Non-Biomass Renewable Forms of Energy

L.D. Danny Harvey
Department of Geography
University of Toronto

Email: harvey@geog.utoronto.ca

Reminder:

- All C-free energy options face serious constraints and problems
- To have a chance at being able to deploy enough C-free power to avoid dangerous anthropogenic interference (I.e.: CO2 < 450 ppmv), energy efficiency must play a predominant role
- Constraints on population growth and human greed also important
- Otherwise, there is no hope.

Solar Energy

- Solar flux intercepted by the Earth is 10,000 times present demand for all forms of secondary power (10.5 TW, 300 EJ/yr)
- Using PV panels at 10% conversion efficiency, 4% of the world's desert area – or 440,000 km2 – would be needed to produce this much power
- Cumulative production so for is only 24 km2 (?) (18000 times less)
- Using solar-thermal power generation with 20% sunlight to AC conversion efficiency, 2% of the world's desert area would be needed

PV Electricity Issues:

- Efficiencies
- Resource constraints
- Energy Payback time
- Cost, storage

PV Cell and Modules Efficiencies

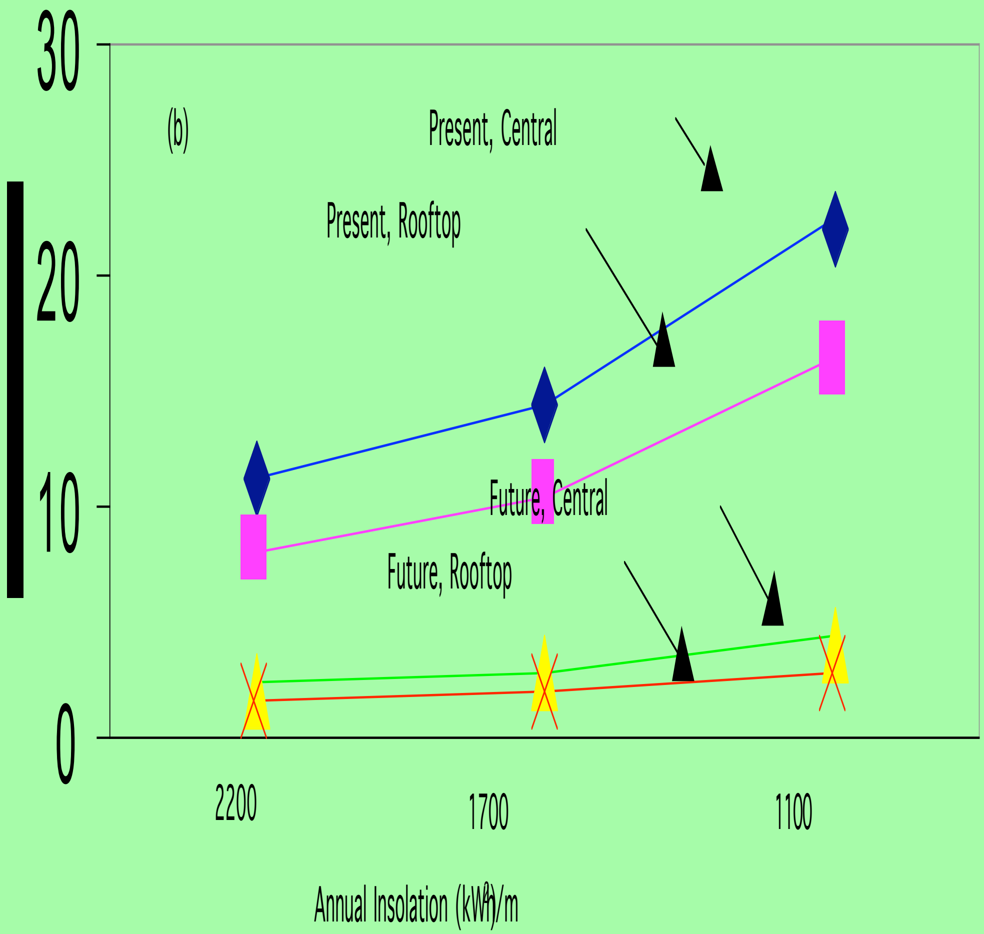
Table 9.1 Efficiencies of the best laboratory PV cells and modules achieved as of January 2000 for various technologies at a temperature of 25°C. The electrical output decreases by 0.5% for each degree Celsius warming for all cell types except a-Si, where the temperature effect if close to zero (Green, personal communication, 2002). Source for efficiencies: Green (2001).

