Nomenclature

What is a Wind Turbine

• **Turbine: Rotor**
  Assemblage of Blades

• **Generator**
  Nacelle

• **Tower**
  Guyed, Freestanding

• **Foundation**

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Nomenclature

- Mid-80s HAWT
- Internal Ladder
- w/ Fall Restraint
- Work Platform
- Tip Brakes
- “Rocket” Tower
Wind Energy Conversion Devices

• Drag Devices
  HAWT (Seldom)
  VAWT (Often)
  First Choice of “Inventors”

• Lift Devices
  HAWT (Dominant)
  VAWT (Rare)
Configuration: Axis of Rotation

HAWT

VAWT

Paul Gipe & Assoc.
Vertical Axis Wind Turbine (VAWT) Configurations

"H"  DELTA  DIAMOND  "Y"  PHI

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VAWTs
ϕ Darrieus
2 Blades

DAF-Indal
Atlantic Wind Test Site, PEI

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Giromill

Articulating Straight Blade VAWT

Dansk Vindkraft, 1980, RisøDenmark

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Horizontal Axis Wind Turbine (HAWT) Configurations

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One-Blade

Rival Calzoni, Central Italy

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Two Blades

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Three-Blades

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Tehachapi Pass, California
Applications
How Wind Energy is Used

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Applications--Off-the-Grid

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Applications--Farms

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Electric Vehicle Charging

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Single Turbine Interconnection

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Multiple Turbine Cluster

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Multiple Turbine Cluster

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Applications--Wind Power Plants

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Whitelee, Glasgow, Scotland
Wind Plant Arrays--Rectilinear

160-250 kW: Mojave, California

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Wind Plant Arrays
Linear

Dikes, Breakwaters, Canals

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Wind Plant Arrays
Linear

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Wind Plant Arrays
Ridgetops

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Wind Plant Arrays
Ridgetops

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Campania, Italy
Wind Turbine Size

• In Wind Energy—Size Matters
  Rotor Diameter or Swept Area
• Not Generator Size!

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Medium-Size & Large Wind Turbines

Paul Gipe, wind-works.org
## Specific Capacity & Specific Area

### Sample Specific Capacity Specific Area

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Rotor Dia.</th>
<th>Swept Area $m^2$</th>
<th>Rated Power kW</th>
<th>Specific Power $W/m^2$</th>
<th>Specific Area $m^2/kW$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vestas</td>
<td>V80</td>
<td>80</td>
<td>5,027</td>
<td>1,800</td>
<td>358</td>
<td>2.8</td>
</tr>
<tr>
<td>Vestas</td>
<td>V82</td>
<td>82</td>
<td>5,281</td>
<td>1,650</td>
<td>312</td>
<td>3.2</td>
</tr>
<tr>
<td>GE</td>
<td>1500</td>
<td>71</td>
<td>3,959</td>
<td>1,500</td>
<td>379</td>
<td>2.6</td>
</tr>
<tr>
<td>GE</td>
<td>1500SL</td>
<td>77</td>
<td>4,657</td>
<td>1,500</td>
<td>322</td>
<td>3.1</td>
</tr>
<tr>
<td>GE</td>
<td>100-1.6</td>
<td>100</td>
<td>7,854</td>
<td>1,600</td>
<td>204</td>
<td>4.9</td>
</tr>
</tbody>
</table>

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Annual Energy Production Relative to Rated Power & Rotor Area

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Renewable Tariffs Launched

Average Wind Speed (m/s)

Million kWh/yr

GE 1500 71

GE 1500 77

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Annual Energy Production Relative to Rated Power & Rotor Area

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Renewable Tariffs Launched

4 4.5 5 5.5 6 6.5 7 7.5 8 8.5 9

Average Wind Speed (m/s)

0 2 4 6 8 10 12

Million kWh/yr

N80 2500
N90 2300

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Annual Energy Production Relative to Rated Power & Rotor Area

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## IEC Large Wind Turbine Classes

(Wind speed in m/s)

<table>
<thead>
<tr>
<th></th>
<th>High Wind</th>
<th>Medium Wind</th>
<th>Low Wind</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual Average Wind Speed</td>
<td>$V_{ave}$</td>
<td>10</td>
<td>8.5</td>
<td>7.5</td>
</tr>
<tr>
<td>Reference Wind Speed</td>
<td>$V_{ref}$</td>
<td>50</td>
<td>42.5</td>
<td>37.5</td>
</tr>
<tr>
<td>50-year Return Gust Speed</td>
<td>1.4 $V_{ref}$</td>
<td>70</td>
<td>59.5</td>
<td>52.5</td>
</tr>
<tr>
<td>1-year Return Gust Speed</td>
<td>1.05 $V_{ref}$</td>
<td>52.5</td>
<td>44.6</td>
<td>39.4</td>
</tr>
<tr>
<td>Turbulence Intensity at 15 m/s</td>
<td>$I_{15}$</td>
<td>A 18% B 16%</td>
<td>A 18% B 16%</td>
<td>A 18% B 16%</td>
</tr>
<tr>
<td>a</td>
<td>2 3</td>
<td>2 3</td>
<td>2 3</td>
<td>2 3</td>
</tr>
</tbody>
</table>

