Developments in Wind Turbines
Terrestrial to Offshore

Dr. Curran Crawford

Living Without Oil Lecture Series, Part One
An Elder Academy Event
February 22, 2020
Outline

Meteorology

‘Conventional’ Technology Overview

Deployment & Economics

Offshore Wind Energy

Airborne Wind Energy Systems (AWES)
Meteorology

Origins of the Wind

Characterizing the Wind

The Earth’s Boundary Layer
Ultimately, winds arise from uneven heating of the earth

- Solar radiation
  - Typically absorbed first by land & water
  - Transferred by various mechanisms back to air
- Energy absorption varies spatially & temporally
  - E.g. Water, desert, forest, etc.
- Sets up temperature, density and pressure differences
- Leads to forces to re-establish equilibrium
- Hence the flows of air we call wind
- Typical coastal example
  - Water is a moderator - relatively constant temperature
  - During the day, land heats up, creating low pressure region
  - Onshore breeze as air over water is relatively cool
  - Overnight, land cools and wind stops, or may reverse
  - Go to Nitinat lake to observe
At the scale of an individual turbine, winds are greatly affected greatly by local conditions

- **Topology**
  - Top of a hill
  - Sheltered valley
- **Surface conditions**
  - Rough trees
  - Smooth dessert
  - Lakes and oceans
- **Built-up areas**
  - Urban areas (Carpman 2011)
  - Individual houses, barns, etc.
  - Other turbines!
Wind power density is a cubic function of wind speed

\[ P_{\text{density}} = \frac{1}{2} \rho V^3 \]

\[ P_{\text{turbine}} = \frac{1}{2} \rho V^3 C_P A \]

- \( C_P \) ranges from 0.1 to 0.59
  - Betz limit \( \frac{16}{27} \)
- Capture area \( A \) growing with diameter \( D^2 \)
Meteorology

Origins of the Wind

Characterizing the Wind

The Earth’s Boundary Layer
Standard wind speed measurement tools: NRG and RM Young are the most common

Wind vane, cup anemometer

Sonic anemometers and temperature sensor

Windmill anemometer
LiDAR is playing an increasingly large role
Wind speeds vary on a number of time scales

Figure 2.1 Wind spectrum from Brookhaven based on work by van der Hoven (1957)
Weibull probability density function $f(U)$ describes annual hourly average wind speeds.
Wind roses are used to display directional wind information

- Binning of azimuthal direction measurements
- Length indicates relative probability
- Example for CIMTAN site in Kyuquot
Meteorology

Origins of the Wind
Characterizing the Wind
The Earth’s Boundary Layer
Wind turbines typically operate in the boundary layer

- 200 – 500 m boundary layer height
- Boundary layer influenced by:
  - Strength of the geostrophic wind
  - Surface roughness
  - Coriolis effects
  - Thermal effects
Boundary layer profiles vary greatly over time with prevailing conditions

WRF simulations for Pritzwalk
Wind turbines always operate in an unsteady environment
‘Conventional’ Technology Overview

Historical Development
Basics of Wind Energy Extraction
Aerodynamics is Complicated!
Improving Performance
Structures & Drivetrains
The power in the wind has been used for thousands of years, first for transportation.
Wind has been used since first century AD to directly do mechanical work

- Pumping water (irrigation and drainage)
- Grinding grain

Persian Windmill
A little wind turbine taxonomy

- HAWT: horizontal axis wind turbine
- VAWT: vertical axis wind turbine (cross-flow, etc.)
Up to 200,000 windmills in Europe at their peak, and were already adaptive structures
The farm windmill is an iconic image

- Note large number of blades
- Self-furling tail
Charles Brush in the US, 1880/1890s

- 56 foot diameter & 144 wood blades
- Lasted 20 years
- 12 kW peak power
- Recharged 408 batteries to illuminate 350 incandescent lamps, three electric motors and two arc lights
Wind turbine (Jacobs) used in North America before transmission lines reached rural areas

- 30,000 units installed
- Passive control
The oil crises of the 1970’s were the impetus for modern wind turbines

- The Danish industry grew out of the farming industry
- Started small, and incrementally built
- Locally owned-operated machines - social license
- Government subsidies/support as no domestic fossil resources
Vestas is an example of a Danish manufacturer that originally made farming equipment.
The US hired aerospace engineers and large companies, and didn’t succeed