Technology		Laboratory Efficiency (%)	
		Cell	Module
x-Si		24.7	22.7
p-Si		18.8	15.3
a-Si	Single junction	12.7[a]	12.0[a]
a-Si	Multi-junction	13.5	10.4
CdTe		16.4	10.6
CIGS		18.4	16.6
GaAs (3-junction)		34.0[b]	---
Dye-sensitized		6.5	4.7

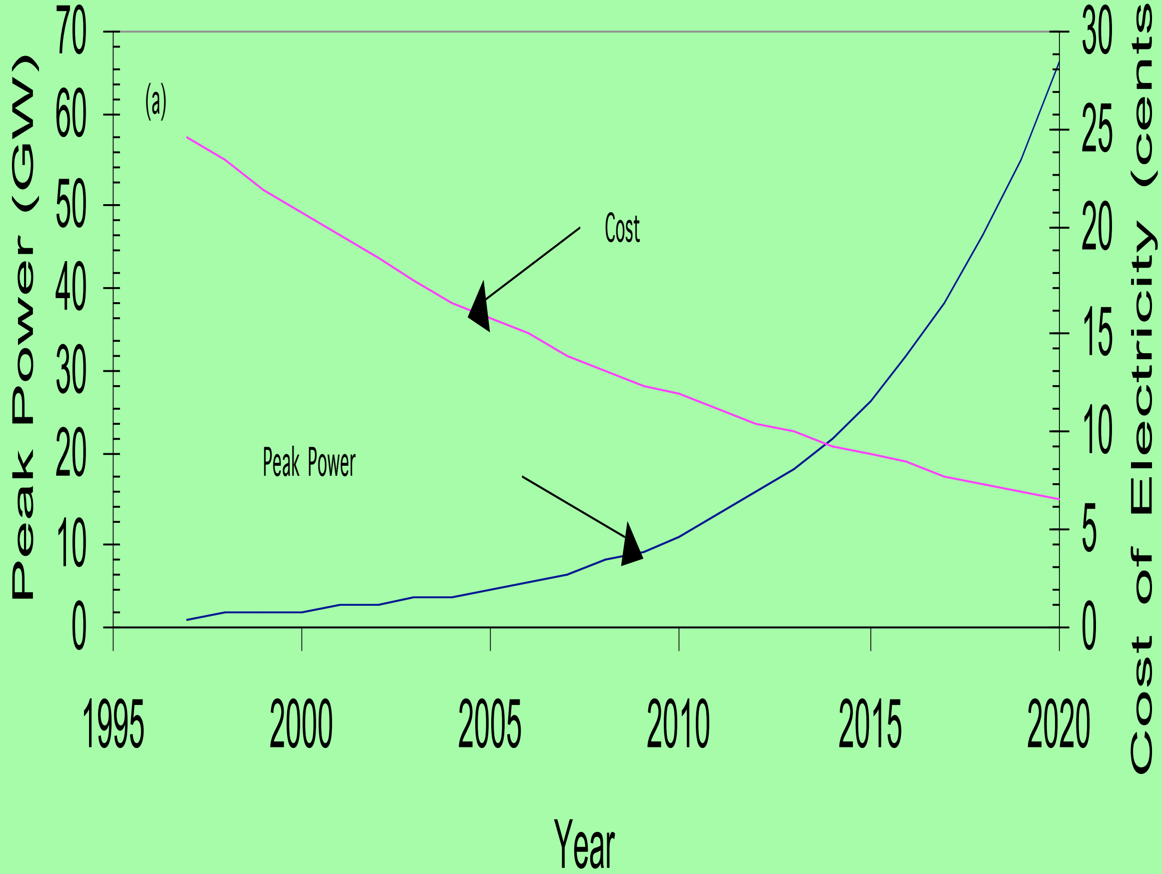
Resource constraints on thin-film PV

Table 9.7 Material constraints on thin-film PV technologies. Cd=cadmium, Te=tellerium, Se=selenium, Ga=gallium, In=indium, Ge=germanium, Ru=ruthenium, DS=dye-sensitized. Source: Andersson (2000), except that SMC and GMC have been modified to reflect the system efficiencies assumed in the first column							
Technology, system efficiency	Metal	Loading (g/m^2)	1998 Reserves (Gg)	1997 Production (Mg/yr)	Sources	S_{MC} (TW_p)	G_{MC} (GW_p/yr)
GaAs, 30%	Ga		110	54	Bauxite, coal ash		
	As						
CIGS, 20%	Se	4.8	70	2200	Copper ore	2.9	92
	Ga	0.53	110	54	Bauxite, coal ash	42	20
	In	2.9	2.6	200	Zinc ore, coal ash	0.18	14
CdTe, 15%	Cd	6.3	600	20000	Zinc ore	14.3	476
	Te	6.5	20	290	Copper ore	0.46	6.7
a-SiGe, 10%	Ge	0.44	2	63	Zinc ore, coal ash	0.5	14
DS	Ru	0.1	6	11	Platinum group metals	6	11

