By Dr. Rudy Schlaf

Wind Energy

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Photo from: http://serdarguler.deviantart.com/art/Wind-turbines-92959540

Horizontal Axis Turbines

- Most popular design
- Horizontal designs use airfoils similar to wings of planes
- Lift is used to drive the rotor
- Slow speeds are preferred to reduce drag losses (remember from planes, that most energy goes into combatting drag at higher than 'optimum' speeds. Low speeds yield a higher lift component



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Principles of Wind Turbine Aerodynamic Lift

Horizontal Axis Turbines

- Propeller shaft is connected to a gear box to increase rotational speed
- Output drives a generator
- Control:
 - Anemometer measures wind speed
 - Wind vane measures wind direction
 - Yaw drive adjusts orientation of propeller
 - Blade pitch can be adjusted to optimize rotational speed depending on wind conditions





- Advantages of vertical designs are that they work with any wind direction, that the mechanics are in the base for easy access, and that there are lesser stresses on the tower since stabilizing wires can be used to hold the top.
- Disadvantages: Not self-starting ('wings' need forward rotation to generate tangential force component), cannot be turned out of the wind for protection, high centrifugal stresses in the wings (all mass on the outside of the rotor), force not constant during a rotational cycle-this causes resonant phenomena and certain rotational speeds need to be avoided.

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Physics of Wind Power

- Wind turbines convert KE of flowing air into electrical energy
- The power that can be extracted is proportional to the KE of a cylinder of air moving at wind speed v through A per time t.
 - Air density: 1.23 kg/m³ (at 1 bar/15 C).
- Note that the power is proportional to v³!
 - This is basically the same formula that was derived for the amount of energy going into air resistance when driving a car.
 - This excludes a majority of the earth surface from economically viable wind power installations



hoop

Physics of Wind Power: Betz' Law

- Wind turbines convert KE in the air into KE of a 'shaft' that drives a generator.
- This implies that the air will have less KE after passing the wind turbine.
- The turbine also 'swirls' the air, resulting in a widening of the flow
- A wind turbine cannot extract all KE from the air (otherwise the air would be at a standstill and block further flow)
- Betz' law predicts the power that can be extracted depending on the air speed before (v₁) and after (v₂) the turbine.
- Theoretical maximum: Most power (59.3%) can be extracted when v₂ is 0.33v₁.
- This implies that a wind turbine must be optimized for a particular wind speed.



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From: D.J.C. MacKay: Sustainable Energy-without the hot air, UIT Cambridge, 2009 <u>http://en.wikipedia.org/wiki/Betz' law</u>

Example: Vestas 3.0 MW Turbine

• Blade length: 66m

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• 'Swept area': $9,852 \text{ m}^2$

Power curve V112-3.0 MW

- Rated for 3.0 MW (one of the biggest turbines right now)
- At high wind speeds max RPM is constant through blade pitch adjustment.
 - This avoids overloading the generator
 Doubling the wind speed would yield 8x power flux through generator...
 - Why do they not design bigger generators for the turbines?
 - High winds do not occur often. Hence it is more economical to design for the average wind load.

blade pitch is varied to maintain



http://www.vestas.com/Files/Filer/EN/Brochures/Vestas_V_112_web_100309.pdf

V112-3.0 MW

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One turbine for one world

vestas Wind Power $(10\frac{\text{m}}{\text{s}}) = \frac{1}{2}\rho Av^3$

$$= \frac{1}{2} 1.23 \frac{kg}{m^3} 9852m^2 1000 \frac{m^3}{s^3}$$

=6,060kW

Compare with output power of ~2,600 kW (\Rightarrow power coefficient=0.43)

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Energy Output of Wind Turbines



- Wind speed varies strongly (see above graph)
- Energy output of wind turbines depends on the annual distribution of wind speeds at a given location (green curve).
- The power curve of the wind turbine (center graph) should match the wind distribution (it becomes obvious here why they can limit the turbine at higher wind speeds...not much lost due to the infrequent occurrence of high winds).
- The energy output can be estimated by multiplying the two curves. This yields the energy output curve (bottom graph) per wind speed.
 - This curve shows how many kWh are put out at particular wind speeds in a given year
- The area under the output curve corresponds to the annual energy output of the turbine.



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Windspeed (m/s)



From: http://www.nrel.gov/wind/coe.html, and D.J.C. MacKay: Sustainable Energy-without the hot air, UIT Cambridge, 2009

How Many Wind Turbines Per Area?

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- Wind turbines slow down the wind, and disturb the flow in a wider area than their immediate rotor diameter
 - The added width is needed to handle the airflow due to the lower air speed post-turbine...
- It turns out that a spacing of about 5 times the rotor diameter ensures that the turbines do not interfere much with each other.
 - A comparable statement in Lu et al.: loss is smaller than 20% if there is a minimum of 7 rotors distance downstream and 4 rotors perpendicular.

