Wind speed vs. height above the ground

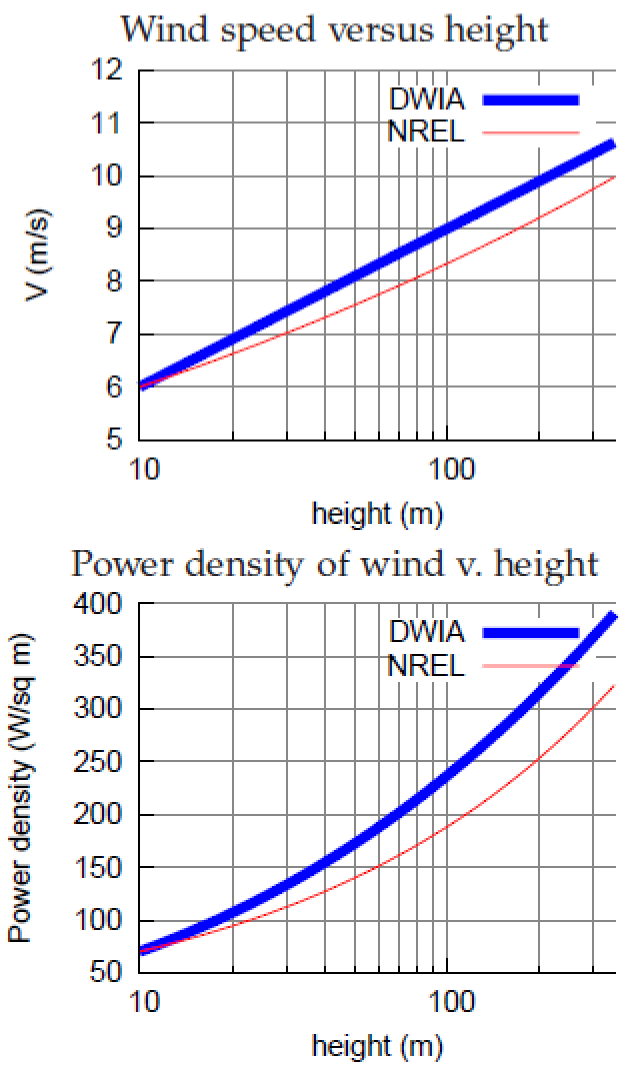


Figure B.7. Top: Two models of wind speed and wind power as a function of height. DWIA = Danish Wind Industry Association; NREL = National Renewable Energy Laboratory. For each model the speed at 10 m has been fixed to 6 m/s. For the Danish Wind model, the roughness length is set to $z_0 = 0.1$ m. Bottom: The power density (the power per unit of upright area) according to each of these models.

Power density varies as v^3 !

Bottom line:
Large, tall turbines are much more efficient than small ground based microturbines.

Source: McKay page 266

Calculation of energy per unit area of earth's surface:

Assuming v=6 m/s, 50% efficiency

$$\frac{\text{power per windmill}}{\text{land area per windmill}} = \frac{\frac{1}{2}\rho v^3 \frac{\pi}{8} d^2}{(5d)^2} = \frac{\pi}{200}\frac{1}{2}\rho v^3 = 0.016 \times 140\,\text{W/m}^2 = 2.2\,\text{W/m}^2.$$

From McKay

Siemens: "Pictures of Future" Sept09

Horns Rev II under construction off the coast of Denmark: 210 MW total projected delivered power

Winds are stronger in the ocean, e.g. North Sea

This can boost the energy estimate by ~50% to **3.0W/m²**.

It is useful to express energy capacity in W/m^2 for comparison with other technologies later on such as photovoltaic

Estimate of wind resource for UK

Area of shallow offshore coast of UK: 40,000 km^2.

Assuming turbines evenly spaced to a depth of 15 km along the entire length of UK coastline (3000 km):

This yields 15 x 3000 = 45000 km^2.

Assuming an average power per unit area of **3W/m²** this yields:

$(45000\ km^2)x(10^6\ m^2)/(1\ km^2)x(3W/m^2) = 135\ GW = 1.35x10^8\ kW$

Convert to kW-h/day:

$1.35x10^8\ kW)x(24h/day) =$ **$3.24x10^9$ kW-h/day**

Population of UK = **61.4 million**

Per capita energy produced = $(3.24x10^9\ kWh/day)/(61.4x10^6\ persons) =$ **53 kWh/day/p**

This is ~40% of the average UK consumption of **130 kWh/d/p**

However, is it really feasible to achieve this kind of density of wind turbines considering the demands for space by shipping not to mention environmental and aesthetic opposition?

