Fall Term – 2013

Woodrow Wilson School 585b

Living in a Greenhouse: Technology and Policy

Week Ten, November 29, 2013
Renewable electricity

Robert Socolow
Phil Hannam, AI

Reminder:
Michael Oppenheimer and Gabriel Vecchi

IPCC AR5

Bowl 1, 4:30 today

Reminders:

Course Deadlines:

Nov. 12 (last week): Second Interim paper
Nov. 19 (last night): Second short paper

Dec. 11: Third Problem Set
Now on Blackboard
Collaboration encouraged
Discussion on Dec. 2 (2-4pm) Room TBD

Jan. 14 (Dean's Date): Term Paper due

Wherein is the appeal of renewable energy?

Wherein is the appeal of renewable energy?

I. Metaphysical arguments

II. Technological

III. Environmental

IV. Social/Political

V. Economic

Wherein is the appeal of renewable energy?

I. Metaphysical arguments

- **a. Forever: Won't use it up**
- **b. Romantic**
- **c. “Soft” (a counter-cultural alternative: simple/non-hierarchic, promoting autonomy/autarchy and self-reliance)**
- **d. Decentralized, a good in itself**
- **e. Post-modern, where we're going**
- **f. Not fossil and not nuclear (the least bad alternative)**

II. Technological

- **a. Sweet, exciting, an open-ended engineering challenge, elegant, interesting**

III. Environmental

- **a. Low impacts on local and regional air and water**
- **b. Doesn't scar the Earth (gentle)**
- **c. Non-carbon: low CO_2 emissions**

IV. Social/Political

- **a. Domestic (here at home)**
- **b. Resilient**
  - **i. Because it is decentralized**
  - **ii. Because it is another option alongside the others (diversity of supply)**
- **c. Fostering remote rural development, because it can be grid-independent**

V. Economic

- **a. Profitable, not vulnerable to variable fuel cost, costs are coming down**
- **b. Promotes innovation and the new industries on which economic development can be built**

What is on the other side of the ledger?

I. Metaphysical arguments

a. Large centralized systems (windfarms on and off-shore, biomass plantations, solar systems in the desert) are more of the same: corporate-run, .. Neither soft nor romantic.

b. Aesthetic intrusion on landscapes

II. Technological

a. Intermittent forms are an incomplete solution requiring back-up or storage.

b. Unpredictability brings further complications

III. Environmental

a. Large demands on land

IV. Social/Political

a. Subsidies are abundant, buying off interest groups – farmers, venture capitalists

b. Subsidies are regressive

V. Economic

a. Subsidies are self-defeating, disguise limited competitiveness, don’t promote innovation.

Renewables:

Three classification schemes

Flux estimates

Classification #1: Direct vs. Modified

Direct collection from the sun without prior natural amplification (often called “solar” energy):

solar thermal

PV

Modified by natural systems before collection

biomass (storage in organic molecules)

hydro (storage in ice and snow)

wind

ocean wave

ocean thermal (storage as heat in surface water)

ocean tidal (*renewable, but not solar*)

Geothermal (not renewable or solar)–Geothermal heat is mined! But it is included in “renewable energy” today.

Classification #2: Intermittency

How significant is the intermittency problem?

- Minor (biomass, ocean thermal, geothermal, hydro*)
- Major (wind, PV, solar thermal, ocean wave)

* Hydro in some locations varies seasonally and from year to year but it is generally available at constant rate from day to day.

Classification #3: Thermodynamic

Low-entropy, “work,” “organized” as opposed to “random”

- Mechanical (hydro, wind, ocean wave, ocean tidal)
- Electrical (PV from photons)
- Chemical (biomass)

Thermal (“random motion”), at various temperatures:

- Solar thermal (temperature can be raised by focusing)
- Ocean thermal
- Geothermal

Energy fluxes from human activity

Location	Population (10^6)	Primary energy (EJ/yr)	Area (m^2)	Average Flux (W/m^2)	Fraction of 250 W/m^2 solar flux
World's surface	7000	500	$5.1*10^{14}$	0.031	0.00012
U.S. (48)	309	103	$7.8*10^{12}$	0.42	0.0017
New Jersey	8.8	2.5	$2.0*10^{10}$	4.0	0.016

What is a typical land use flux for hydropower (power out divided by drainage basin area)?

$P = (dM/dt)g(\Delta H)$.   (1)

P is the power out.
dM/dt is the water flow rate through the turbines.
ΔH is the "head."
g is the acceleration of gravity ($9.8\ m/s^2$)
Assume 100% conversion of falling water to electricity.

Substitute in (1): $dM/dt = \rho(dR/dt)A$. *Then* $P = \rho g(\Delta H)(dR/dt)A$

ρ is the density of water ($10^3\ kg/m^3$).
dR/dt is the rainfall rate (m/yr).
A is the basin area.
Assume no evaporation.

Choose $\Delta H = 30\ m$, $dR/dt = 1\ m/yr$. *Find* **$P/A = 0.01\ W/m^2$**. ***Tiny!***

Windpower

Wind electricity

2.5 MW Nordex wind turbine (80-m tall)
Grevenbroich, Germany

Source: Danish Wind Industry Association

Source: Hal Harvey, TPG talk, Aspen, CO, July 2007

Several wind slides (those labeled “Succar”) are drawn from:

Global Prospects for Wind Energy Part 1

Fundamentals, Trends and Resources

Samir Succar

ssuccar@princeton.edu

Mechanical and Aerospace Engineering 328

Energy for a Greenhouse-Constrained World

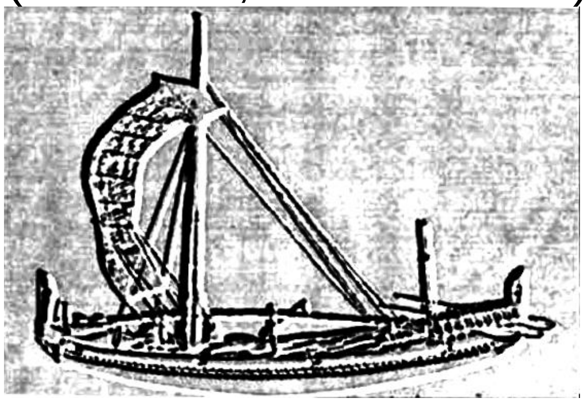
Lecture 15

1 April 2008

Historical Developments in Wind Energy

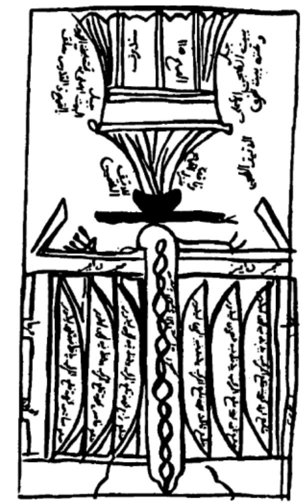
Source: B. Sorensen, Ann Rev Energy Env 20:387-424 1995

Sailing
(~3000 BC, Mediterranean)



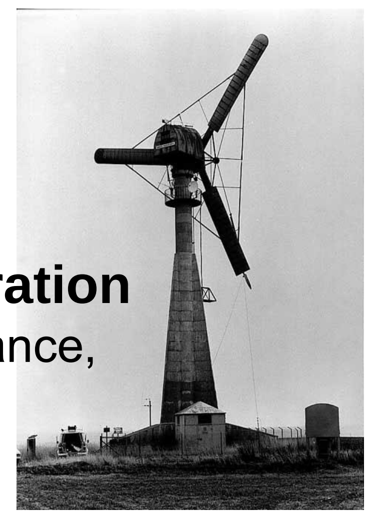
Egyptian Ship, ca 2500 BC

Grain Milling, Rice Pounding and Crop Irrigation
(~644-800AD, Persia)



Persian Windmill ca. 1300

Wind Power Generation
(1880's, Denmark, France, US, Germany)

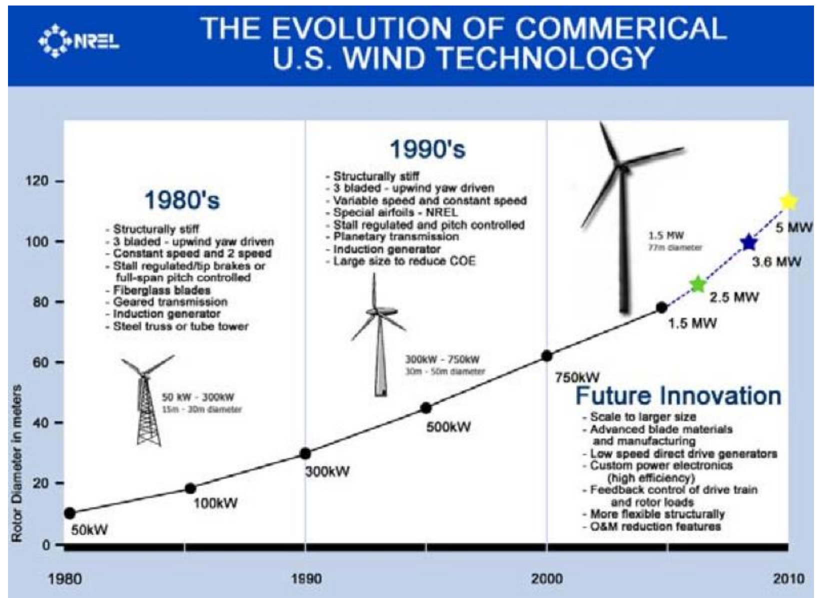


Danish AC-producing 200kW turbine at Gedser 1959 (J. Juul)

12kW DC Turbine Cleveland, USA 1887 (C.F. Brush)

