | 200  | 243  |
| 5        | 4.5   | 5.49| 3621 | 352   | 284  | 247 | 319  | 348  | 350  | 376 | 313  | 253  | 211  | 260  | 308  |
| 6        | 5.5   | 6.49| 4434 | 423   | 288  | 225 | 279  | 422  | 479  | 458 | 458  | 344  | 303  | 347  | 408  |
| 7        | 6.5   | 7.49| 4387 | 393   | 232  | 137 | 192  | 417  | 493  | 492 | 556  | 412  | 337  | 367  | 459  |
| 8        | 7.5   | 8.49| 3898 | 295   | 150  | 75  | 112  | 170  | 449  | 556 | 480  | 409  | 353  | 372  | 477  |
| 9        | 8.5   | 9.49| 3333 | 288   | 115  | 37  | 62   | 102  | 360  | 525 | 342  | 271  | 361  | 393  | 477  |
| 10       | 9.5   | 10.49| 2433 | 195   | 87   | 13  | 45   | 53   | 252  | 421 | 175  | 142  | 291  | 334  | 425  |
| 11       | 10.5  | 11.49| 1593 | 126   | 53   | 12  | 13   | 31   | 123  | 276 | 136  | 54   | 198  | 224  | 347  |
| 12       | 11.5  | 12.49| 1079 | 108   | 41   | 3   | 8    | 16   | 180  | 68  | 16   | 105  | 159  | 305  |
| 13       | 12.5  | 13.49| 714  | 80    | 32   | 3   | 4    | 14   | 33   | 101 | 39   | 10   | 40   | 117  | 241  |
| 14       | 13.5  | 14.49| 489  | 59    | 28   | 0   | 4    | 2    | 20   | 65  | 21   | 3    | 24   | 70   | 193  |
| 15       | 14.5  | 15.49| 304  | 35    | 11   | 1   | 3    | 1    | 11   | 46  | 4    | 2    | 7    | 41   | 142  |
Planning small wind turbine systems – Resource assessment - Siting

> Turbulence is the standard deviation of wind speed (horizontal or vertical) and wind direction around the average.
## Planning small wind turbine systems – Software tools

<table>
<thead>
<tr>
<th></th>
<th>Alwin</th>
<th>BLADED</th>
<th>Greenius</th>
<th>RETscreen</th>
<th>SWT Yield Estimator</th>
<th>WASP</th>
<th>WindFarm</th>
<th>WindFarmer</th>
<th>WindPro</th>
</tr>
</thead>
<tbody>
<tr>
<td>License</td>
<td>Freeware</td>
<td>Commercial</td>
<td>Commercial</td>
<td>Freeware</td>
<td>Freeware</td>
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<td>Commercial</td>
<td>Commercial</td>
<td>Commercial</td>
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<tr>
<td>Yield Estimation</td>
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<td>o</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td>Noise Calculation</td>
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<td>o</td>
<td>o</td>
<td>o</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>Calculation of Profitability</td>
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<td>o</td>
<td>x</td>
<td>x</td>
<td>o</td>
<td>o</td>
<td>o</td>
<td>x</td>
<td>o</td>
</tr>
</tbody>
</table>

Source: Quaschning [4]
Planning small wind turbine systems - Technology

> Turbines with vertical axis
  > Savonius Turbine
  > Darrieus Turbine
  > H-Turbine

> Turbines with horizontal axis
Planning small wind turbine systems - Technology

> Rotors using aerodynamic drag

> Rotors using aerodynamic lift
Planning small wind turbine systems - Technology

> Power control by rotor blade pitching

> Passive stall control with fixed blade
Planning small wind turbine systems – Standard - Certification

> International standard for small wind energy systems – IEC 61400 –XX

> Certification organisations:

> Cooperation of certification institutes with harmonised measurements and evaluations:

MEASNET
> www.measnet.org

> The Microgeneration Certification Scheme
> www.microgenerationcertification.org

> Small wind certification organisation: certifications according to the AWEA Small Wind Turbine Performance and Safety Standard
> www.smallwindcertification.org
Planning small wind turbine systems – Wind energy association

> The European Wind Energy Association,
  > www.ewea.org

> RenewableUK, formerly British Wind Energy Association
  > www.bwea.com/small/index.html

> American Wind Energy Association
  > www.awea.org
Wind Energy Conversion
Wind Energy Conversion – momentum theory

