Small Wind 101:
A Primer for Remote Power

Framkvæmdastjóri 112
Technical Seminar
March 13, 2013

Mike Bergey
Bergey Windpower Co.

BERGEY WINDPOWER

Mike Bergey

- Working in small wind since 1976
- Twice president of the American Wind Energy Association (AWEA)
- AWEA Board for 27 years
- Chaired AWEA Small Wind Committee for 22 years
- Chairs AWEA Small Wind Turbine Certification Standards Committee - AWEA 2009-9.1
- President, Distributed Wind Energy Association

Bergey Windpower Co.

A World Leader in Small Wind

- Established in 1977
- Focus on small wind turbines for distributed applications – on-grid & off-grid
- Serve consumer, commercial, & industrial markets
- Over 9,000 installations, covering all 50 States and over 100 countries
- Ranked #1 in the World in Small Wind

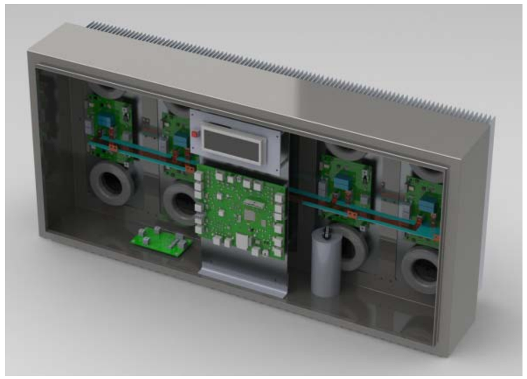
Bergey Products

1 kW
2.5m Dia.

6 kW
6.2m Dia.

10 kW
7m Dia.

Towers: Multiple styles, 60 – 160 ft.



Custom Inverters & battery chargers

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Strong Products: 1, 5 & 10 kW

1 kW

7.5/10 kW

6 kW

50 kW
(in development)

Why Small Wind & Solar Hybrid Systems?

Diesel Generators are Wonderful!

Except for …

- Diesel fuel cost have gone up with oil prices
- Often fuel logistics adds high costs for very remote sites
- Use as prime power, 24/7, requires regular minor and major maintenance
- 99.9+% reliability requires dual generators
- Most are operated a low load … which causes problems

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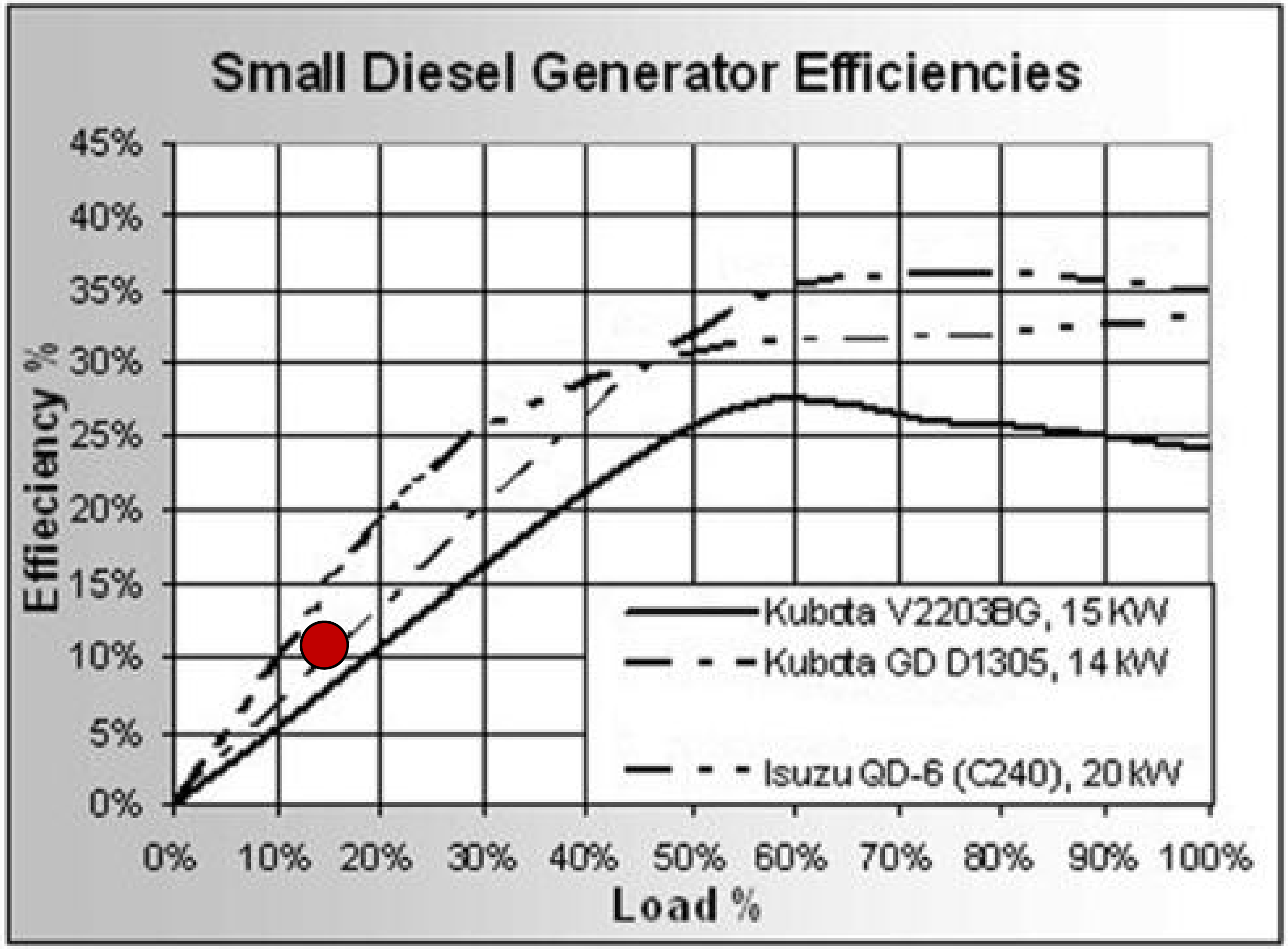
Low Loads are Bad for Diesels



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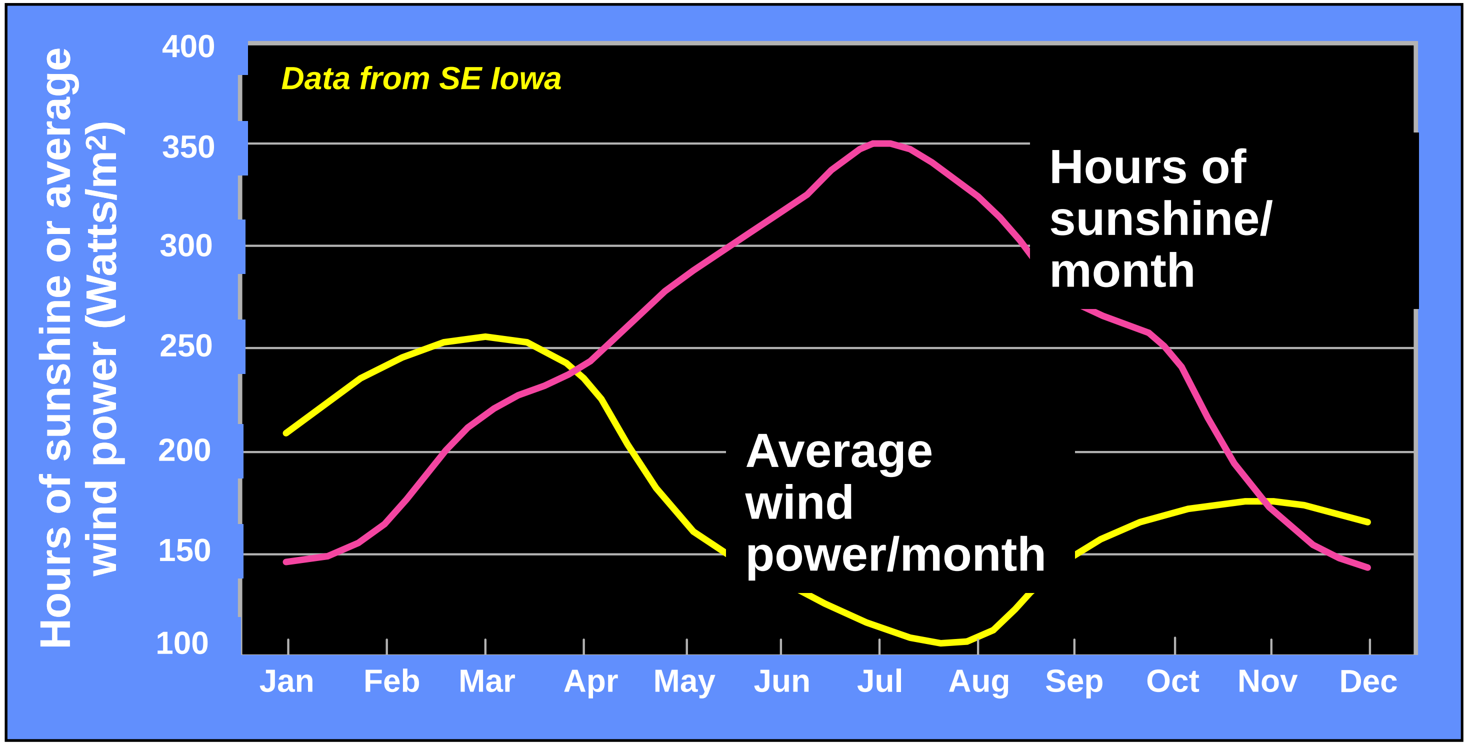
Wind Turbines and Diesels are Complimentary

Characteristic	Wind	Diesel
Capital Cost	High	Low
Operating Cost	Low	High
Logistics Burden	Low	High
Maintenance Requirements	Low	High
Available on Demand	No	Yes

Together, They Provide a More Reliable and Cost-Effective Power System

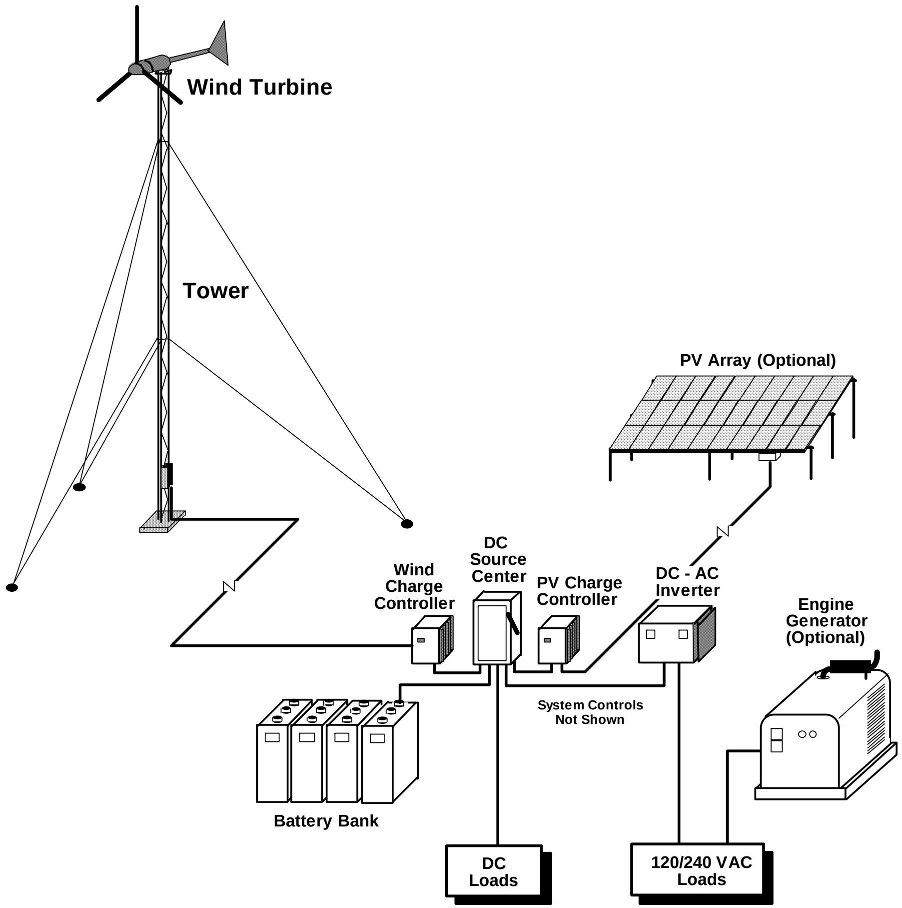
Wind and Solar Resources are often Seasonally Complimentary



Wind/Solar/Diesel Hybrid Systems

The Smart Way to Power Remote Sites

- Provides 24/7 Power with Diesel Run Times Reduced to ~ 10 - 20%
- Renewables Typically Supply 50 - 90% of Energy
- “DC-Bus” Architecture is same as “Cycle-Charge Diesel” Systems, but with Renewables Added