Adapted from McKay, page 61

Grouse Mountain wind turbine

•nominal power **1.5 MW** (at “design wind speed”)

•74m blade length, 37.3m blade length

•height 65m

•2.7m/s minimum speed, 25 m/s maximum speed

•12,500VAC (matched to North Vancouver grid)

•Estimated to generate 25% of resort electricity

From Grouse Mountain website

Grouse Mountain wind turbine

1.5 MW nominal output for 1 year = (1500 kW)X(365days)X(24 hours) = **13.1×10^6 kWh**

Actual projected electricity generation: **2×10^6 kWh** (Grouse website)

(lower because wind is usually below the design wind speed)

Capacity factor = Actual power/nominal power = 2×10^6 kWh/13.1×10^6 kWh = **15%**

This seems low, but is consistent with the low average wind velocity in Vancouver.

How many households would this supply?

- Projected electricity generation: 2×10^6 kWh (Grouse website)
- Average BC residential electricity usage: 11,000 kWh per household*

(2×10^6 kWh)/(11,000kWh) = 180 households (not the 400 stated in the website)

*BC Hydro website

Economics of Wind Production:
Cost per kW of generation infrastructure

Nominal power = power delivered at design wind speed (upper end of wind range)

Capacity factor= fraction of nominal power output that is actually achieved due to calm days

Typical capacity factor is 20-40%

Typical cost: ~ 900-1,400 $/kW of nominal power production capacity

Estimate cost per kW of power production:
Assume 1400 $/kW nominal

Assume capacity factor of 1/3 (33%)

This gives (1400 $/kW)/(1/3) ~ **4200 $/kW**

(note: this does not include the cost of the transmission lines and the access roads)

For comparison a new state of the art coal plant cost about **3000 $/kW** of installation cost, but then we have to pay for the fuel forever.

Compare with Site C Dam Proposal (Northeastern BC):

Projected Capital cost: **$7.9x10^9$**

Nominal capacity: **1100 MW**

Site C dam (artist's impression)

Projected yearly energy produced: 5100 GWh/yr
This works out to actual projected capacity of:

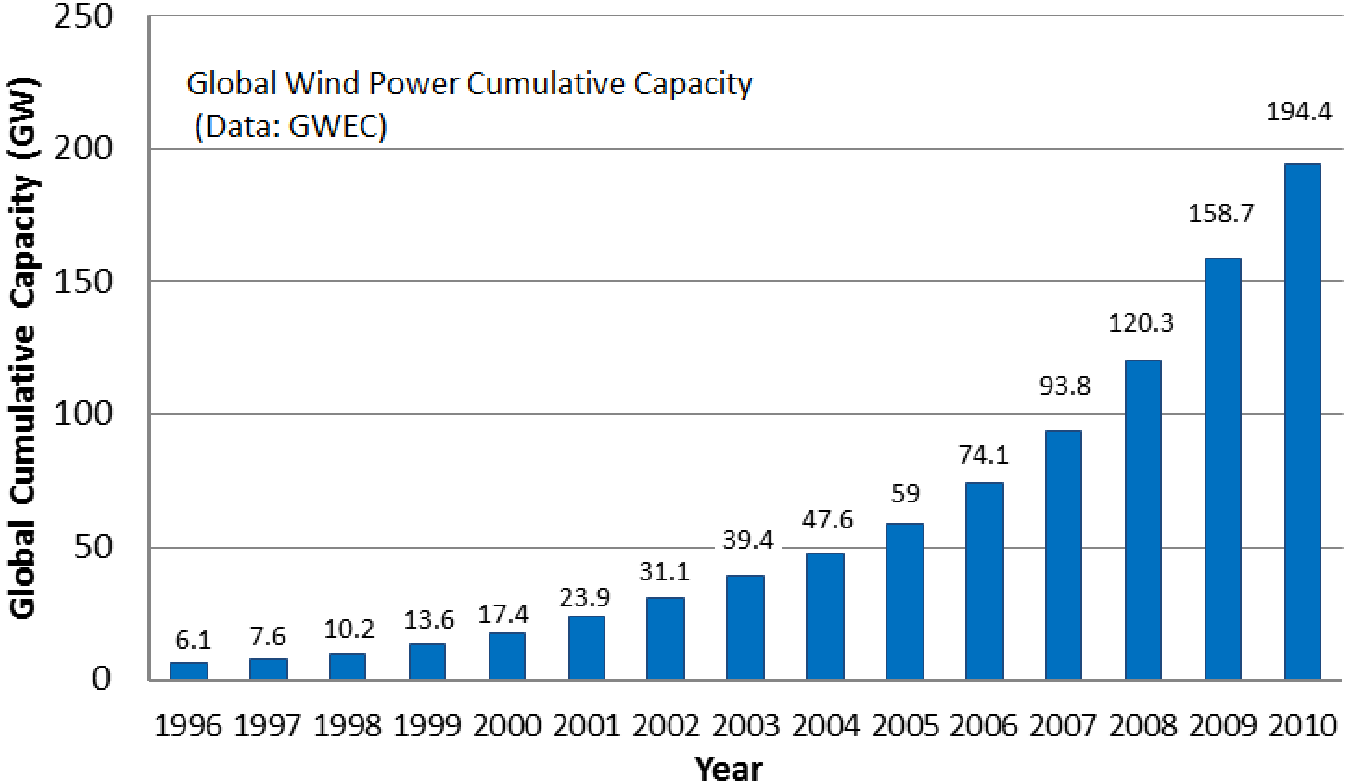
($5.1x10^{12}$ W-hr/year)/(365*24hr/year) **582 MW**