$I_{15}$: Characteristic value of hub-height turbulence intensity at a ten-minute average wind speed of 15 m/s

a: Slope parameter used in the turbulence intensity equation

Note: 10-minute averages, hub height wind speed. Air density: 1.225 kg/m³.


---

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Size Today

- 3 MW
- 10,000 m²
- 10,000,000 kWh/yr
- 250 t

Hvide Sande, Denmark

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Rotor Overspeed Controls

• All Wind Turbines Must Have Some Form of Rotor Overspeed Control--All
  Micro: Dynamic Brake OK
  Mini: Dynamic Brake Maybe OK
  Household-size: Dynamic Brake Typically Not Sufficient

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Rotor Overspeed Controls

• No Aerodynamic Controls
• Furling
  - Vertical
  - Horizontal
• Tip Brakes
• Parachutes
• Pitching Blade Tips
• Spoilers
• Variable Pitch
  - Pitch to Feather
  - Pitch to Stall

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Overspeed Controls
Furling-Vertical

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Rotor Controls
Furling-Horizontal

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Overspeed Controls
Pitching Blade Tips

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Overspeed Controls
Variable Pitch
• Pitch-to-Feather

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Lessons
From 30+ Years of Experience

• No Panaceas
• No Cheap Solutions
• No Breakthroughs--No Miracles
• Numbers Matter
• Experience Matters
• Size Matters

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Lessons

• Always Check the Numbers
  Vortec: The Numbers Didn’t Add Up

• Always Check the References
  Vortec: References Discredited in the USA

• Always Google
  Vortec: Ducted Turbine Critics on the Web

• Always Go to the Library
  . . . Or to Your Neighborhood Bookstore!
  Lots of Wind Books Now Available

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Lessons

• Always Be Wary of “New” Designs
Scams, Frauds, & Flakes
Tell-Tale Signs

• Heavy on Hype--Weak on Experience
• Fancy Web Site
  Web Sites are Much Cheaper than Real Turbines
• Aggressive Marketing
  Watch for Multi-Level Pyramid Schemes
  “Get in on the Ground Floor”
• “New” Design, “Not Like The Others”
  Often VAWTs, Squirrel Cage, Ducted (DAWT)
Scams, Frauds, & Flakes
Tell-Tale Signs

- Patents
  Rarely Mean Anything
- Works at Low Speeds (<3 m/s)
  There’s Little Power in Low Winds
- Silent!
  Yes, Because They Seldom Do Anything
- Doesn’t Kill Birds
  Yeah, right!

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Fundamentals of Wind Energy

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Power in the Wind

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

Where \( \rho \) is air density (kg/m\(^3\)), 
\( A \) is area (m\(^2\)), and 
\( V \) is velocity (m/s); thus 
\[ 2V^3 = 8P \]

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Seasonal Wind Distribution

Avg. Monthly Wind Speed (mph)

<table>
<thead>
<tr>
<th>Month</th>
<th>Amarillo, Texas</th>
<th>Erie, Penn.</th>
<th>San Francisco, Calif.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mar</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Apr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>May</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>June</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>July</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aug</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sept</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oct</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nov</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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Rayleigh Wind Speed Distribution

[Graph showing the frequency of occurrence for wind speeds of 5 m/s, 6 m/s, and 7 m/s.]

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Speed, Power, & Height

\[ \frac{V}{V_0} = \left( \frac{H}{H_0} \right)^\alpha \]

\[ \frac{P}{P_0} = \left( \frac{H}{H_0} \right)^{3\alpha} \]

Where \( \alpha \) is the surface friction coefficient.