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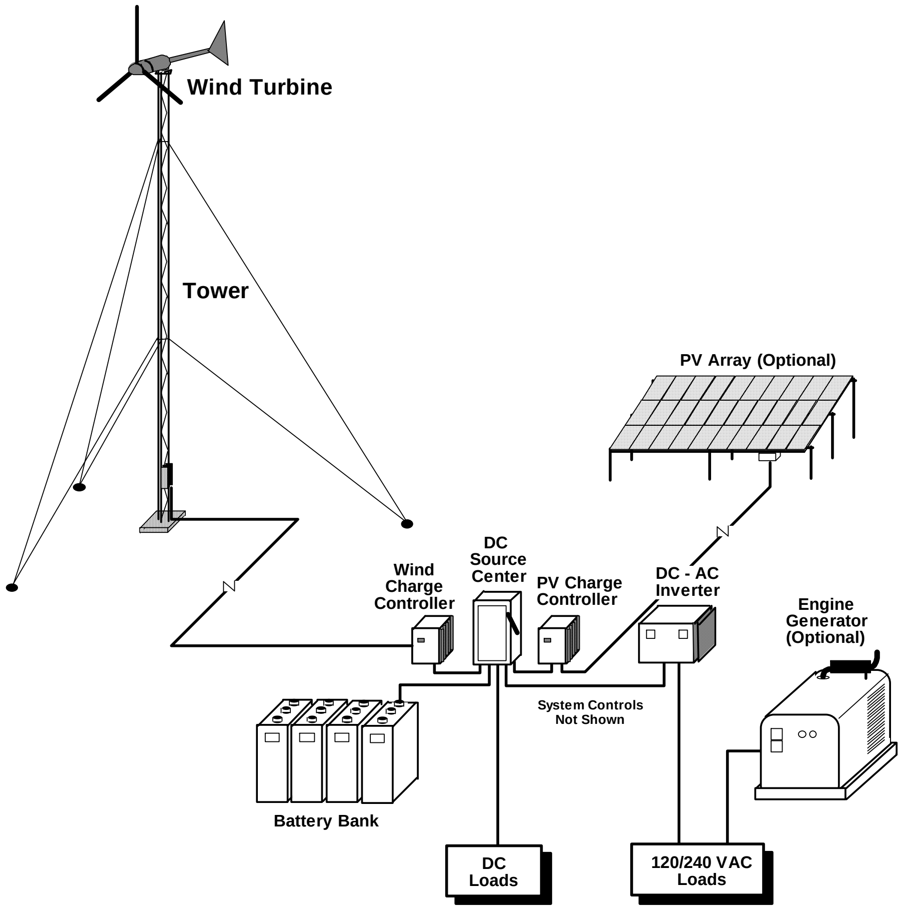
Wind/Solar/Diesel Hybrid Systems

The Smart Way to Power Remote Sites

- One or More DC Wind Turbines & Solar Arrays
- 1 - 3 Days of Battery Storage
- Back-up Diesel Generator for Low Wind / Solar Periods
- Advanced “Consumer” Inverters for AC, Diesel Starting, and Diesel Battery Charging



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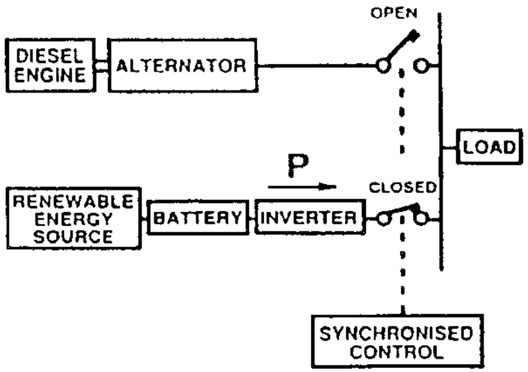
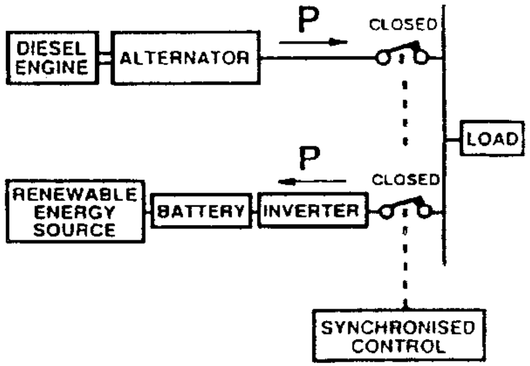
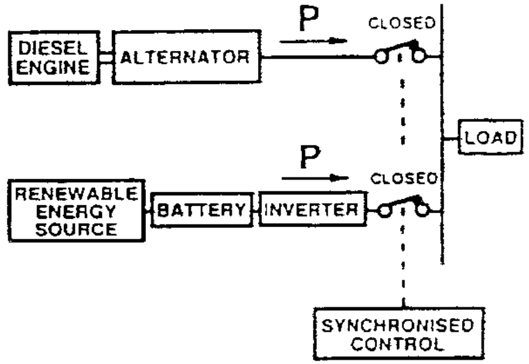
Advanced Inverter Systems



Normal Operation



Low Battery



High Load

Bi-Directional Inverters, which Include Battery Charging and Load Transfer Capabilities, Allow Back-up Diesels to be Used Efficiently

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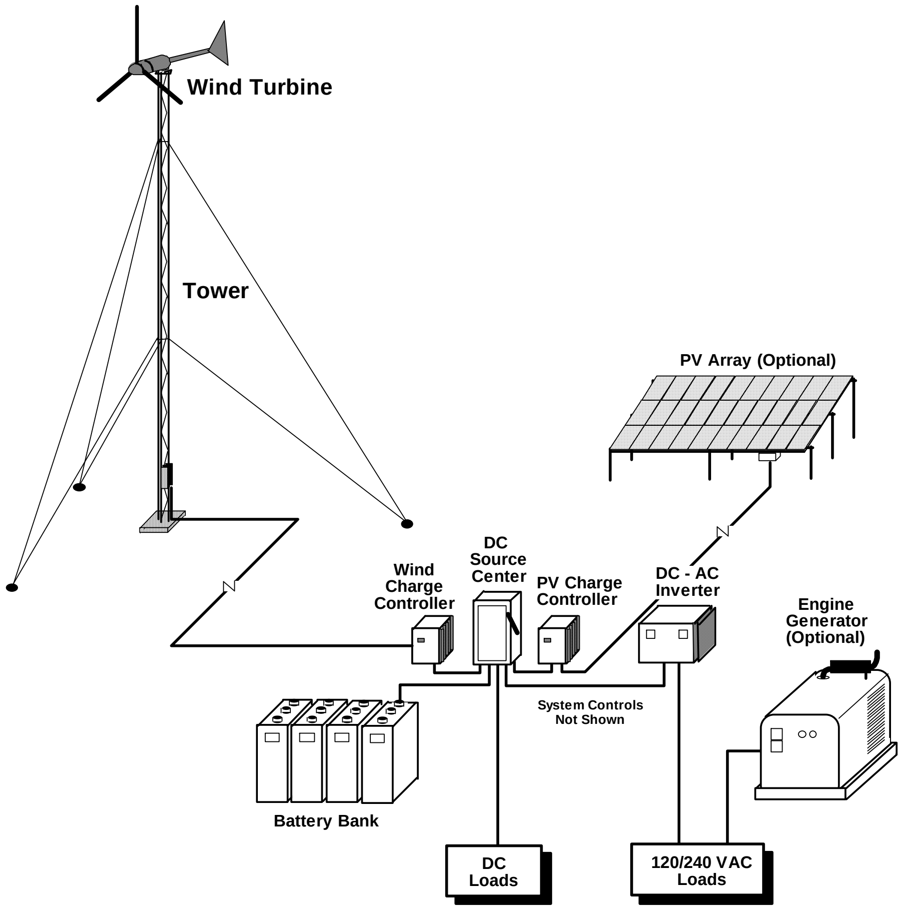
Hybrid Operational Modes

1. **Battery Normal: Wind & Solar Charging, Diesel Off**
2. **Battery High: Wind & Solar Regulate Output**
3. **Battery Low: Inverter Starts Diesel, Transfers AC Load & Charges Battery with Diesel at Most Efficient Power Level; Wind & Solar Charging … Reverts When Battery Charged**



Typical Telecom Project Metrics

- **Equipment:** BWC 7.5 kW Wind Turbine, 2 kW Solar, ~ 60 kWh Battery Bank, 15 kW Diesel, Controls, & Monitoring
- **Load:** 1.5 kW continuous, plus DC air-conditioning; ~ 50 kWh/day
- **Performance:** 80% Annual Fuel Savings
- **Cost:** $110,000
- **OPEX Savings:** ~ $25,000/year, fuel & diesel O&M ($1.25/liter)
- **Green Attributes:** Saves 600 tons of greenhouse gases and 3.6 tones of air pollutants over 30 year life

Safaricom
Masai Mara Game Reserve
Kenya

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Part 1:
Understanding the Fuel

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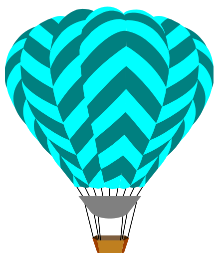
Wind Energy

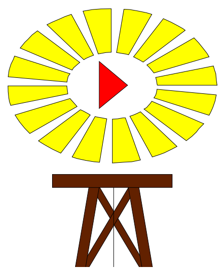
- Created by Uneven Solar Heating
- Wind Energy is Kinetic Energy ... Mass & Momentum
- Wind Energy is Proportional to Velocity Cubed (V^3) ... If Velocity is Doubled, Power Increases by a Factor of Eight ($2^3 = 8$) ... Small Differences in Average Speed Cause Big Differences in Energy Production
- Wind Resources are Abundant
- Distributed ... Most Areas Have Sufficient Wind for Off-Grid Power Applications
- Wind is Intermittent

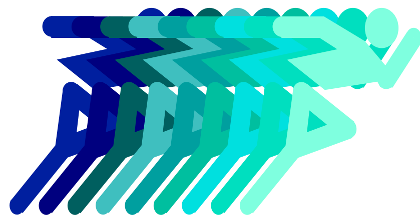
Power in the Wind (W/m^2)

= 1/2 x air density x swept rotor area x (wind speed)^3

ρ | A | V^3







Density = P/(RxT)

- P - pressure (Pa)
- R - specific gas constant (287 J/kgK)
- T - air temperature (K)

kg/m^3

Area = πr^2

m^2

Instantaneous Speed

(not mean speed)

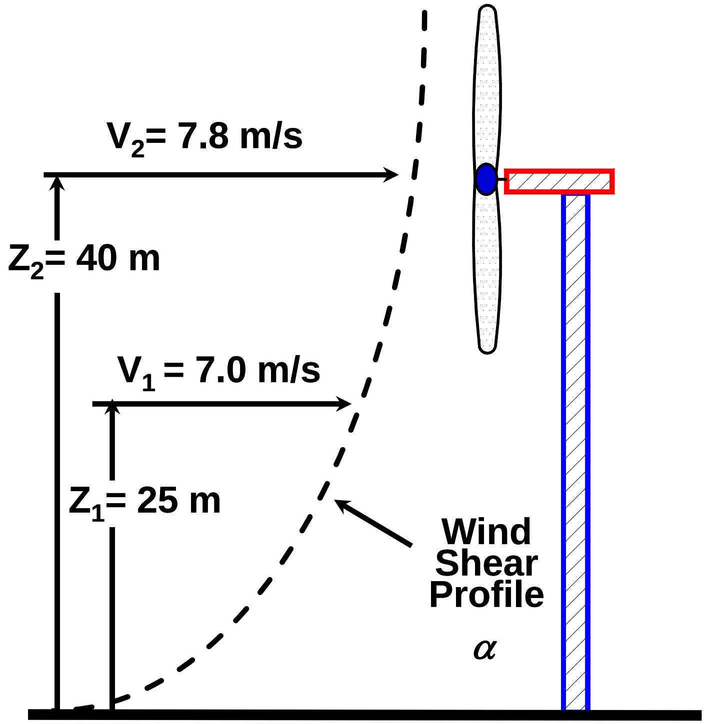
m/s

Graphic courtesy of AWS Scientific

Wind Shear

The change in horizontal wind speed with height

- A function of wind speed, surface roughness (may vary with wind direction), and atmospheric stability (changes from day to night)
- Wind shear exponents are higher at low wind speeds, above rough surfaces, and during stable conditions
- Typical exponent (α) values:
  - .10 - .15: water/beach
  - .15 - .25: gently rolling farmland
  - .25 - .40+: forests/mountains



$$\alpha = \frac{\text{Log}_{10}\,[V_2/V_1]}{\text{Log}_{10}\,[Z_2/Z_1]} \qquad V_2 = V_1(Z_2/Z_1)^{\alpha}$$