Succar

Wind Turbines: Growing Scale



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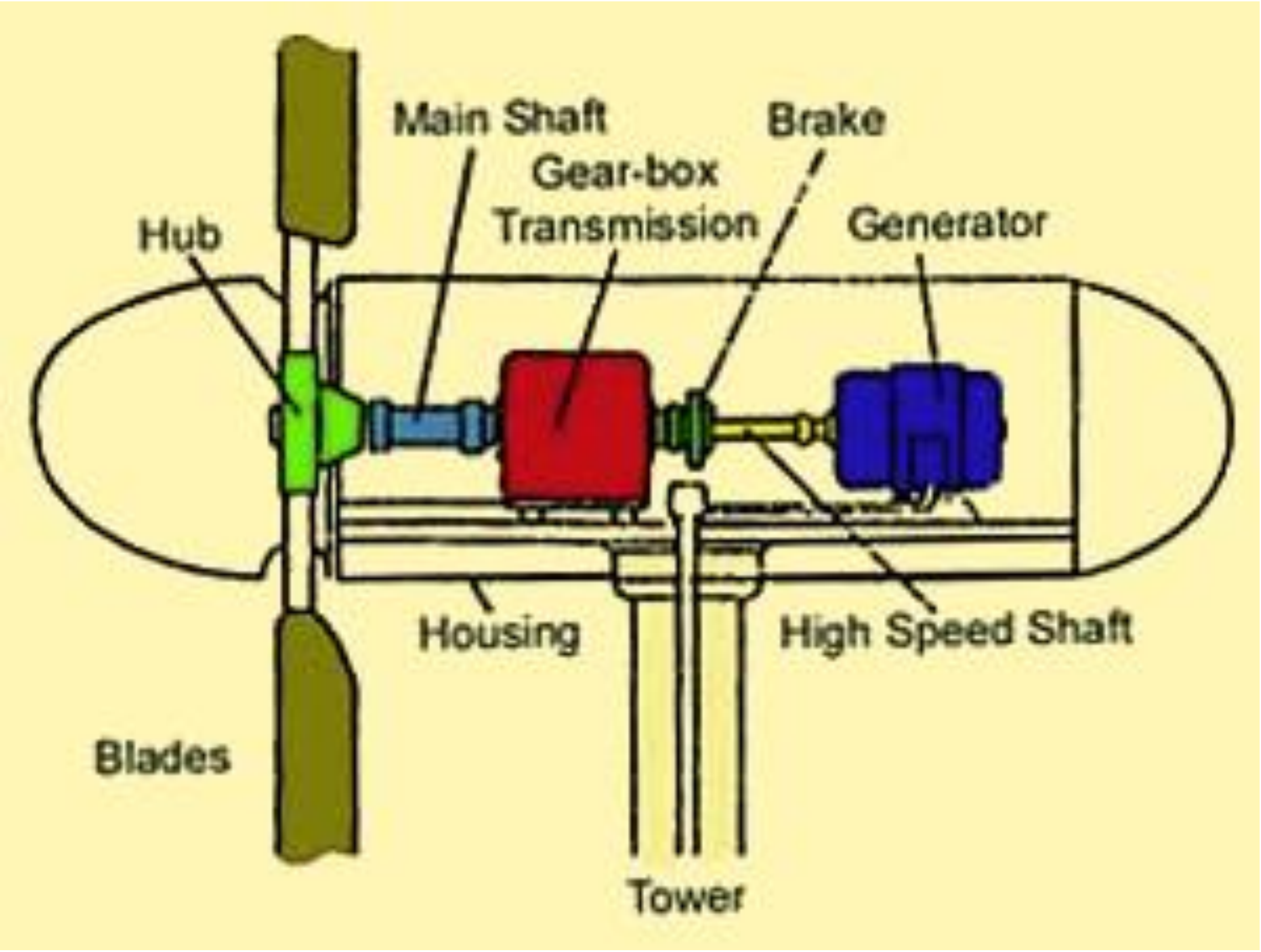
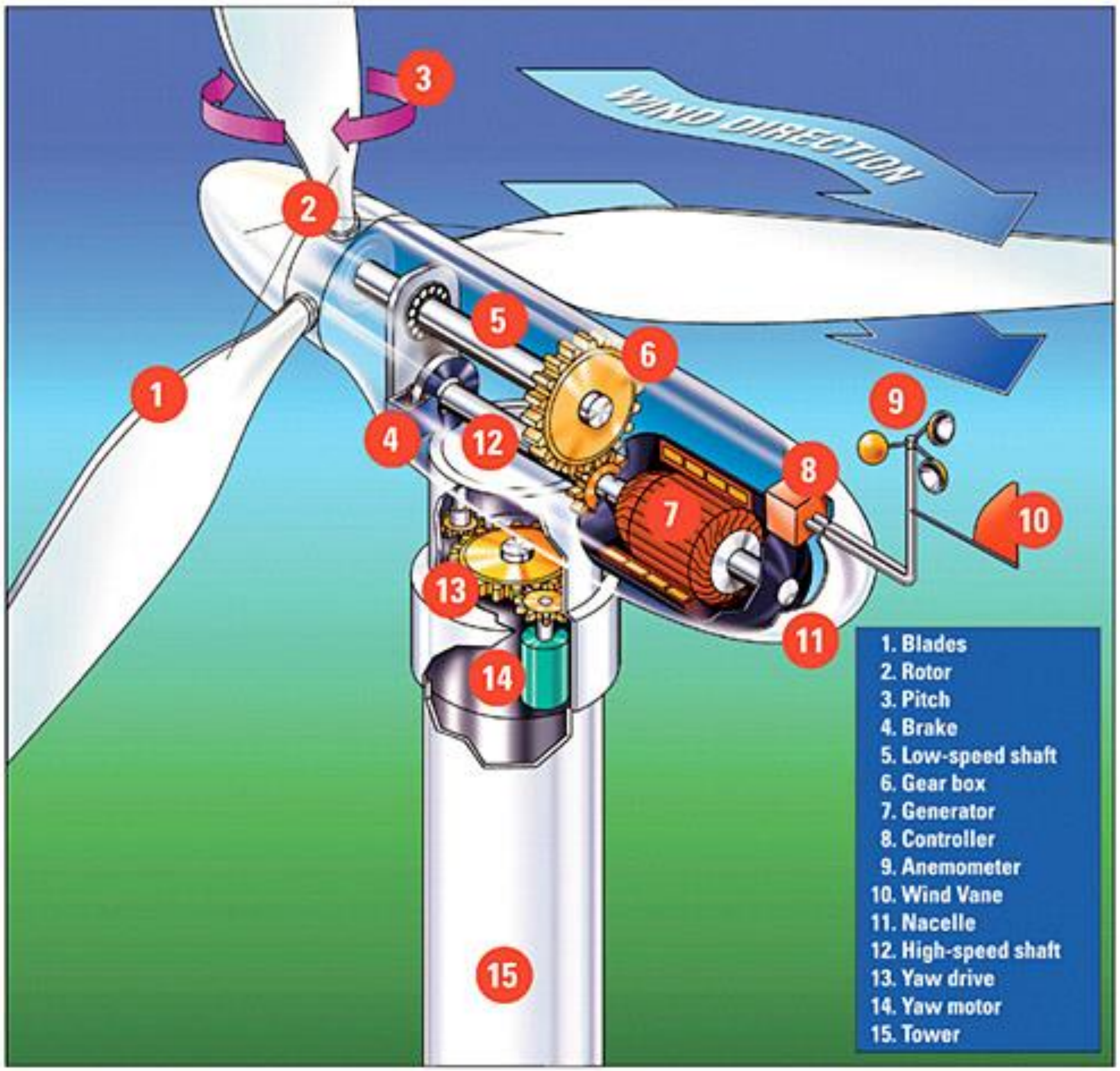
Innards of a wind turbine



More innards



Variable wind

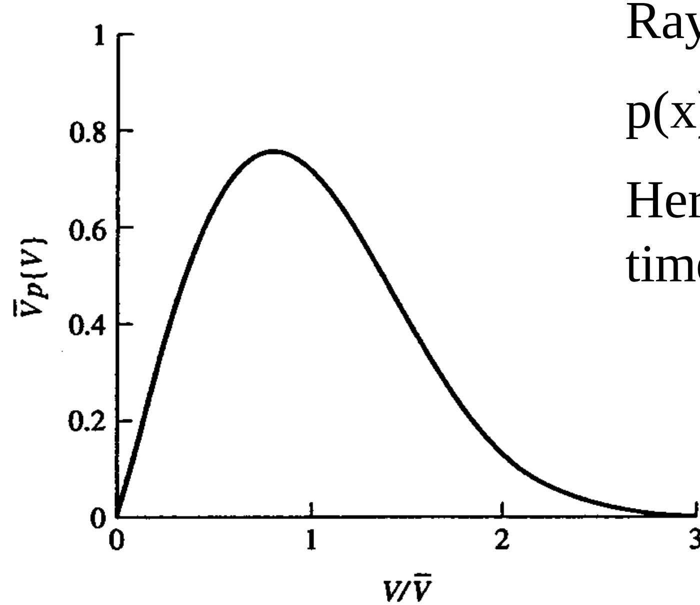


Figure 7.19 A probability distribution $p\{V\}$ of wind speed at a site for which the average speed is $\overline{V}$ shows low values at low and high speeds and a maximum near the average speed.

Rayleigh distribution:

$p(x) = (\pi\, x/2)\exp(-\,\pi x^2/4)$

Here, $x = v/\langle v\rangle$; $\langle v\rangle$ = time-averaged velocity.

Intervals of high winds dominate total power collected. If an *average* output power per unit of area intercepted is **400 W/m^2**, the *average* wind is **$\langle v\rangle$ = 7.0 m/s.** This is the Class-3/Class-4 boundary, if $\langle v\rangle$ is measured at 50m above the surface.

Table 4: Classes of wind power density in the U.S. wind atlas[a]

Wind power class	P Wind power density at 10 meters *watts per m^2*	V Wind speed at 10 meters *m per sec*	Wind power density at 50 meters *watts per m^2*	Wind speed at 50 meters *m per sec*
1	0–100	0–4.4	0–200	0–5.6
2	100–150	4.4–5.1	200–300	5.6–6.4
3	150–200	5.1–5.6	300–400	6.4–7.0
4	200–250	5.6–6.0	400–500	7.0–7.5
5	250–300	6.0–6.4	500–600	7.5–8.0
6	300–400	6.4–7.0	600–800	8.0–8.8
7	400–1,000	7.0–9.4	800–2,000	8.8–11.9

Commercially interesting

$$P = (6/\pi)\left(\tfrac{1}{2}\rho V^3\right),\ \rho = 1.2\ \mathrm{kg/m^3}.$$

a. The categories are specified in terms of power densities at 50 meters height; the vertical extrapolation is based on a wind-speed power law with a $^1/_7$ height exponent, and mean windspeeds are estimated from the power density assuming a Rayleigh distribution and standard sea-level air density.

Table 5: U.S. wind energy resources[a]

	Percent of U.S. land area	Wind electric potential	
		TWh per year	*Percent of U.S. generation, 1990*
No land-use restrictions			
Wind classes ≥ 5	1.2	1,400	51
Wind classes ≥ 3	21.0	16,700	596
"Environmental" restrictions			
Wind classes ≥ 5	0.8	900	33
Wind classes ≥ 3	18.0	14,300	509
"Moderate" restrictions			
Wind classes ≥ 5	0.6	700	25
Wind classes ≥ 3	13.6	10,800	384
"Severe" restrictions			
Wind classes ≥ 5	0.4	500	17
Wind classes ≥ 3	5.7	4,600	165

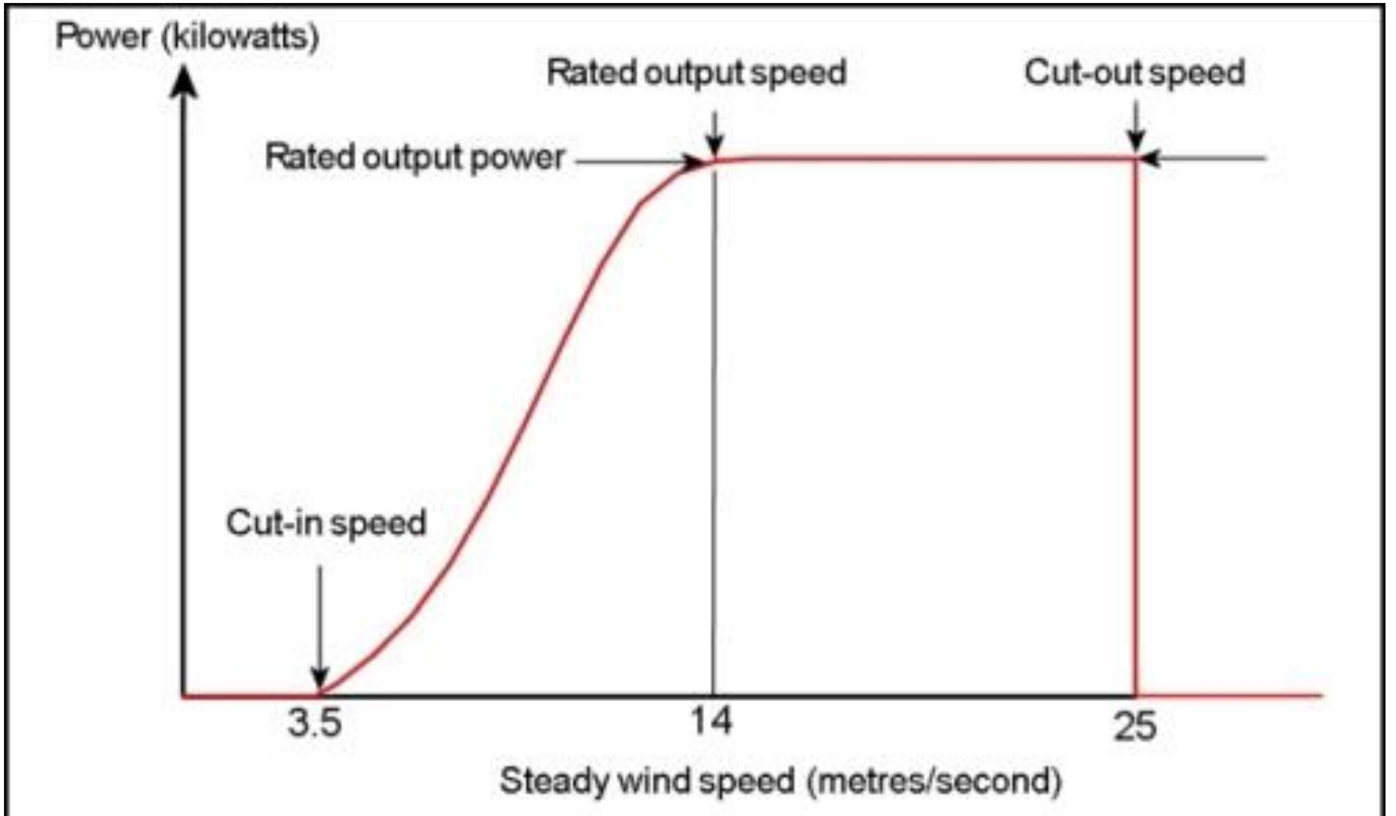
a. See footnote 15, p. 19 for definitions of land-use restrictions. Source: Elliott, 1991 [10, 26].

