Developments in Wind Turbines
Terrestrial to Offshore

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Living Without Oil Lecture Series, Part One
An Elder Academy Event
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University of Victoria | Institute for Integrated Energy Systems

SSDL Sustainable Systems Design Laboratory

PRIMED | Pacific Regional Institute for Marine Energy Discovery

Outline

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

$$P_{density} = \frac{1}{2}\rho V^3$$

$$P_{turbine} = \frac{1}{2}\rho V^3 C_P A$$

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

Standard wind speed measurement tools: NRG and RM Young are the most common

Wind vane, cup anemometer

Windmill anemometer

Sonic anemometers and temperature sensor

LiDAR is playing an increasingly large role

Wind speeds vary on a number of time scales

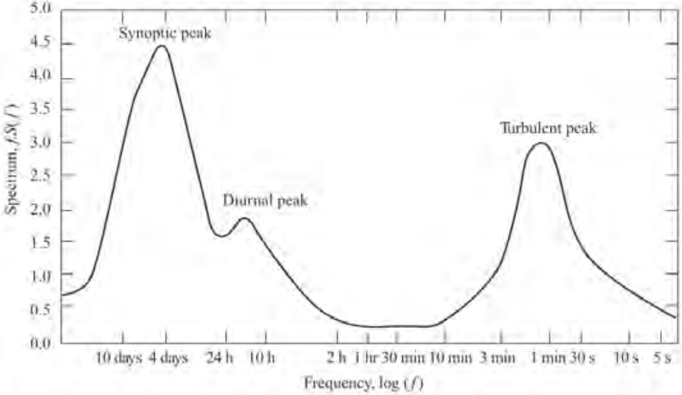


Figure 2.1 Wind spectrum from Brookhaven based on work by van der Hoven (1957)

Weibull probability density function $f(U)$ describes annual hourly average wind speeds

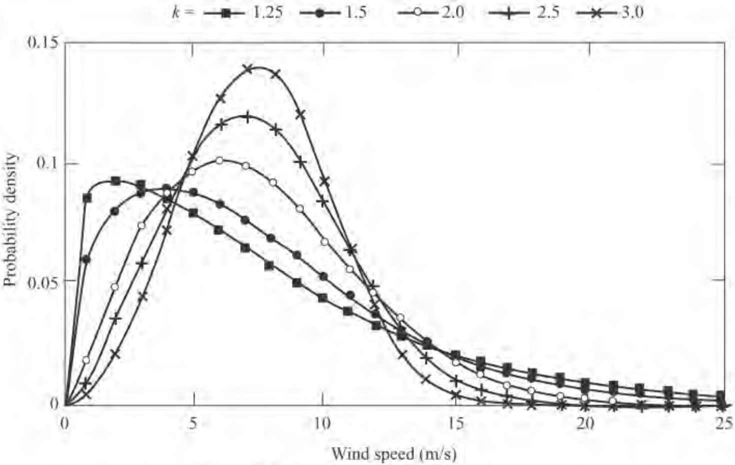
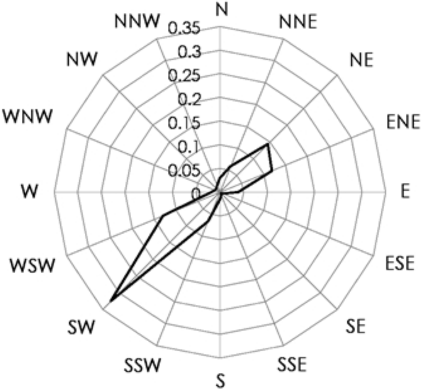


Figure 2.2 Example Weibull distributions

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

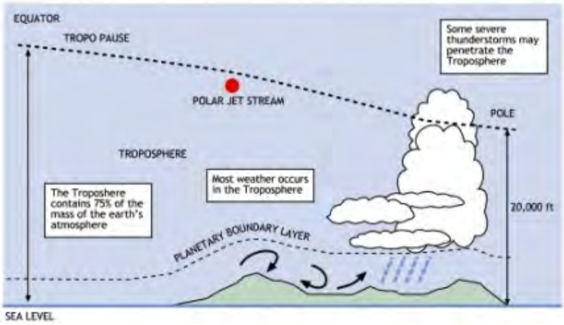
Origins of the Wind

Characterizing the Wind

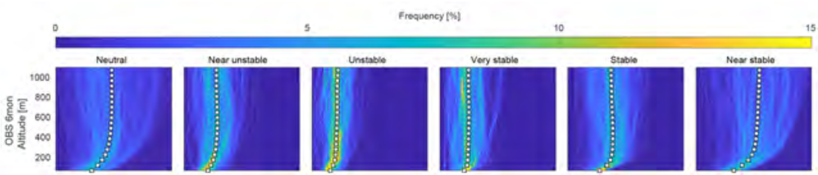
The Earth's Boundary Layer

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

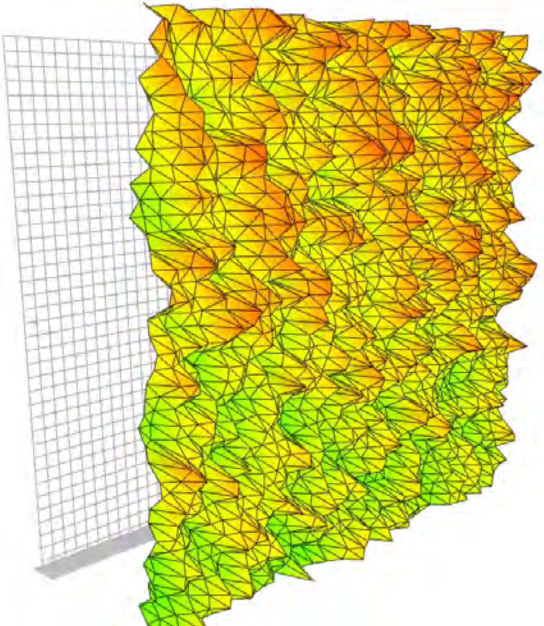


Boundary layer profiles vary greatly over time with prevailing conditions



WRF simulations for Pritzwalk

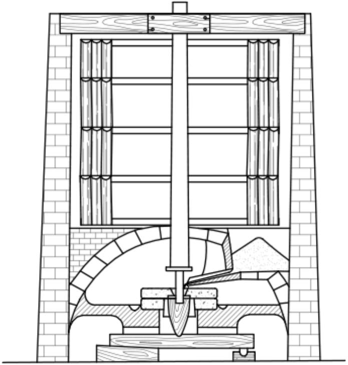
Wind turbines always operate in an unsteady environment

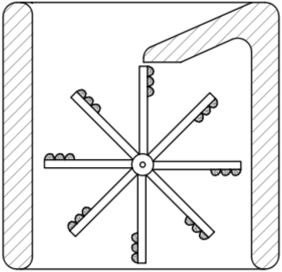


The power in the wind has been used for thousands of years, first for transportation

Wind has been used since first century AD to directly do mechanical work

- Pumping water (irrigation and drainage)
- Grinding grain



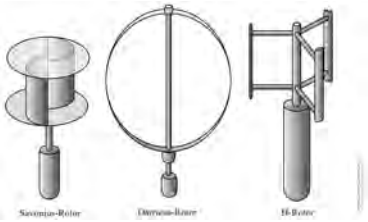


Persian Windmill
Source: http://en.wikipedia.org/wiki/File:Perzsa_malom.svg

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

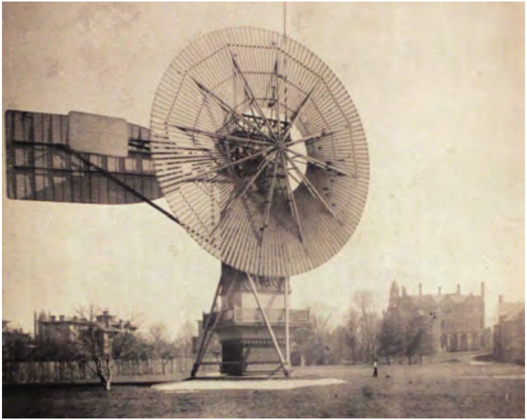
Danish windmill
Source: http://en.wikipedia.org/wiki/File:DK_Fanoe_Windmill01.JPG