Graphic courtesy of AWS Scientific

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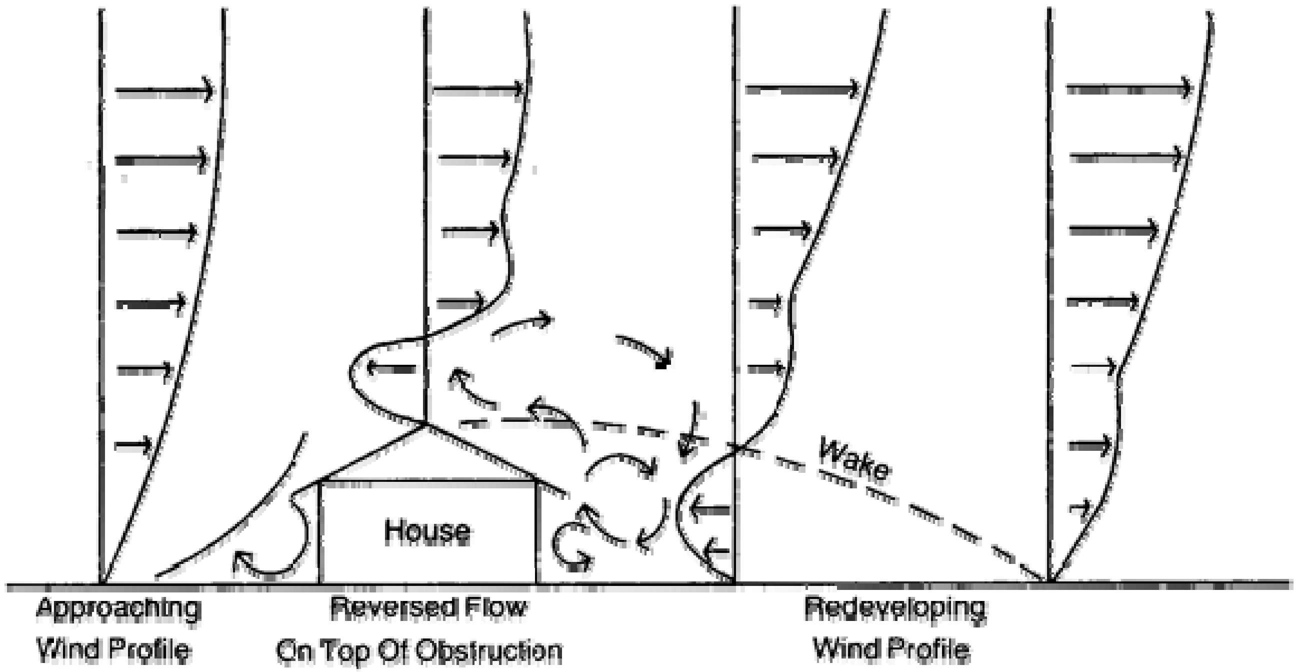
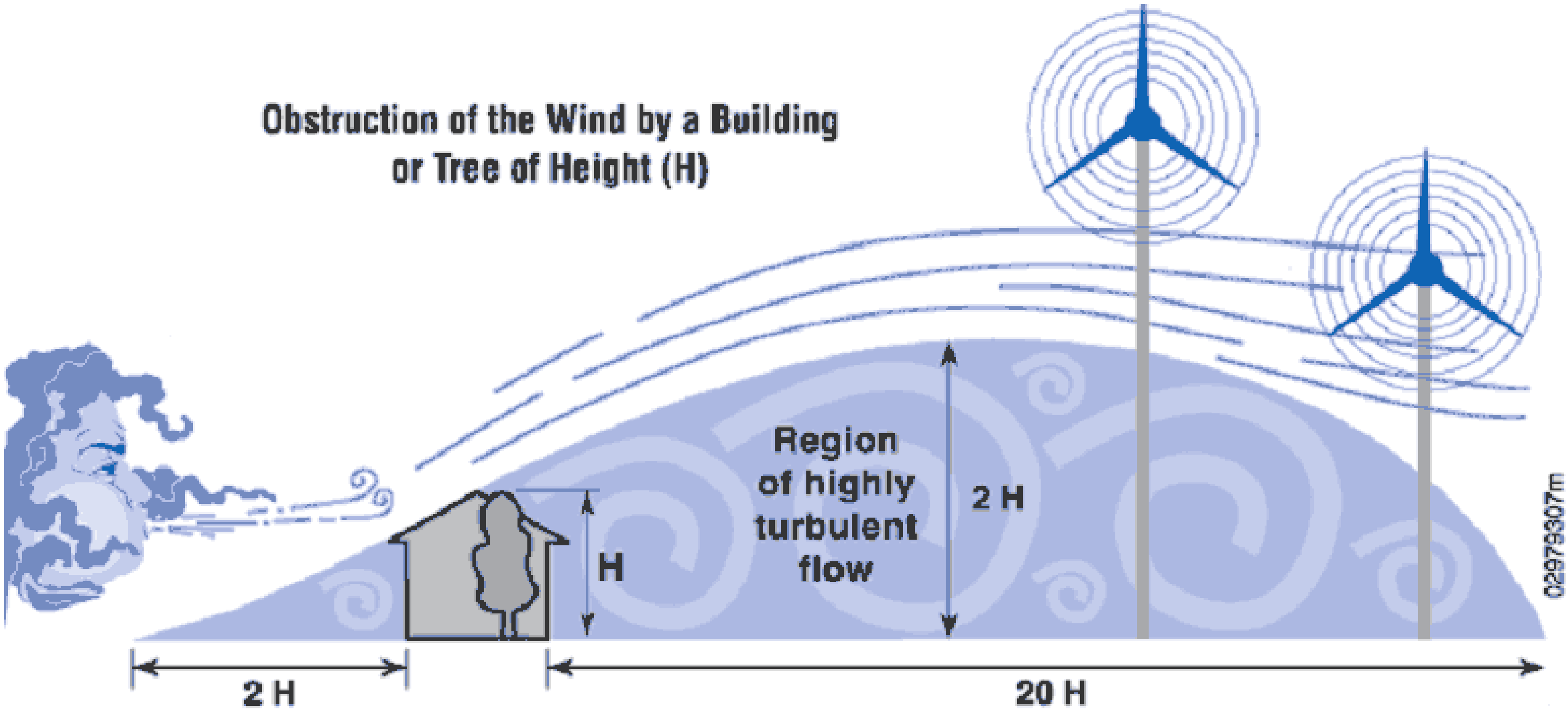
Turbulence



Turbulence cuts performance by reducing the effectiveness of the blades

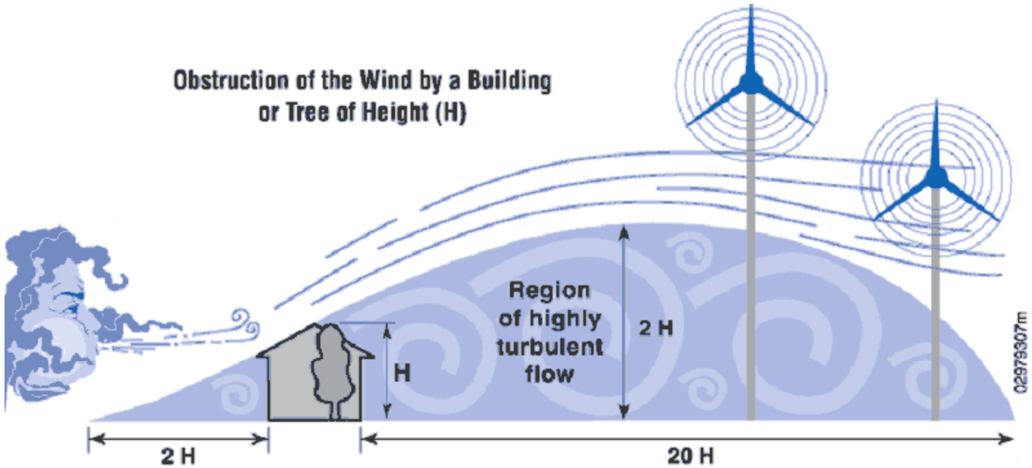
Height or Distance Needed



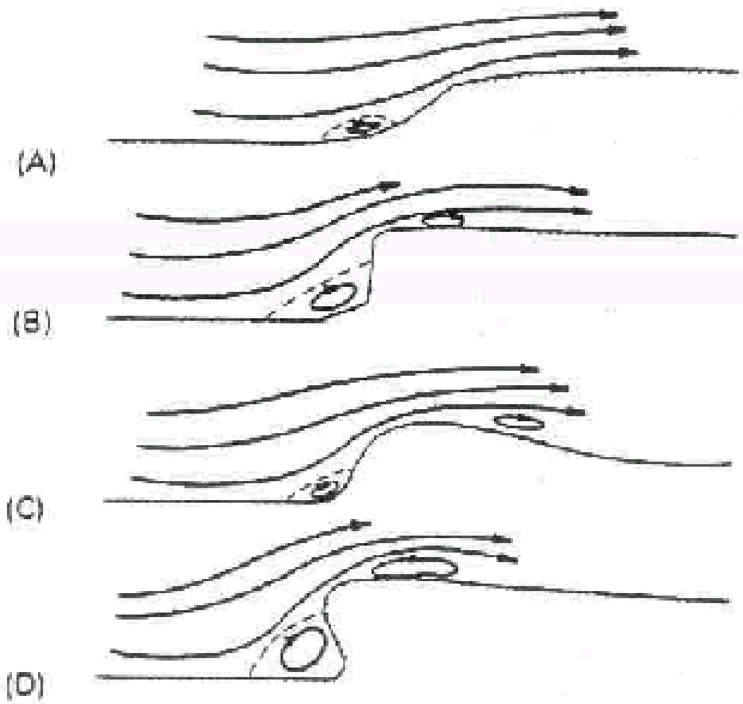
Rule-of-Thumb: Be <u>at least</u> 30 ft. above obstacles within 300 ft.

Tower Height Matters

Putting a Wind Turbine on a Short Tower is Like Putting a Solar Array in the Shade



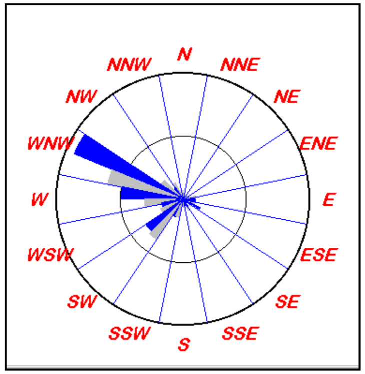
Avoid Cliffs

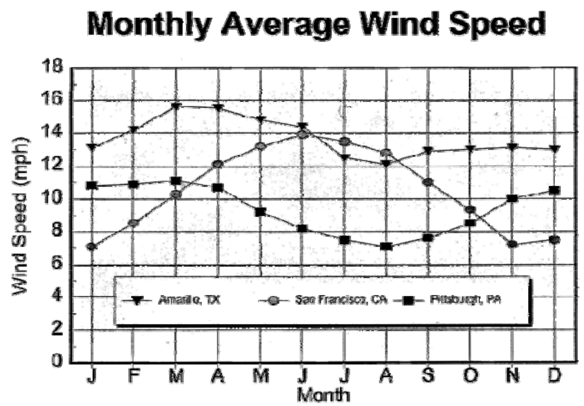


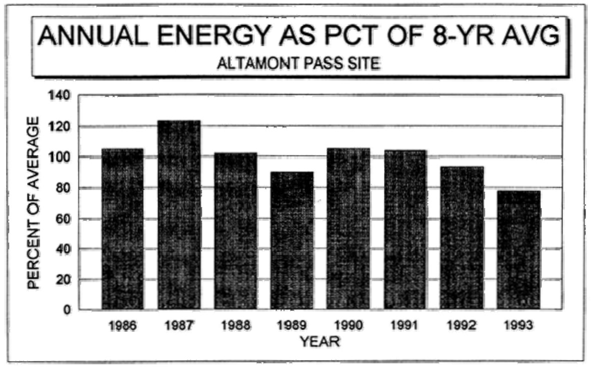
AutoFurl (passive furling) needs horizontal flow through the rotor

Additional Considerations

- **Wind turbine performance diminishes with altitude**
- **Sites have "Prevailing Wind Direction" … useful in considering effects of obstructions and multi-turbine array layout**
- **Wind resources vary seasonally and annually**