530 GW_{av}/50 Mha

≈1 W/m^2

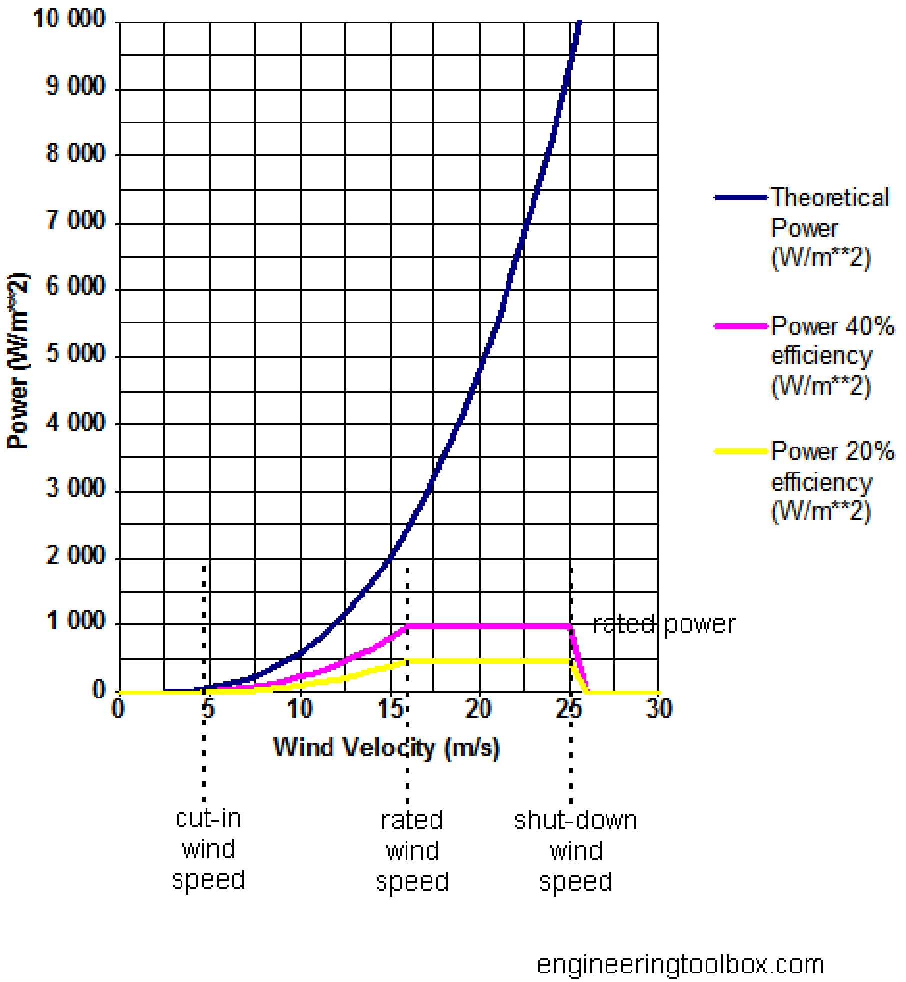
U.S. 2008 power consumption: 4300 TWh.

Power curve: cut-in and cut-out



Typical wind turbine power output with steady wind speed.

Below rated power, a characteristic conversion efficiency



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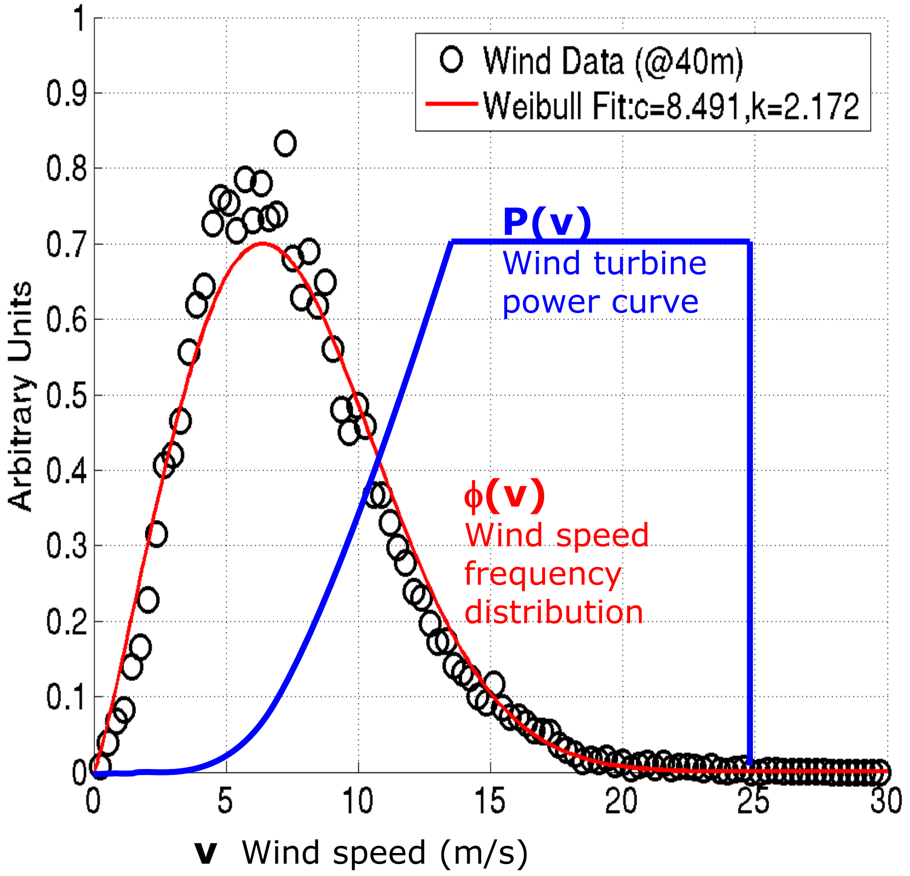
Power curve and real wind



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Wind:Variable & Unpredictable

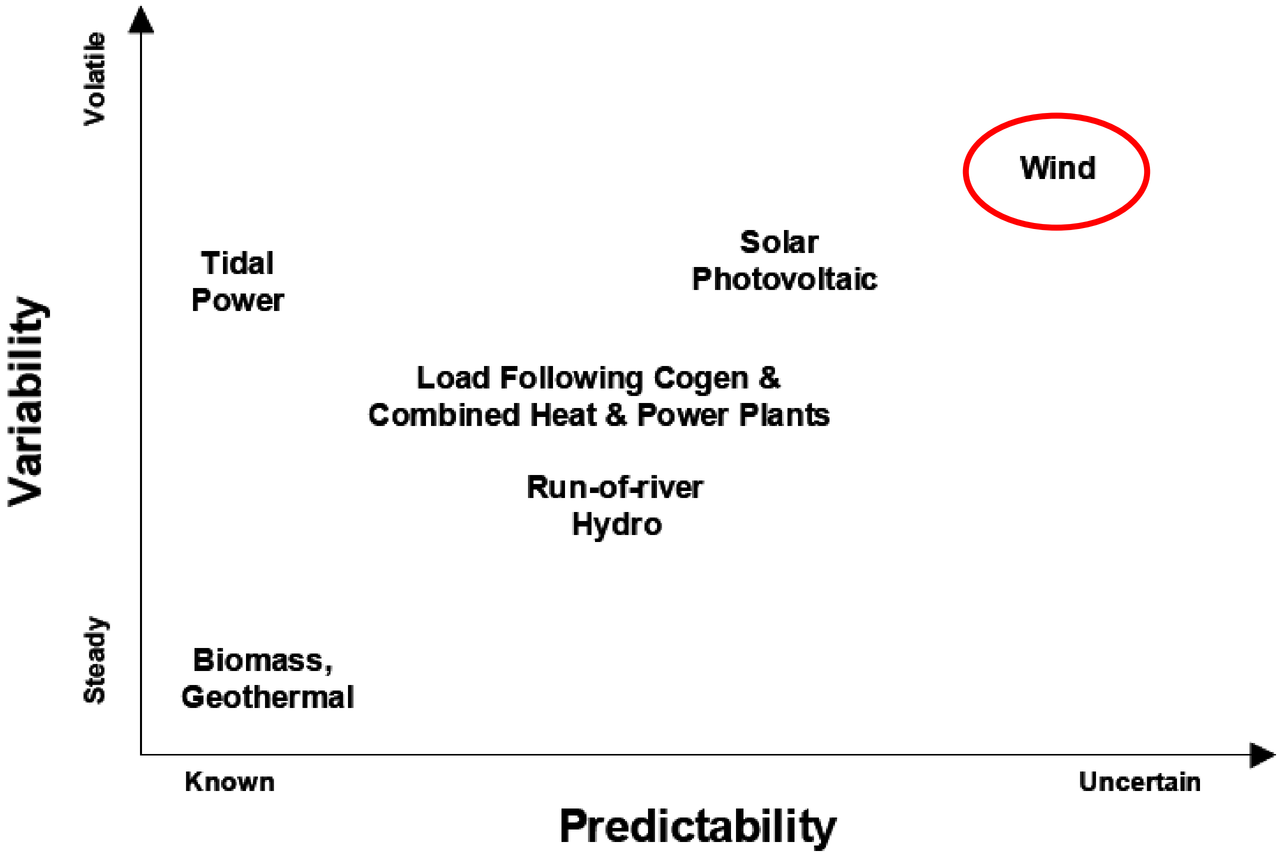

Figure 3.1 Variability and Predictability of Non-dispatchable Generating Resources.

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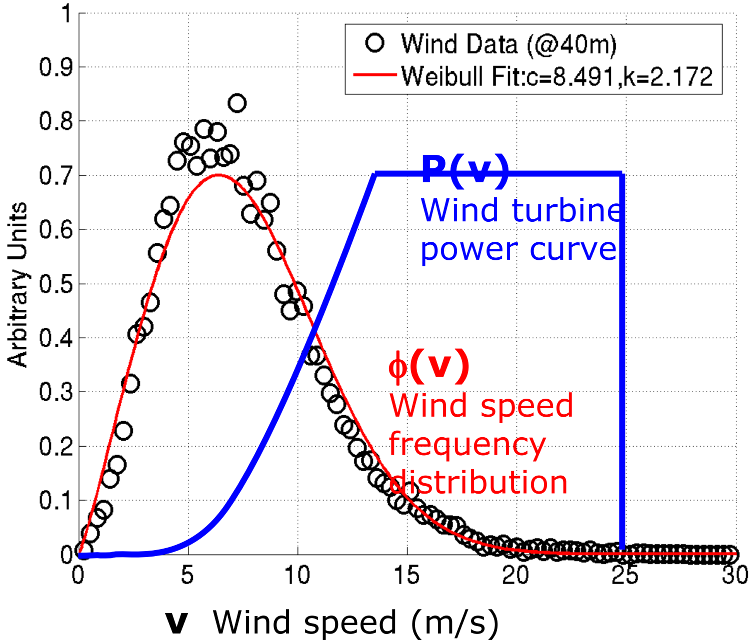
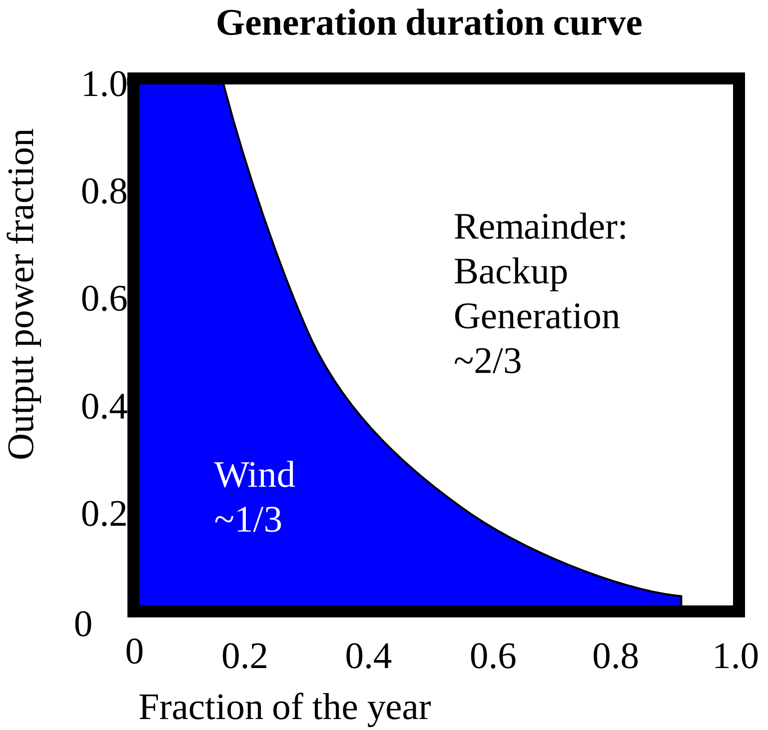
Back-up power for base-load





- Rated Power is delivered by wind 20% of the year.
- Typical Capacity Factor for wind alone is ~ 30%.
- Back-up power needed at 100% of rated power.
- Current best partner for wind (best load follower) is natural gas .
- Add storage, and new options open.