- NASA, Westinghouse, GE, Boeing, United Technologies
- Go big or go home didn’t work
- US’s current turbines (e.g. GE) are essentially Danish imports
Mod-1 turbine in action - note downwind orientation
Canada unfortunately backed the wrong (4 MW) horse

- Again, go big or go home didn’t work
- VAWTs didn’t win out
  - Cyclic loading, complex aerodynamics
And so, we have the modern 3-bladed, upwind “Danish-concept” machines you see around today.
“Danish-concept” turbines continue to grow in size

Source:
Same size evolution seen in the US

Manufactures typically offer a range of rotor sizes suited for different conditions

- Vestas 4 MW nominal rating line
  - Common nacelle, various tower heights
  - Range of wind speeds
‘Conventional’ Technology Overview

Historical Development
Basics of Wind Energy Extraction
Aerodynamics is Complicated!
Improving Performance
Structures & Drivetrains
Wind energy is extracted through a step change in static pressure, which affects velocities around the rotor.

Figure 3.1  The energy extracting stream-tube of a wind turbine.
The actuator disc model is the most basic model of an energy-extracting disc

- Rotor doing work on the flow: \( P = T U_D \)
- Basis of many analysis approaches (BEM, CFD, porous disc experiments)

![Diagram of an energy-extracting actuator disc and stream-tube](image)
BEM theory is based on the assumption of independent radial streamtubes (annuli)

- Blades exert pressure forces on flow due to local aerodynamic loading

Figure 3.13  A blade element sweeps out an annular ring
There are various ways to understand the lift generated on an airfoil

- Local velocities determine pressures around the airfoil creating lift
- Sheared flow (and separation) create drag

Figure A3.15  The pressure distribution around the NACA0012 aerofoil at $\alpha = 5^\circ$
‘Conventional’ Technology Overview

Historical Development
Basics of Wind Energy Extraction
Aerodynamics is Complicated!
Improving Performance
Structures & Drivetrains
The flow around a wind turbine rotor is complex and fundamentally governs the power capture and loads.
Wake simulations are key for individual machines and arrays
Vertical axis turbine wakes are even more challenging to simulate

Experiments remain challenging even for steady-state, given scales and accuracy requirements involved

IEA Task 29 Mexico rotor experiment
Our trailer-based test rig for towed & parked testing
‘Conventional’ Technology Overview

Historical Development
Basics of Wind Energy Extraction
Aerodynamics is Complicated!
Improving Performance
Structures & Drivetrains
Various ideas are used and tried to improve aerodynamic performance

Vortex generators

Serrated trailed edges

Turbuncles
Modern machines operate in variable speed mode and pitch control modes

- Region I pitch used to assist in start-up
- Region II pitch constant and speed varied
- Region III speed constant and pitch varied to maintain rated power
Instantaneous power always fluctuating
‘Conventional’ Technology Overview

- Historical Development
- Basics of Wind Energy Extraction
- Aerodynamics is Complicated!
- Improving Performance

Structures & Drivetrains
Large quantities of reinforcing steel to transfer in loads from tower to base
Foundation bolts ready for tower installation
Various types of towers used, but the uniformly tapered tubular tower is the standard

- Guyed and lattice/multi-element towers structurally efficiency
- But aesthetics plays a key role

![Image of various types of wind turbines including tubular steel, tubular concrete, lattice, three-legged, and guy-wired pole towers.]
Towers are frequently manufactured locally in 3–4 sections and bolted together on-site
Doubly-fed induction generators with gearboxes have been the emergent norm for drivetrains.
Enercon has used exclusively electrically excited direct-drive generators for decades - heavy nacelles!
Siemens (formerly Bonus) Gamesa has a direct drive permanent magnet machine
Wind turbine blades are massive composite structures
Blades are made up of composite layups
We can simulate composite wind turbine structures accounting for material variability

- Bayesian approach accounting for natural property variation and model deficiencies
The fundamental square-cube law continues to be ‘broken’

Capture area $\propto D^2$

Mass $\propto D^3$

- LM 107.0 P blade (2019) - 220 m dia, 55 t mass
LM 107.0 P blade
Reducing blade weight as machines grow is a chief concern

- Reduce aerodynamic loads
  - Reduce gravity bending moments
  - Further reduce structural requirements

GE fabric blade concept (canceled in 2014)
Transportation becomes a challenge!