Greek windmill
Source: http://en.wikipedia.org/wiki/File:Windmill_Antimahia_Kos.jpg

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

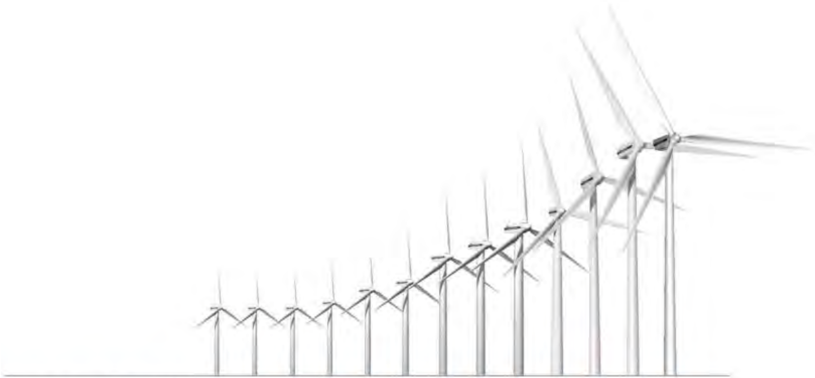
Wind turbine (Jacobs) used in North America before transmission lines reached rural areas

- 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

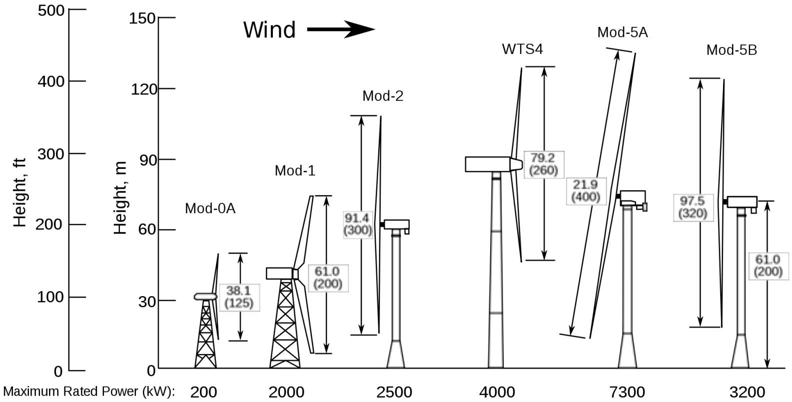
Vestas is an example of a Danish manufacturer that originally made farming equipment



Product/Rotor diameter (m)	V15	V17	V19	V20	V25	V27	V39	V44	V47	V52	V66	V80	V90
Year of installation	1981	1984	1986	1987	1988	1989	1991	1995	1997	2000	1999	2000	2002
Capacity (kW)	55	75	90	100	200	225	500	600	660	850	1750	2000	3000
MWh/year	217	265	301	346	481	647	1304	1581	1947	2530	4705	6768	9152

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



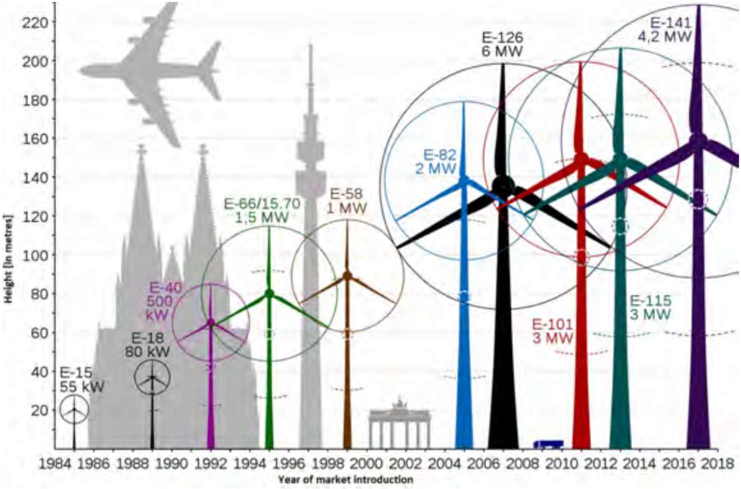
Mod-1 turbine in action - note downwind orientation

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

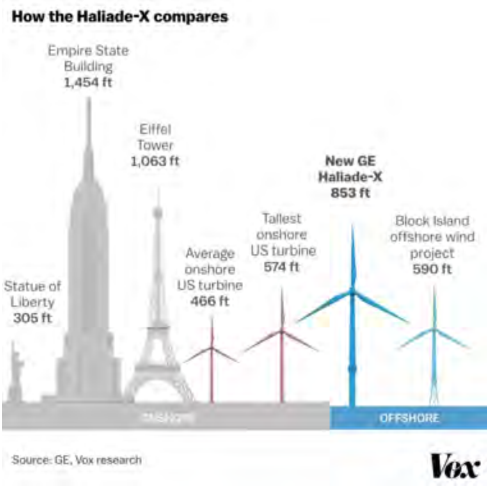
And so, we have the modern 3-bladed, upwind "Danish-concept" machines you see around today

"Danish-concept" turbines continue to grow in size



Source:
https://www.cleanenergywire.org/factsheets/german-onshore-wind-power-output-business-and-perspectives

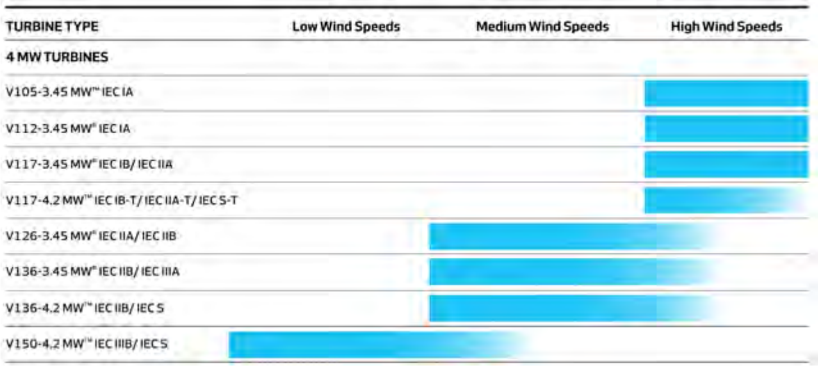
Same size evolution seen in the US



Source: https://www.vox.com/energy-and-environment/2018/3/8/17084158/wind-turbine-power-energy-blades

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



Wind energy is extracted through a step change in static pressure, which affects velocities around the rotor

