GEOS 24705 / ENST 24705

Lecture 13: mechanical -> mechanical
(wind: the modern version)
Wind increasing sharply
Currently ~2% of world electricity (< 1% of total power) but growing

*World Resources Institute, from IEA data*
Why is wind power so large in scale?
Because must be high to get good wind

Turbine total power is a function of both area & wind speed:
\[ P = \frac{1}{2} r A v^3 \cdot C_p \]

....microwind (with short towers) is **inherently** inefficient. Qualitatively different than microhydro....
Economics of old-style windmills

Wind power is a function of both area & wind speed:

\[ P = \frac{1}{2} r A v^3 \cdot C_p \]

….Here we have small area, short tower…. Also “drag” rather than “lift”-type windmills, so

These windmills may never have recovered the energy they took to manufacture .. They are energy transfer devices, forged by coal-fired factories in the East and used to pump water in the West.
Micro-wind is not the norm

World’s largest wind turbine, Enercon E-126, 126 m. rotor diameter (413 feet), 6 MW rated (likely 7+ in practice).

*Picture: installation in Emden, Germany*
Wind turbines in general getting larger...

10 x increase in rotor diameter

-> 100 x increase in power

max 50 kW in 1980s, > 5 MW today
But “big” is still small… by comparison, each generator in Dresden nuclear is > 800 MW

Size of wind turbines is growing

Percentage of turbines installed in the U.S. in various size classes from '98 to '06

Source: AWEA
...turbines also getting more efficient

Large size helps efficiency approach Bentz’s law limit of 59%

(tsrm = “tip speed ratio”, \(\frac{v_{\text{blade}}}{v_{\text{wind}}\)}

With ideal turbine tsr should be as high as possible. In practice tsr of about 5-6 gives best performance
TSR limit and large turbine size mean wind turbines must turn slowly

\[ \text{tsr} = \frac{v_{\text{blade}}}{v_{\text{wind}}} \]

\[ v_{\text{blade}} = \omega R = 2\pi f R \]

\[ \text{tsr} = \frac{\omega R}{v_{\text{wind}}} \]

or \[ f = \text{tsr} \cdot \frac{v_{\text{wind}}}{(2\pi R)} \]

For 40 m blades, \( f \) must be \( \sim 50/240 \sim (1/5) 1/s \) or \( \sim 12 \text{ rpm} \).

i.e. big wind turbines take \( \sim 5 \text{ s per revolution} \)

Ideally tsr should be as high as possible. In practice tsr of about 5-6 gives best performance.
Can’t extract wind power at all wind speeds

In low-wind regime, adjust blade pitch for optimal torque (optimal power generation)
In high-wind regime, protect turbine from too much torque with sub-optimal blade pitch
In very high-wind regime, feather blades, disconnect from the grid, and apply brake.

Typical turbine power output: note that “rated” wind produces *maximum* power! Rated power is not realistic for everyday. Wind variability means 30% typical capacity factor – assume a wind turbine even if sited well produces 30% of its rated power. *(Image from Partnerships for Renewables)*
Why three blades?

Optimal trade-off of competing factors...
One Bladed Machines

- Need to operate at a higher tip speed ratio to capture maximum power
  - Noisier
  - High drag losses (drag proportional to $\lambda^3$)
- Counterweight negates much of the material savings
Two Bladed Machines

- Slightly higher tip speed ratio than 3 bladed machines
  - Slightly noisier
  - Slightly higher drag losses
- Less sensitive to changes in $\lambda$
- Lighter structure
Three Bladed Machines

- Balance between high $C_p$ and sensitivity to tip speed ratio
- Visually appealing

* More mechanically balanced than 2-blade systems – more constant stresses on tower
Four+ Bladed Machines

- Higher rotor material costs with no additional power potential
- Very sensitive to $\lambda$
- Increased torque and thrust cause higher gearbox and tower costs

Note – this picture is a drag turbine, not a lift turbine, so somewhat deceptive
How do meet AC grid requirements with wind?