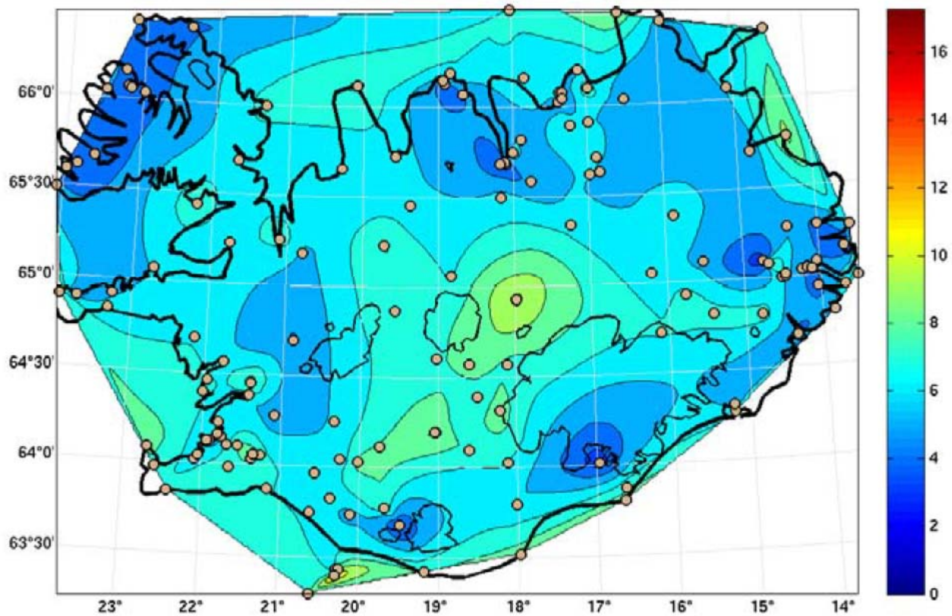




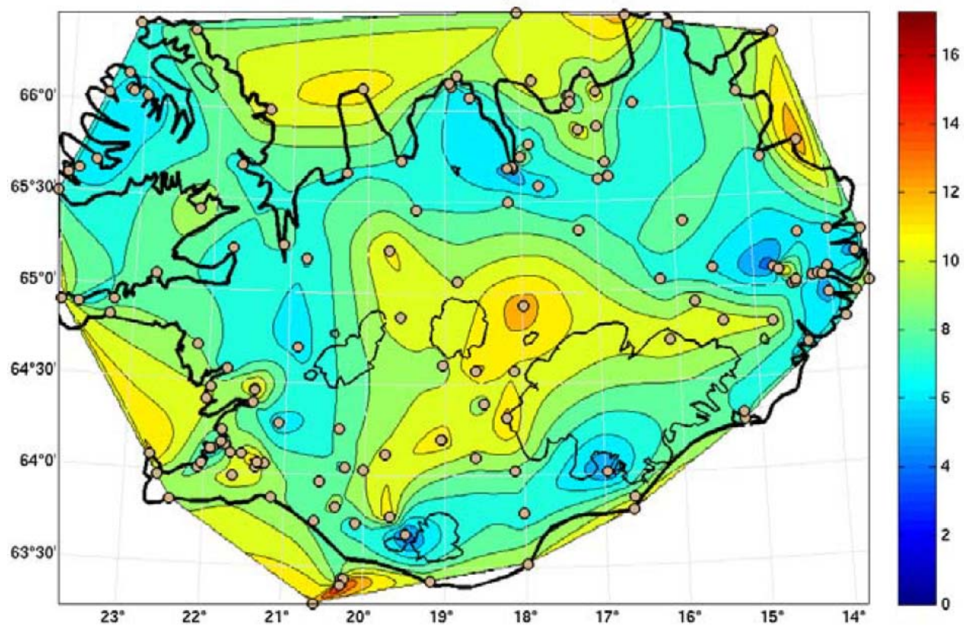
What's the wind resource where I need energy?

Wind Maps

Iceland, 90m
Warm Season
(May - August)

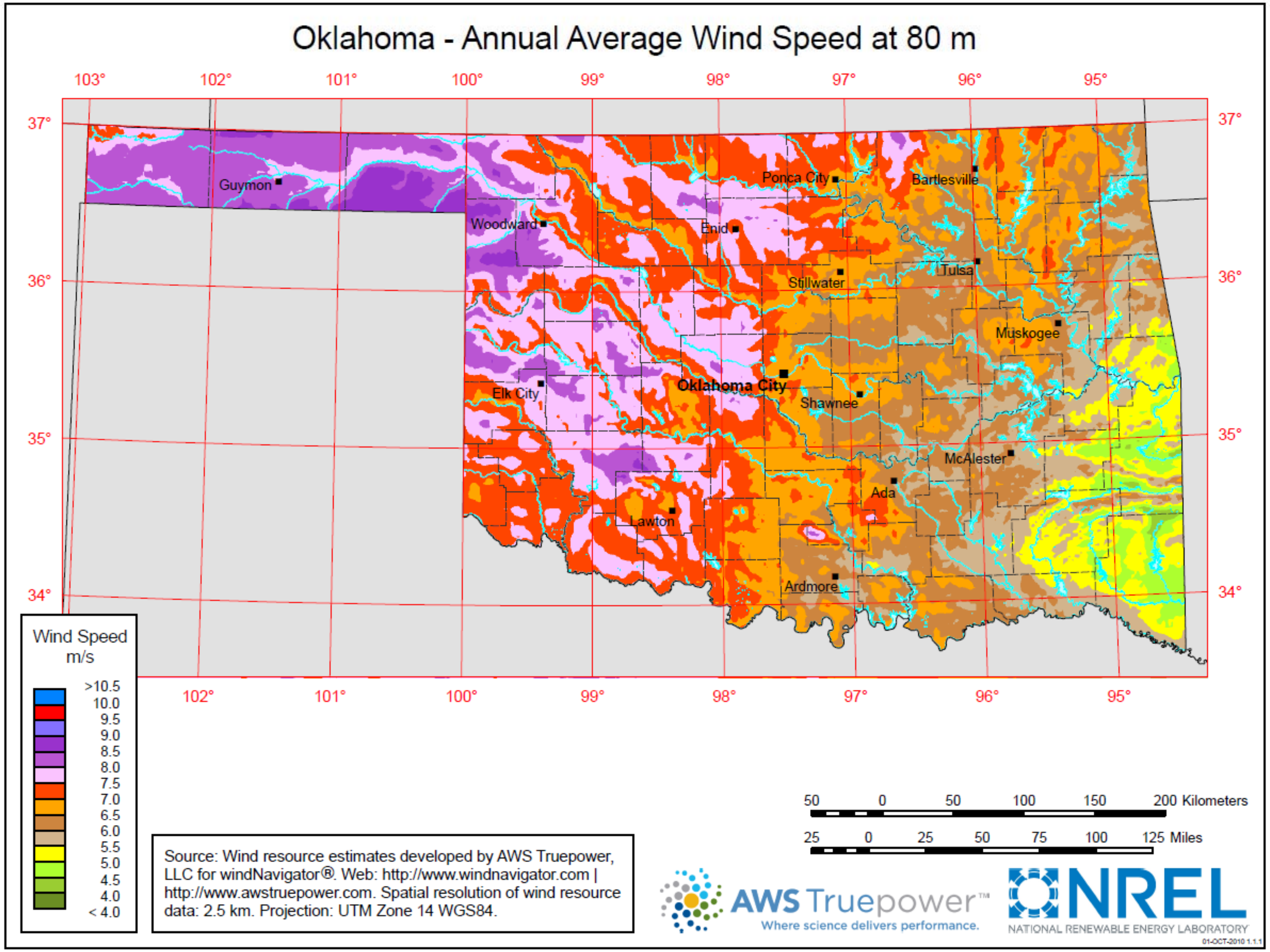


Iceland, 90m
Cold Season
(Sept - April)

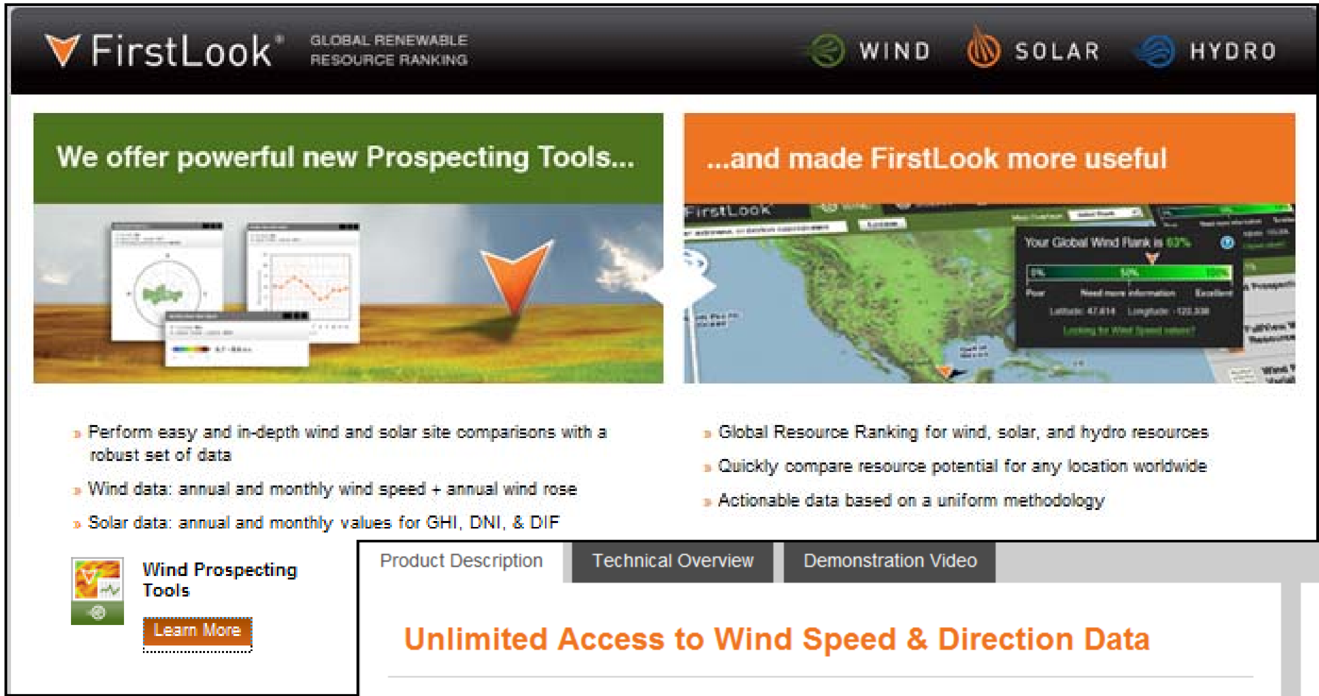


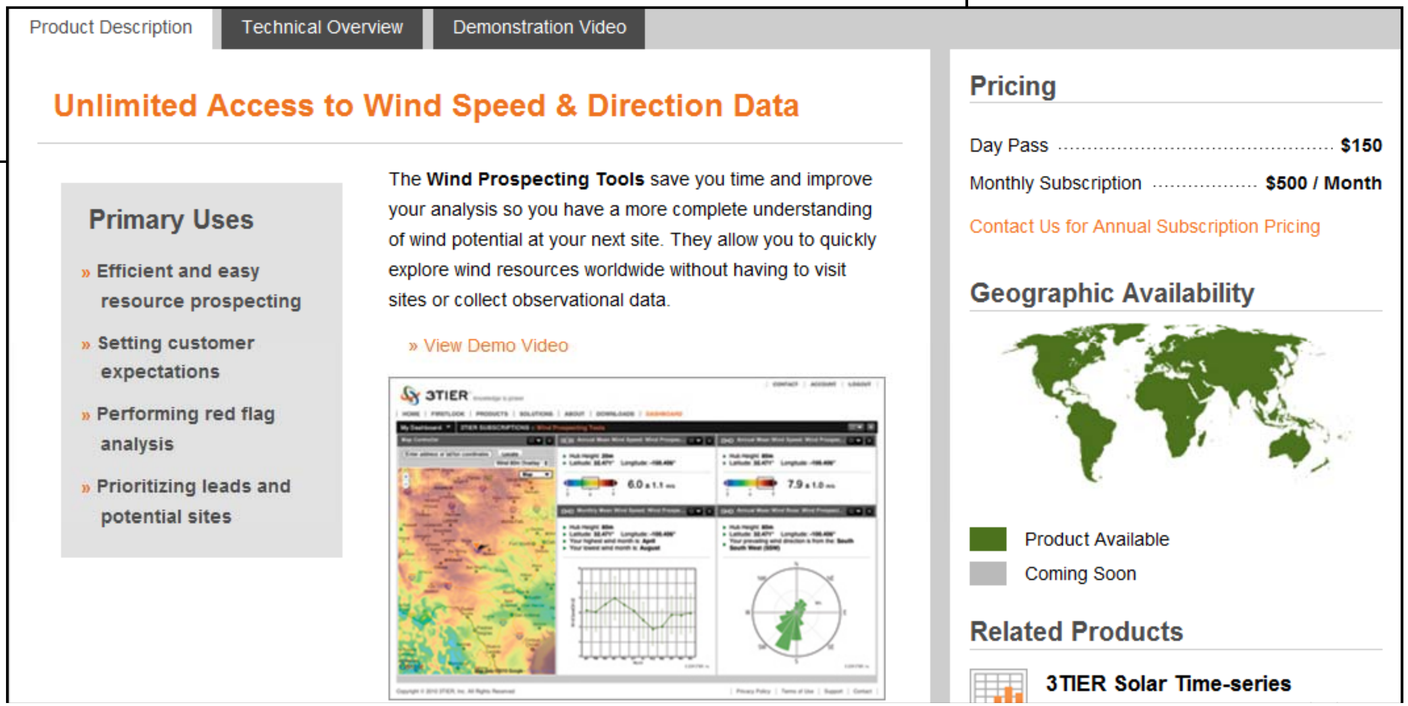
Source: Univ. of Iceland "IceWind" project