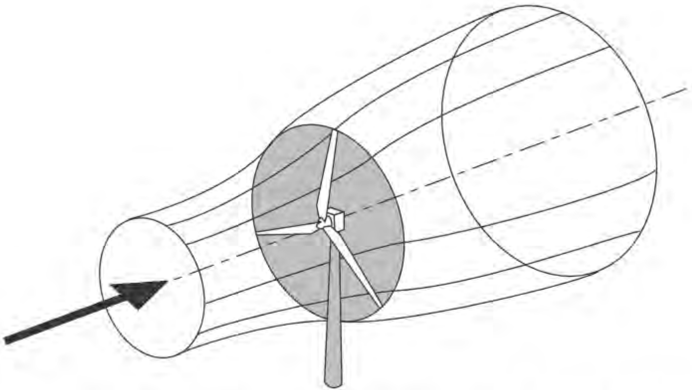


Figure 3.1 The energy extracting stream-tube of a wind turbine

The actuator disc model is the most basic model of an energy-extracting disc

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

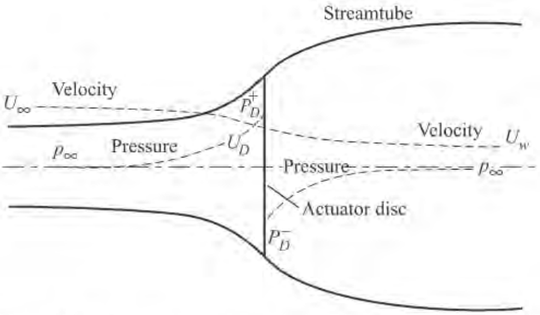


Figure 3.2 An energy extracting actuator disc and stream-tube

BEM theory is based on the assumption of independent radial streamtubes (annuli)

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

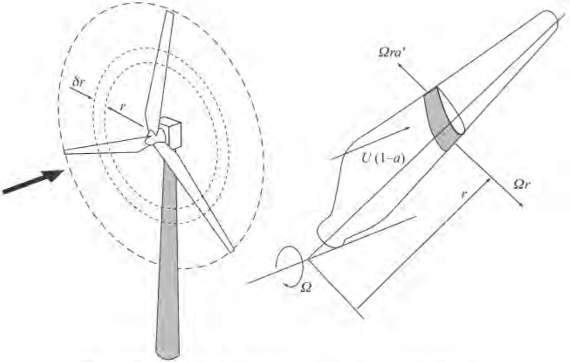


Figure 3.13 A blade element sweeps out an annular ring

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

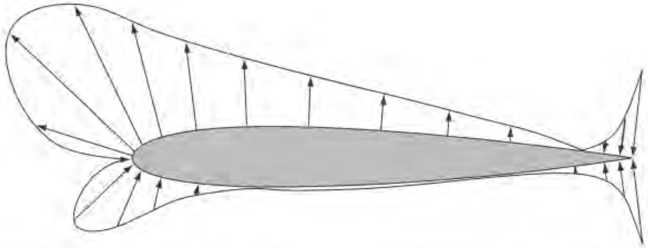
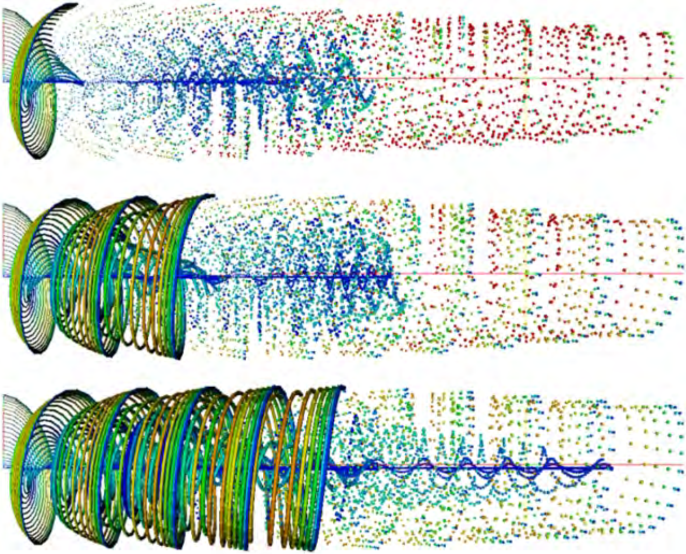


Figure A3.15 The pressure distribution around the NACA0012 aerofoil at $\alpha = 5^{\circ}$

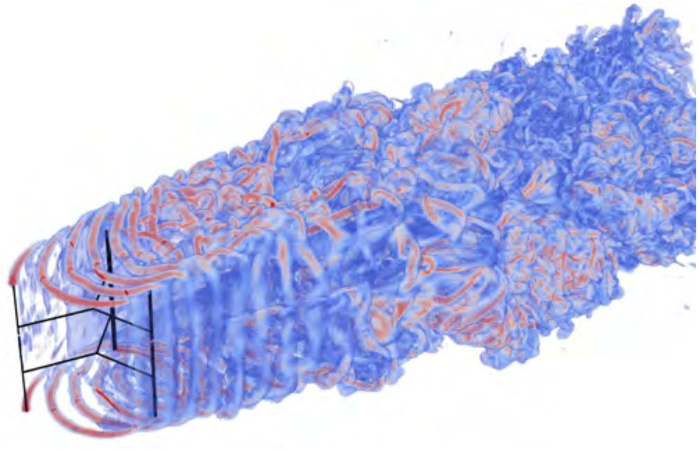
The flow around a wind turbine rotor is complex and fundamentally governs the power capture and loads

(**http://i.imgur.com/qruVcnu.jpg**)

Wake simulations are key for individual machines and arrays



Vertical axis turbine wakes are even more challenging to simulate



(http://www.gauss-centre.eu/gauss-centre/EN/Projects/EnvironmentEnergy/chatelain˙VAWT.html?nn=1345670)

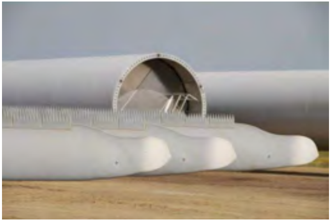
Experiments remain challenging even for steady-state, given scales and accuracy requirements involved

IEA Task 29 Mexico rotor experiment

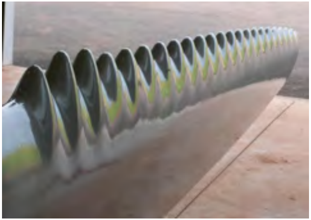
Our trailer-based test rig for towed & parked testing

Various ideas are used and tried to improve aerodynamic performance

Vortex generators



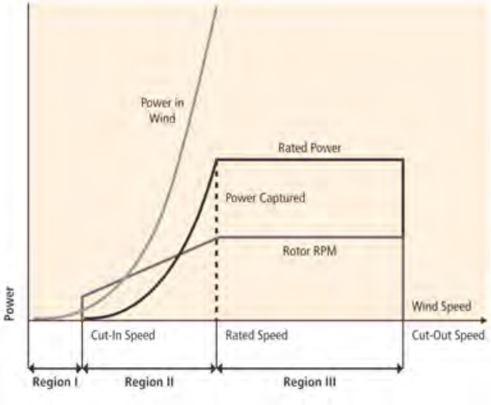
Serrated trailed edges



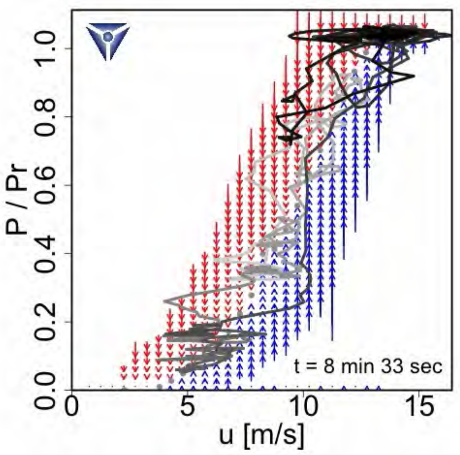
Turbuncles

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



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

Tubular steel tower | Tubular concrete | Lattice tower | Three-legged tower | Guy-wired pole tower

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

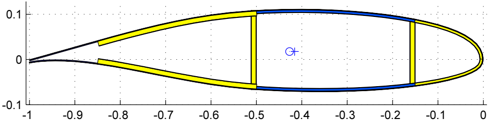
Enercon has used exclusively electrically excited direct-drive generators for decades - heavy nacelles!