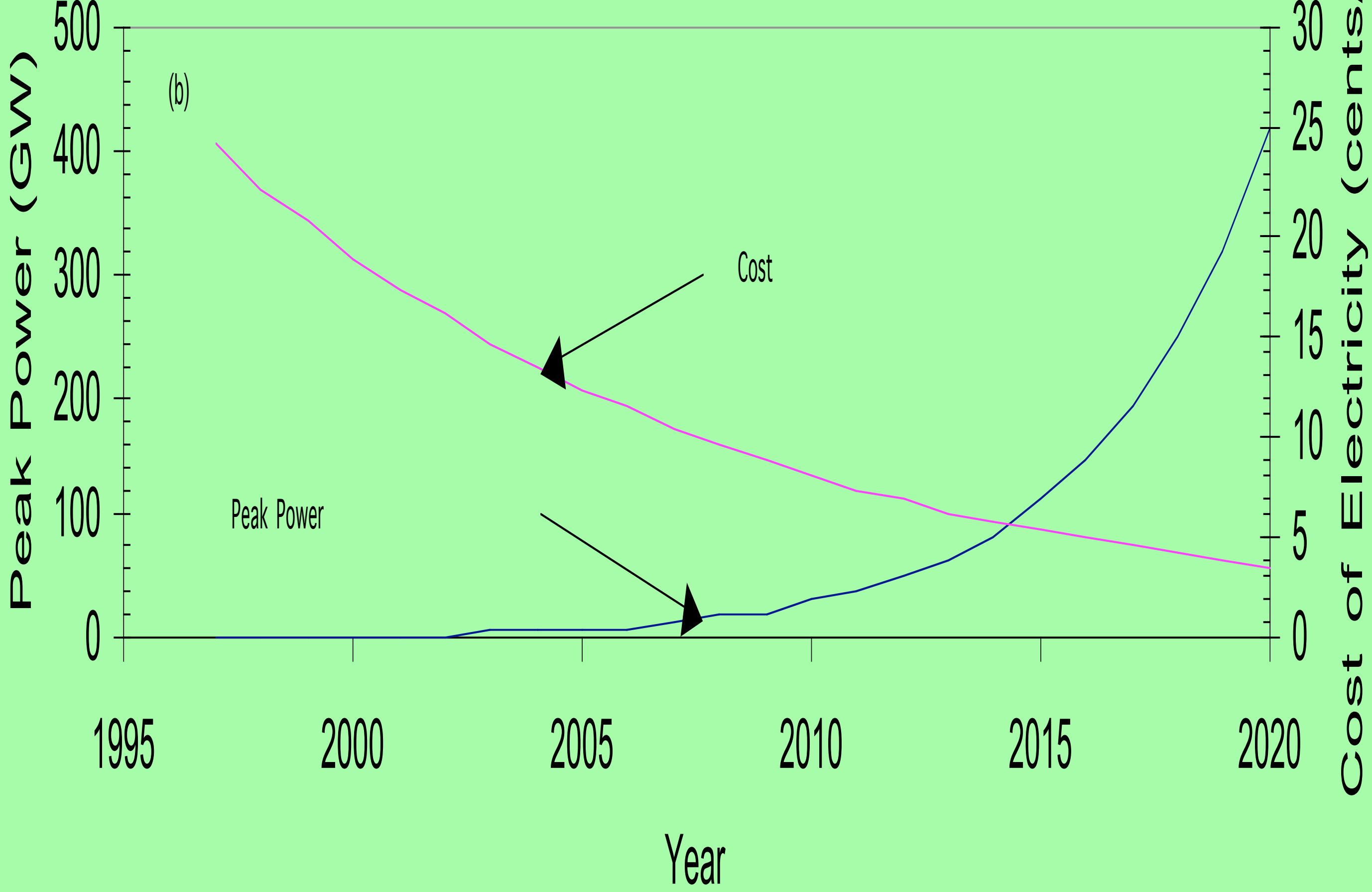
Energy Payback Time for a-Silicon PV Electricity



20%/yr growth, progress ratio=0.8



30%/yr growth, progress ratio=0.8



Solar Thermal Electricity Generation – Parabolic Trough

- Use mirrors to concentrate direct-beam solar radiation to heat a circulating fluid (I.e.: synthetic oil at 390 C)
- 35-60% collection efficiency
- From that, produce steam to drive a steam turbine – 30-35% efficiency
- Net efficiency up to 18%
- Boosting the steam temperature to 490 C with natural gas projected to give 40% turbine efficiency

Solar Thermal Electricity Generation – Central Tower

- Concentration sunlight onto a central tower
- Create molten salt or synthetic oils (T > 500 C)
- Steam turbine
- Can continue generating electricity throughout the night (although at declining efficiency)

Building-Integrated Active Solar Thermal Energy

- Flat-plate collectors, alone or integrated with PV panels, giving solar "cogeneration" – simultaneous production of electricity and useful heat
- Evacuated tube collectors – high collection efficiency
- Can be used for: space heating with storage, hot water heating, dehumidification via desiccant wheels, cooling via single- or double-effect absorption chillers

Economies of scale in district heating and cooling systems lead to the prospect of *seasonal* underground storage of solar thermal energy collected in summer for use in winter, and (elsewhere within the system) of winter coldness for summer air conditioning

Pilot projects involving 20 houses or so are underway in Attenkirchen (Germany) and Anneberg (Sweden)

High-temperature Underground Storage of Thermal Energy

Table 18.3 High-temperature underground thermal energy storage systems in operation as of 1999. Source: Sanner (1999)

Location	Start date	Energy source	Loading T	Unloading T	No. and depth of wells or boreholes, or cavern volume	Capacity
ATES Systems						
Utrecht University, The Netherlands	1991	Cogen	90°C		2 @ 260 m	<7200 GJ
Reichstag, Berlin, Germany	1998	Cogen	70°C	60-20°C	2 @ 320 m	
Houge Bourch hospital, The Netherlands	1998	Cogen				
BTES Systems						
Kullavik, Sweden	1983	Solar	60°C	50-40°C	200 @ 8m	14-29 GJ
Vaulruz, Switzerland	1983	Solar	54°C	40-5°C	horizontal pipes, 1.2-1.6 m deep	600 GJ
Groningen, The Netherlands	1984	Solar	60°C	50-30°C	360 @ 20 m	3600 GJ
Neckarsulm, Germany	1998	Solar	80°C		168 @ 30 m	
CTES Systems						
Avesta, Sweden	1982		115°C	70°C	15000 m^3	2900 GJ
Lyckenbo, Sweden	1983	Solar	80-90°C	80-55°C	104300 m^3	20000 GJ