From: D.J.C. MacKay: Sustainable Energy-without the hot air, UIT Cambridge, 2009 X.Lu et al.: Proc. Natl. Academy of Sciences 106(27), pp. 10933-8, 2009 Photo: <u>http://www.adamscountywind.com/Revised%20Site/Windmills/Other%20Issues/Flicker%20Noise%20&%20Other%20Issues.htm</u>



Wind Power Dependence on Height

By Dr. Rudy Schlaf

- Wind typically has a larger velocity higher up
- This is a result of friction with the earth surface
- The 'wind profile power law' defines the wind velocity v at height h depending on a known reference velocity v_{ref} at a reference height h_{ref} .
- This implies that more power can be generated the higher turbines are located above the surface.
- The small α suggests the velocity difference is not much, but since power~v³ a significant power increase is seen.

$$\frac{v}{v_{ref}} = \left(\frac{h}{h_{ref}}\right)^{\alpha}; \ \alpha \sim 0.143$$

v=velocity
h=height
ref=reference values
 α =power coefficient



From: http://en.wikipedia.org/wiki/Wind_profile_power_law

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Wind Power Depending on Height: Some Numbers

Wind power density

Estimates of wind power density are presented as wind class, ranging from 1 to 7. The speeds are average wind speeds over the course of a year,^[8] although the frequency distribution of wind speed can provide different power densities for the same average wind speed.^[9]

Class	10 m (33 ft)		30 m (98 ft)		50 m (164 ft)	
	Wind power density (W/m ²)	Speed m/s (mph)	Wind power density (W/m ²)	Speed m/s (mph)	Wind power density (W/m ²)	Speed m/s (mph)
1	0 - 100	0 - 4.4 (0 - 9.8)	0 - 160	0 - 5.1 (0 - 11.4)	0 - 200	0 - 5.6 (0 - 12.5)
2	100 - 150	4.4 - 5.1 (9.8 - 11.5)	160 - 240	5.1 - 5.9 (11.4 - 13.2)	200 - 300	5.6 - 6.4 (12.5 - 14.3)
3	150 - 200	5.1 - 5.6 (11.5 - 12.5)	240 - 320	5.9 - 6.5 (13.2 - 14.6)	300 - 400	6.4 - 7.0 (14.3 - 15.7)
4	200 - 250	5.6 - 6.0 (12.5 - 13.4)	320 - 400	6.5 - 7.0 (14.6 - 15.7)	400 - 500	7.0 - 7.5 (15.7 - 16.8)
5	250 - 300	6.0 - 6.4 (13.4 - 14.3)	400 - 480	7.0 - 7.4 (15.7 - 16.6)	500 - 600	7.5 - 8.0 (16.8 - 17.9)
6	300 - 400	6.4 - 7.0 (14.3 - 15.7)	480 - 640	7.4 - 8.2 (16.6 - 18.3)	600 - 800	8.0 - 8.8 (17.9 - 19.7)
7	400 - 1000	7.0 - 9.4 (15.7 - 21.1)	640 - 1600	8.2 - 11.0 (18.3 - 24.7)	800 - 2000	8.8 - 11.9 (19.7 - 26.6)

• Power density doubles when going from 10m to 50m height.

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Wind Power Potential

- 1% of the total solar power absorbed by the earth is converted to KE of the atmosphere
 - Total sun power reaching earth: $1.740 \times 10^{17} W$
- If it were distributed uniformly this would corresponding to a total wind power of about 3.4×10^{14} W on the land mass.
 - World power use (2002): 14.3×10¹²W
 - US power use: (2008): 3.3×10¹²W
 - When making comparisons, keep in mind that wind power is electrical, and that 59.3% is the theoretical maximum for extraction.
- Of course, wind power is not homogeneously distributed.
 - Land areas receive less, oceans more
 - US is one of the better wind places, but also has large areas where wind power is not economically feasible

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Global Onshore Wind Power Potential



- Map shows 'feasible' power potential that could be extracted as electricity (wooded/permafrost/urban was excluded)
- Note W/m² scale (compare to max insolation of ~ 1000 W/m²)
 - Suitable mid west states have power density of about 3-4 W/m².
 - Compare with biofuels at 0.01% conversion efficiency corresponding to 0.0001x5000Wh/24h=0.021W/m².
 - Compare with PV at 5% corresponding to 0.05x5000Wh/24h=10.4W/m².