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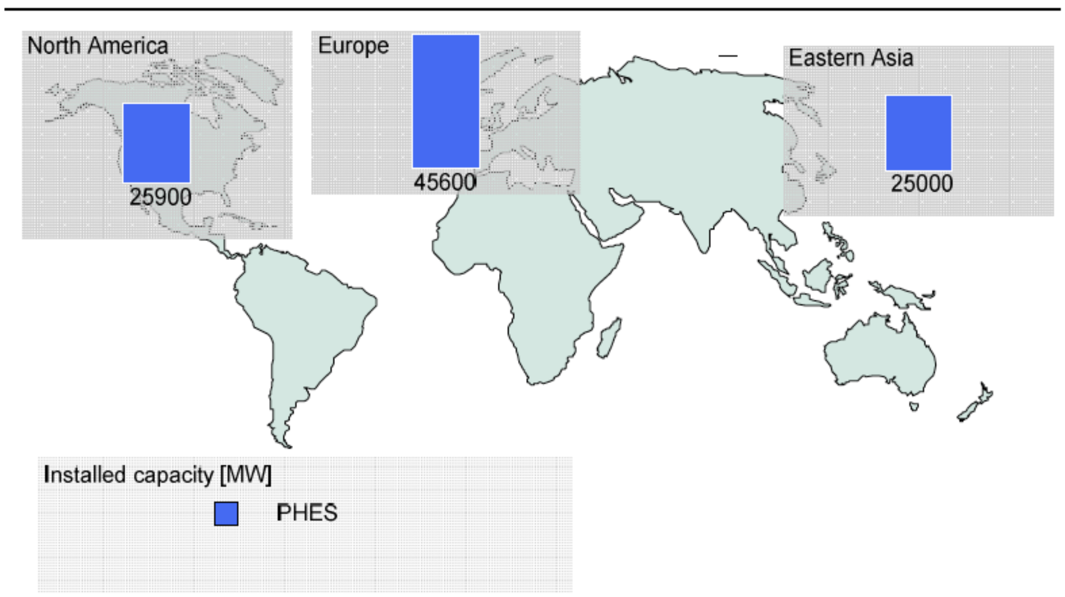
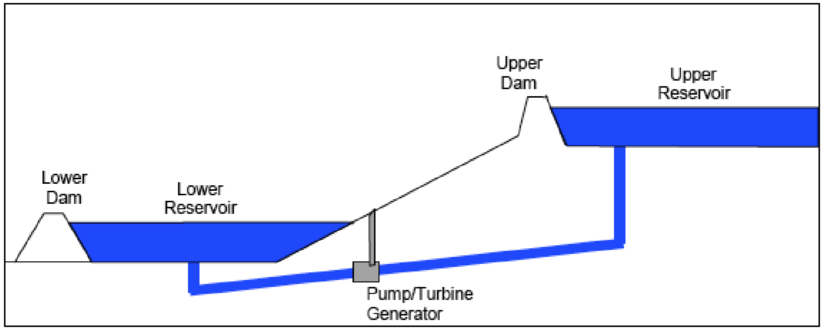
Pumped Hydroelectric Storage

- Current energy storage capacity is largely comprised of pumped hydro plants in mountainous areas
- Extension of pumped hydro is strongly limited due to
  - lack of appropriate sites (esp. in the windy but flat Great Plains and Upper Midwest)
  - often long distances to supply and to demand centres
  - heavy environmental impacts





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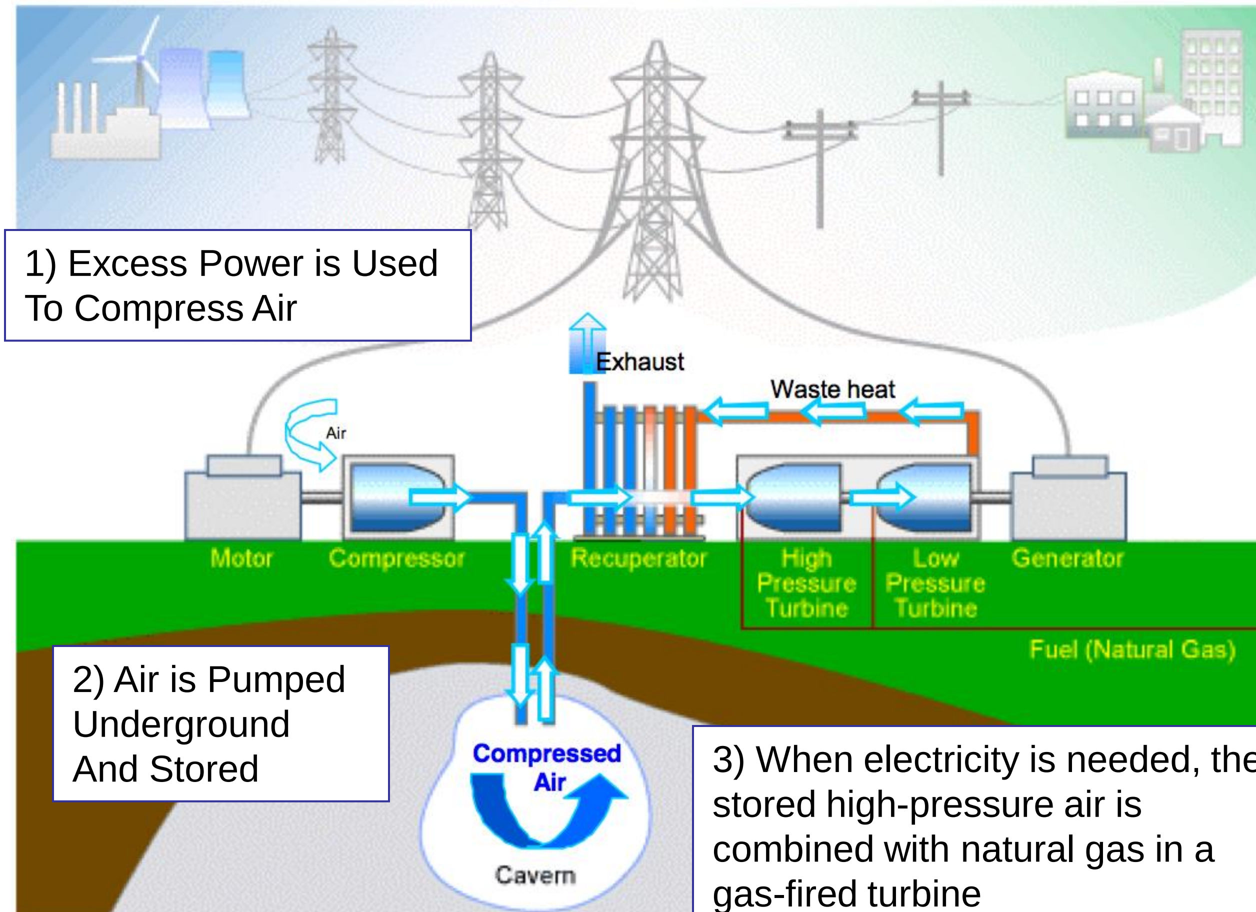
Compressed Air Energy Storage (CAES)



1) Excess Power is Used To Compress Air

2) Air is Pumped Underground And Stored

3) When electricity is needed, the stored high-pressure air is combined with natural gas in a gas-fired turbine

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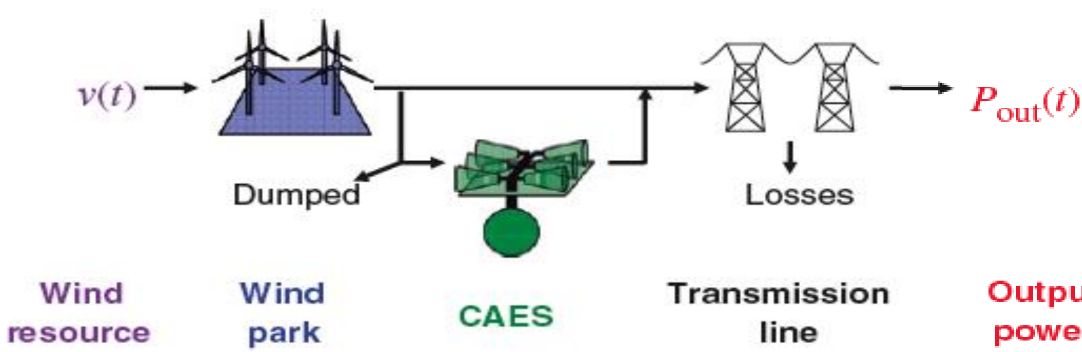
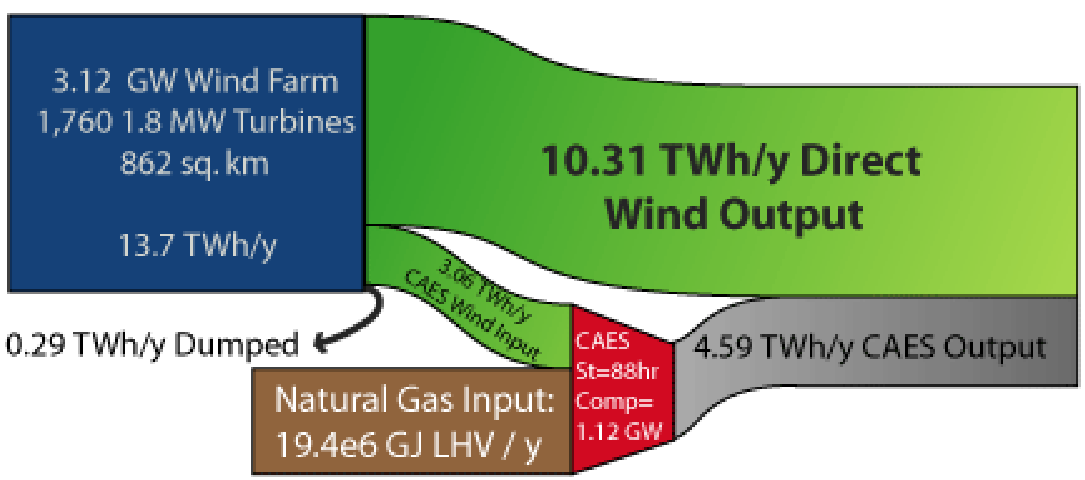
Wind + CAES: Baseload Power



= 2,000 MW at 85% Capacity Factor



14.9 TWh/y

69% Wind, 31% CAES

86.5 gCO_2/kWh

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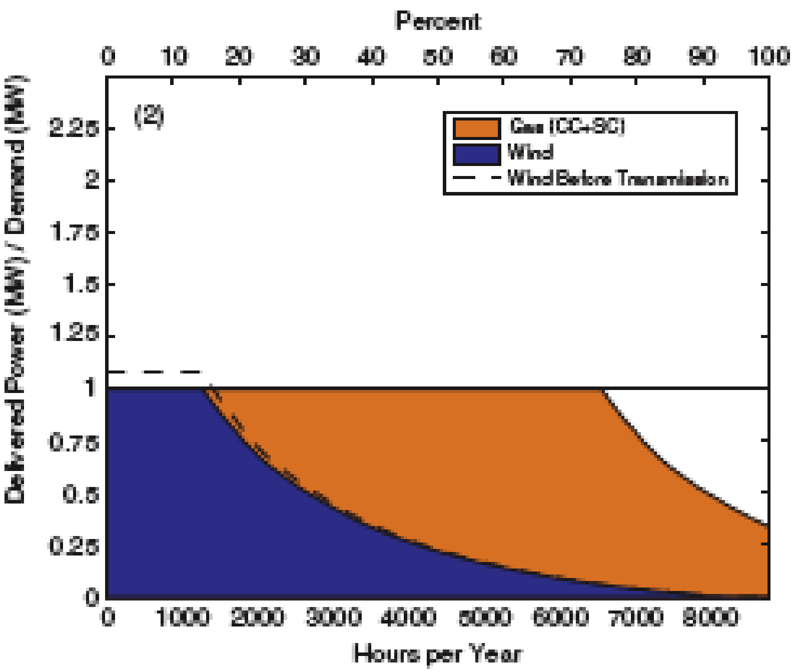
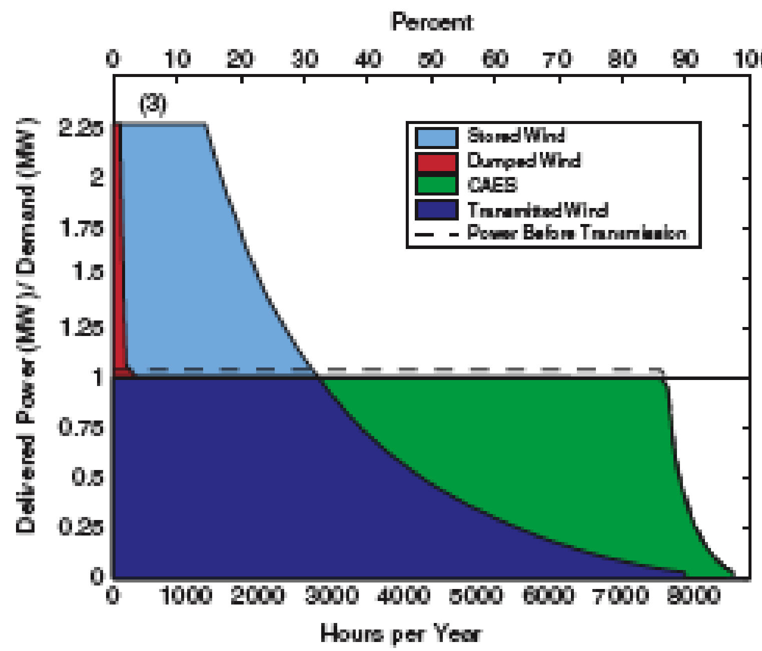
Wind/Gas vs Wind/CAES