Reminder: Many forms of passive utilization of solar energy are also possible (might be classified as energy efficiency):

- Daylighting
- Passive ventilation (driven by temperature differences arising from differential solar heating)
- Passive heating, especially with high thermal mass

Wind Energy

Zeroth-order Analysis

- An area of 523 x 523 km, fitting comfortably inside N and S Dakota, could generate the total US electricity production of 1998 (3834 TWh)
- Issues – timing, location, volatility, and predictability

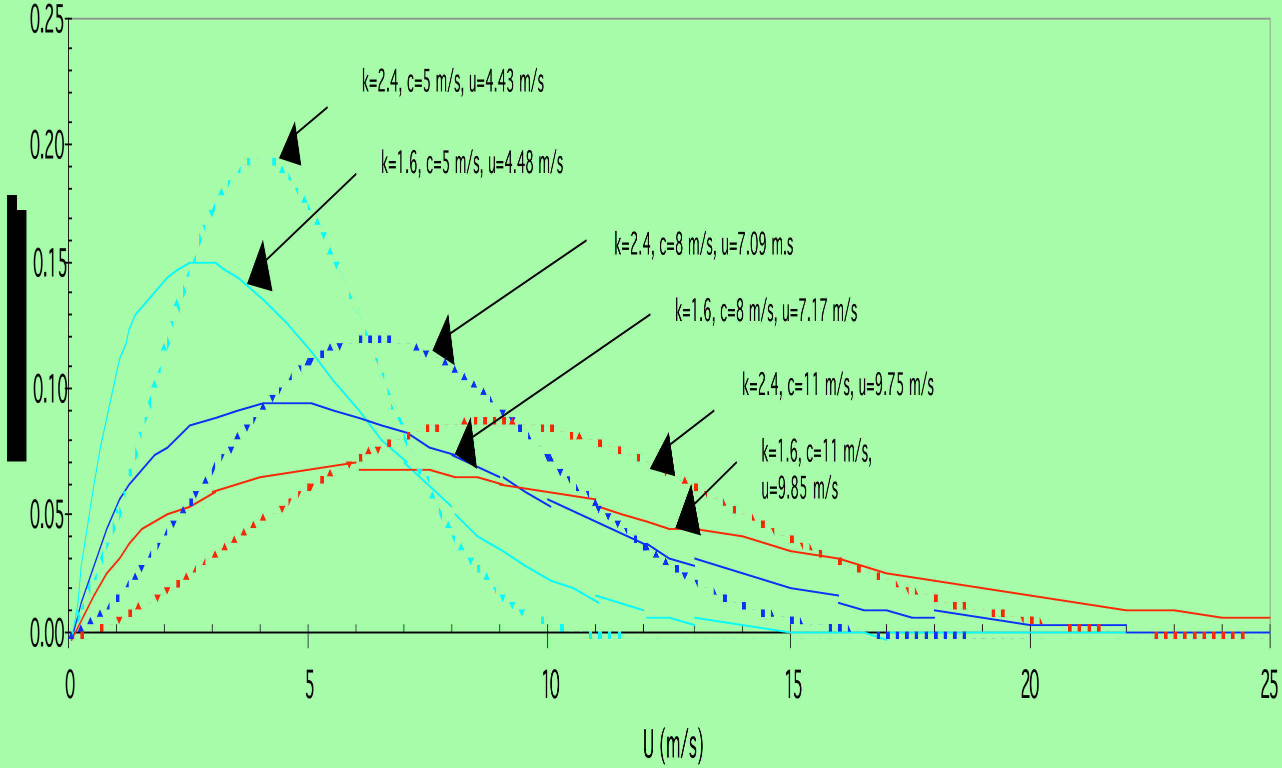
Techniques to deal with fluctuations:

- Build wind farms – some cancellation of fluctuations occurs
- Use asynchronous rather than synchronous generators
- Short-term storage (minutes): flywheels, supercapacitors, superconducting magnetic storage
- Mesoscale wind forecast models (1 to several hours in advance)
- Hydroelectric reservoirs, CAES
- Regenerative fuel cells, 60-75% round-trip efficiency claimed (note: this is not an electrolyzer/fuel cell combination or reversible electrolyzer)
- Create and store chiller water or hot water when there is surplus output, for use in a district cooling or heating system (a strategy being considered for Denmark).