Detailed Digital Maps:
Upper Air Data + GIS + Math



Subscription Web Based Wind Maps





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Integrated On-line Performance Tools

Bergey WindCad Performance & Economics Evaluation Tool

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Turbine Production   Financial Analysis   Saved Sessions   Contact Us

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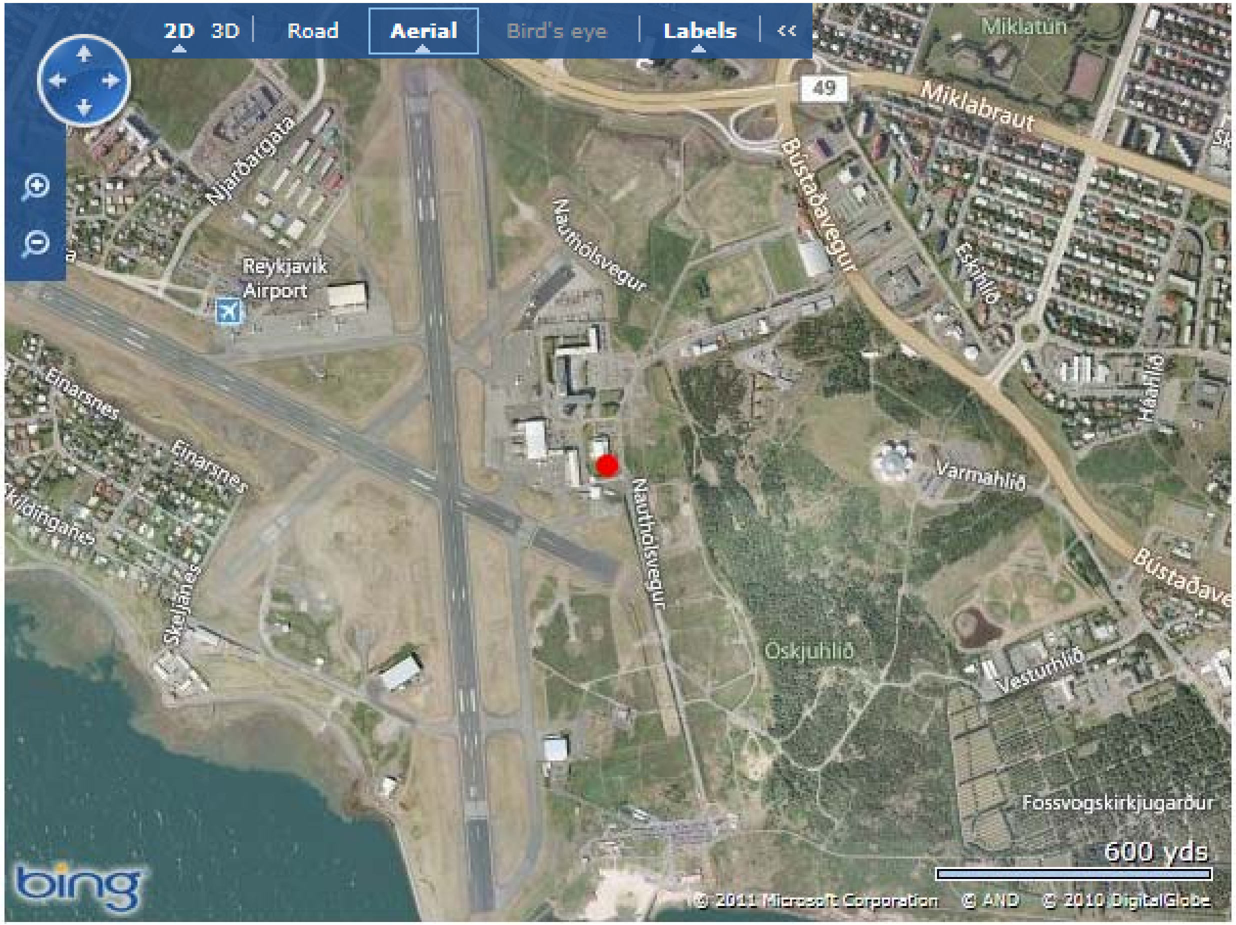
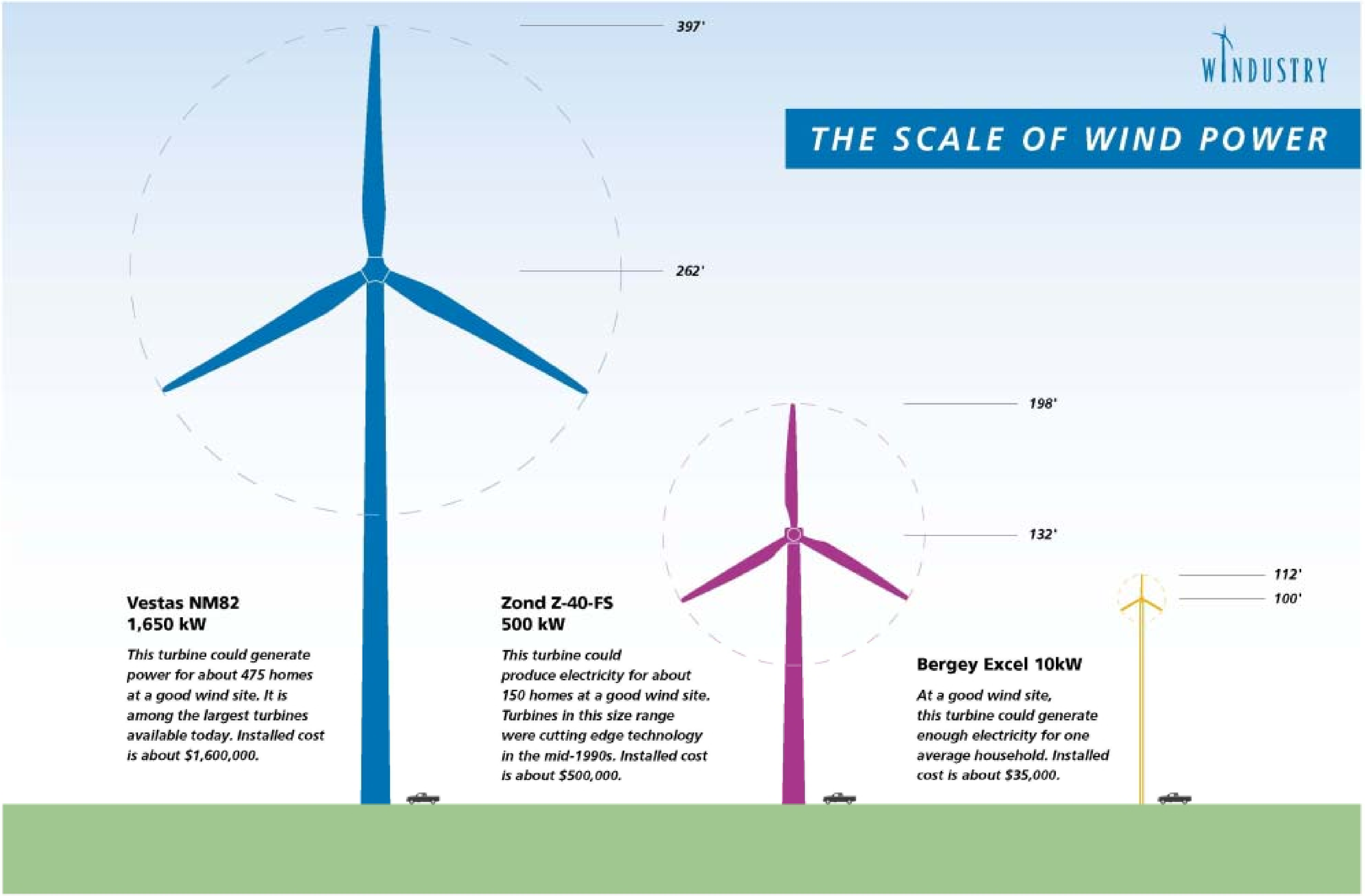
Turbine Production:



Turbine Selection	Bergey Excel 10
Nameplate Capacity [kW]	10.0
Rotor Diameter [m]	7.0
Site Location:	
64.129239° latitude -21.930458° longitude	
Average Wind Speed [mph]	14.85
Tower Height [ft]	100.0
Altitude [ft]	150.0
Weibull K	3.0
Wind Shear	0.18
Turbulence Factor [%]	5.0
Average Output Power [kW]	2.4
Daily Energy Output [kWh]	58.7
Monthly Energy Output [kWh]	1,784.5
Annual Energy Output [kWh]	21,414.4
Hub Average Wind Speed [mph]	14.9
Air Density Coefficient	1.0
Operating Time [%]	96.4

Part 2:
Small Wind Turbine Technology

Small and Large Wind are Different

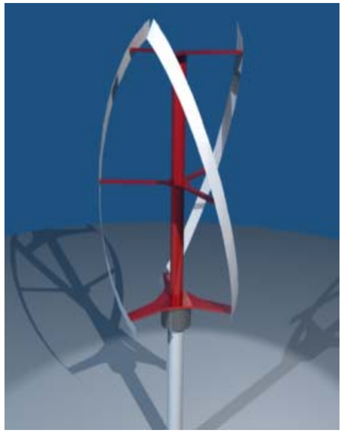


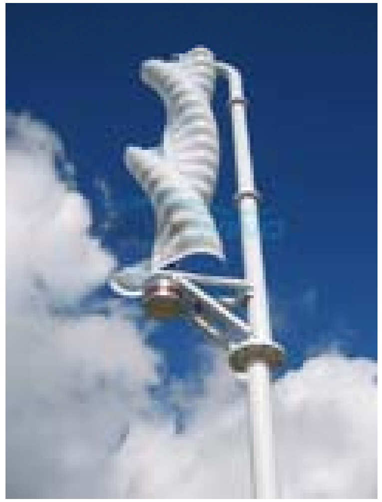
Modern Small Wind Turbines:

High Tech, High Reliability, Low Maintenance

- Products from 200 W – 100 kW
- Technically Advanced, Sophisticated & Simple
- Very Low Maintenance Requirements
- Certified Products Available

Turbine Configurations



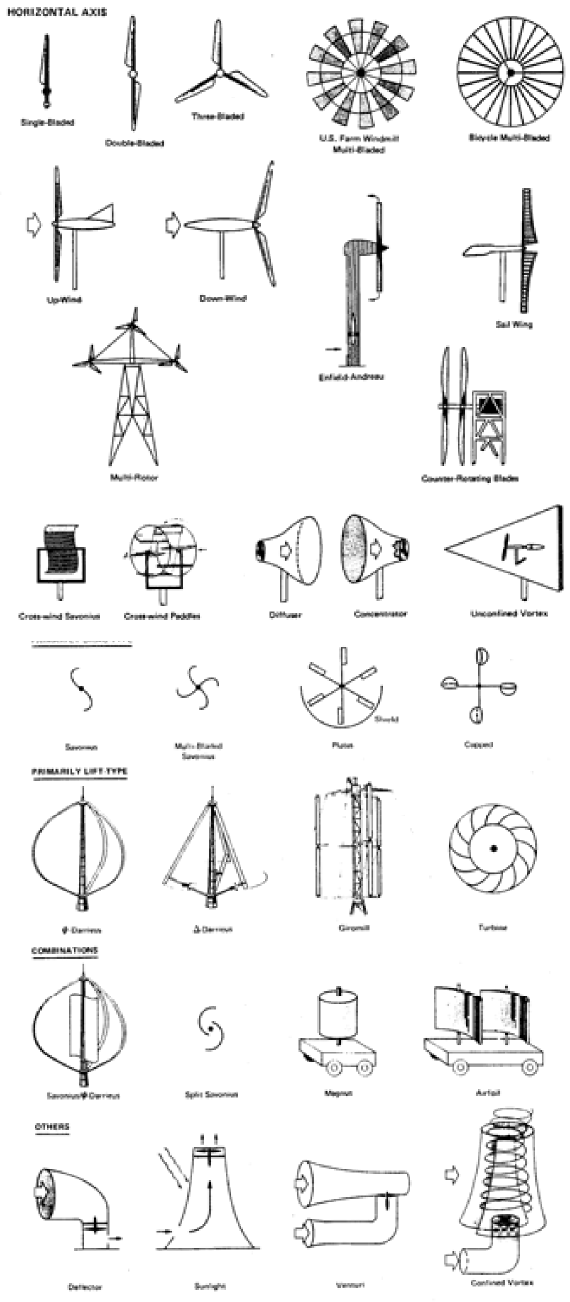


Horizontal-axis
(HAWT)
99%
Market Share

Vertical-axis
(VAWT)
1%
Market Share

Turbine Configurations

- ❖ **Hundreds of possible configurations ... most are bad or terminally uncompetitive**
- ❖ **Bad configurations keep getting "re-invented", wasting time and money:**
  - ❖ **Savonius (drag-type) Vertical-Axis Rotor in dozens of variations**
  - ❖ **Concentrators / Diffusers**
- ❖ **Uncompetitive, but pretty**
  - ❖ **Darrieus (lift-type) Vertical-Axis Rotors**