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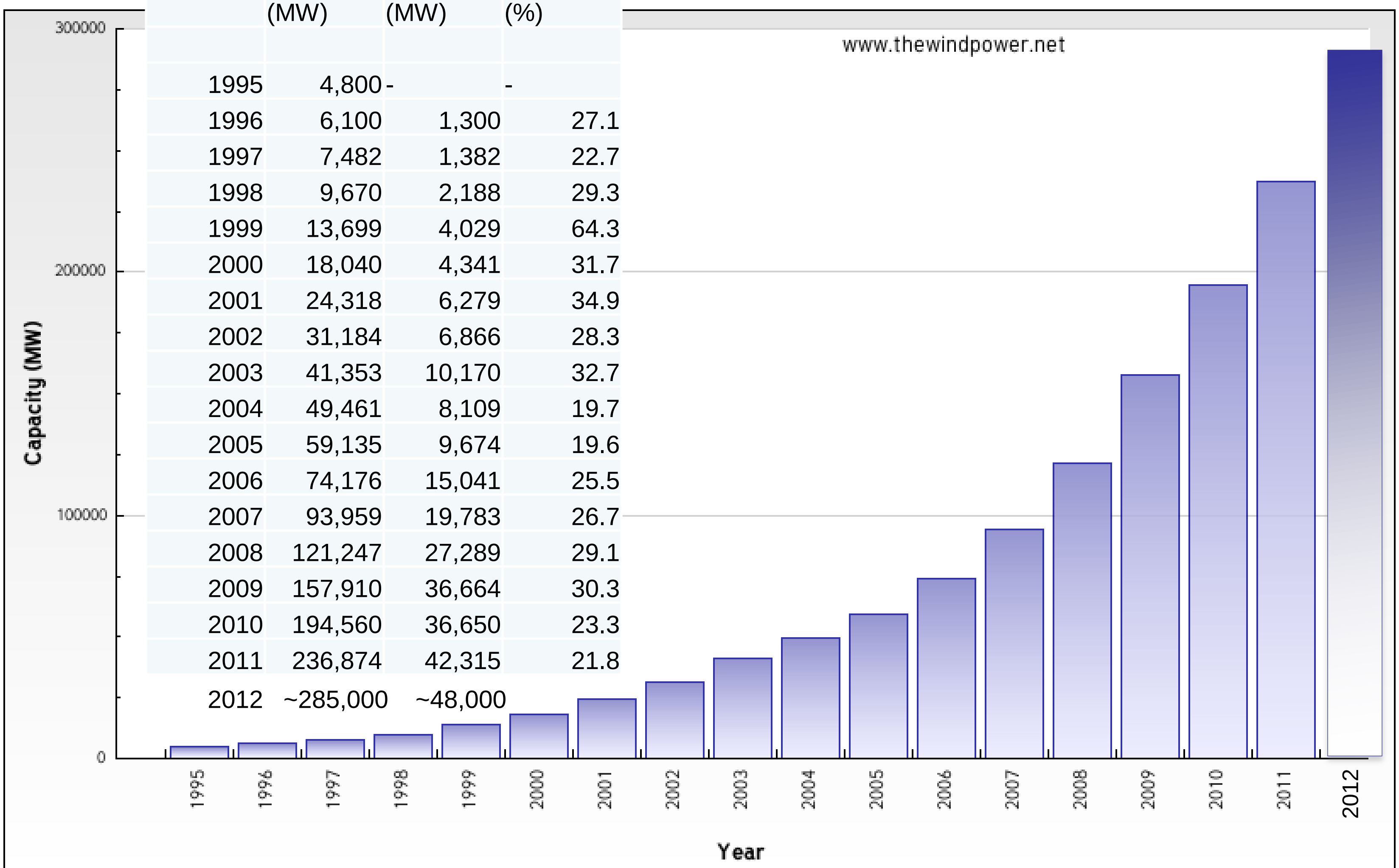
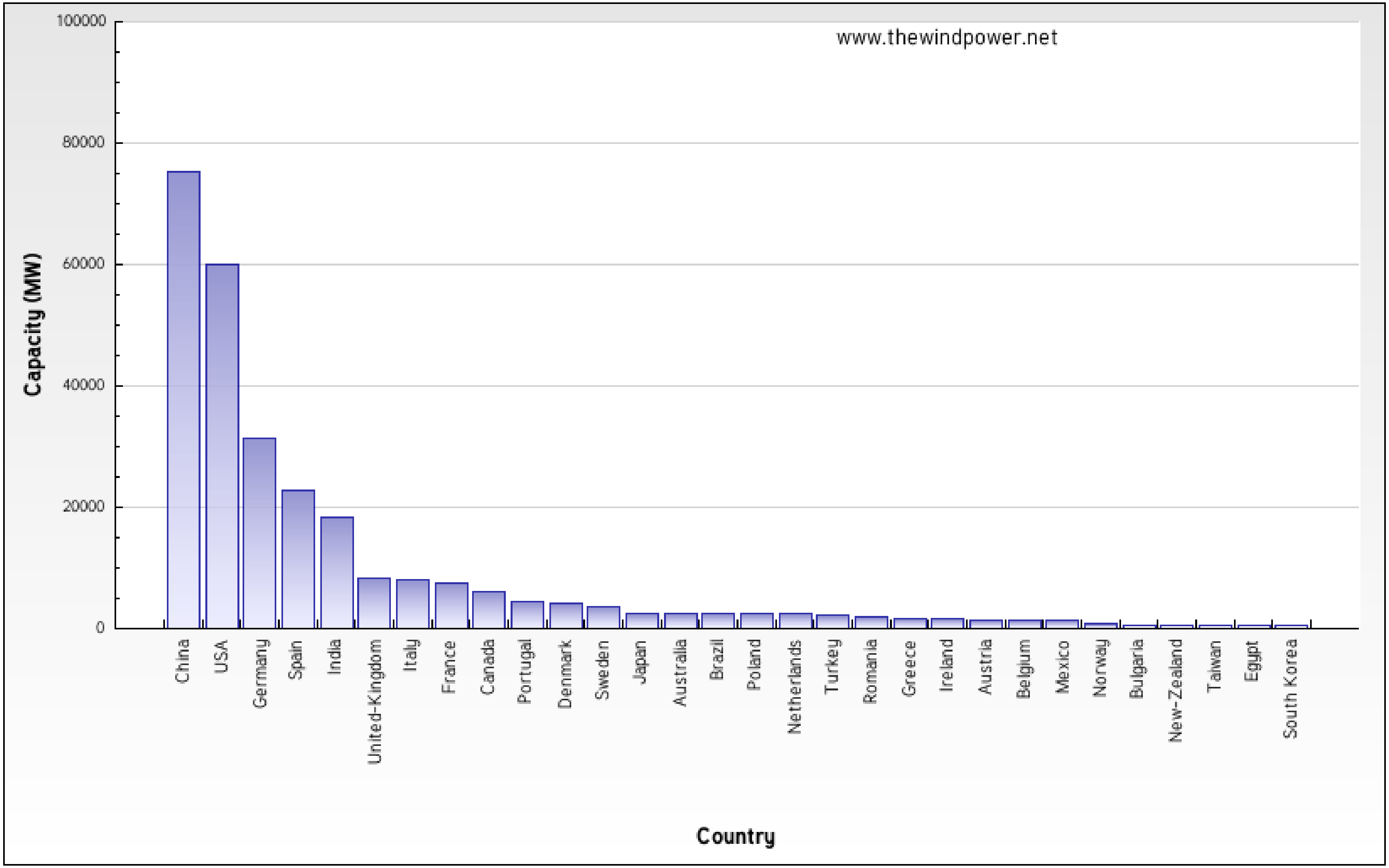
Global wind power

Global wind power capacity

Year	Capacity (MW)	Growth (MW)	Growth (%)
1995	4,800	-	-
1996	6,100	1,300	27.1
1997	7,482	1,382	22.7
1998	9,670	2,188	29.3
1999	13,699	4,029	64.3
2000	18,040	4,341	31.7
2001	24,318	6,279	34.9
2002	31,184	6,866	28.3
2003	41,353	10,170	32.7
2004	49,461	8,109	19.7
2005	59,135	9,674	19.6
2006	74,176	15,041	25.5
2007	93,959	19,783	26.7
2008	121,247	27,289	29.1
2009	157,910	36,664	30.3
2010	194,560	36,650	23.3
2011	236,874	42,315	21.8
2012	~285,000	~48,000	