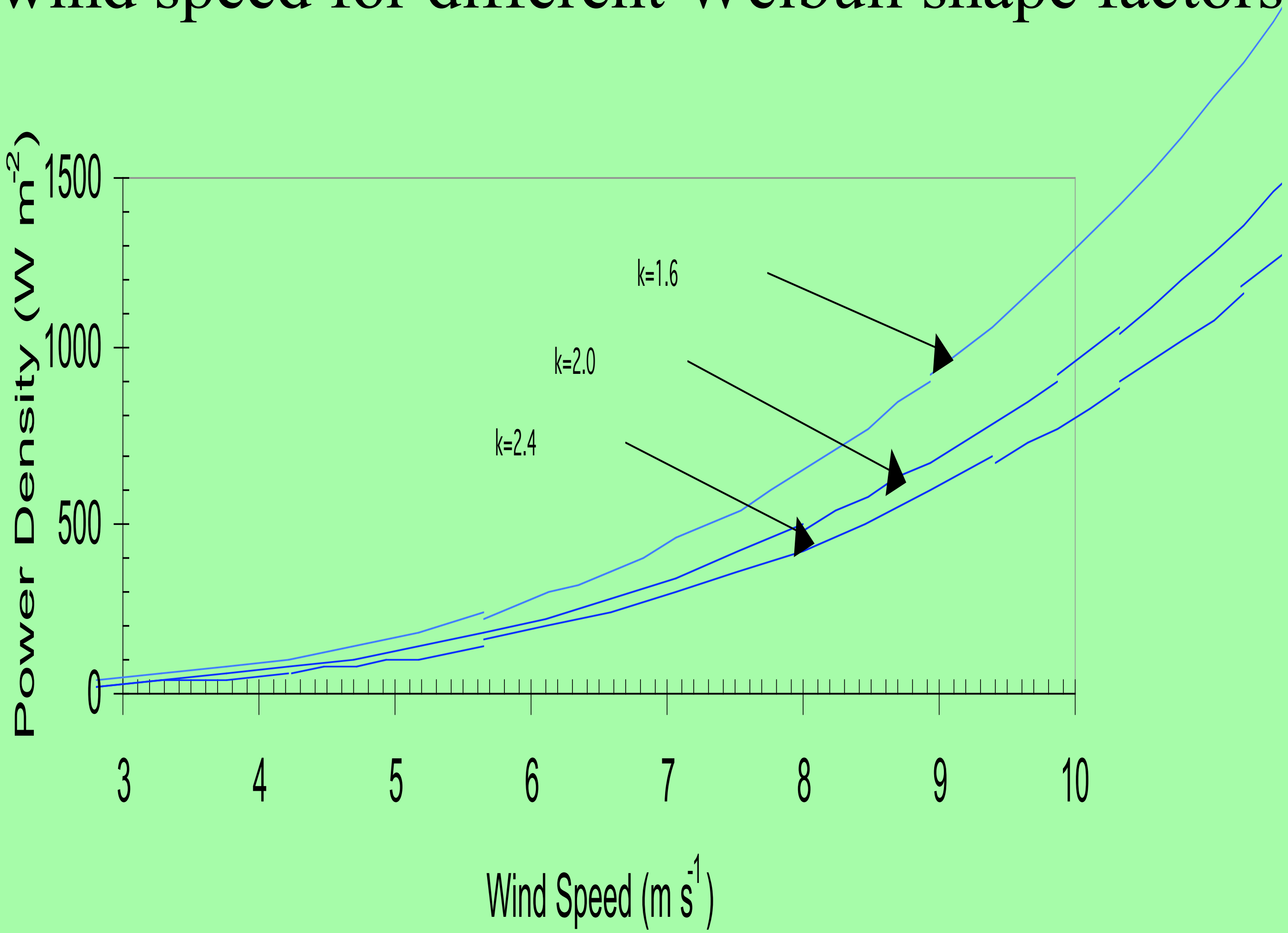
Weibull Velocity Distribution, where c = scale factor (m s^{-1}) and k=shape parameter

$$f(u) = \frac{k}{c}\left(\frac{u}{c}\right)^{k-1} \exp\left[-\left(\frac{u}{c}\right)^{k}\right]$$