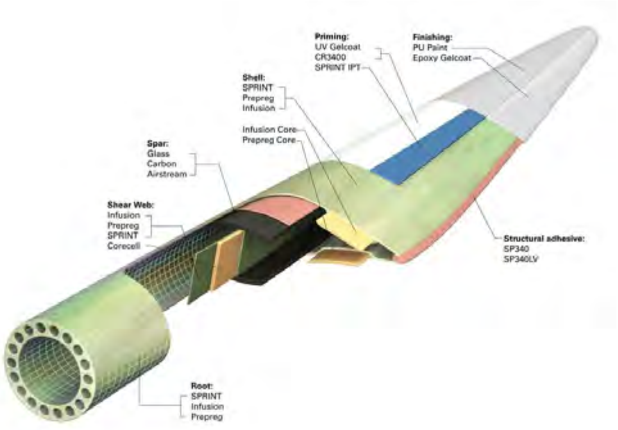
Siemens (formerly Bonus) Gamesa has a direct drive permanent magnet machine

Wind turbine blades are massive composite structures

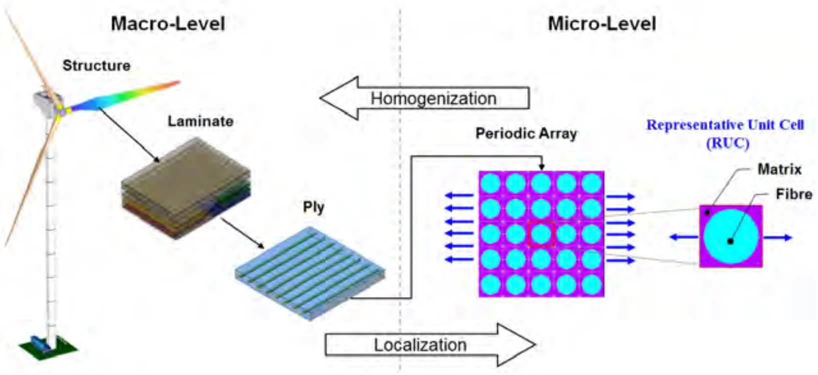
(https://www.themanufacturer.com/articles/fishing-fibreglass-hull-embraces-blade-production/)

Blades are made up of composite layups





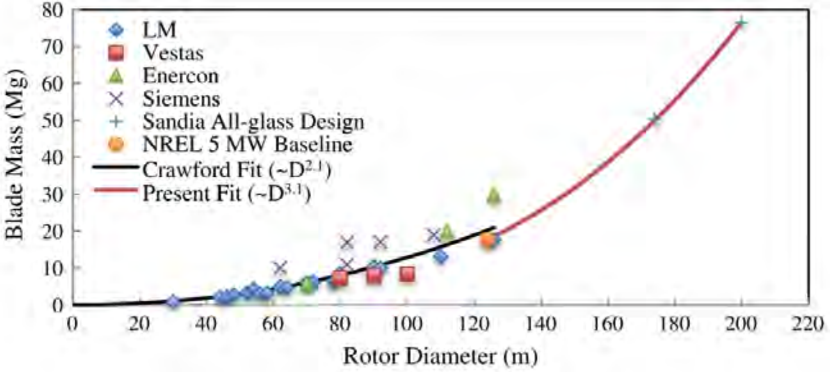
We can simulate composite wind turbine structures accounting for material variability



- Bayesian approach accounting for natural property variation and model deficiencies

The fundamental square-cube law continues to be 'broken'

$$\text{Capture area} \propto D^2$$
$$\text{Mass} \propto D^3$$

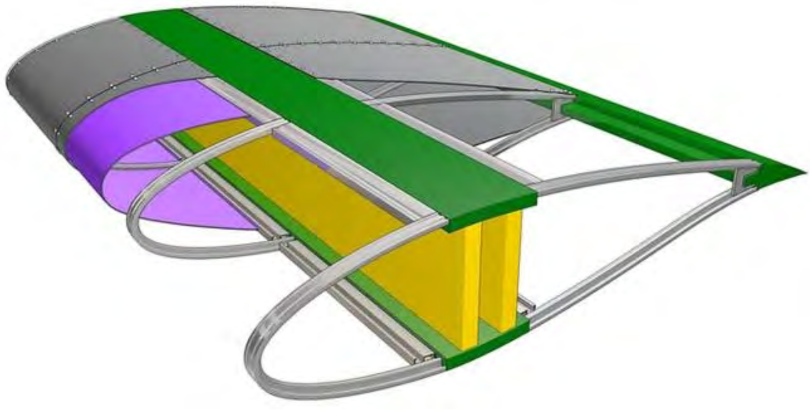


- LM 107.0 P blade (2019) - 220 m dia, 55 t mass

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

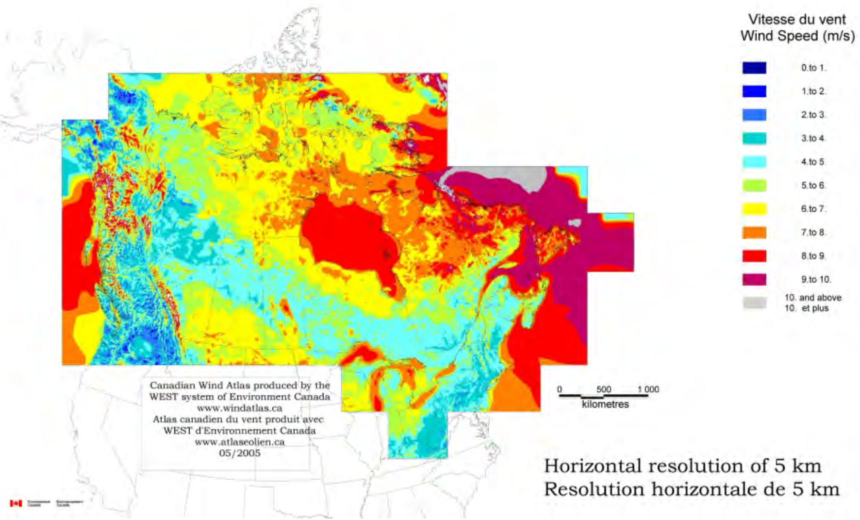


GE fabric blade concept (canceled in 2014)

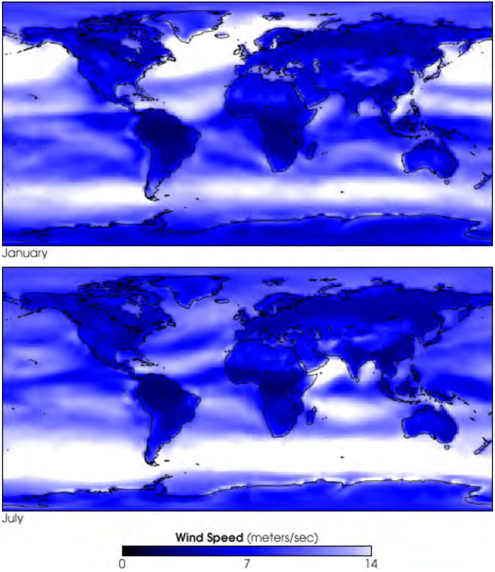
Transportation becomes a challenge!