Global Onshore Wind Energy Potential

- Maps show 'feasible' annual wind energy potential onshore (A) and offshore (B) per country in PWh
- Compare annual energy usage:
 - -World: 125 PWh
 - –US: 29 PWh
- On and off-shore potential of the US: 88 PWh (~3x consumption)



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Fig. 2. Annual wind energy potential country by country, restricted to installations with capacity factors >20% with siting limited. (A) Onshore. (B) Offshore. From: X.Lu et al.: Proc. Natl. Academy of Sciences 106(27), pp. 10933-8, 2009

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Wind Distribution in the US

data: 2.5 km. Projection: Albers Equal Area WGS84

- The US has one of the • worlds largest high wind areas.
- >6.5 m/s Wind speeds at • 80 m height are considered suitable for exploitation

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- How much area would we need to cover our currently used 33.6 TWh/day (=1.4 TW)output power (wind makes electricity, hence we do not need to compare with fossil fuel energy use)?
- At 4 W/m^2 an area of 3.5×10^{11} would be needed. This corresponds to 350,000 $km^{2}(=136,700 \text{ sq.miles})$ $= 370 \text{ miles x } 370 \text{ miles})^{L}$



Energy Laboratory nnovation for Our Energy Future

United States - Annual Average Wind Speed at 80 m

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Seasonal Wind Energy Potential



• Graph compares US wind energy potential with US <u>electricity</u> consumption

- Note different scales for each curve. Offshore potential already matches the US electricity consumption.
- In summer there is less wind...(but solar cells typically work better...)

From: X.Lu et al.: Proc. Natl. Academy of Sciences 106(27), pp. 10933-8, 2009

Energy Balance of Wind Power

- Kubiszewski et al. paper conducted a 'meta-analysis' of 114 published individual analyses of operating and conceptual wind turbines
- Their 'boundary conditions' included construction, operation and decommissioning (incl. materials recycling) energy costs





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Energy Balance of Wind Power



Fig. 3. EROI for operational wind turbines below 1 MW as a function of power rating in kilowatts.

- Only turbines with < 1MW output were examined (no reliable data yet for the current generation of 2-3 MW turbines)
- It was found that there is a clear trend to higher energy out/in ratios ("EROI"=energy return on investment)
- This is related to the non-linearly higher power output of larger turbines
 - Large turbines access larger wind speeds due to higher tower(power~v³), rotor proportional to tower hight (swept area~r²)

From: I.Kubiszewski et al.:Renewable Energy 35, pp. 218-25, 2010

Comparison of Wind Power Energy Balance to Others

- Wind power compares favorably to other alternative energy conversion schemes
 - note: biofuels was
 added based on
 numbers in papers
 discussed in class
 - -note(2): Large discrepancy of the coal value with the study by Cleveland (next slide)



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Fig. 6. EROI for power generation systems. Nuclear (1) represents the average and standard deviation for the entire sample of analyses reviewed by Lenzen [14]. Nuclear (2) omits the extreme outliers from Lenzen's survey, and thus represents a better assessment of what the EROI for nuclear is likely to be. See text for description of further sources.

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Fossil Fuel and Biofuels Energy Balance

- Cleveland paper discusses fossil fuel energy return over time
- Remarkable:
 - Oil and coal yield drops strongly over time. This indicates depletion of easy-access resources causing pursuit of more difficult and energy intensive resources
 - The paper states that the overall quality of the crude extracted product has deteriorated over time further lessening the EROI
 - Gasoline has only an EROI of 6-10 due to refinery energy costs
 - Corn ethanol is in the noise of the graph
 - Much cited 'vast oil shale' resources have low EROI
 - Coal liquefaction (Fischer-Tropsch) is similar to corn ethanol
- It is difficult to directly compare EROI numbers due to the different 'benefit to society' inherent in different energy sources (Wind and solar make electricity, but are intermittent, coal can only sensibly be used for thermal applications etc...)
- Further points to consider: What is the quality of the input energy compared to the output? Fossil fuel extraction uses a lot of gasoline/diesel/ electricity but returns crude oil that has to be refined



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Wind Power Cost

- Wind power costs (per installed peak capacity) are down-trending as global capacity increases
- Between 1990 and 2001 prices fell almost 50%
- 2001 price per installed W:
 - 0.8-1.2 Euros (~\$1.1-1.6)
 - Compare with current costs of \$5-6/W for solar
- It is difficult to estimate how much it would cost to build capacity to provide the entire US power needs due to the different wind curves in varying locations etc...



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"Micro-Generation" Wind Turbines

- Ampair 600 micro wind turbine
 rotor diameter: 1.7m
- Prospectus lists a "reference power" of 723W ("into battery")
- Looking at the power curve reveals that it will be more likely to get ~100W (=876kWh/year) or probably less in a windy (>6 m/s) region.
- Listed price is about \$3,000. For this one can expect about 1800kWh/year (from their graph) or 876kWh/year (our calc.) in a 6 m/s region. Assuming a 20 year life time, ~10-20c/kWh would result.
- Average US home would need about 10-20 such turbines (and batteries etc...)
- Promising for off-grid applications.



AEP (kAH/yr) at 28V

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vithout the hot air, UIT Cambridge, 2009

By Dr. Rudy Schlaf Wind Power Summary

- Wind power potential of the US is about 3x current power use (or better, since wind yields electricity)
- Energy balance is one of the best of the renewables (~15-20, probably better with current 3 MW designs)
- Economies of scale have driven the price per W down into the \$1 range
 - -Bigger turbines are better.
- Energy density per area is low, i.e. a large part of the US would need to be plastered with wind turbines
- Conclusion: Wind power has the potential to satisfy a significant part of the US energy needs.