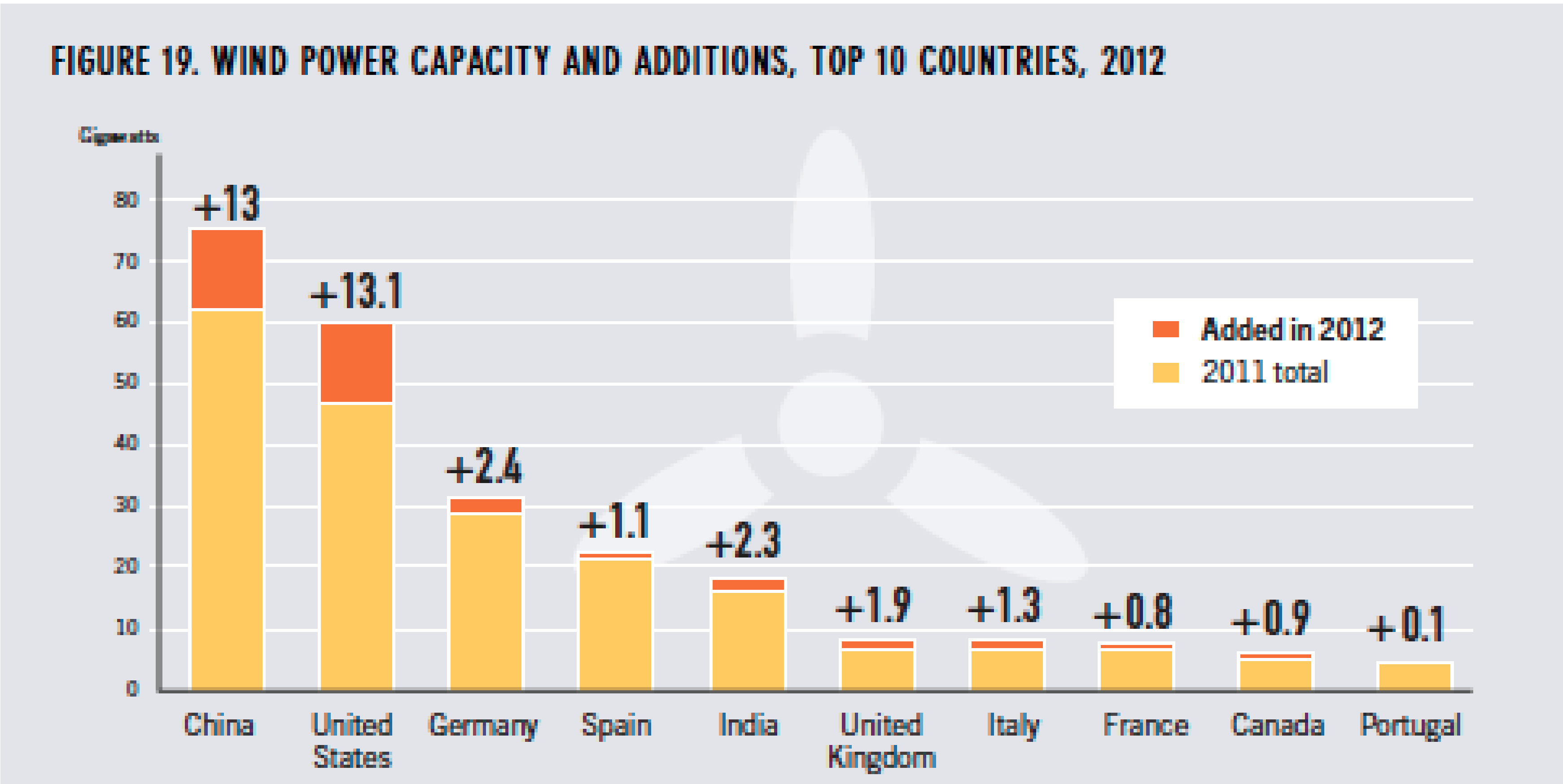


Windpower installed, 2012



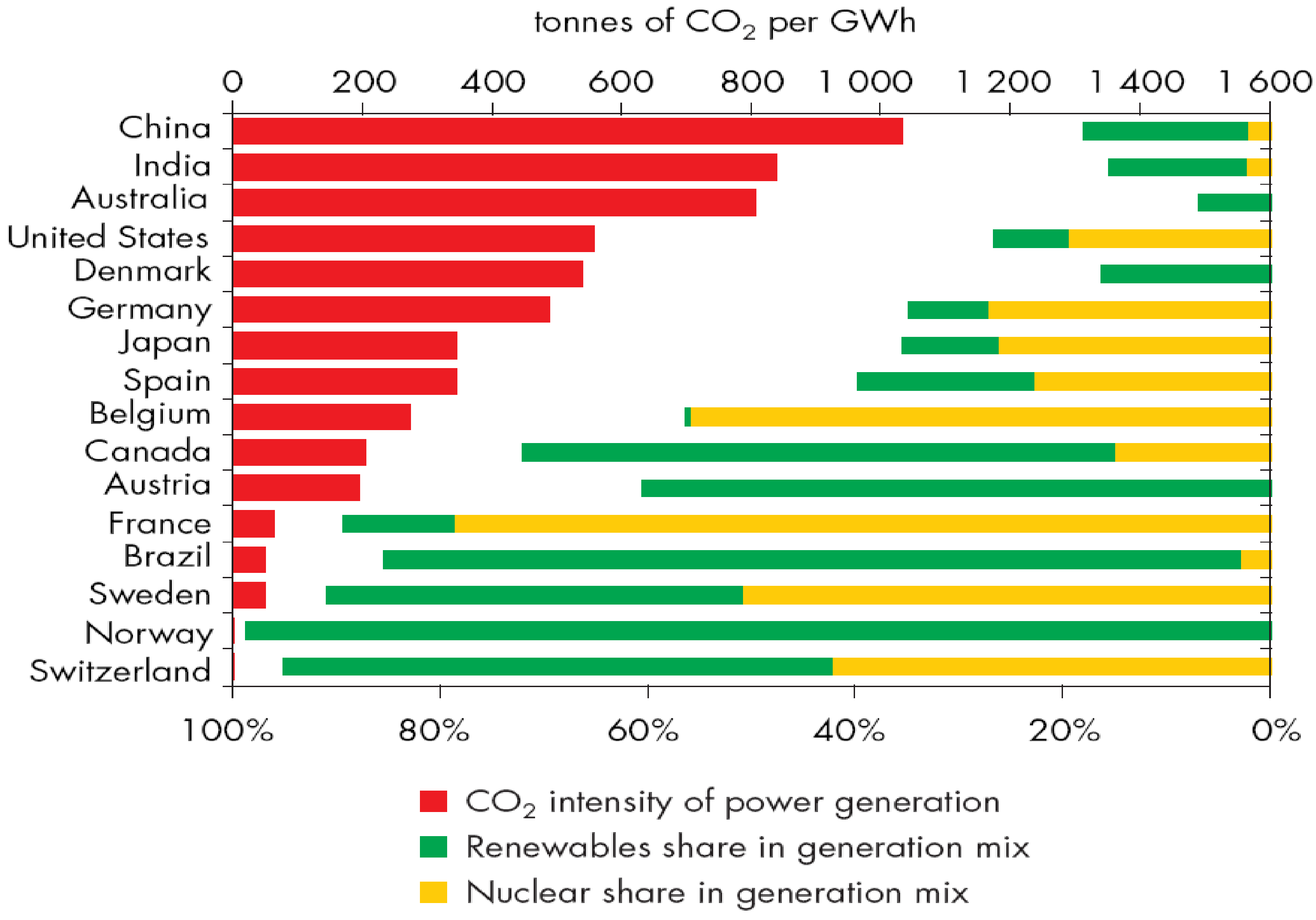
Source and data: http://www.thewindpower.net/statistics_countries_en.php

Windpower capacity by country, 2011 and 2012



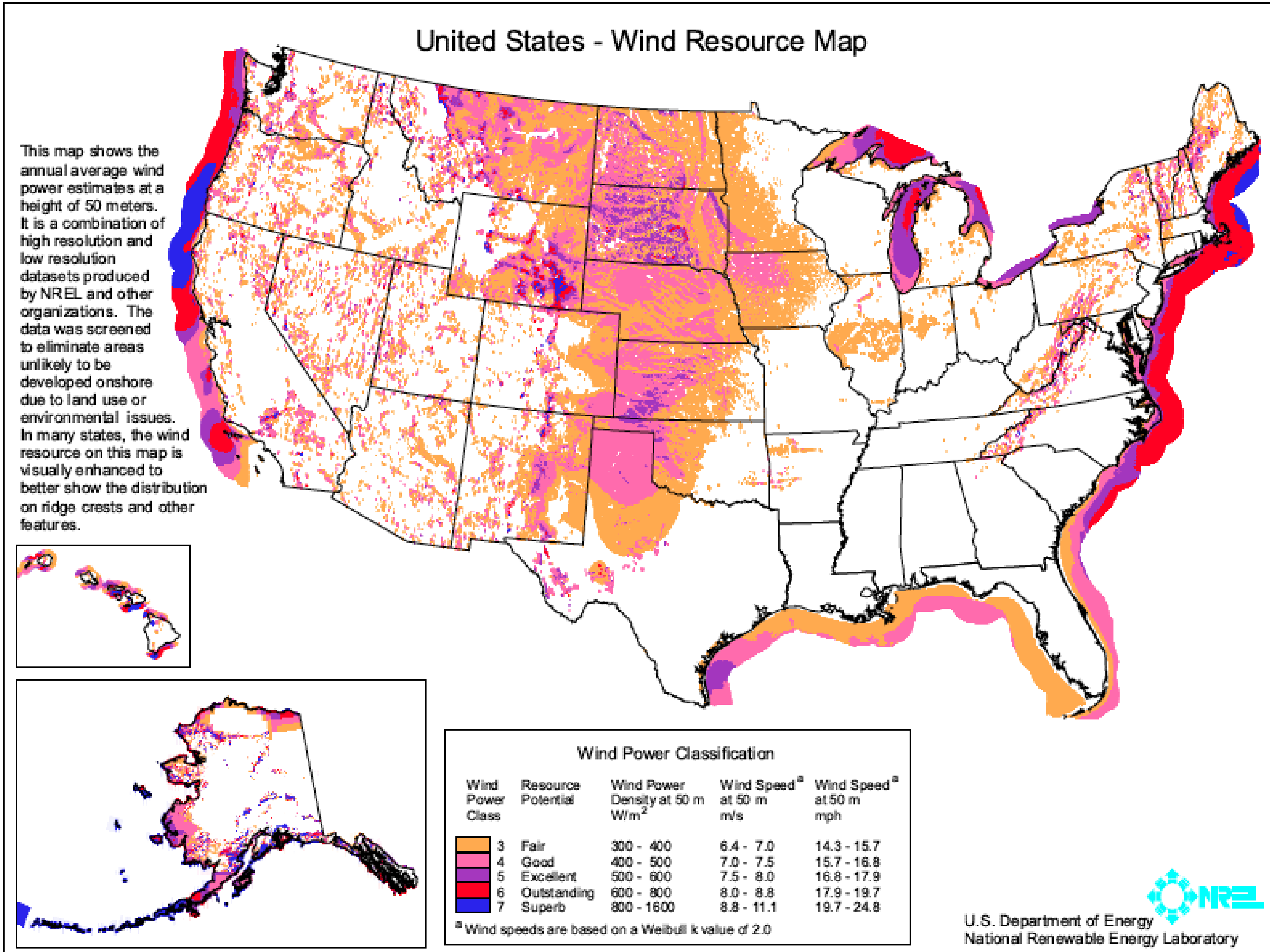
Source: REN21, 2013

Power Sector CO_2 Emissions & Shares of Nuclear Power & Renewables, 2004



Source: WEO 2006

Excellent wind in the Great Plains and Offshore



Something new under the sun?

October 12, 2010, NYT

Google and Good Energy have “agreed to invest heavily” in a transmission backbone

$5 billion project. $200 million initial investments from each.

350-mile, 6000 MW transmission line.

Federal waters, 15-20 miles offshore.

Simplifies permitting

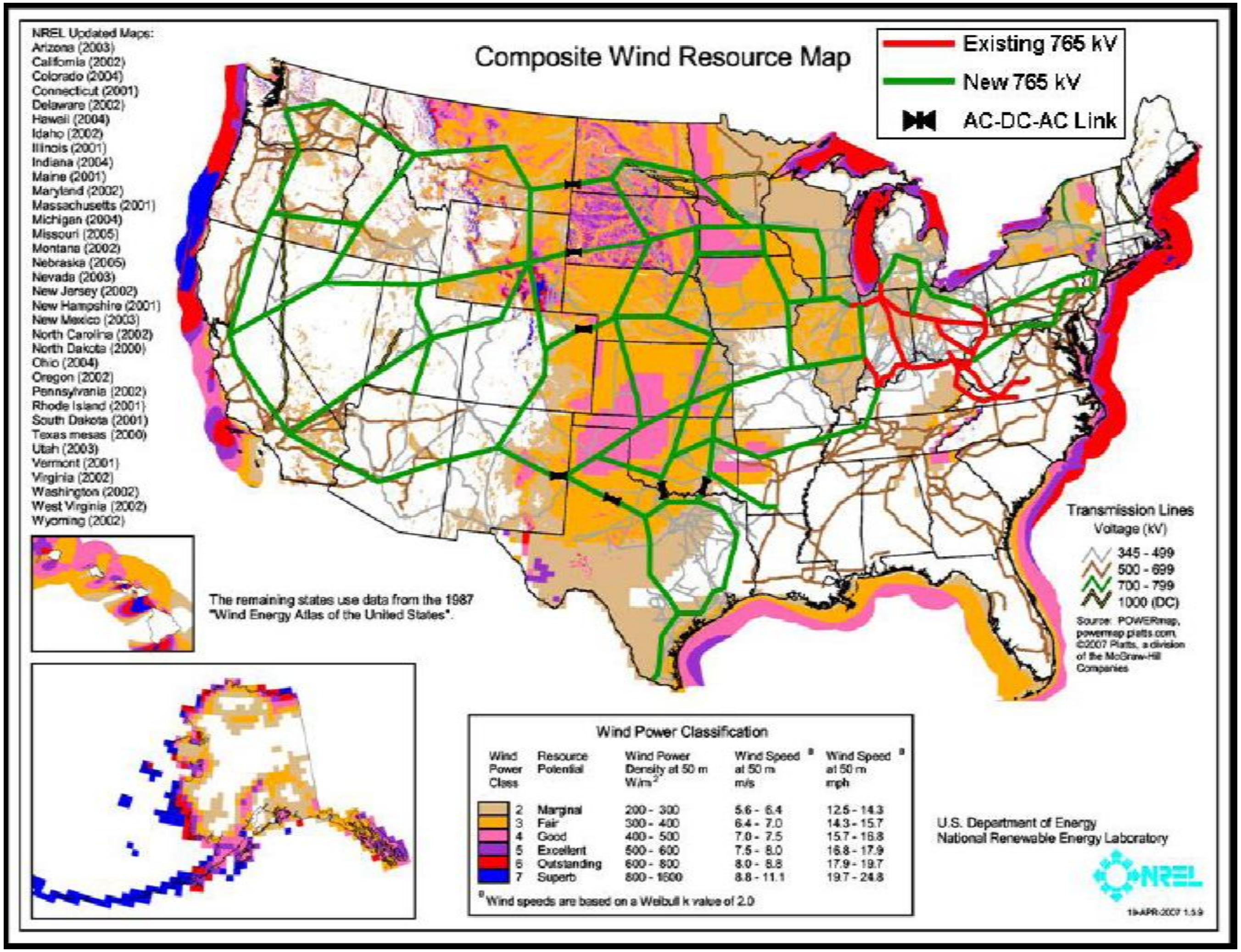
Matches scales of production and transmission

Bypasses congestion: Virginia nukes to NJ?