- *Can’t do:* constant rotational velocity matched with direct drive to 60 Hz grid

- Constant low velocity matched to grid via gearbox

- Dual-speed velocity with 2 switchable rotor electromagnets

- “Wild” AC converted to DC then back to AC via inverter ("variable-speed" wind)
Generator mounted in nacelle

Diagram source: Nordex
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Generator mounted in nacelle:
Methods of meeting AC grid requirements with wind:

**Can’t do:**
- Constant rotational velocity matched with direct drive to 60 Hz grid. *Turbine would rotate too fast.*

**Viable strategies:**
- Constant low velocity matched to grid via gearbox
  *Most commercial wind does this*

- Dual-speed velocity with 2 switchable rotor electromagnets *allows use of wider range of wind speeds*

- “Wild” AC converted to DC then back to AC via inverter (*“variable-speed” wind*). *Swaps the inefficiency of gears for the inefficiency of rectification/inversion. Better electronics are making this strategy more viable.*
AC wind generator requirements and problems

- Minimizing maintenance is key since generator is on top of tower – must be simplest and most robust possible

- For this reason wind turbines use induction generators (magnetic field in rotor is purely induced, no moving electrical contacts, very simple)

- But any inductance pushes voltage out of phase with current... *inductance causes current to lag voltage*

\[ V_{\text{induced}} = -L \frac{dI}{dt} \]

- Capacitance has opposite effect, would cause current to *lead* voltage
If voltage is out of phase with current:

- If voltage is 90 degrees out of phase with current, *cannot do work*
- Induction generators (or motors) produce small phase lags - grid power is a combination of in-phase and purely out-of-phase components.
- Apparent power produced is $P_{app} = I_{rms} \times V_{rms}$, but in-phase part that can do work ("active power" $P_W$) is less
- Out of phase part is "reactive power" (also called $VA_{rs}$)
- Ratio of $P_W/P_{app}$ is the "power factor"

![Diagram showing kVA power, heat component, work done, and circulating component with P_W and VA_{rs} labels.](image)
If voltage is out of phase with current..

- You can think of the active power as flowing from the generator to the load and then doing work there.
- The reactive power, on the other hand, sloshes back and forth but does no work.
- If you are producing reactive power, you need a bigger generator to do the same amount of work, because some of its apparent power is useless.
- Reactive power can be lost in heating the transmission wires, in turn producing a voltage drop: both bad!

(For physics people, these losses occur because transmission lines have inductive reactance.)
Managing reactive power on the grid

- Obviously the grid operators want to minimize reactive power.
- All inductive loads (e.g. induction motors, transformers) and induction generators produce/draw current that lags voltage.
  
  Terminology: sometimes this is written as “producing lagging reactive power”, sometimes it is written as “consuming reactive power”, as opposed to capacitors that “produce” it. That latter is horrible & misleading language.

- Need to put capacitors in system to “balance” system and bring current back in line with voltage.
- Grid specifications demand that generators must produce power that is only 5% reactive...\textit{except for wind farms which are often exempt (!!!)}

- That exemption is only unproblematic because wind is such a small fraction of electricity generation ... but will become more contentious if wind increases. \textit{Who pays for reactive power management?}
Wind farm exemption...

“FERC Order 661a sets a requirement for 0.95 power factor capability at the point of interconnection..... ISO NE’s Large Generator Interconnection Agreement (LGIA Item 9.6.1) requires that power plants be capable of continuous operation in the range of 0.95 power factor leading to 0.95 power factor lagging. The LGIA presently exempts wind plants from this requirement. The project team recommends that this exemption be eliminated for large wind plants.”


FERC = “Federal Electricity Regulatory Commission”
ISO-New England = regional grid operator
How much wind is there, and where is it?

United States - Annual Average Wind Speed at 80 m

Illinois is a middling state for wind (outside Lake Michigan)

Wind is currently 0.5% of IL electricity production.

Current IL electricity use: 16 GW (~ 1kW/person)

Elect. demand growing 1.5%/yr (i.e. will double in 45 years).