- Localized manufacturing
- Offshore advantages

Canadian distribution of wind resource at 50 m



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

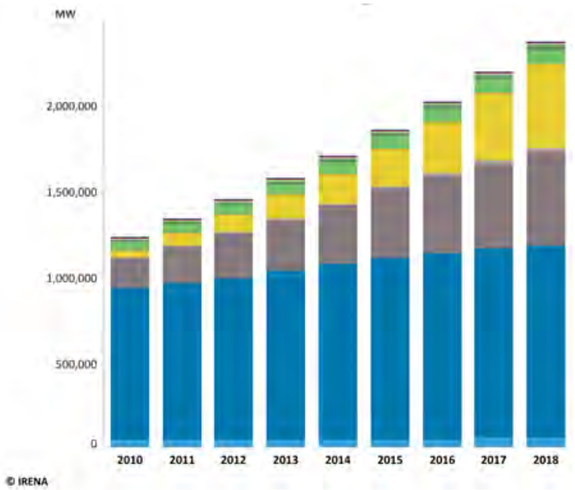
The fact that the wind resource is distributed is also a challenge

- 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



Stack: Hydro, wind, solar, biomass

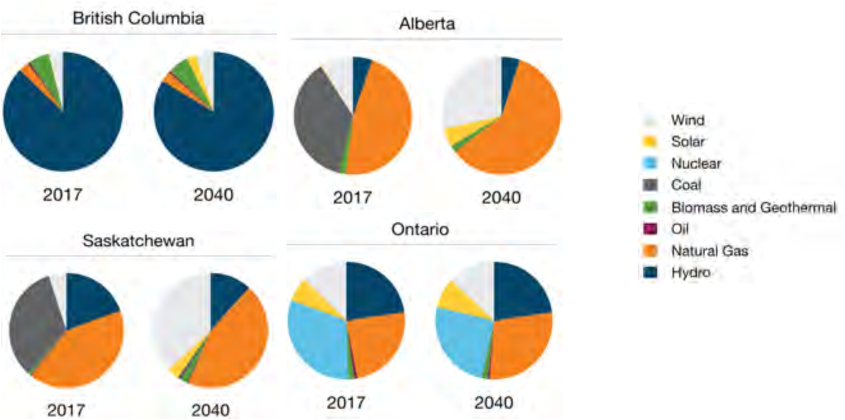
Source: https://www.irena.org/Statistics/View-Data-by-Topic/Capacity-and-Generation/Statistics-Time-Series

Although still a relatively small contributor overall, wind is growing as a % of global electricity *energy* mix

	Hydropower	Solar[1]	Biomass	Wind	Geothermal	All Renewables	Renewable Generation (GWh)
2006	16.7%	0.1%	1.2%	1.1%	0.3%	19.4%	3,488,055
2007	16.4%	0.1%	1.3%	1.3%	0.3%	19.3%	3,644,173
2008	16.6%	0.1%	1.3%	1.7%	0.3%	20.0%	3,822,689
2009	17.2%	0.1%	1.5%	2.2%	0.4%	21.3%	4,064,206
2010	16.6%	0.3%	1.6%	2.6%	0.3%	21.3%	4,319,733
2011	16.4%	0.4%	1.7%	3.0%	0.3%	21.7%	4,582,578
2012	16.3%	0.6%	1.8%	3.4%	0.3%	22.4%	4,891,891
2013	16.2%	0.8%	1.8%	3.7%	0.3%	22.9%	5,161,742
2014	16.3%	1.0%	1.9%	4.2%	0.3%	23.6%	5,506,624
2015	15.9%	1.2%	2.1%	4.7%	0.3%	24.2%	5,830,656
2016	16.3%	1.6%	2.2%	5.3%	0.3%	25.8%	6,210,928

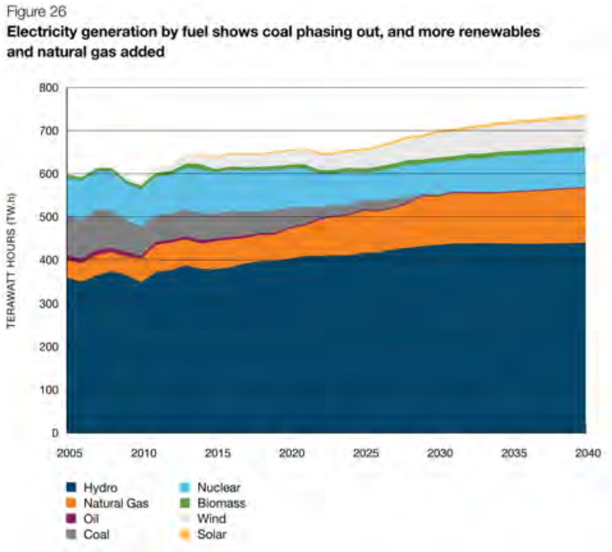
Source: https://www.nrel.gov/docs/fy18osti/70231.pdf

Electricity generation (capacity) type highly regional



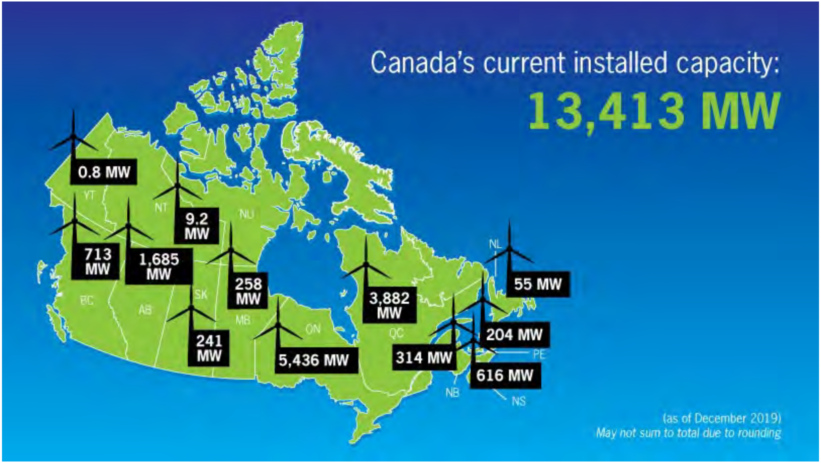
Source: https://www.cer-rec.gc.ca/nrg/ntgrtd/ftr/2019/index-eng.html

National Energy Board electricity generation (TWh) forecast



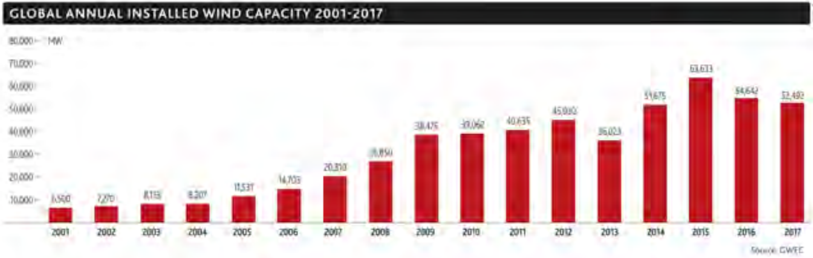
Source: https://www.cer-rec.gc.ca/nrg/ntgrtd/ftr/2019/index-eng.html