Smoothes out wind variability

Still needs wind subsidy/carbon tax.

765 kV backbone for 350 GW wind



19,000 miles of new 765 kV line.

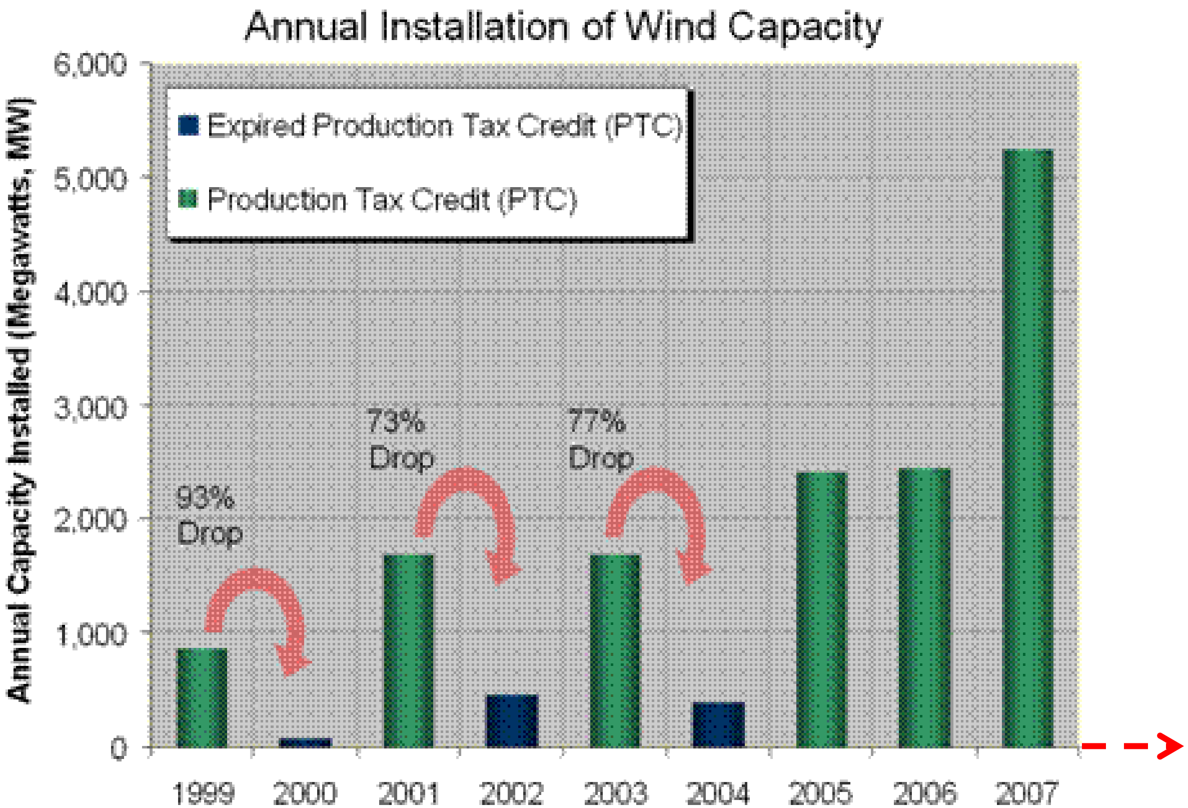
$60 billion.

Source: American Electric Power, 2007. http://www.aep.com/about/i765project/docs/WindTransmissionVisionWhitePaper.pdf.

Policy-Dependent Growth

Production Tax Credit: A federal 1.9 ¢ tax rebate for every kWh of wind energy produced over the first ten years of operation.

Expires every 1-3 years.



"PTC Due to Expire this December": True in 2008 and again in 2012!

See: http://www.businessweek.com/ap/2012-11-29/colo-dot-senators-press-for-wind-tax-credit-extension

Succar

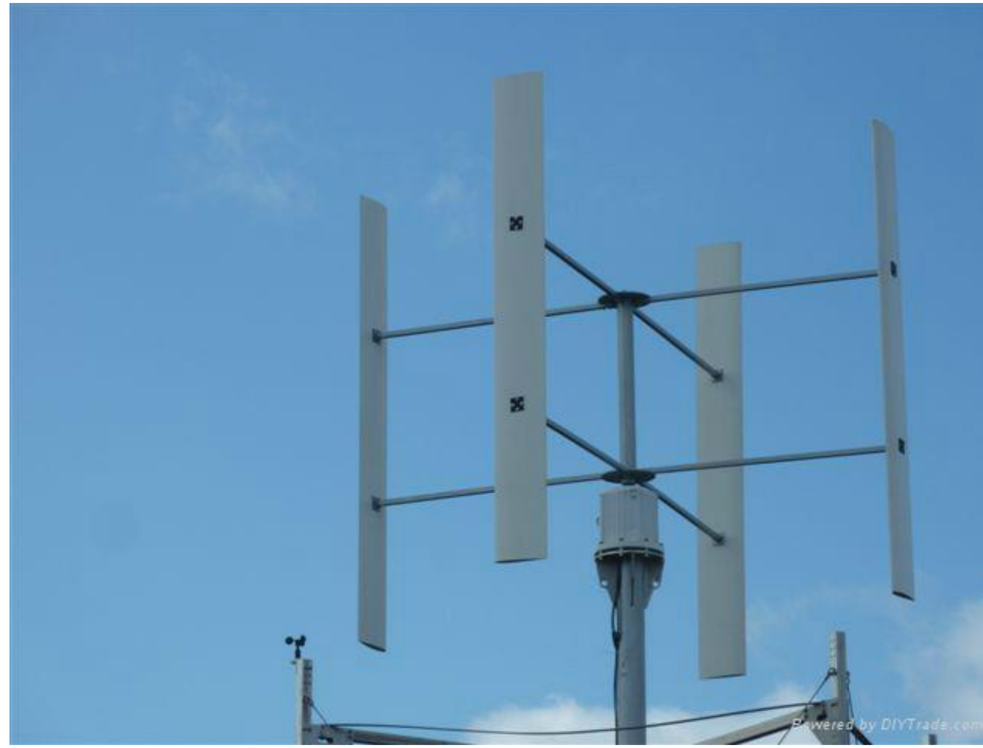
Land area per unit of windpower

Start with a free-stream wind flux of 400 W/m^2. Air flow is modified as energy is extracted. The maximum extractable fraction of wind energy, relative to the energy in the free stream, 16/27 = 59% (the Betts limit). A typical value for this ratio for commercial machines is **25%**, in which case the power extracted divided by the windmill frontal area (a disk) is 400(0.25) = 100 W/m^2

A typical spacing between windmills on a windfarm is 5D x 10D, where D is the blade diameter. Then land area/area intercepted by one windmill = $50*D^2/(\pi D^2/4) = 64$, and the power available per unit of land area is (100/64) W/m^2 = **1.6 W/m^2**, less than 1% of incident sunlight. *Note: the land can be used for pasture or agriculture at the same time. Little land is required for the towers.*

Vertical axis wind turbines

Darrieus wind turbine



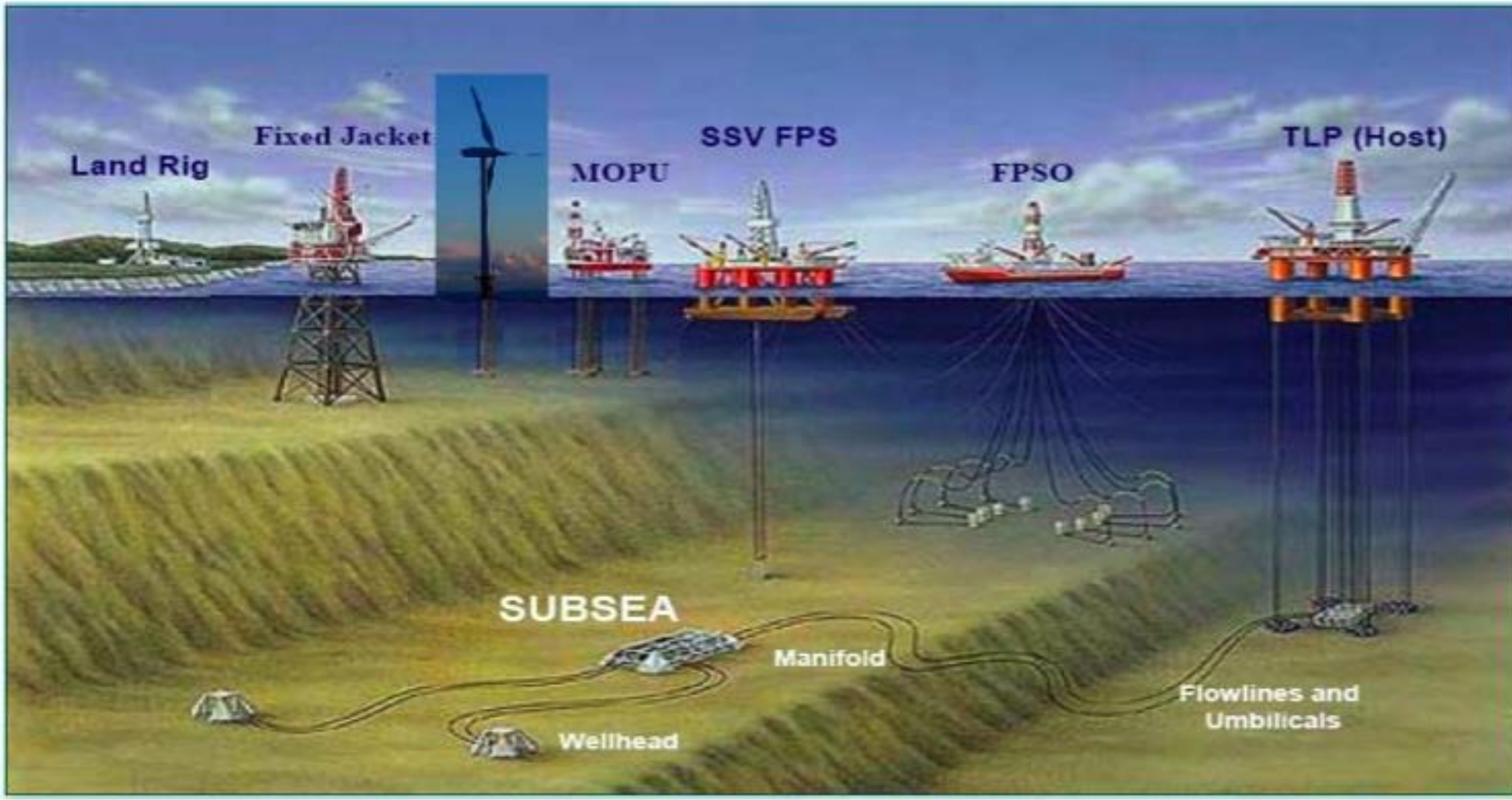
Having the generator and gearbox near the ground lowers the tower cost and simplifies maintenance, but only slow winds are found near the ground.

Wind Farms – Out of Sight

Offshore New Jersey: 96 turbines, 346 MW, 16 to 20 miles from coast. $1 billion project. Power "starting in 2013."

