GEOS 24705 ENST 24705 ENSC 21100

Lecture 15

Wind II, Hydro

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Energy in a flow, wind power: $v^3$ dependence is strong!

Energy/mass = ½ $v^2$ + g h + $\frac{p}{\rho}$

**kinetic**  **gravitational**  **pressure gradient**

Power = energy/mass * mass/volume * volume/time

Flow $f = \frac{\text{mass}}{\text{time}}$

\[ P = \varepsilon \cdot \rho \cdot A \cdot v \]

*energy density is kinetic term: $\varepsilon = \frac{1}{2} v^2$

\[ P = \frac{1}{2} \rho A v^3 \]
Early windmills symbolize American West


Note timing: 1854 invention but sales boom 1880s

OK land rush, 1889

Images: IronMan Windmill Co.
All early wind turbines are “drag” turbines.

Blades “pushed” around by impact of air striking them.

James Blyth, Scotland, 1887
vertical axis “drag” type

Charles Brush, Cleveland, 1888
17 m diameter
12 kW electricity
Modern wind turbines are “lift” turbines
Blades “pulled” around by low-pressure as air flows over airfoil shape
Don’t need to touch every air molecule

Lift blades can generate more force than drag turbines –
extract more of wind’s energy
Much cheaper since need fewer blades

Image: Green Rhino Energy
Wind turbines extract energy by slowing wind but can’t get all the kinetic energy, would need to stop the flow.

Wind turbine disturbs the flow, makes a "cone" of high -> low velocity.

Max power extracted when slow flow down by 66%:

\[ \frac{v_2}{v_1} = \frac{1}{3} \]

Limit to power extracted is then \( \frac{16}{27} = 0.59 \) (Betz’s law)

Images: (T) FTexploring.com (B) Wikimedia
Max efficiency only occurs for ideal blade speed

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

Betz’s law limit only achievable if turbine goes fast –

...if wait too long can’t extract energy...

....but if go too fast wind can’t adjust properly around blade

With ideal turbine tsr should be as high as possible.. In practice tsr of about 5-6 gives best performance
Actual windpower is less than rated power

Rated power is that under optimal (designed-for) wind

Betz’ law: 59%, or ~ 50% in practice recoverable (*this is rated power*)

... Then capacity factor ~ 30% (*of rated power*)

→ Total recoverable from wind kinetic power ~ 15%
Low energy density drives wind turbines to be large power extracted scales with cross-sectional area

<table>
<thead>
<tr>
<th>Product/Rotor diameter (m)</th>
<th>V15</th>
<th>V17</th>
<th>V19</th>
<th>V20</th>
<th>V25</th>
<th>V27</th>
<th>V39</th>
<th>V44</th>
<th>V47</th>
<th>V52</th>
<th>V66</th>
<th>V80</th>
<th>V90</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (kW)</td>
<td>55</td>
<td>75</td>
<td>90</td>
<td>100</td>
<td>200</td>
<td>225</td>
<td>500</td>
<td>660</td>
<td>850</td>
<td>1750</td>
<td>2000</td>
<td>3000</td>
<td></td>
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<tr>
<td>MWh/year</td>
<td>217</td>
<td>265</td>
<td>301</td>
<td>346</td>
<td>481</td>
<td>647</td>
<td>1304</td>
<td>1581</td>
<td>1947</td>
<td>2530</td>
<td>4705</td>
<td>6768</td>
<td>9152</td>
</tr>
</tbody>
</table>

Image: Vestas
Wind turbine size continues to increase

What drives that change?

2016 U.S. mean new-build rotor diameter = 108 m
(Wiser & Bolinger 2017)

Image: EWEA via Terra Magnetica
Wind turbine size continues to increase

What drives that change?

- More x-sectional area = more power
- Higher wind speeds at altitude

Image (plane): Jeffrey Millstein
Image: EWEA via Terra Magnetica
Power carried by wind is a function of cube of wind speed

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

Also area \( \alpha \) square of diameter, and higher hub allows longer arms

Microwind (short towers) is inherently inefficient.
Wind scale is now huge

Most turbines now installed are ~2 MW. Record is 8.8 MW (2018, Vestas V164) 9.5 MW to be installed off Belgium (V164)

R. Enercon E-126, 126 m. rotor diameter (413 feet), 6 MW rated (likely 7+ in practice).

L. Clipper Liberty, 2.5 MW
Generator mounted in nacelle
Note gearbox to allow turning slowly, as needed for large turbine
Nacelle is heavy: 70 tons for Vestas 2.8 MW (excluding rotor and blades)
Generator is a minor component of cost.

Electronics (power converter/transformer) are over 3x generator cost. Gearbox costs almost as much as the tower does.
U.S. windpower increases in fits and starts

Source: AWEA project database

From: Wind Technologies Report 2016, Wiser and Bolinger
U.S. windpower increases in fits and starts
Development driven by presence / absence of federal subsidies:

*Production tax credit = 2.3 c/kWh for 10 years (or take ITC, 30% upfront cost)*

Now ramping down and will end after 2019 unless new legislation passed

From: Union of Concerned Scientists, data from DOE 2013 and AWEA 2014

Extended 5 more years in 2014, phasing out 2017-2019
Wind now makes up ~ 1/3 of new electric generation in the Interior region, over 50% of installations in 2007-2016 but, windpower still makes up only 6% of electricity generation.

Source: ABB, AWEA, GTM Research, Berkeley Lab

From: Wind Technologies Report 2016, Wiser and Bolinger
U.S. isn’t leading in wind penetration

Denmark, Portugal are small countries with backup from European grid

Source: Berkeley Lab estimates based on data from GWEC, EIA, and elsewhere

From: Wind Technologies Report 2016, Wiser and Bolinger
What’s driving wind power growth in U.S.?