Total estimated commercially viable wind resource: ~ 7 GW? (estimates vary widely).
Wind Project Installations by State (Top Ten States)

- **Texas**: 9,410
- **Iowa**: 3,670
- **California**: 2,794
- **Washington**: 1,980
- **Minnesota**: 1,809
- **Oregon**: 1,758
- **Illinois**: 1,547
- **New York**: 1,274
- **Colorado**: 1,246
- **North Dakota**: 1,203

**Most Capacity Additions in 2009**
- Texas: 2,292
- Indiana: 905
- Iowa: 879
- Oregon: 691
- Illinois: 632
- New York: 568
- Washington: 542
- North Dakota: 488
- Wyoming: 425
- Pennsylvania: 388

**Fastest Growth in 2009**
- Arizona: 10x (first utility-scale project)
- Indiana: 7x
- Maine: 2.75x
- Massachusetts: 1.5x
- Others: Various states with different growth rates.
Lake Michigan and offshore are among highest wind potential areas

But cost of installation is high...
Wind increasing sharply

Far less important at present, but more potential growth

World Resources Institute, from IEA data
Floating turbine platforms are expensive at present...

First operational deep-water high-capacity turbine operational Sept. 2009 (Hywind, 2.3 MW rated turbine, North Sea, 220 m deep water).

Install cost is $26/W rated, $90/W actual (!!!) Compare to $1-2/W for fossil or hydro, ~$1-2/W rated ($3-6/W actual) for onshore wind.
Summary lessons about wind

- Wind is a diffuse resource (~ 2 W/m²). There’s a lot of it, but it has a very low energy density /area.

- Hydro is even more diffuse world-wide (< 0.3 W/m²) but can be concentrated, so turbines smaller & costs lower.

- The atmosphere is a very inefficient heat engine!
  \[ \frac{2 \text{ W/m}^2}{200 \text{ W/m}^2} \rightarrow 1\% \text{ efficiency of extraction} \]

- Some wind is commercially viable ($3-6/W_{\text{actual}}$).

*Is it optimal to use the atmosphere as a heat engine?*
Two main energy conversions using sunlight are both called “solar”

• **Solar thermal** – use mirrors to concentrate sun and heat something and drive a heat engine, which then turns a generator and makes electricity

• **Solar photovoltaic** – convert sunlight -> electricity directly in a semiconductor via the photoelectric effect.
Solar thermal: building a better heat engine than the atmosphere (skip one mechanical step)

2 of 9 (354 MW total) SEGS parabolic trough solar thermal installations in Barstow, California, starting 1984, built by Luz Int. …which went bankrupt. Still operational.
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Solar thermal: Proven technology, and heat is store-able

Diagram: source unknown (from the Green Technology Blog)
Power towers aim for higher efficiency

By concentrating bigger mirror area on central tower, can produce hotter temperatures and so higher Carnot limit

11 MW solar thermal PS10 “power tower” in Seville, Spain (govt. subsidized by 0.21 euro cents/kWh)
Power towers aim for higher efficiency (higher T)

BrightSource power tower. Company just received govt. guaranteed loan of $1.37B to build Ivanpah project in Mojave Desert in CA, 400 MW of new capacity: $3.4/W install cost. Given 25% capacity -> $13/W true. CA has 33% RPS standard
Solar photovoltaic – skip mechanical step entirely and go directly from radiation to electricity

Photoelectric effect produces free electrons and a current in semiconductor material, if given an extra conductive path. Necessarily produces DC – current flows in one direction only, since photoelectric effect pushes electrons in only one direction. Voltages typically very low.
Barriers to use of solar photovoltaic are economics

40 MW solar PV farm, Brandis, Germany, built by First Solar, CdTe / CdS on glass (2nd generation cells). Effective subsidy up to 45 euro cents/kWh (subsidy is 10x cost of coal-fired power)
Barriers to use of solar photovoltaic are economics

Cost of solar panel itself appears cheap at $2 / \( W_p \) (2010 prices)

But, typical install cost are more like $7-12 / \( W_p \)

And be careful of advertised power! As with wind, solar PV powers are given at some putative peak insolation (1000 W/m\(^2\)), not the actual conditions that a panel would encounter. \( W_p \neq W_{\text{actual}} \)

Average insolation is only ~ 1/4 of peak (plus there are cloudy days). 1/5 of peak power is reasonable estimate for average.

Install price then becomes > $40/W_{\text{actual}}

*Hard to compete with fossil fuels plants even when fuel is free!*  

No plausible efficiency gains would get around this problem.

Solar panels are more efficient at using sun’s energy than is wind... but are more expensive anyway.