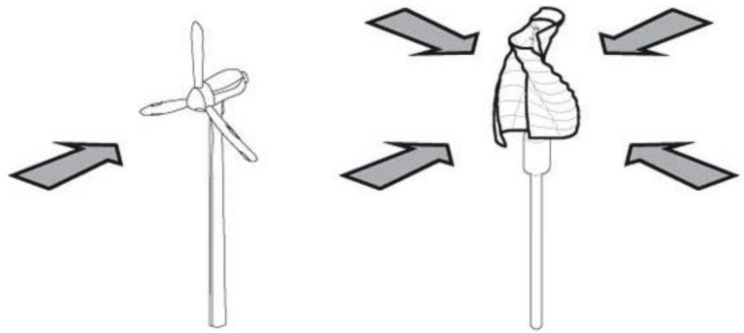


Bozos & Hucksters

- **Bozo:** Clueless on physics and engineering - don't know what they don't know
- **Huckster:** Aware that their claims are bogus and don't care
- General public wants to believe that there's been a performance and cost breakthrough
- Identification: 1) Performance claims that exceed Betz Limit (59.3%) or really short towers
- Vertical-axis is a favorite

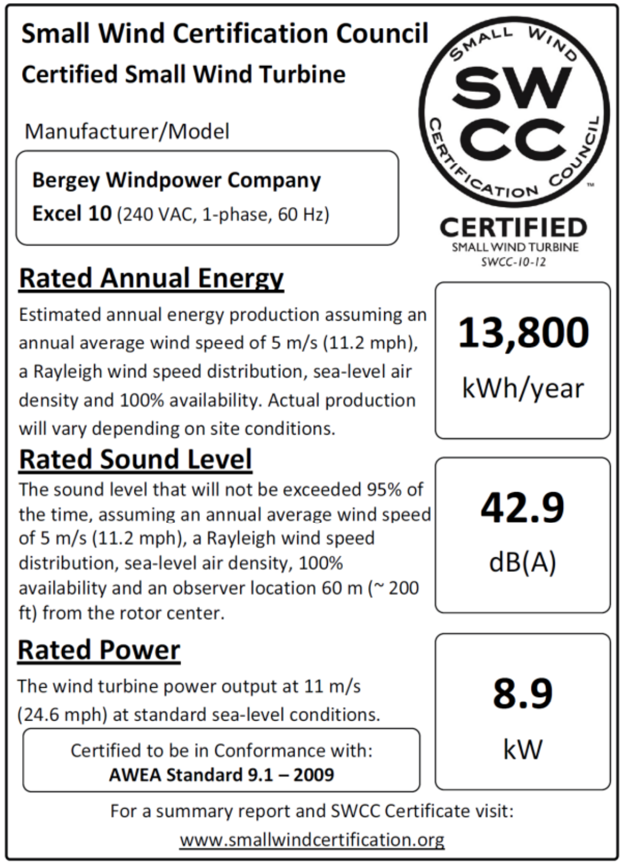
Common False Claims – Beware!

- “50% more efficient that conventional wind turbines”
- “Superior because it accepts wind from all directions”
- “Works well in turbulence”
- “Our technology eliminates the need for tall towers”
- “Bird friendly”



AWEA Certification Standard

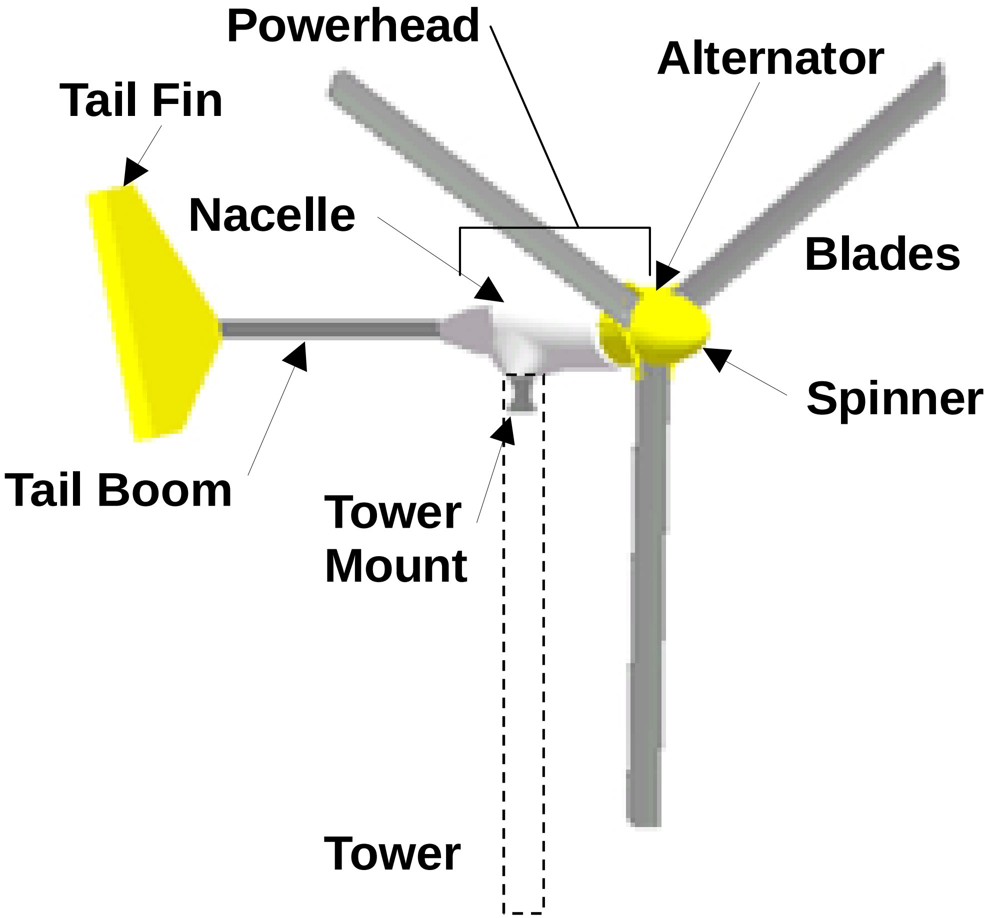
- Sets Rated Power at 11 m/s (25 mph)
- Introduces “AWEA Estimated Annual Energy” modeled after EPA Estimated Mileage for cars
- 6 month duration test; 90% availability requirement
- Detailed structural analyses (based on IEC 61400-2)
- Certifications issued by SWCC (smallwindcertification.org) or other agency
- “Same” standard adopted in UK & Japan



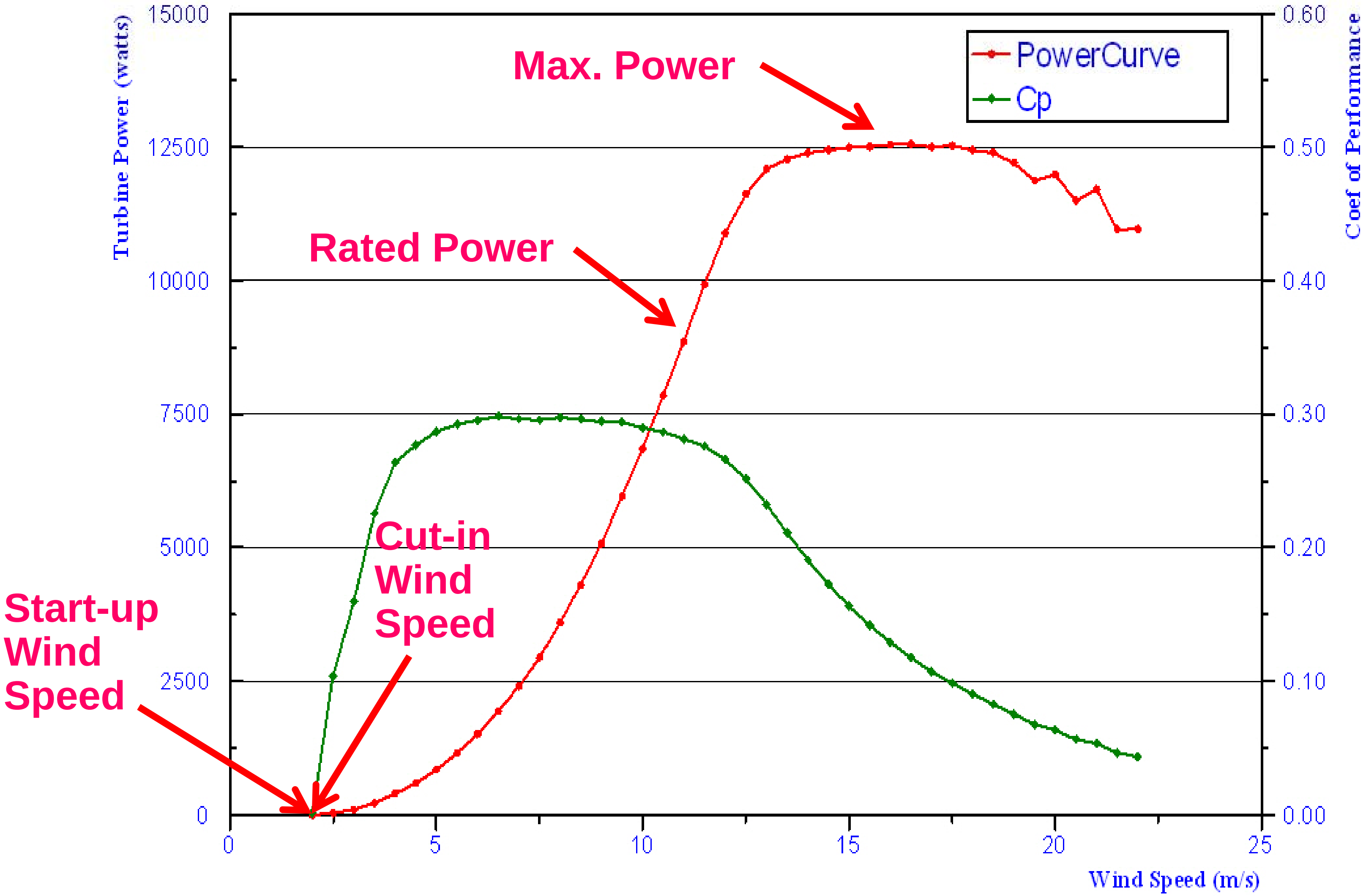
Generic Small Wind Turbine

Mechanically Simplicity ...
Few Moving Parts

- 3 Blade Rotor - Fixed Pitch
- Special “Integrated” Direct Drive Permanent Magnet Generator
- Tail Aligns Rotor to Wind
- Passive Overspeed Protection by Furling, either Up or to Side; or with mechanical blade pitch system
- No Mechanical Brake ... Shutdown with Electrical Braking

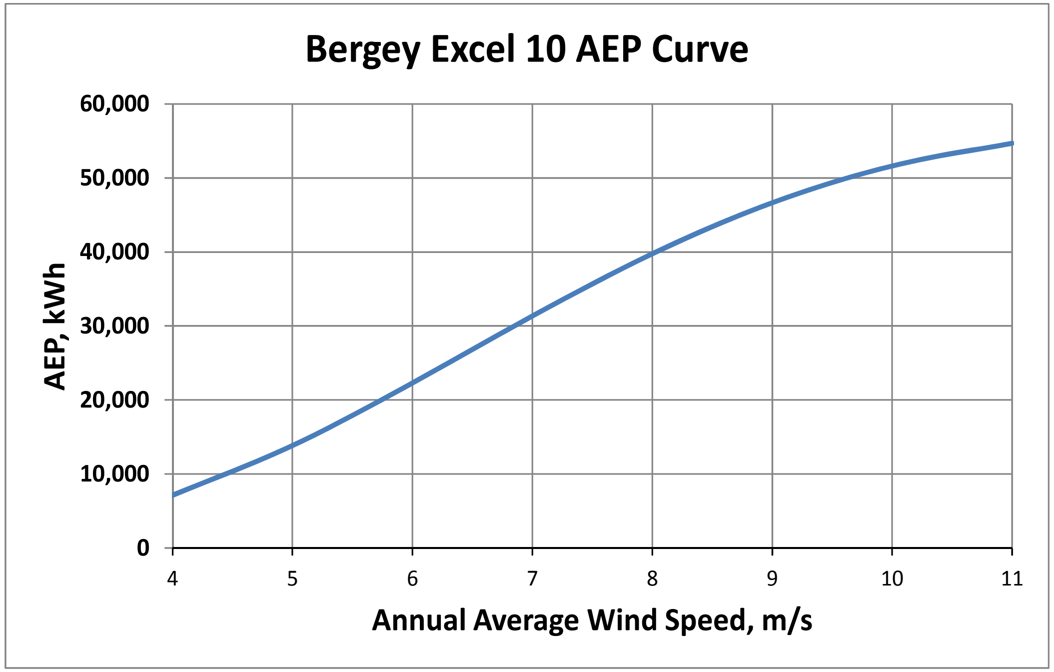


Performance: Power Curve



Manufacturer's Annual Energy Output Ratings

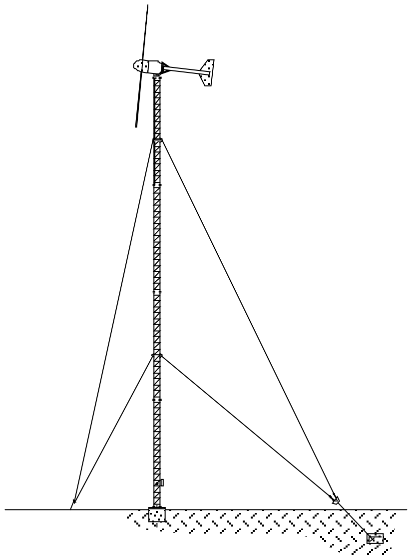
Hub Height Annual Average Wind Speed (m/s)	Estimated Annual Energy Production (kWh)
4	7,135
5	13,842
6	22,300
7	31,342
8	39,755
9	46,652
10	51,626
11	54,685