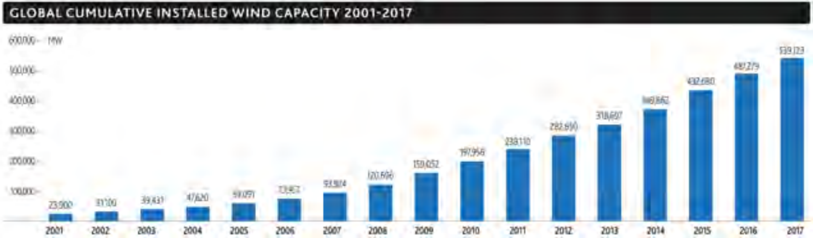
Installed wind capacity in Canada



Source: https://canwea.ca/wind-energy/installed-capacity/

Globally, wind power continues to expand through new build and re-powering





Source: http://www.gwec.net

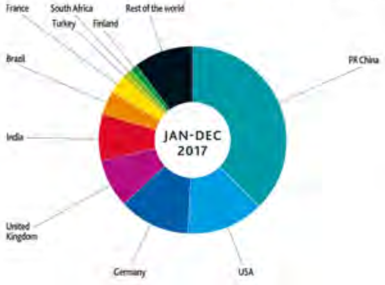
Future growth to continue

Source: http://www.gwec.net

- 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

TOP 10 NEW INSTALLED CAPACITY JAN-DEC 2017



Country	MW	% Share
PR China	19,660	37
USA	7,017	13
Germany	6,581	12
United Kingdom	4,270	8
India	4,148	8
Brazil	2,022	4
France	1,694	3
Turkey	766	1
South Africa	618	1
Finland	535	1
Rest of the world	5,182	10
Total TOP 10	**47,310**	**90**
World Total	**52,492**	**100**

TOP 10 CUMULATIVE CAPACITY DEC 2017

Country	MW	% Share
PR China	188,392	35
USA	89,077	17
Germany	56,132	10
India	32,848	6
Spain	23,170	4
United Kingdom	18,872	4
France	13,759	3
Brazil	12,763	2
Canada	12,239	2
Italy	9,479	2
Rest of the world	82,391	15
Total TOP10	**456,732**	**85**
World Total	**539,123**	**100**

Source: http://www.gwec.net

Turbines typically have a 20 yr design life and machine size growth is rapid

(https://www.desertsun.com/story/tech/science/energy/2018/10/24/palm-springs-iconic-wind-farms-could-change-drama

- Repowering with fewer, larger machines

Disposal/recycling is becoming an issue

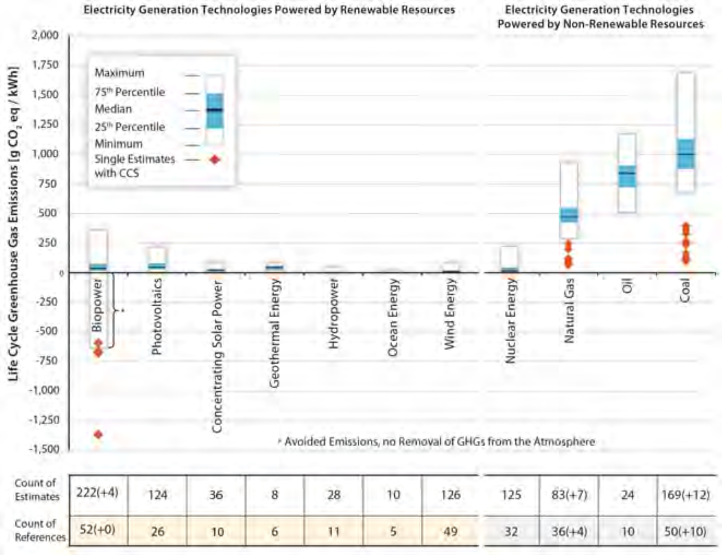
Wyoming landfill example (2019)

Playgrounds aren't going to cut it...

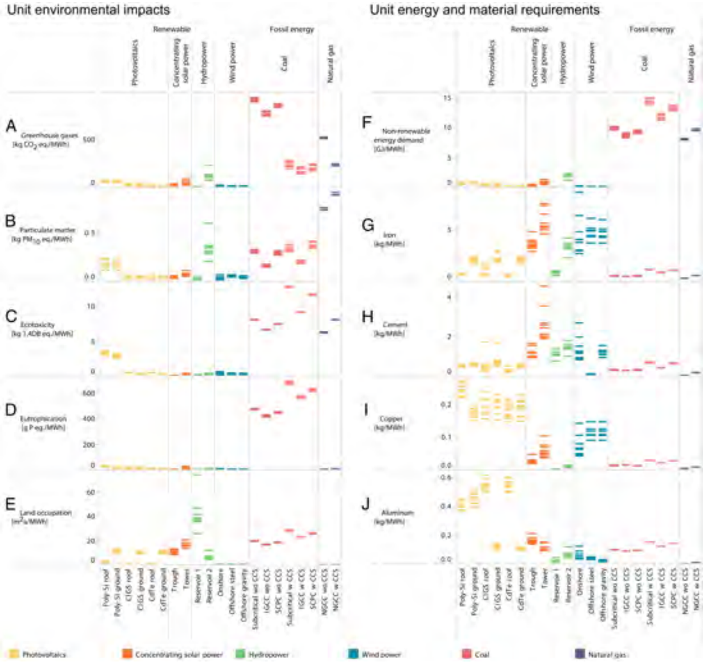
Pyrolysis current option

(http://www.renewableenergyfocus.com/view/319/recycling-wind/)

Regardless, the GHG LCA of wind is very good



(Moomaw et al. 2011)



(Hertwich et al. 2015)

Many projects have been developed over last 15 years

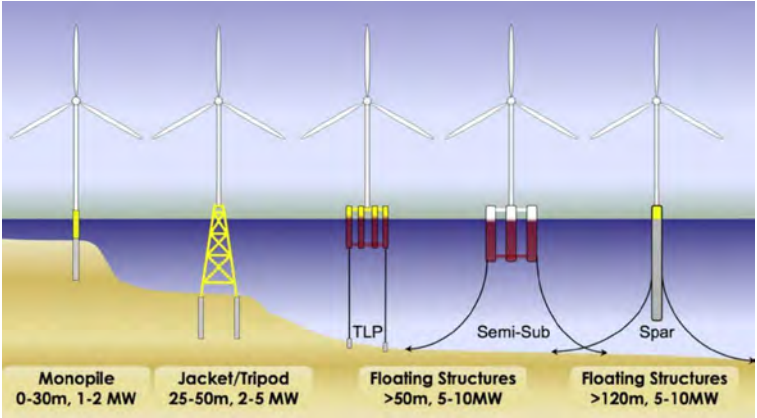
Country Details

	MW connected	Turbines connected
UK	9,945	2,225
GERMANY	7,557	1,48
DENMARK	1,703	559
NETHERLANDS	1,118	365
BELGIUM	1,556	318
SWEDEN	192	80
FINLAND	71	19
IRELAND	25	7
SPAIN	5	1
PORTUGAL	8	1
NORWAY	2	1
FRANCE	2	1