- Localized manufacturing
- Offshore advantages
Deployment & Economics

Wind Resource

Installed Capacity Growth
Decommissioning
Canadian distribution of wind resource at 50 m

Horizontal resolution of 5 km

Resolution horizontale de 5 km
Global average windspeeds at 50m height - Class IV 7m/s+

(http://visibleearth.nasa.gov/view.php?id=56893)
The fact that the wind resource is globally distributed is a key attraction and motivator to harness it

- Very large potential resource
- Potential for GHG reductions in most economies
- Avoidance of conflict
  - Fuel source not a geopolitical commodity
  - Proliferation proof
- Relatively labour intensive
  - Jobs sell energy ideas (look at marketing for oilsands, pipelines, etc)
  - Wind prospecting & siting
  - Localized manufacturing of large components
  - Civil works
The fact that the wind resource is distributed is also a challenge

- Low energy (power) density compared to fossil & nuclear
  \[ P_{density} = \frac{1}{2} \rho V^3 \]
- Transmission to load centres
- Local impacts
  - Nearby residents vs. landowners
  - Visual (aesthetics & flicker)
  - Acoustic
  - Wildlife
- Variable
  - Intermittent?
  - Capacity factor impact on design & economics
  - Implications for integration – a whole other talk!
Deployment & Economics
  Wind Resource
  Installed Capacity Growth
  Decommissioning
Global installed renewable generation continues to grow with wind making a large contribution after hydro.
Although still a relatively small contributor overall, wind is growing as a % of global electricity energy mix

Source: https://www.nrel.gov/docs/fy18osti/70231.pdf
Electricity generation (capacity) type highly regional

National Energy Board electricity generation (TWh) forecast

Figure 26
Electricity generation by fuel shows coal phasing out, and more renewables and natural gas added
Installed wind capacity in Canada

Source: https://canwea.ca/wind-energy/installed-capacity/
Globally, wind power continues to expand through new build and re-powering.
Future growth to continue

Recent auction results, subsidy-free (2020-2022 delivery)
- €0.025/kWh (Alberta)
- €0.015/kWh (Mexico)
- Wholesale elec price for 700 MW Hollandse Kust (Netherlands)
China has like in many other areas dominated the picture.

Source: http://www.gwec.net
Deployment & Economics

Wind Resource
Installed Capacity Growth
Decommissioning
Turbines typically have a 20 yr design life and machine size growth is rapid


- Repowering with fewer, larger machines
Disposal/recycling is becoming an issue

Wyoming landfill example (2019)
Playgrounds aren’t going to cut it...
Pyrolysis current option

(http://www.renewableenergyfocus.com/view/319/recycling-wind/)
Regardless, the GHG LCA of wind is very good

(Moomaw et al. 2011)
Unit environmental impacts

- **A** Greenhouse gases (kg CO₂-eq/MWh)
- **B** Particulate matter (kg PM₁₀-eq/MWh)
- **C** Ecotoxicity (kg T,ADP-eq/MWh)
- **D** Eutrophication (g P-eq/MWh)
- **E** Land occupation (m²/MWh)

Unit energy and material requirements

- **F** Non-renewable energy demand (GJ/MWh)
- **G** Iron (kg/MWh)
- **H** Cement (kg/MWh)
- **I** Copper (kg/MWh)
- **J** Aluminum (kg/MWh)

**Legend:**
- Orange: Photovoltaics
- Red: Concentrating solar power
- Green: Hydropower
- Blue: Wind power
- Pink: Coal
- Blue: Natural gas

(Hertwich et al. 2015)
Offshore Wind Energy
EU Genesis
Offshore Resource & Development
Floating Offshore
Many projects have been developed over last 15 years
Some growing pains, but now mature

- London Array (2013): 630 MW, 175x Siemens 3.6-120
- 370 MW Phase 2 abandoned in 2014
Optimal support structure is dictated by water depth and bottom geotechnics.
Offshore transformer stations

Lillgrund

Nysted
Installation has lead to specialized equipment
Servicing has also spawned a specialized industry
Offshore Wind Energy
EU Genesis
Offshore Resource & Development
Floating Offshore
Canada, and BC in particular, has a large offshore wind resource
BC’s coastal remoteness and bathymetry motives the investigation of floating offshore wind
Offshore turbines shift the proportion of costs to Balance of Station (BOS) and increases total costs

Offshore reference turbine CAPEX breakdown ($5,600/kW)$

- 2018: €2.45M/MW = $3,700/kW CND
- Site C: $10.7B/1100 MW = $9,727/kW *(55% capacity factor vs. wind rated power metric)