- \( 1/7 \) (0.14), Low Grass Prairies
- \( 1/4 \) (0.25), Suburbs
- 0.40, Urban

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Increase in Wind Speed with Height

\[ V = V_0 \left( \frac{H}{H_0} \right)^{\alpha} \]

Wind Shear Exponent
- 0.1
- 0.14 (1/7)
- 0.2
- 0.25

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Increase in Power with Height

\[ P = P_o \left( \frac{H}{H_o} \right)^{3\alpha} \]

- Wind Shear Exponent
  - 0.1
  - 0.14 (1/7)
  - 0.2
  - 0.25

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### Change in Wind Speed & Power with Height

<table>
<thead>
<tr>
<th></th>
<th>2 X Height 25 to 50 m</th>
<th>5 X Height 10 to 50 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind Speed</td>
<td>1.1</td>
<td>1.25</td>
</tr>
<tr>
<td>Wind Power</td>
<td>1.35</td>
<td>1.99</td>
</tr>
</tbody>
</table>

1/7 (0.14), Low Grass Prairies

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Annual Energy Output (AEO) Estimating Methods

- **Back-of-the-Envelope (Swept Area)**
  Simple Approximation
- **Power Curve & Speed Distribution**
  Method Used by the Pros
  Accuracy Dependent Upon Data
- **Manufacturers’ Tables**
  Dependent Upon Honesty of Manufacturer
- **Software**
  Must Know Assumptions Used (RETScreen)

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Energy in the Wind
Annual Energy Output (AEO)
Annual Energy Production (AEP)

\[
AEO = \frac{1}{2} \rho A V^3 \eta \quad (8,760 \text{ hrs/Year})
\]

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Rotor Dimensions

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## Tararua New Zealand Yields

**Tararua Wind Plant New Zealand Specific Yields**  
**Vestas V47**

<table>
<thead>
<tr>
<th></th>
<th>Diameter</th>
<th>Swept Area</th>
<th>Specific Yield</th>
<th>Approximate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>kWh/yr</strong></td>
<td>m</td>
<td>m$^2$</td>
<td>kWh/m$^2$/yr</td>
<td>Approximate</td>
</tr>
<tr>
<td>Low</td>
<td>1,457,901</td>
<td>47</td>
<td>1,735</td>
<td>840</td>
</tr>
<tr>
<td>Median</td>
<td>2,500,000</td>
<td>47</td>
<td>1,735</td>
<td>1,440</td>
</tr>
<tr>
<td>High</td>
<td>3,050,622</td>
<td>47</td>
<td>1,735</td>
<td>1,760</td>
</tr>
</tbody>
</table>


---

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AEO Medium & Large Turbines

AEO for Large Wind Turbines
Per Square Meter of Swept Area

Average Annual Wind Speed (m/s)

Average Annual Wind Speed (mph)

Thousand kWh/year/m²

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## Net Generation from Wind Plants

<table>
<thead>
<tr>
<th></th>
<th>Net</th>
</tr>
</thead>
<tbody>
<tr>
<td>Availability</td>
<td>98%</td>
</tr>
<tr>
<td>Electrical</td>
<td>97%</td>
</tr>
<tr>
<td>Array Interference</td>
<td>90%-95%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>86%-90%</strong></td>
</tr>
</tbody>
</table>

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Relative Size of Small Wind Turbines

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AEO for Small Wind Turbines
Per Square Meter of Swept Area

Average Annual Wind Speed (m/s)

Average Annual Wind Speed (mph)

Thousand kWh/year/m²

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Measures of Productivity

• **Capacity (Plant) Factor**
  Misleading Indicator
  Used for Fossil-Fired Plants
  Not Suited for Wind Energy Use

• **kWh/kW/yr (for Planning Purposes)**
  When Sufficient Data is Unavailable

• **Annual Specific Yield (kWh/m²/yr)**
  The Only Measure Specific to Wind Energy
Equivalent Capacity Factor for Specific Rated Capacity

![Diagram showing the relationship between Annual Specific Yield (kWh/m²/yr) and Capacity Factor for different Specific Capacity kW/m².](image-url)

- **Capacity Factor**
- **Annual Specific Yield (kWh/m²/yr)**
- **Specific Capacity kW/m²**: 0.2, 0.3, 0.4, 0.5, 0.6

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## Typical Yields (kWh/kW/yr)

<table>
<thead>
<tr>
<th>Country</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>1,500</td>
<td>1,800</td>
</tr>
<tr>
<td>France</td>
<td>1,400</td>
<td>1,900</td>
</tr>
<tr>
<td>Spain</td>
<td>1,700</td>
<td>2,100</td>
</tr>
<tr>
<td>Denmark</td>
<td>2,000</td>
<td>2,500</td>
</tr>
</tbody>
</table>

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Measures of Cost

- $/kW of Installed Capacity
  Often a Misleading Indicator

- $/m^2 of Installed Swept Area
  Most Useful When Resource is Unknown

- $/kWh/yr of Annual Generation
  Most Important Criteria in the End

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Sources of Information

- Trade Magazines
- European Wind Reports
- German Market Survey
- Books
- Web Sites
- Workshops
Trade Magazines

- Windpower Monthly
- WindStats
- WinDirections
- RE World
- New Energy
- Neue Energie
- North American Windpower
- Systèmes Solaires

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Measured Performance Data

- Power Curves
- Noise
- Power Factor
- Flicker

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