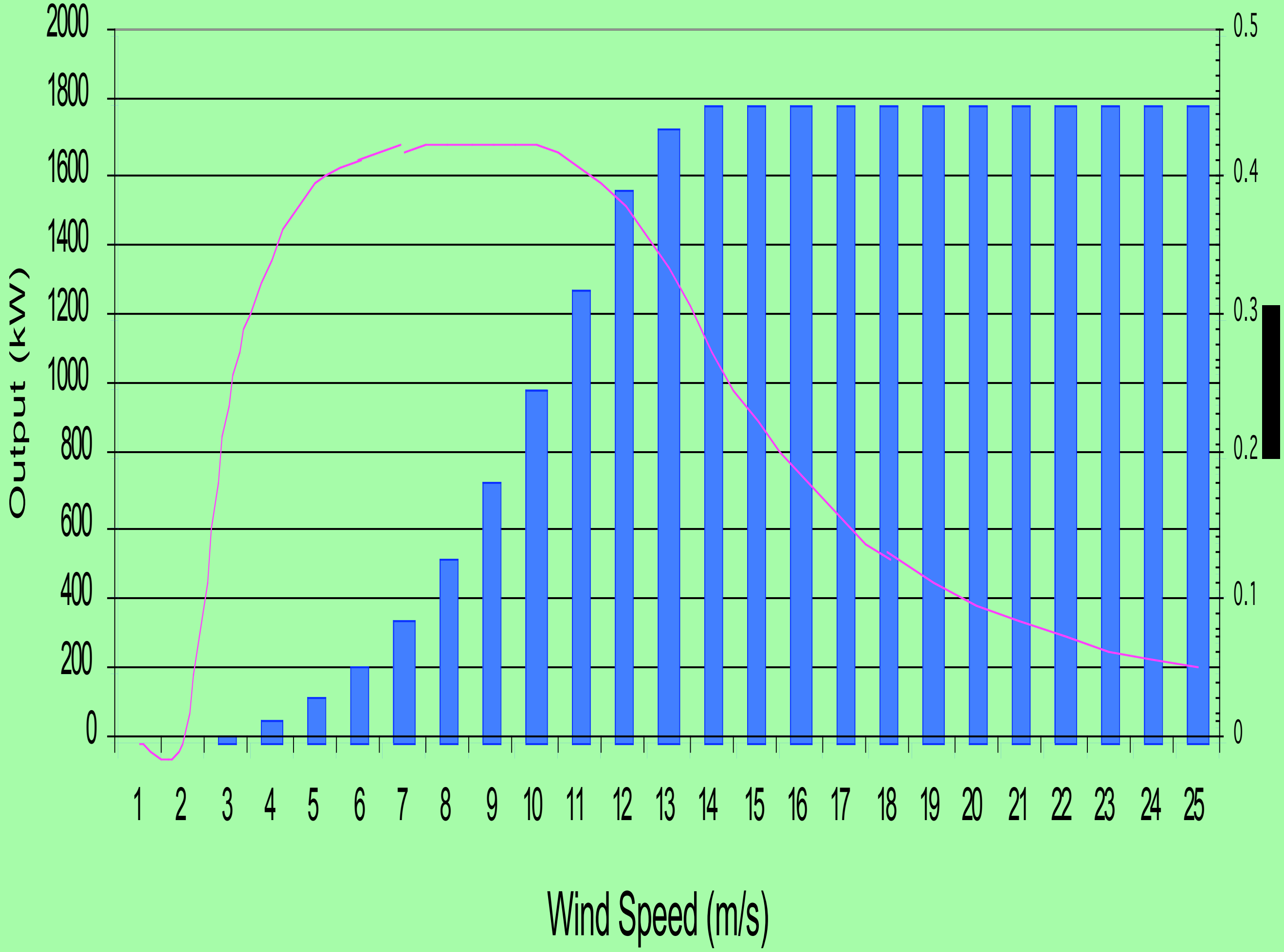
Wind Speed Distributions



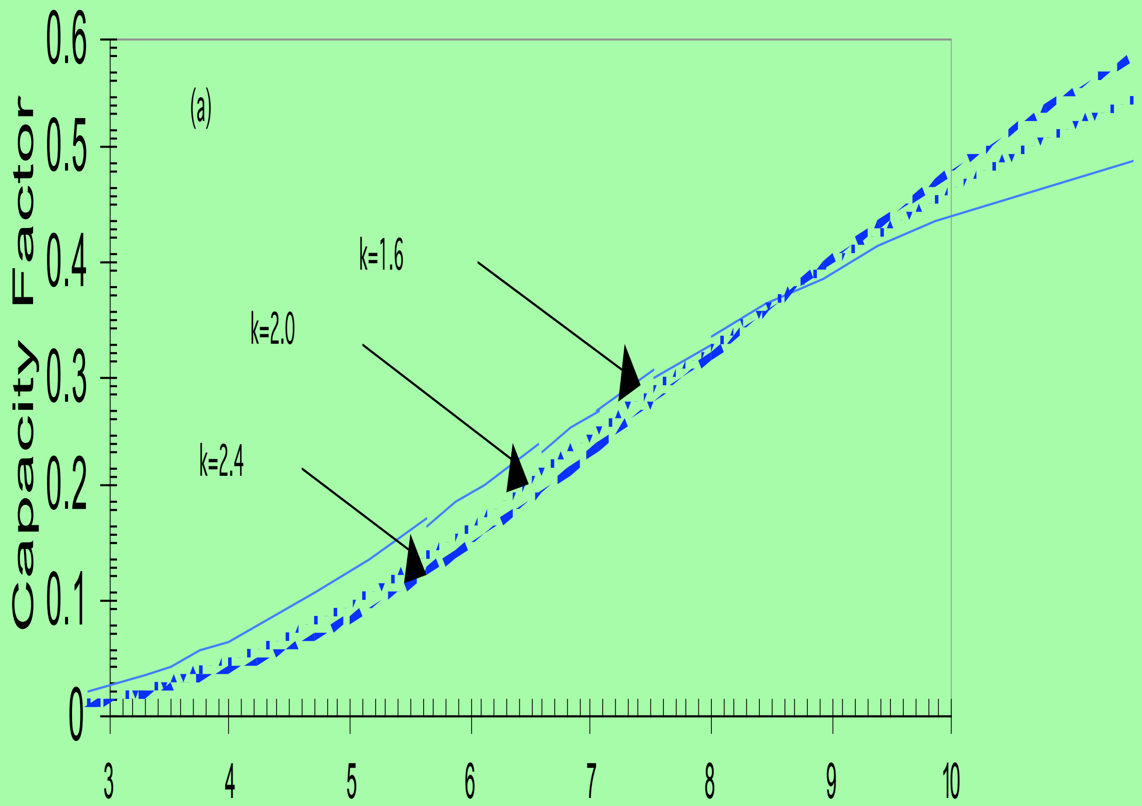
Power Density (perpendicular to wind) vs mean wind speed for different Weibull shape factors