> Wind energy is the kinetic energy of an air mass \( m \) moving at a velocity \( v \)

\[
E_{\text{kin}} = \frac{1}{2}mv^2
\]

> The mass \( m \) of the moving air at a given time \( t \) can be described as:

\[
m = tm
\]

\[
E = \frac{1}{2}tmv^2
\]

> If the moving air with the air density \( \rho \) passes through a cross-sectional area \( A \) at a velocity \( v \), then the mass flow is:

\[
m = \rho Av
\]

\[
E = \frac{1}{2}\rho Av^3
\]

> With

\[
P = \frac{E}{t}
\]

\[
P = \frac{1}{2}\rho Av^3
\]

\( E_{\text{kin}} \): kinetic energy [Nm]
\( m \): moving mass [kg]
\( v \): velocity [m/s]
\( \rho \): air density [kg/m³]
\( A \): cross-sectional area [m²]

\( P \): power [Nm/s=W]
Wind Energy Conversion - power coefficient

> Energy from the wind can only be extracted by reducing the flow velocity, which means a widening of the cross-section as the air mass remains unchanged.

> The ratio between the extracted power and the power of the undisturbed mass flow is the power coefficient $c_p$.

> $c_p$ reaches its maximum at the ratio between the velocity $v_1$ before and the velocity $v_2$ after the turbine of $1/3$.

> $c_{p\text{max}} = 0.593$

\[
P = c_p \frac{1}{2} \rho A R v^3
\]

$v$: velocity [m/s]
$P$: power [Nm/s=W]
$\rho$: air density [kg/m$^3$]
$A_R$: rotor swept area [m$^2$]

Source: Hau [2]
Wind Energy Conversion – tip speed ratio

> While extracting power from the wind, the rotor will impart a spin to the wake in opposite to the torque of the rotor

> The power coefficient $c_p$ is dependent on the ratio between the tangential velocity of the rotor blades and the undisturbed air flow, called the tip speed ratio $\lambda$

Source: Hau [2]
Wind Energy Conversion – tip speed ratio

\[
P = c_p \frac{1}{p} \rho A_R v^3
\]

\(v\): velocity [m/s]
\(P\): power [Nm/s=W]
\(\rho\): air density [kg/m³]
\(A_R\): rotor swept area [m²]
\(c_p\): power coefficient

\[\text{tip speed ratio } \lambda = \frac{\text{tip speed of rotor blade}}{\text{wind speed}}\]
Wind speed to wind power

\[ P = c_p \frac{1}{2} \rho A_R v^3 \]

- \( v \): velocity [m/s]
- \( P \): power [Nm/s=W]
- \( \rho \): air density [kg/m\(^3\)]
- \( A_R \): rotor swept area [m\(^2\)]
- \( c_p \): power coefficient

Doubled wind velocity means 8 times more power to harvest by turbines.
Wind speed to wind power (calculation example)

\[ P = \frac{1}{2} \rho A R v^3 \]

- \( v \): velocity [m/s]
- \( P \): power [Nm/s=W]
- \( \rho \): air density [kg/m³]
- \( A_R \): rotor swept area [m²]
- \( c_p \): power coefficient
- \( \rho = 1,225 \frac{kg}{m^3} \) (air density)
Wind speed to turbine power

Summing up:

> The tip speed ratio (TSR) is the ratio between the rotational speed of the tip of a blade and the current velocity of the wind

> If we operate the turbine always at its optimal TSR (e.g. 7 for a three-wing-turbine) then we ensure the system’s best power coefficient $c_p$

> But how can we ensure this at dynamically changing wind velocity
Determination of the turbine curve – wind tunnel

> Test setup in the wind tunnel with matching Windy Boy

> Set the operating condition „constant voltage“ for the Windy Boy
Determination of the turbine curve – wind tunnel

> Measuring the output power for different voltages at constant wind speed

> Determination of MPP for different wind speeds
Determination of the turbine curve – measurement campaign

> Execution of measurement campaigns (wind speed, output power of wind turbine) with different curves and comparing the output power of the turbine
Determination of the turbine curve – measurement campaign

> Determine the best turbine curve for different wind speeds
Determination of the turbine curve – calculation