Wind is biggest installation type, but not always in obvious locations.

Figure: Wiser and Bolinger 2016

Note: Numbers within states represent cumulative installed wind capacity and, in brackets, annual additions in 2016.
Wind installations follow wind resources
Wind installations follow wind resources

United States - Annual Average Wind Speed at 80 m

Electrical transmission is not where the wind is
Wind is increasing now because prices are competitive.

LCOE = “levelized cost of electricity”

= capital cost * financing + discounted future (earnings − operation cost)

(Note that these costs are after subsidies, which lower costs ~ 30%)
Wind power levelized cost differs by location costs cheapest in “wind belt” where wind speed is highest stronger wind = more electricity from the same turbine

PPA is “power purchase agreement” guaranteed price provided in long-term contract
Offshore wind is much more expensive. Wind is stronger but costs much larger. Cheaper in Europe, but still exceeds onshore.

PPA is “power purchase agreement.” Guaranteed price provided in long-term contract.
Why expensive?

expensive towers, undersea cables to land

Integrated Solutions
For Offshore Wind Farms

Onshore DC/AC Converter Station & AC Substation
For far offshore wind farms DC often provides the best techno-economic solution for transmission to the shore. Leader in HVDC with over 30,000 MW of installed capacity worldwide, GE has developed efficient grid connections.

Offshore AC Substation
To connect the offshore wind farm to the onshore electricity network or to an AC/DC converter station, GE supplies several types of offshore wind substations, such as self-floating and self-installing solutions.

Haliade® 150-6MW
Built upon GE's Pure Torque* technology for reliability, the turbine features a 6 MW direct-drive permanent magnet generator and is suitable for all offshore conditions.

Offshore AC/DC Converter Station
To convert the power generated by the wind turbines in alternating current (AC) to direct current (DC) for transmission to shore, GE offers the HVDC MaxSine® VSC technology for sustainable grid connections.

From wind turbine installation to grid connection
- A reliable, efficient and high yield offshore wind turbine
- An innovative AC platform and efficient transmission over long distances with HVDC technology

GE Renewable Energy

Non proportional scale image, *Trademark of General Electric Company
Why expensive? also technology constraints because of location - maintenance extremely difficult, so need to make turbines reliable

- Want more power per tower: bigger turbines
- Very simple generators to minimize chance of breakage
  - No electrical connection to rotor. Either
    - **Induction generators** – no brushes on rotor
      *Drawback – asynchronous (power is out of phase)*
    - **Permanent magnet generators** – must use neodymium
      *Drawbacks – heavy, + exacerbates shortage of rare earth elements.*
  - No gearbox
    - trend toward **direct-drive generators**
      *Drawback – generators must be even bigger (ca. 4 m diameter), so nacelle is even heavier.*
Only one offshore project in U.S., off Rhode Island

- Deepwater Wind (Block Island), 30 MW, completed 2016
  
  *first conceived of as massive 385 MW*

- Contracted electricity price 24.4 cents/kWh
  
  *RI wholesale rate is typ. 3-4 cent/kWh, 6 times less*

  *Project does serve Block Island which had locally high rates, but costs borne by ratepayers throughout RI*

- Contract initially rejected by RI Public Utilities Commission as excessive to ratepayers

- Approval required state law to remove the requirement that RIPUC approve only projects that are “commercially reasonable”
Why so much offshore wind in Europe?

30 MW in U.S.  15,780 MW in Europe

Top: Denmark, (Copenhagen)

Bottom: U.K., (Sheringham Shoal)
In Europe, cost discrepancies not so prohibitive for offshore

- offshore waters are shallow, easier to build than in U.S.
  
  *Europe mean depth for new builds ca. 20 m, earliest farms < 5 m* 
  *(but Block Island only 23-28 m, depth can’t explain its much higher costs)*

- land is crowded, so few locations for cheap onshore wind

- electricity by conventional sources is expensive
  
  *no cheap natural gas to lower wholesale rates*

- countries are willing to subsidize, & experience lowers costs

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New build offshore wind depth and distance from shore

*data: IWES.Fraunhofer.de*
Very little of U.S. continental shelf is shallow

*remember mean depth of European offshore farms < 20 m*

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**GW by Depth (m)**

<table>
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<th>Region</th>
<th>0 - 30</th>
<th>30 - 60</th>
<th>&gt; 60</th>
</tr>
</thead>
<tbody>
<tr>
<td>New England</td>
<td>100.2</td>
<td>136.2</td>
<td>250.4</td>
</tr>
<tr>
<td>Mid Atlantic</td>
<td>298.1</td>
<td>179.1</td>
<td>92.5</td>
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<td>S. Atlantic Bight</td>
<td>134.1</td>
<td>48.8</td>
<td>7.7</td>
</tr>
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<td>California</td>
<td>4.4</td>
<td>10.5</td>
<td>573.0</td>
</tr>
<tr>
<td>Pacific Northwest</td>
<td>15.1</td>
<td>21.3</td>
<td>305.3</td>
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<td>Great Lakes</td>
<td>176.7</td>
<td>106.4</td>
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<td>Gulf of Mexico</td>
<td>340.3</td>
<td>120.1</td>
<td>133.3</td>
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<td>Hawaii</td>
<td>2.3</td>
<td>5.5</td>
<td>629.6</td>
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<td><strong>Total</strong></td>
<td>1,071.2</td>
<td>628.0</td>
<td>2,451.1</td>
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*figure: NREL, via BOEM factsheet*
And winds are not strong in shallow U.S. shelf sites

7 m/s is about limit for onshore wind, must be higher to justify offshore

the **only** overlap of shallow and windy is the MA, CT, RI shelf
Very little of U.S. continental shelf is shallow

*remember mean depth of European offshore farms < 20 m*

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