Power Output and Efficiency vs WindSpeed for the Enercon E-66 wind turbine



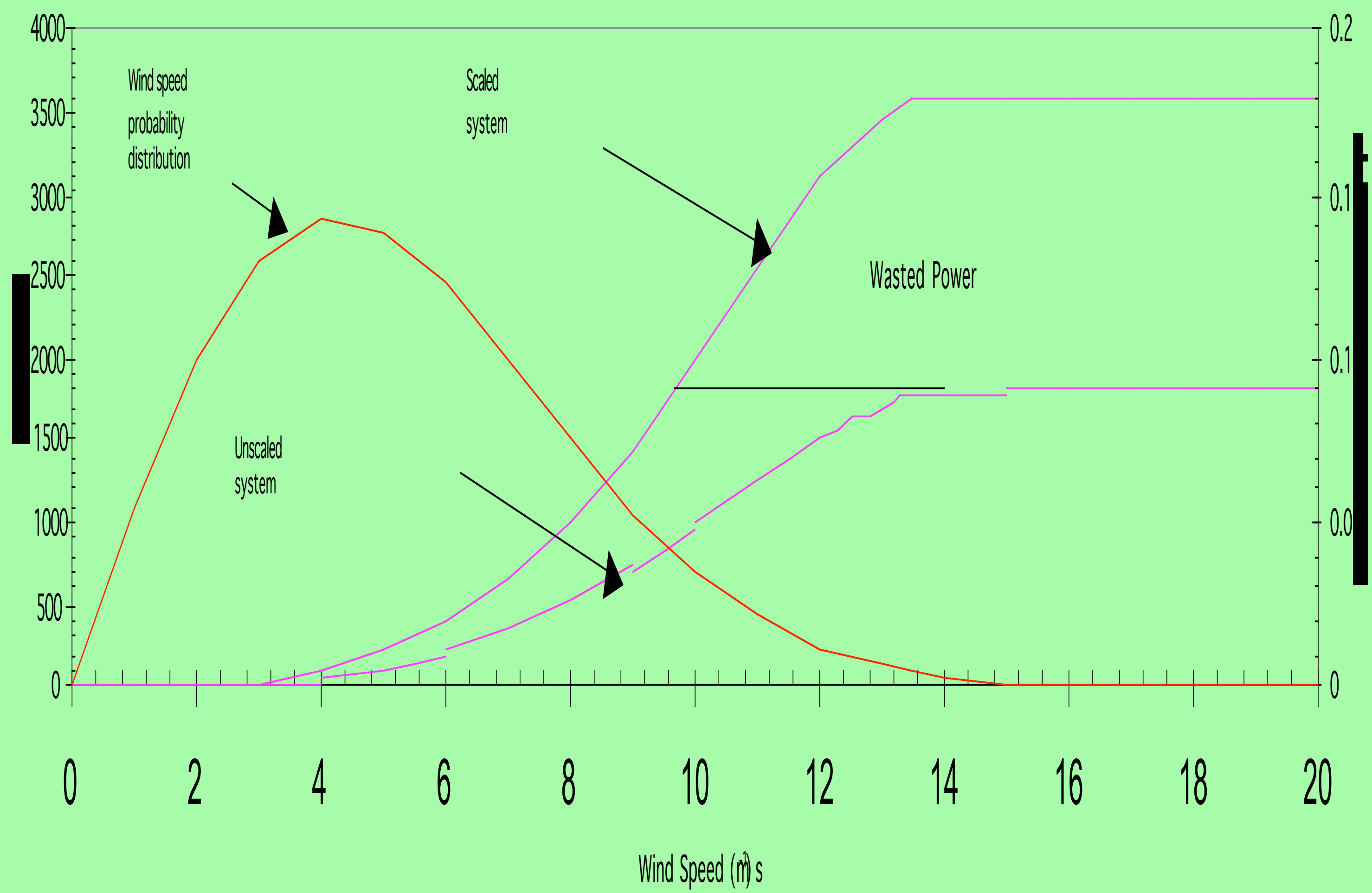
Capacity Factor vs Mean Wind Speed for the E-66 for different Weibull shape parameters



The correct credit for wind can be computed based on the amount of non-wind generation capacity needed, with and without wind turbines, to have the same Loss-of-load probability (LOLP)

- For wind generation up to 10% of total generation, the capacity credit roughly equals the capacity factor for dispersed wind turbines
- For large penetration (25-50%), the capacity credit is 50-75% of the capacity factor
- This large credit arises because the forced-outage rate of fossil power plants in North America is 8%, compared to 2% in modern wind turbines

Deliberate Oversizing of a Windfarm by factor of 2 but not of the transmission line