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

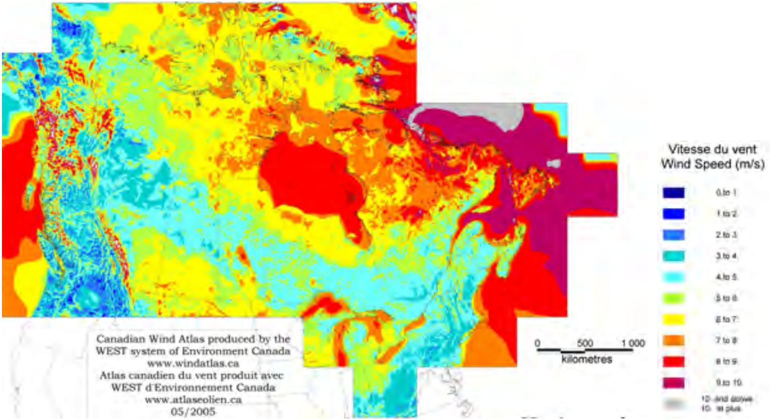
Lillgrund

Nysted

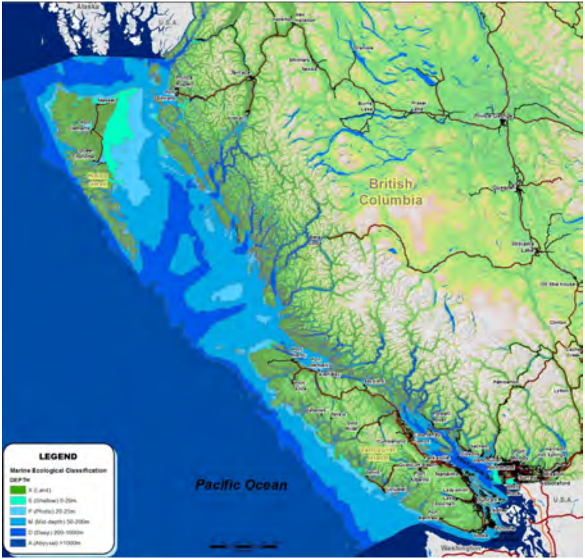
Installation has lead to specialized equipment

Servicing has also spawned a specialized industry

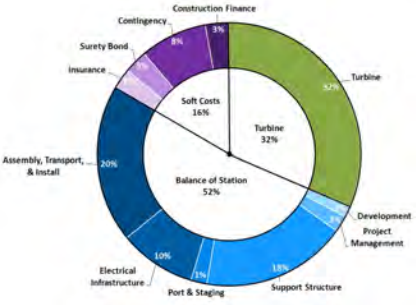
Canada, and BC in particular, has a large offshore wind resource



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)[1]

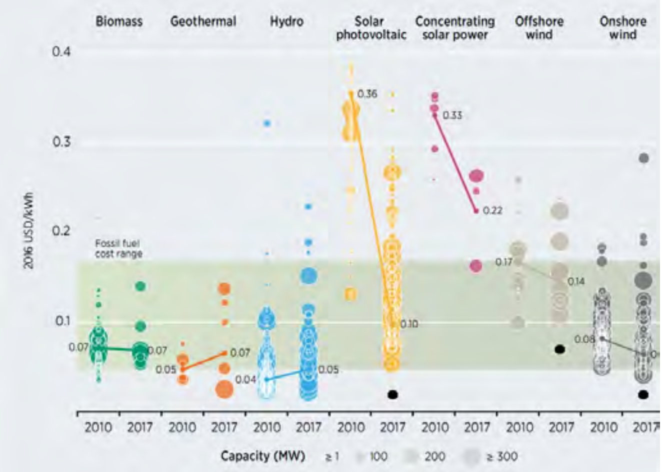
- 2018: €2.45M/MW = $3,700/kW CND
- Site C: $10.7B/1100 MW = $9,727/kW *(55% capacity factor vs. wind rated power metric)

[1] Tegen et al. 2012.

Continued drive towards larger machines

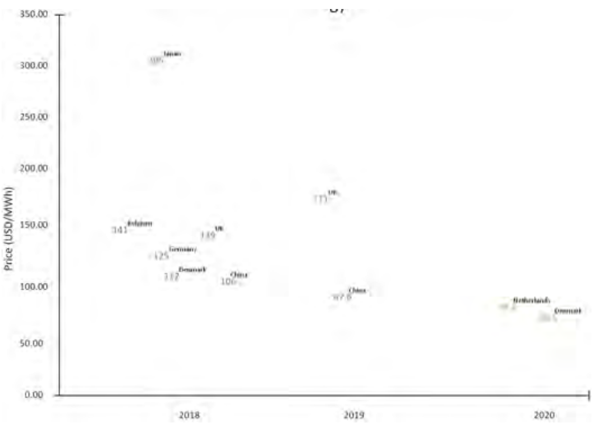
Nov 2019 commissioning

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



(http://euanmearns.com/a-review-of-recent-solar-wind-auction-prices/)

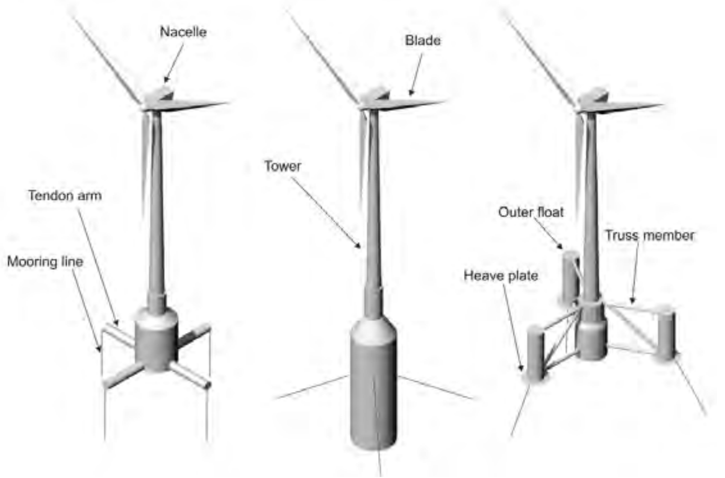
Recent data on offshore wind auctions



- 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

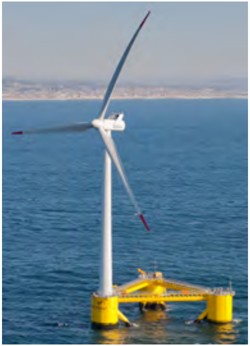
Floating offshore in first (array) project stages

- 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)



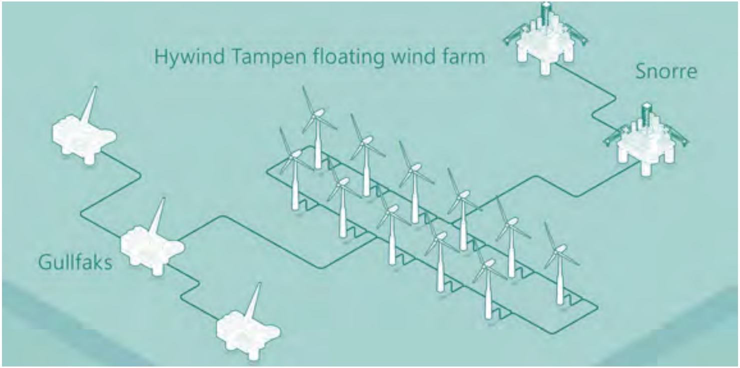
(b) Windfloat V80 2 MW (2011)

(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)

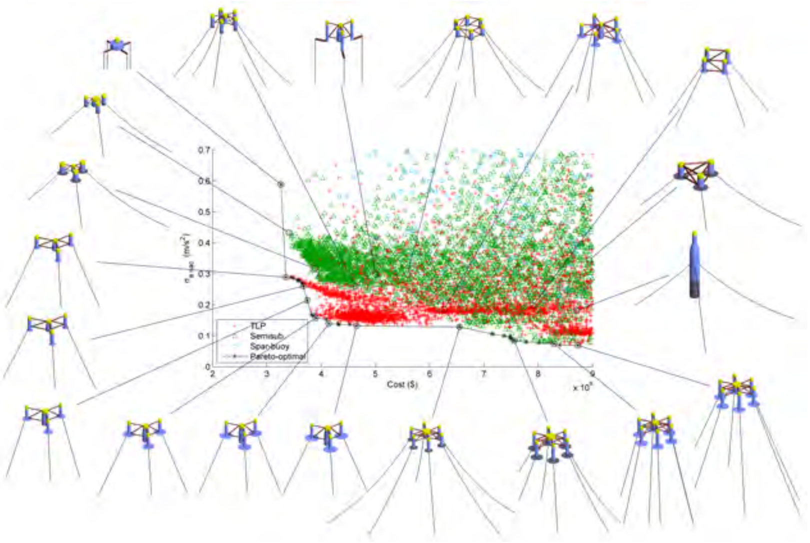


- 88 MW: 11x Siemens Gamesa Renewable Energy (SGRE) 8.0-167 DD turbines = 35% of platform power demand
- Concrete (vs steel) spars
- 250–300 m water depth