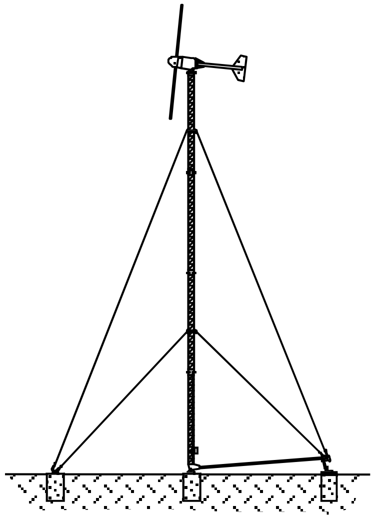
Towers

Numerous Options

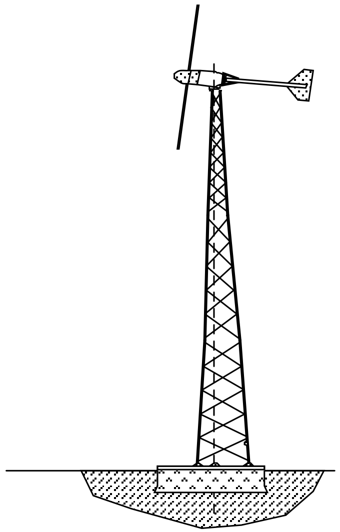
Towers of 18 - 37 m (60 - 120 ft) Recommended for Most Situations



Guyed-Lattice



Guyed Tilt-up



Self-Supporting Lattice

Monopole

Lowest Costs → **Highest Costs**

Technical Challenge

- **Difficult Operating Environment:**
  - Energy Inflows from 38 W/m2 (4 m/s) to 94,500 W/m2 (54 m/s)
  - 7,000+ Operating Hours per Year
  - 75 Million Cycles per Year: > 2 Billion in 30 Year Life
  - High Gusts, High Turbulence, Lightning, Icing, Salt, Spray, Sand, Etc.
  - Difficult Maintenance Environment
- **Dispersed Installations Means Expensive Maintenance & Repairs**
- **Reliability is Paramount**

Reliability and Maintenance

- **Turbines Operate Unattended and Automatically, Even in Severe Weather**
- **Reliability and Maintenance Requirements are Design Specific ... Look for:**
  - Simplicity of Design
  - Fiberglass Blades
  - Direct Drive, Brushless, Generators
  - Heavy Weight Structural Elements
  - Corrosion-Resistant Materials and Finishes

  ... and Check Supplier Reputations!
- **Best Available Units Require No Scheduled Maintenance and can Operate for 6-20 Years Without Attention**
  - Inspection Recommended Every 2 Years
  - At 6-20 Years, Blade Leading Edge Tape Must be Renewed
- **Typical Design Operating Life is 30 Years (Some Small Turbines Have been Operating for More Than 60 Years!)**

Shopping for Small Wind Systems

- Unlike solar, product quality is design specific
- Look for a verifiable track record – otherwise your project will be part of the beta test
- Turbine should be certified or under test for certification
  - SWCC, Intertek, or British MCS
- Company's financial strength / stability can be an issue (to avoid orphaned products)

Top Off-Grid Manufacturers

- Bergey Windpower (USA)
- Kestrel (South Africa)
- Sonkyo (Spain)
- Bornay (Spain)
- Northern Power (USA)
- Kingspan (Ireland/UK)

End of First Session

Questions?

Part 3:
Design of DC-bus Hybrid Systems

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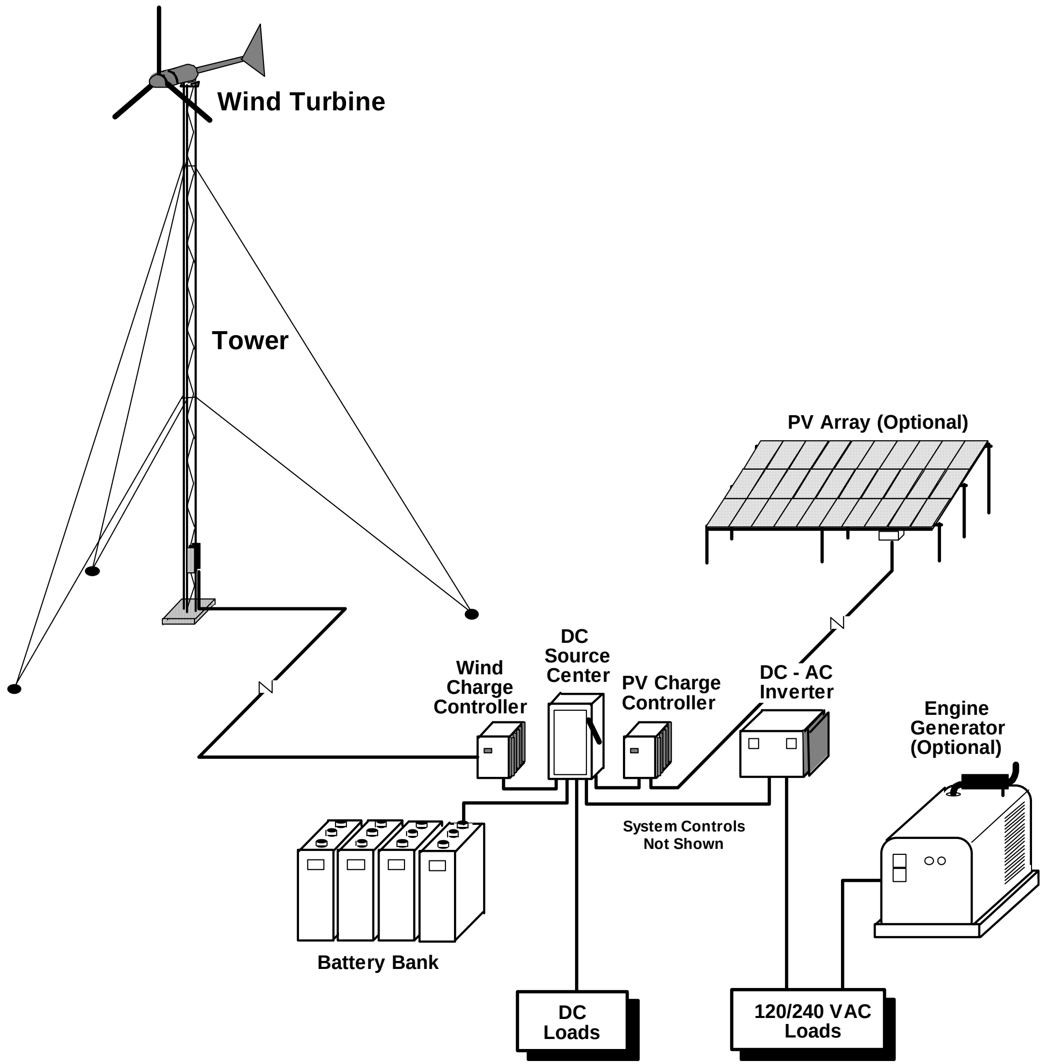
Major Components

1. **Wind Turbine(s)**
2. **Solar Array(s)**
3. **Battery Bank**
4. **Inverter(s)**
5. **Diesel Generator**



Steps in Design

1. Use Best Available Information and Experience from Similar Installations to Establish Load (kWh/day) Requirements
   - "Load Counting" Method is Common
   - Penalty for being wrong is more fuel consumption or more costs, not lower reliability

Steps in Design

2. Convert AC Energy Requirements to DC Using Balance-of-System (BOS) Efficiency, Such As:
   - Battery Net Efficiency = 85%
   - Inverter Net Efficiency = 90%
   - Wiring Net Efficiency = 96%
   - "Controls" Net Efficiency = 90%

Total BOS Efficiency = ~65%

Steps in Design

3. **Use Best Available Information to Establish Annual / Monthly Average Wind Speed Estimates**

Wind and Solar Resources

Month	Average Wind Speed (m/s)*	Solar Resource (kWh/m2/day)
Jan	5.2	3.3
Feb	5.4	4.1
Mar	5.8	4.2
Apr	6.1	4.6
May	5.8	5.2
Jun	5	6.1
Jul	4.8	6.2
Aug	3.9	6.2
Sep	4.4	5.6
Oct	5	5.1
Nov	4.8	4.5
Dec	5.4	3.9
Annual	5.1	4.9

[* at 10m height]

Steps in Design

4. **Establish Site Conditions and Other Parameters Necessary for the Performance Model - Calculate Turbine Performance (Daily Energy Output) for Each Month**

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Bergey WindCad Performance & Economics Evaluation Tool

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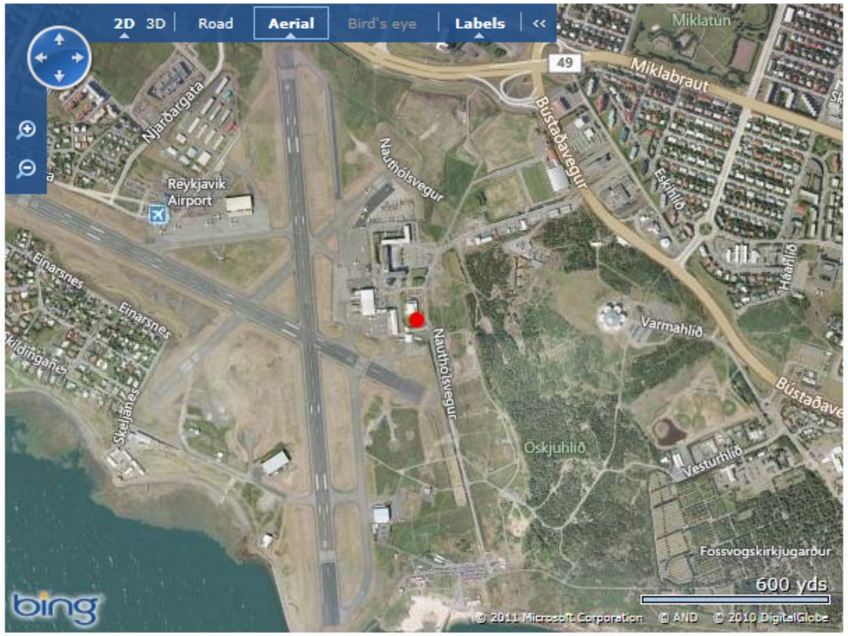
Turbine Production:



Turbine Selection	Bergey Excel 10
Nameplate Capacity [kW]	10.0
Rotor Diameter [m]	7.0
Site Location:	
64.129239° latitude -21.930458° longitude	
Average Wind Speed [mph]	14.85
Tower Height [ft]	100.0
Altitude [ft]	150.0
Weibull K	3.0
Wind Shear	0.18
Turbulence Factor [%]	5.0
Average Output Power [kW]	2.4
Daily Energy Output [kWh]	58.7
Monthly Energy Output [kWh]	1,784.5
Annual Energy Output [kWh]	21,414.4
Hub Average Wind Speed [mph]	14.9
Air Density Coefficient	1.0
Operating Time [%]	96.4

Steps in Design

5. **Use Best Available Solar Resource Information to Establish Monthly Average Peak Sun Hours or kWh/m2/day**
   - **First Approximation: PSH x Array Size = Daily Energy**

Wind and Solar Resources

Month	Average Wind Speed (m/s)*	Solar Resource (kWh/m2/day)
Jan	5.2	3.3
Feb	5.4	4.1
Mar	5.8	4.2
Apr	6.1	4.6
May	5.8	5.2
Jun	5	6.1
Jul	4.8	6.2
Aug	3.9	6.2
Sep	4.4	5.6
Oct	5	5.1
Nov	4.8	4.5
Dec	5.4	3.9
Annual	5.1	4.9

[* at 10m height]