$^1$Tegen et al. 2012.
Continued drive towards larger machines

**Haliade-X 12 MW**

- 12 MW capacity
- 220-meter rotor
- 107-meter long blades
- 260 meters high
- 67 GWh gross AEP
- 63% capacity factor
- 38,000 m² swept area

**Wind Class IEC: IB**

- Generates double the energy as previous GE Haliade model
- Generates almost 45% more energy than most powerful wind turbine available on the market today
- Will generate enough clean power for up to 16,000 European households per turbine, and up to 1 million European households in a 750 MW configuration windfarm

Nov 2019 commissioning
Costs continue to fall over time with larger machines and more deployments

(https://euanmearns.com/a-review-of-recent-solar-wind-auction-prices/)
Recent data on offshore wind auctions

- Site C estimates: 0.02–0.07 USD/kWh
- 2018 German offshore wind auction average: 0.053 USD/kWh
- 2020 Shell/EDP Massachusetts Mayflower project: 0.058 USD/kWh
Offshore Wind Energy
EU Genesis
Offshore Resource & Development
Floating Offshore
Floating offshore in first (array) project stages

- Tension-leg, spar buoy (ballast), and buoyancy stabilized platform concepts
Developers have proposed a wide range of floating platforms and in some cases tailored turbines

(a) Hywind 2.3 MW (2009)
(b) Windfloat V80 2 MW (2011)
(c) Sway 7 kW (2011); bankrupt 2014
Equinor (Statoil) Hywind Scotland (2017)

- 30 MW: 5x Siemens 6.0-154 turbines
- 65% capacity factor demonstrated
- 95–120 m water depth (potential to 800 m depth)
Equinor (Statoil) Hywind Tampen (2022)

- 88 MW: 11x Siemens Gamesa Renewable Energy (SGRE) 8.0-167 DD turbines = 35% of platform power demand
- Concrete (vs steel) spars
- 250–300 m water depth
Principle Power WindFloat Atlantic (2020)

- 25 MW: 3x Vestas V164-9.0 MW turbines in 100 m water depth
- Grid-connected to Portugal
- Plans for 30 turbines, 150 MW total
There is a wide design space for offshore floating platforms
The design of offshore turbines themselves have some shifted constraints leading to different ideas

- Very large (> 10 MW) machines become self-induced fatigue dominated
- Relaxed TSR limits may lead to 2-bladed HAWTs, or at least lower loads in 3-bladed machines
- VAWTs place the generator lower down
Airborne Wind Energy Systems (AWES)

AWES Advantages
AWES Challenges
Other AWES Markets
How crazy the idea of airborne wind sounds depends on what you’re talking about

▶ There are a range of universities, companies and conferences on this topic!
▶ High-altitude vs. more realistic lower altitudes (< 1000 m)
  ▶ High altitude jet stream looks good on paper
  ▶ Airspace restrictions
▶ Drastically reduced structure for a very big capture area

Source: http://www.makanipower.com
Many concepts are being proposed

Pumping or drag modes the most common and powerful
Airborne Wind Energy Systems (AWES)

AWES Advantages

AWES Challenges

Other AWES Markets
Control 24x7, 365

SSDL lab AWES system
Continuity of power output for pumping-mode

1. Kite pulls the tether outwards
2. This rotates the generator, producing electricity
3. Once tether reaches its end a small amount of power is lost as the kite is retracted and the cycle starts again
4. A second kite on each generator rotates in an opposing cycle to ensure a constant process
5. A twenty-kite farm will produce enough energy for 5,500 homes

KPS (exited 2019)
Pumping mode takeoff & landing strategies

Ampyx
Unique strategies are possible
Removing tether drag is advantageous

Rachel Leuthold et al
Offshore and MW scale just makes things harder!

Makani/GoogleX/Alphabet/Shell (exited this week!)
Weight is key, but so is aero, cost, control, scaling...

100m² Kitepower prototype
Airborne Wind Energy Systems (AWES)

AWES Advantages
AWES Challenges
Other AWES Markets
Offgrid diesel replacement
Wind has driven ship transport for thousands of years, and is returning

- Flettner rotors exploit Magnus effect
- Enercon’s transport ship - 30–40% fuel savings

- Leverage modern technologies - 10–30% fuel savings
  - Kiteboarding
  - Non-linear control

Source: http://en.wikipedia.org/wiki/File:E-Ship_1_achtern.JPG

Source: www.skysails.info
Thanks for listening!

Dr. Curran Crawford

E-mail curranc@uvic.ca