Capacity factor ~582MW/1100MW = **53%**

Cost per kW of actual power: $$7.9x10^9$/582,000 kW = **13,700 $/kW**

Installation cost is almost three times that of wind power

World Wind Power Installed Capacity (nominal power)



Note: Capacity is not the same as power produced!

We must discount these numbers by at least a factor of 0.4

Annualized growth rate of 37%

Wikipedia downloaded 22mar2012

World Installed Wind Capacity 2008

Position 2008	Country	Total Capacity installed end 2008	Added Capacity 2008	Growth Rate 2008	Position 2007	Total Capacity installed end 2007	Total Capacity installed end 2006	Total Capacity installed end 2005
		[MW]	[MW]	[%]		[MW]	[MW]	[MW]
1	USA	**25170,0**	8351,2	49,7	2	16818,8	11603,0	9149,0
2	Germany	**23902,8**	1655,4	7,4	1	22247,4	20622,0	18427,5
3	Spain	**16740,3**	1595,2	10,5	3	15145,1	11630,0	10027,9
4	China	**12210,0**	6298,0	106,5	5	5912,0	2599,0	1266,0
5	India	**9587,0**	1737,0	22,1	4	7850,0	6270,0	4430,0
6	Italy	**3736,0**	1009,9	37,0	7	2726,1	2123,4	1718,3
7	France	**3404,0**	949,0	38,7	8	2455,0	1567,0	757,2
8	United Kingdom	**3287,9**	898,9	37,6	9	2389,0	1962,9	1353,0
9	Denmark	**3160,0**	35,0	1,1	6	3125,0	3136,0	3128,0
10	Portugal	**2862,0**	732,0	34,4	10	2130,0	1716,0	1022,0
11	Canada	**2369,0**	523,0	28,3	11	1846,0	1460,0	683,0
12	The Netherlands	**2225,0**	478,0	27,4	12	1747,0	1559,0	1224,0

WWEA
World Wind Energy Association

World Wind Energy Report 2008

Demand Management

Many renewables suffer from a big problem:

They deliver their power intermittently
In general there is a poor overlap between electricity demand and renewable supply

BC hydroelectricity and wind are inherently complementary:

- Hydro can be ramped up or down very quickly (100MW in 30 min)
- During periods of high wind, hydro production can be ramped down, conserving water in the reservoirs
- During periods of low wind production, hydro can be used.
- Example of complementarity: Peace River Dams (WAC Bennett) and Peace region wind farms.

More direct methods of storing renewable energy:

- Pumped storage
- Batteries (electric cars)
- Hydrogen gas

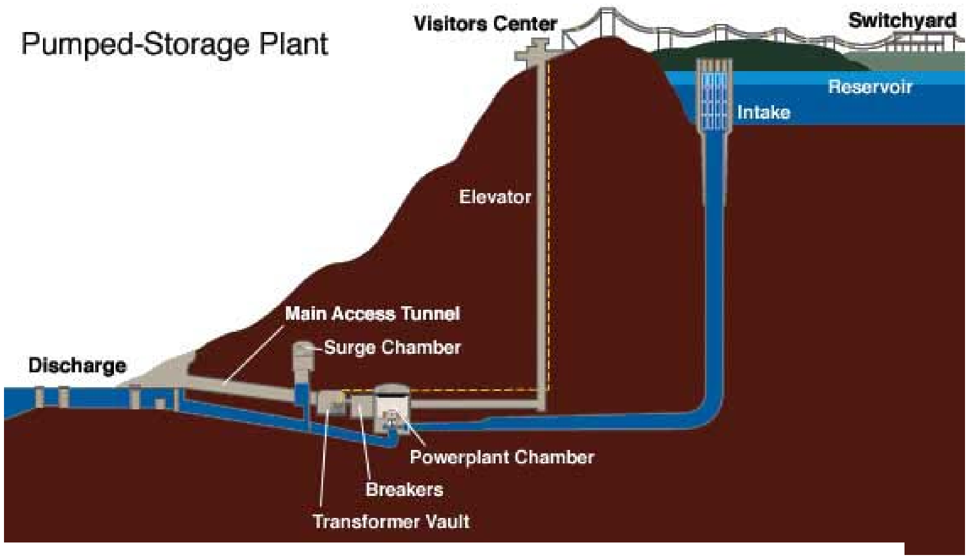
Pumped storage:

- Excess wind power can be used to pump water back up into reservoirs
- This is currently done in several locations in (Wales, Niagara Falls, Switzerland)
- Pumped storage is a useful property of hydroelectric facilities

Example: Robert Moses Niagara Power Plant (NY state)

- A large reservoir is located above the falls
- This upper reservoir is filled at night using pumps run by hydroelectric power that is not needed at that time. The water is pumped from a lower reservoir below the hydro facility.
- The stored water is then diverted through the power turbines during the day to generate excess electricity during high demand periods
- Pumped storage can be very efficient: 75% according to McKay p 191

Pumped Storage



http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

This image from Tenessee valley website leaves out some important details, for example the pumps required to raise the water back to the upper reservoir

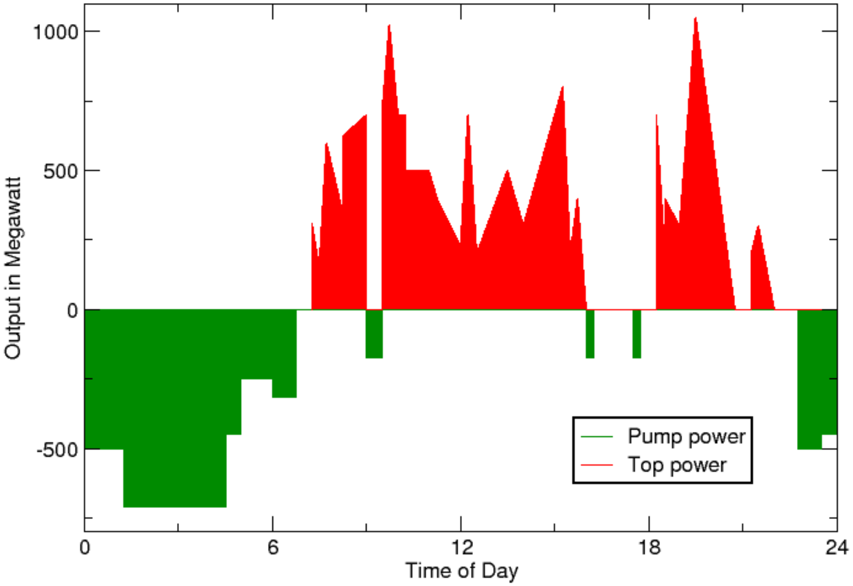


Figure 26.6. Llyn Stwlan, the upper reservoir of the Ffestiniog pumped storage scheme in north Wales. Energy stored: 1.3 GWh. Photo by Adrian Pingstone.

Batteries:

Another interesting idea for matching supply and demand

Electric cars make a lot of sense for many reasons:

- Greenhouse gas emissions are significantly lower for electric cars than for internal combustion cars, even if the electricity comes from fossil fuel burning.
- No wasted energy from refining oil into gasoline: the oil is just burned directly
- Fossil fuel emissions are inherently easier to clean than the emissions from millions of internal combustion engines.
- A fleet of electric vehicles could provide a huge reservoir of stored electricity
- Excess renewable AC electricity could charge the batteries via AC-DC conversion
- Car batteries could sell some portion of their power back to the grid to satisfy momentary peak demand. This would be done in the same way that solar producers use DC power to generate AC power for the grid (DC-AC inverter)

Estimate of Stored Energy Available in Electric Cars:

Assume 30 million electric cars in the future in Britain

Assume 40 kWh batteries on average

This gives:

$(30 \times 10^6)(40\ \text{kWh}) = 1200\ \text{GWh}$ of storage. This is huge.

Compare this to the 3.3 GWh of wind electricity currently generated in Britain. Only a small amount of this storage would be used, even if Britain increased wind generation tenfold