Steps in Design

6. **Calculate "Load Coverage" for each Month**
   - **LC < 100% means back-up required**
   - **LC > 100% means dumped energy**
   - **Recommend Annual Average LC ~ 75% for hybrids with diesel back-up**

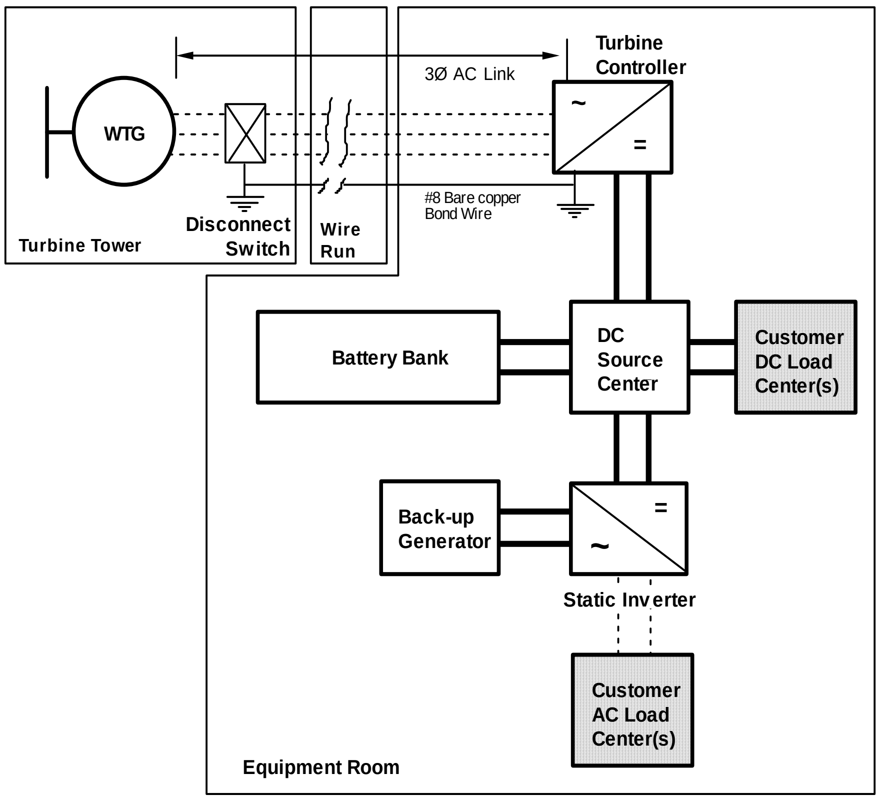
	INPUTS						
Month	1.0 kW Wind Daily Energy Output, kWh	1 kW PV Daily Energy Output, kWh	Wind Daily Energy Output, kWh	PV Daily Energy Output, kWh	Total Daily Energy Output, kWh	Avg. Daily Load	Load Coverage %
JAN	**6.3**	**3.3**	12.6	1.0	13.6	7.70	176%
FEB	**6.9**	**3.7**	13.8	1.1	14.9	7.70	194%
MAR	**7.8**	**4.2**	15.6	1.3	16.9	7.70	219%
APR	**8.6**	**4.6**	17.2	1.4	18.6	7.70	241%
MAY	**7.8**	**5.2**	15.6	1.6	17.2	7.70	223%
JUN	**5.8**	**5.8**	11.6	1.7	13.3	7.70	173%
JUL	**5.3**	**6.2**	10.6	1.9	12.5	7.70	162%
AUG	**3.2**	**6.2**	6.4	1.9	8.3	7.70	107%
SEP	**4.3**	**5.6**	8.6	1.7	10.3	7.70	133%
OCT	**5.8**	**5.1**	11.6	1.5	13.1	7.70	170%
NOV	**5.3**	**4.5**	10.6	1.4	12.0	7.70	155%
DEC	**6.9**	**3.9**	13.8	1.2	15.0	7.70	194%
Annual Ave.	6.2	4.9	12.3	1.5	13.8	7.70	179%

Steps in Design

7. Iterate Calculations to Fit Project Design Goal
   - Minimum Renewables Fraction, or
   - Minimum COE, etc

Steps in Design

8. Choose Complete System Architecture - Single Line Schematic



Steps in Design

9. Size Battery Bank
   - Rule of Thumb: AH Capacity ~ 6 Times Rated Wind + PV Current
   - Higher AH for Telecom, Reduced Diesel Usage, Etc.
   - Lower AH for Larger Systems, Trade Winds, Etc.

Steps in Design

10. Size Inverter
    - Rule of Thumb: Inverter kW = Total Renewables kW
    - Watch for High Surge Requirements (Induction Motors)
    - Bigger is Generally Better

Steps in Design

11. Size Back-up Generator
    - Rule of Thumb: Generator kW = 1.25 x Total Renewables kW
    - Watch for Big Intermittent Loads (eg, commercial ice maker)
    - Too Big is Bad

Steps in Design

12. Complete Balance of Systems Design
    - Tend to Favor Certain BOS Component Suppliers (e.g., Outback or SMA inverters inverters)
    - Design Standardization has Many Benefits

Steps in Design

13. Prepare Equipment & Services Budget

Part 4:
Budgetary Hybrid System Costs

Cost Assumptions

- ❖ Equipment priced at MSRP
- ❖ Existing diesel generator used for back-up

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1 kW Wind / 1 kW Solar Total System Budgetary Cost

Energy Production:
6 – 12 kWh/Day DC
5 – 11 kWh/Day AC

Croatia

Item	Description	Cost
1	1 kW, 24 VDC Wind Turbine	$4,600
2	60 ft. Guyed-Tubular Tower	$2,200
3	1 kW Solar System	$4,500
4	12 kWh VRLA Battery	$3,000
5	2.5 kW Inverter	$2,800
6	DC Source Center	$600
7	Misc. Wiring & Electrical	$400
8	Equipment Cabinents	$4,000
9	Foundations	$1,500
10	Wire Run (80 ft)	$600
11	Shipping & Delivery	$2,500
12	Install Labor & Services	$2,000
13	Misc. Costs	$2,500
	Total:	**$31,200**

6 kW Wind / 2 kW Solar Total System Budgetary Cost

Energy Production:
26 – 60 kWh/Day DC
23 – 54 kWh/Day AC

Nevada, USA

Item	Description	Cost
1	6 kW 48 VDC Wind Turbine	$22,000
2	60 ft. Guyed-Tubular Tower	$9,200
3	2 kW Solar System	$9,000
4	50 kWh VRLA Battery	$12,500
5	7.2 kW Inverter Array	$5,800
6	DC Source Center	$1,200
7	Misc. Wiring & Electrical	$2,900
8	Modified 20 ft Container	$12,000
9	Foundations	$3,500
10	Wire Run (80 ft)	$1,200
11	Shipping & Delivery	$4,000
12	Install Labor & Services	$3,500
13	Misc. Costs	$4,000
	Total:	**$90,800**

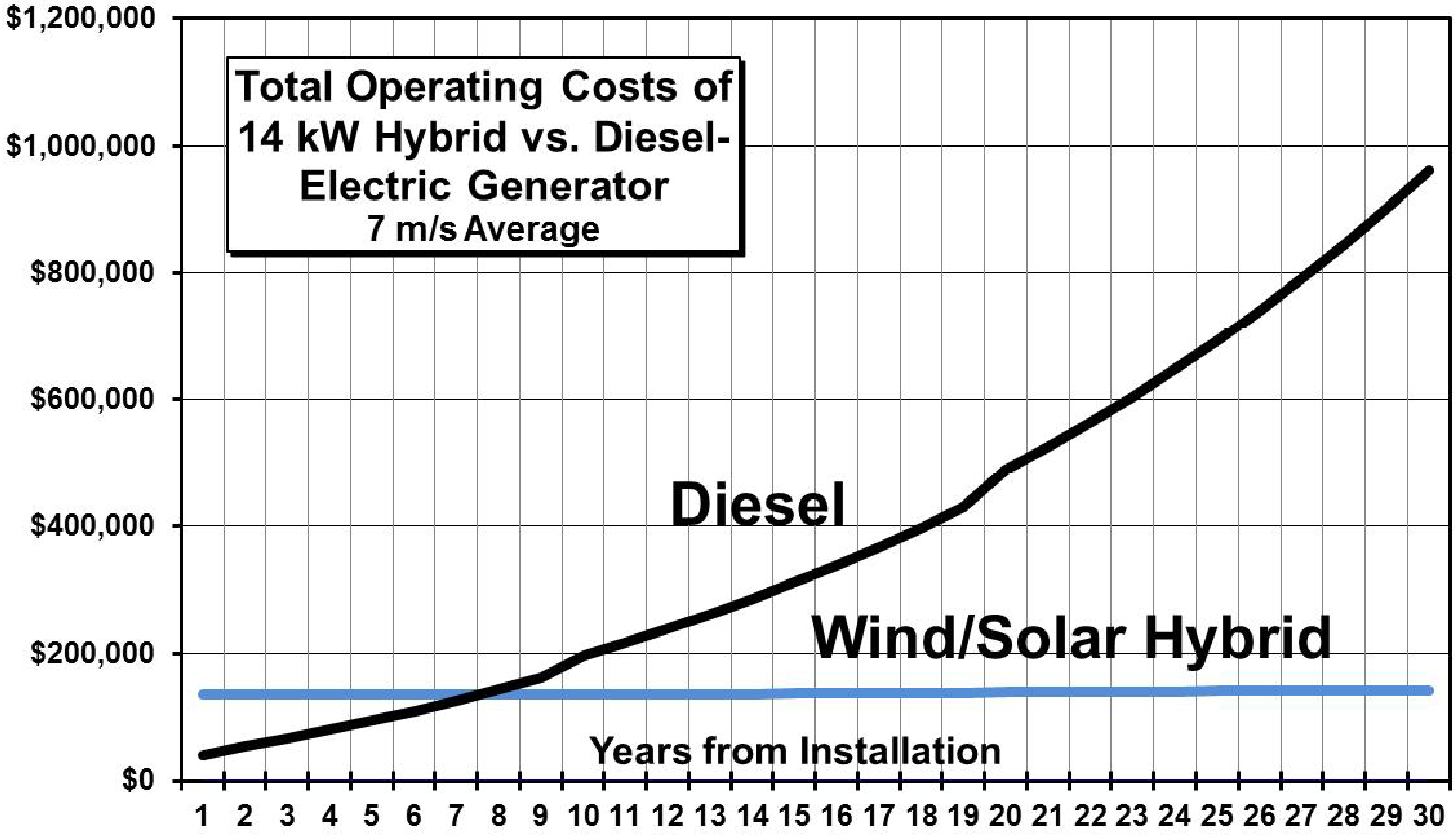
10 kW Wind / 4 kW Solar Total System Budgetary Cost

Energy Production:
55 – 110 kWh/Day DC
50 – 100 kWh/Day AC

Southern Chile

Item	Description	Cost
1	10 kW 48 VDC Wind Turbine	$27,000
2	80 ft. Guyed-Lattice Tower	$18,500
3	4 kW Solar Array	$18,000
4	80 kWh VRLA Battery	$20,000
5	14 kW Inverter Array	$11,000
6	DC Source Center	$1,800
7	Misc. Wiring & Electrical	$3,500
8	Modified 20 ft Container	$13,000
9	Foundations	$5,000
10	Wire Run (80 ft)	$1,400
11	Shipping & Delivery	$5,000
12	Install Labor & Services	$5,000
13	Misc. Costs	$5,500
	Total:	**$134,700**

Typical Life-Cycle Cost Comparison



Part 5:
Examples

Case Study: Navy Beaufort TACTS

- **Equipment:** 2 x BWC 7.5 kW Wind Turbine, 5 kW Solar, ~ 120 kWh Battery Bank, 20 kW Back-up Diesel, Controls, & Monitoring. Three platforms
- **Load:** 2-12 kW, ~ 90 kWh/Day
- **Performance:** 97-100% Annual Fuel Savings
- **Cost:** ~$1.5M each in 1986; $95,000 to replace original wind turbines in 1998 (1 in 1993)
- **Savings:** ~ $80,000/year, fuel & diesel O&M
- **Misc:** Batteries and solar have been replaced; turbine O&M ~ $0

Beaufort TACTS Range
60 miles offshore of Savannah, GA

Case Study: Chandalar Lake, Alaska

- **Equipment:** 2 x BWC 7.5 kW Wind Turbine, 5 kW Solar, ~ 80 kWh Battery Bank, 12 kW Back-up Diesel
- **Load:** VOR Station, 3 kW, ~ 70 kWh/Day
- **Performance:** 90% Annual Fuel Savings
- **Cost:** ~$500K each in 1999; All equipment (and pre-cast foundations) airlifted in with C-130's
- **Savings:** ~ $70,000/year, fuel & diesel O&M
- **Misc:** O&M ~ $0

FAA Chandalar Lake, Alaska
VOR Station

Greenland

Bethel, Alaska

Antarctica

BERGEY WINDPOWER

Conclusion:
Hybrid Systems Make Good Sense

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