Principle Power WindFloat Atlantic (2020)

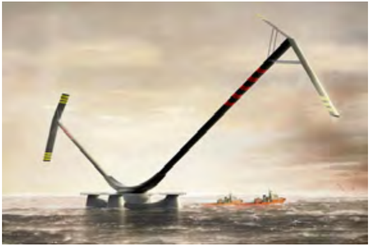
- 25 MW: 3x Vestas V164-9.0 MW turbines in 100 m water depth
- Grid-connected to Portugal
- Plans for 30 turbines, 150 MW total

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)

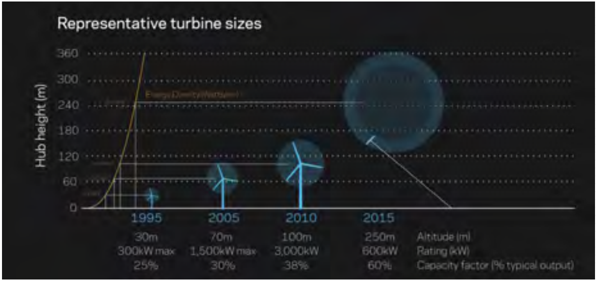
AWES Advantages

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

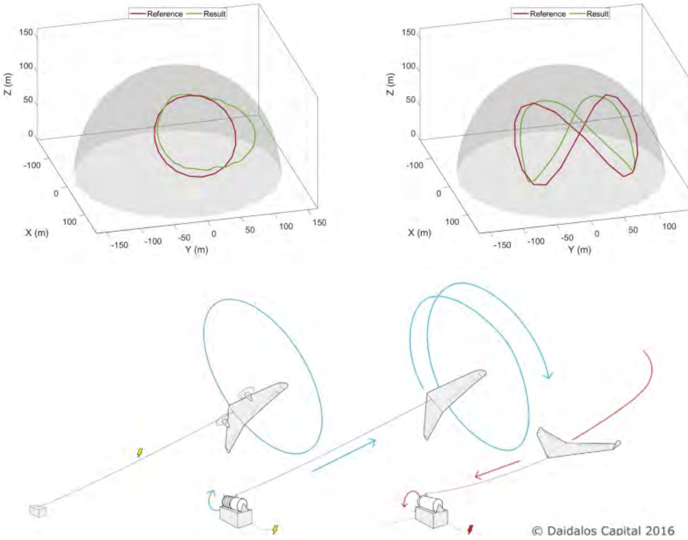


Source: http://www.makanipower.com

Many concepts are being proposed

Sources: http://www.makanipower.com, http://www.kitepower.eu

Pumping or drag modes the most common and powerful

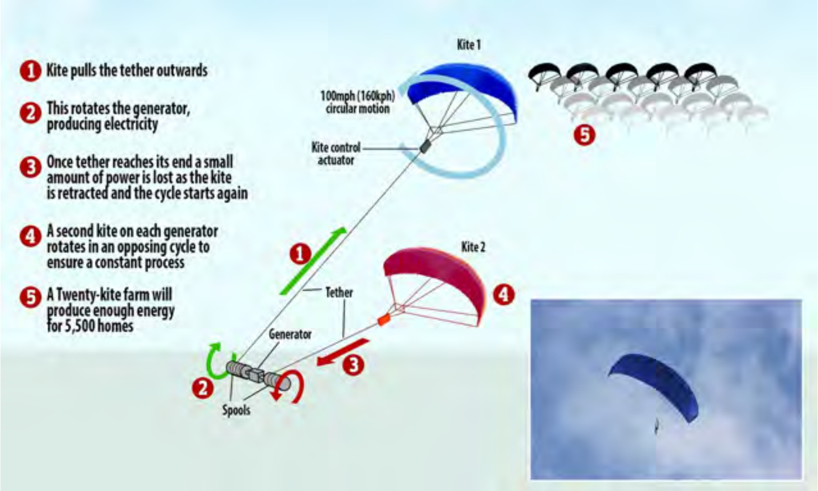


Airborne Wind Energy Systems (AWES)

Control 24x7, 365

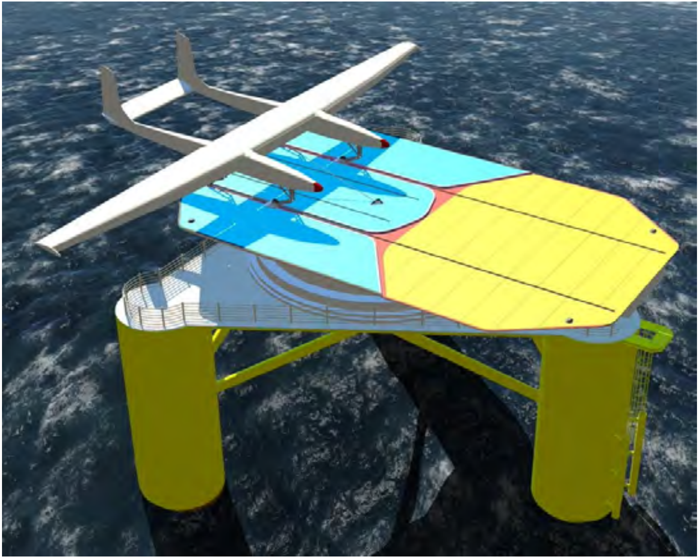
SSDL lab AWES system

Continuity of power output for pumping-mode



KPS (exited 2019)

Pumping mode takeoff & landing strategies

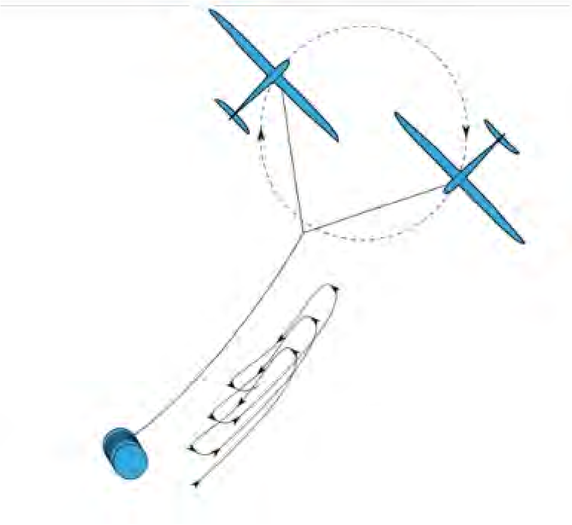


Ampyx

Unique strategies are possible

Enerkite

Removing tether drag is advantageous



Rachel Leuthold et al

Offshore and MW scale just makes things harder!

Makani/GoogleX/Alphbet/Shell (exited this week!)

Weight is key, but so is aero, cost, control, scaling...

$100m^2$ Kitepower prototype

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

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

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

Source: www.skysails.info

Thanks for listening!

Dr. Curran Crawford

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WIND WAVE TIDAL COMMUNITIES

PRIMED | Pacific Regional Institute for Marine Energy Discovery

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