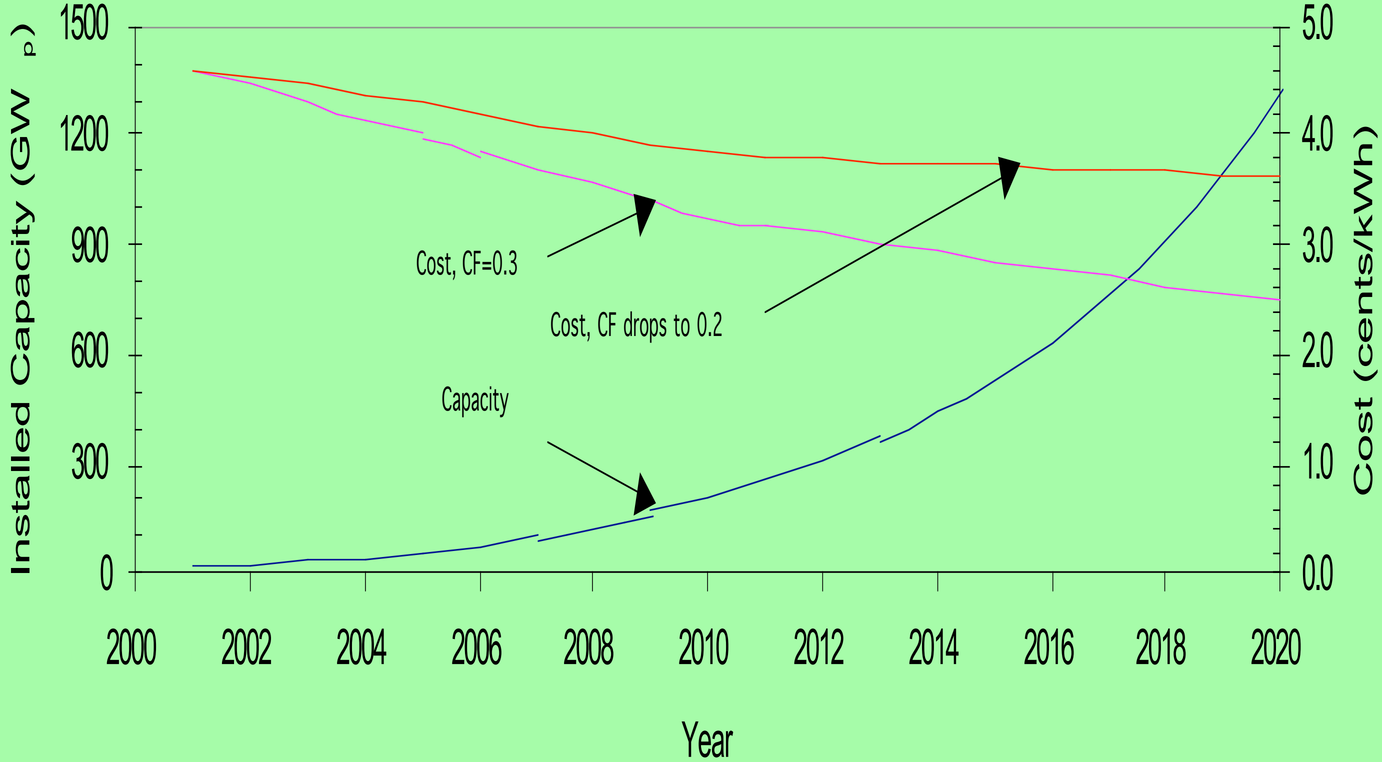


Impact of oversizing windfarms on the delivered cost of electricity (wind farm at \$600/kW, transmission line at \$200/kW)

Box B10.3 Comparison of capacity factors and electricity costs for wind farms that match the transmission line (unscaled) and oversized by a factor of two (scaled). All costs where computed assuming 10% interest, a 20-year lifespan, capital costs as given in the text, and with omission of operation and maintenance costs. For each wind speed, the three electricity cost rows are for turbine, transmission, and total cost (in that order).

Mean Wind Speed ($m\ s^{-1}$)	Turbine Capacity Factor		Transmission Capacity Factor		Extra Average Power due to Oversizing (%)	Cost of Electricity (cents/kWh)	
	Unscaled	Scaled	Unscaled	Scaled		Unscaled	Scaled
5.3	0.147	0.130	0.147	0.260	+77	5.94 1.83 7.67	6.70 1.03 7.73
7.1	0.292	0.222	0.292	0.443	+52	2.99 0.92 3.90	3.90 0.60 4.54
9.7	0.431	0.291	0.431	0.582	+35	2.02 0.62 2.64	2.99 0.45 3.45

30%/yr growth of wind capacity, progress ratio=0.8, fixed or falling capacity factor



Cost perspective:

- US Fossil electricity generating capacity is 589 GW
- According to two of yesterday's speakers, the coal capacity is about 330 GW (I suspect that it is more)
- New NGCC costs about $600/kW
- Onshore wind farms are $900/kW and falling
- Thus, all of the existing coals plants (or most, if the capacity is around 500 GW) can be replaced by wind turbines with NGCC backup for less than the cost of the latest tax cut proposed by Mr. Bush ($680 billion)
- So: making significant reductions in US GHG emissions is a matter of priorities, not of cost.