- Calculation of rotor area and circumference of the blade length
- Choosing the optimal tip speed ratio $\lambda$ for the rotor type (e.g. $\lambda = 7$ for three-bladed rotor)
- Calculation of the rotation of the rotor from the circumferential speed (wind speed times tip speed ratio) divided by the circumference
- Multiplying by 60 to get rotations per minute
- The AC voltage is obtained by multiplying the generator ration with the rotation of the rotor
- The voltage for three-phase generators is indicated between two phases, therefore calculation of the inverter input voltage from the product of the generator voltage and square root 2
- Calculation of power by inserting the calculated variables in the equation:

$$P = \frac{1}{2} \rho A_R \frac{v^3}{c_p}$$

$v$: wind speed [m/s]
$P$: power [Nm/s=W]
$\rho$: air density [kg/m$^3$]
$A_R$: rotor swept area[m$^2$]
$c_p$: power coefficient
Determination of the turbine curve – calculation example

> Blade length: 2.5 m
> Tip speed ratio: 7
> Power coefficient: 0.32
> Air density 1.22 kg/m³
> Generator ratio: 0.5 V/min⁻¹
Optimizing your system
Key feature: turbine curve
Turbine mode with 3-point load curve

3-point load curve

> Good approximation

> Optimized control
Turbine mode with polynomial load curve

Polynomial load curve

\[ P = v^3 \]

> „The real thing”, not just an approximation

> Optimized control

> Continuous load gradient
  (minimized mechanical stress)
Polynomial load curve

Parameters

> $U_{PV \text{ Start}}$
  → start of grid monitoring

> $U_{DC \text{ WindStart}}$
  → start of load curve

> $\text{Wind}_a0 \text{ to } \text{Wind}_a3$
  → amplification of polynom

$$P_{AC}(U_{DC}) = \text{Wind}_a0 + \text{Wind}_a1 \cdot U_{DC} + \text{Wind}_a2 \cdot U_{DC}^2 + \text{Wind}_a3 \cdot U_{DC}^3$$
Windy Boy Setup Tool

> Optimize your load curve  
  (even offline)

> Perfect adjustment of your Windy Boy  
  to your turbine

> Easy-to-use tool  
  all you need in one window

(tab „Software“)
Setting of the load curve – USB-Service-Interface

> Easy upload and download of Windy Boy settings

> Communication e.g. via USB-Service interface
   → latest driver downloadable from SMA website

> Save and reuse your optimized settings
   (for multiple sites)
Setting of the load curve - Bluetooth®

> Direct communication with the Windy Boy via Bluetooth®-connection

> Extract the coefficients from the Windy Boy Setup tool and enter them in the Windy Boy via Bluetooth® and Sunny Explorer

- Wind_a0=Constant deviation of power calculation
- Wind_a1=Coefficient of power calculation based on Udc
- Wind_a2=Coefficient of power calculation based on Udc^2
- Wind_a3=Coefficient of power calculation based on Udc^3
Windy Boy Setup Tool
documentation, chapter 5.4.1

5.4.1 Entering nodes

Enter the values of the nodes for the appointed wind turbine system in the "Nodes" value range. Enter all 7 nodes to construct an optimal power curve.

If you want to construct a power curve with e.g. only 3 nodes (carryover of the 3 point characteristic curve), enter the first point several times in the "Nodes" value range (see figure).

<table>
<thead>
<tr>
<th>Point</th>
<th>DC input voltage [V]</th>
<th>AC feed-in power [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>P2</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>P3</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>P4</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>P5</td>
<td>255</td>
<td>0</td>
</tr>
<tr>
<td>P6</td>
<td>310</td>
<td>800</td>
</tr>
<tr>
<td>P7</td>
<td>390</td>
<td>5000</td>
</tr>
</tbody>
</table>

Once you have entered the values for the individual nodes the power curve is displayed adjusted in the diagram and the software calculates the coefficients (Wind_a0 to Wind_a3) automatically, these finally being transferred to the "Parameters" value range. You can adjust the coefficients to your wind turbine system more exactly once they have been calculated.
Appendix – References


> 5. NASA, Surface meteorology and Solar Energy: http://eosweb.larc.nasa.gov/sse/RETScreen/
Appendix – Software tools

- RETscreen: http://www.retscreen.net/ang/home.php
- SWT Yield Estimator: http://www.renknow.net/, search for „small wind turbine yield estimator“
- WAsP: http://www.wasp.dk/Download/Index.htm
- WindFarm: http://www.resoft.co.uk/English/index.htm
- WindPro: http://www.emd.dk/WindPRO/Frontpage
Let’s be realistic and try the impossible!