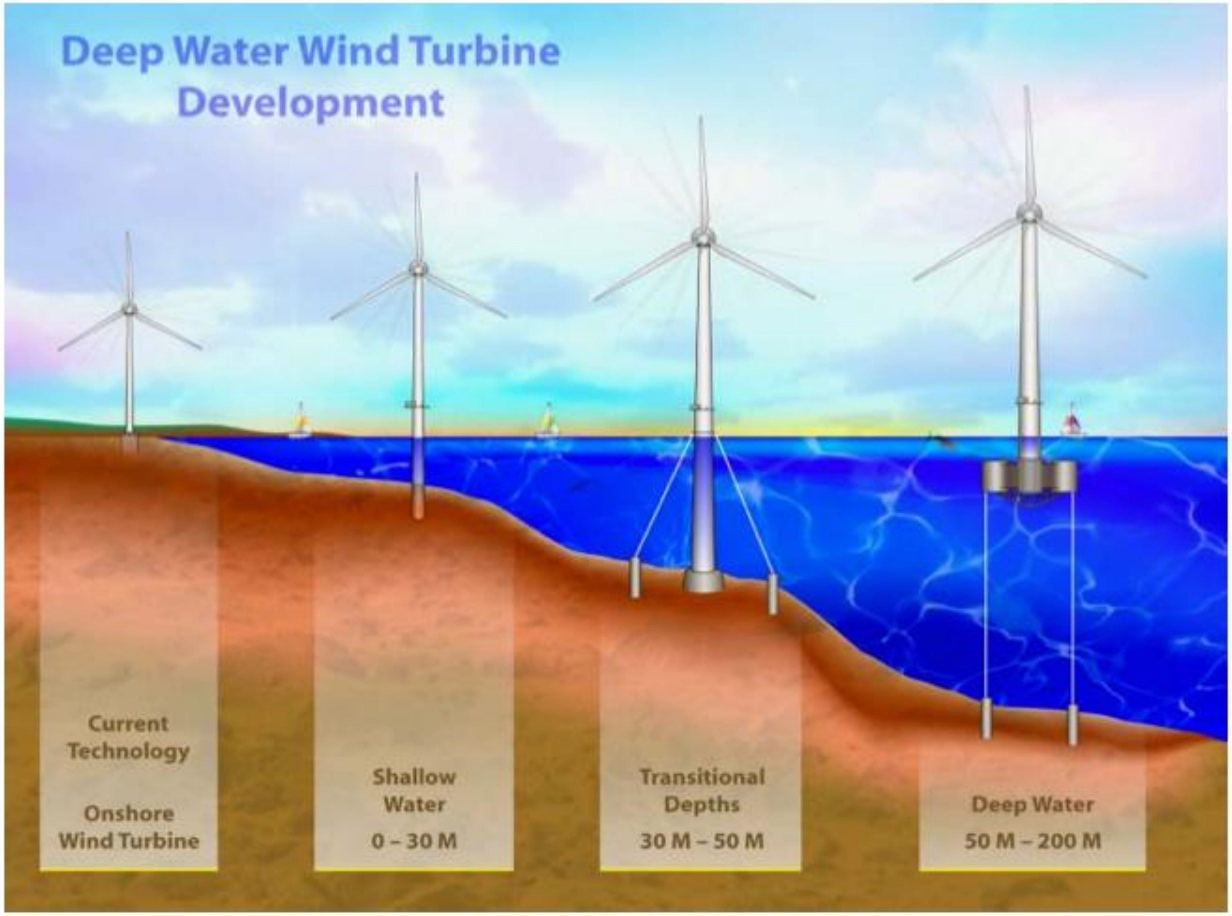
Source: http://www.nytimes.com/2008/10/04/nyregion/04wind.html?ref=nyregion, *New York Times*, October 3, 2008.

50 years for oil and gas



15 years for offshore wind (so far).....

Deep Offshore



Musial, W., Butterfield, S., 2004. Future for offshore wind energy in the United States, conference paper preprint, *National Renewable Energy Laboratory*, report number NREL/CP-500-36313, Golden, Colorado.

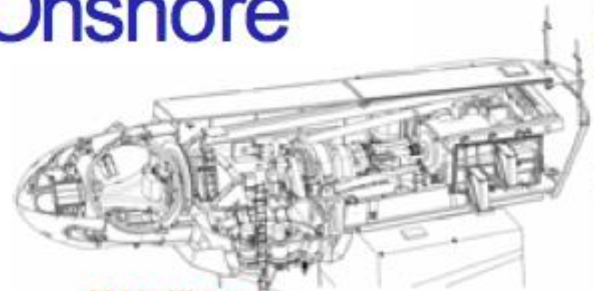
Woody Stoddard of Ocean Wind Energy Systems (OWES), Amherst, MA. (Patents pending)

Succar

Offshore is Definitely Not Onshore

Key Differences

- Hydro-dynamic loads + wind loads
- Highly corrosive salt-laden air
- Dehumidification required to prevent equipment deterioration
- Remote, difficult access - autonomous operation essential
- Visual aesthetics and noise pollution less problematic than on land
- Turbine lower % of costs offshore

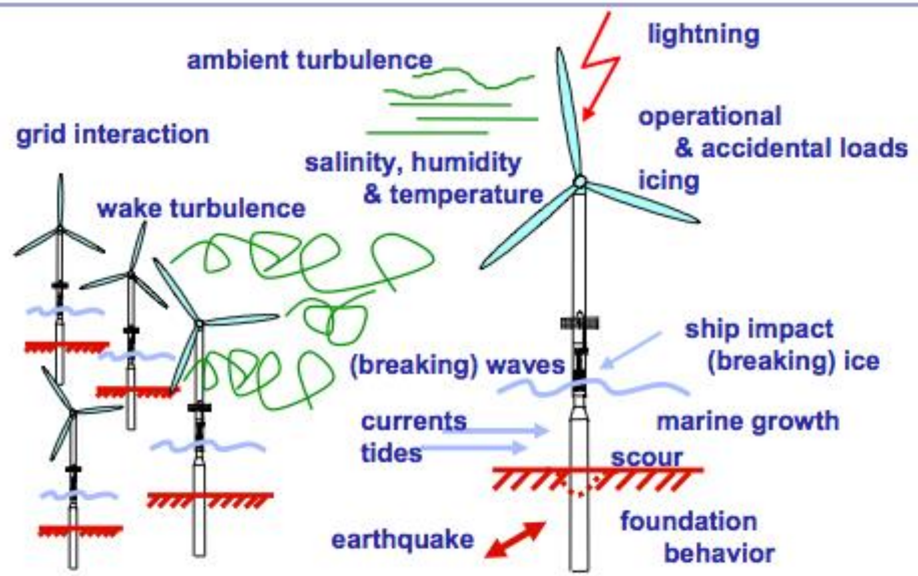


GE 3.6s Offshore

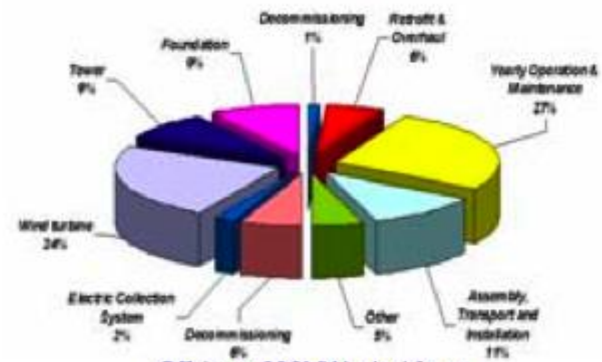
Designs

- Current offshore turbines are derivatives of land-based designs
- Future offshore turbines will be optimized for offshore operation and environment

'Multibrid offshore concept

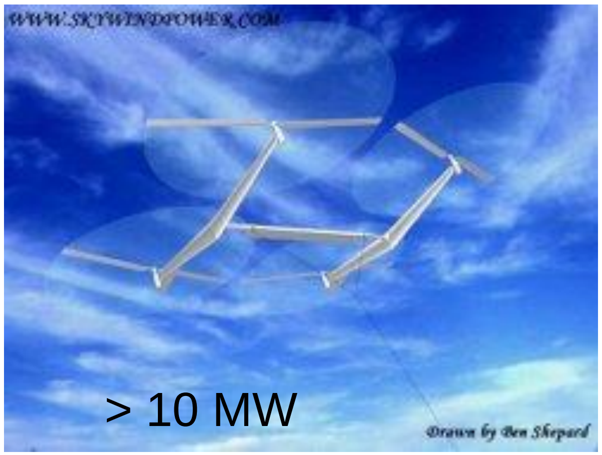


Impacts on Offshore Wind Farm



Offshore 600MW wind farm cost breakdown (DOWEC)

Tethered Wind Turbines and Kites



- Exploitation of wind in the free troposphere (at ~10km) has several cost benefits
  - Energy densities (~5 kW/m^2) are an order of mag. higher than what is available from best wind @ 100m
  - Steady winds at high elevations yields less variable output

Meijaard, J. P., Ockels, W. J., Schwab, A. L., 1999. Modeling of the dynamic behavior of a laddermill, a novel concept to exploit wind energy, http://www.lr.tudelft.nl/asset/webpage/en/laddermill.php

Succar

BREAK

Required readings for Week 11 (1 of 2) Nuclear Power

Hobson, A. (2007). *Physics: Concepts and Connections (4th Ed)*. Chapter 15: The Nucleus and Radioactivity: A New Force. *And* Chapter 16: Fusion and Fission.

Socolow, R. H., & Glaser, A. (2009). Balancing risks: nuclear energy & climate change. *Daedalus*, *138*(4), 31-44.

MIT (2003) "The Future of Nuclear Power: An interdisciplinary MIT study". Available http://web.mit.edu/nuclearpower/pdf/nuclearpower-full.pdf [Read Ch.1 Overview and Conclusions]

Von Hippel, F., ed. (2010). "The Uncertain Future of Nuclear Energy". International Panel on Fissile Materials*. Read Summary and sections 1 and 2 (pages 1-25), sections 6 and 7 (pages 59-72), and policy recommendations (pages 83-85).*

Required readings for Week 11 (2 of 2) Nuclear Power

Acton, J. & Hibbs, M. (2012) “Why Fukushima was Preventable”. Carnegie Endowment for International Peace. Available: http://carnegieendowment.org/2012/03/06/why-fukushima-was-preventable/#

Hylko, J. & Peltier, R. (2010). “The U.S. Spent Nuclear Fuel Policy: Road to Nowhere” Power Magazine. *[Long history of efforts to establish permanent storage for nuclear solid waste in the U.S.]*

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Slovic, P. (1987). Perception of risk. *Science*, *236*(4799), 280-285.

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Recommended readings for Week 11: Nuclear Power

Painter, D. (June 2013). The Nuclear Suppliers Group at the Crossroads. Available: http://thediplomat.com/2013/06/the-nuclear-suppliers-group-at-the-crossroads/1/

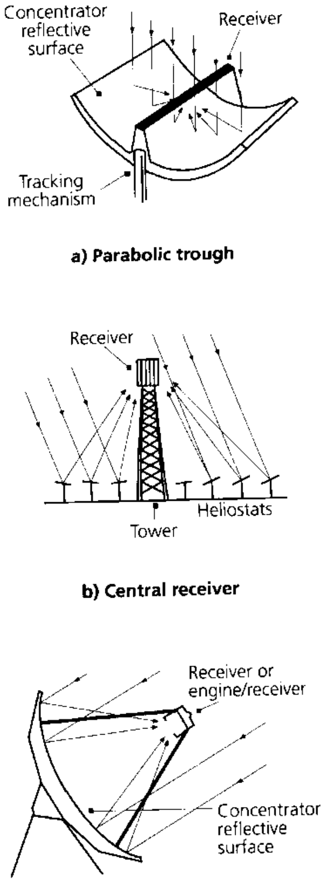
R. Socolow, 2011. "Reflections on Fukushima: a time to mourn, to learn, and to teach." *Bulletin of the Atomic Scientists*, March 21, 2011. (3 pages)

Ross Carper and Sonja Schmid, 2011, The Little Reactor That Could? *Issues in Science and Technology*. Summer 2011, pp. 82-89.

McGoldrick, Fred, 2011, *Limiting Transfers of Enrichment and Reprocessing Technology: Issues, Constraints, Options*. Belfer Center at Harvard University. (~45 pages)

"Solar energy"

Concentrating Solar Power



a) Parabolic trough

b) Central receiver

c) Parabolic dish

FIGURE 3: Three major solar-thermal technologies: the parabolic trough, the central receiver, and the parabolic dish are depicted. Parabolic-trough systems (a) concentrate solar energy onto a receiver tube that is positioned along the line focus of the trough collector. Central-receiver systems (b) have heliostats, or suntracking mirrors, that reflect solar energy to a receiver atop a tower. Parabolic-dish systems (c) use a parabolic two-axis tracking concentrator to focus the sun's rays onto a receiver mounted at the focal point of the dish.

Site: Barstow, CA.

Photo: Noah Kaye, SEIA, April 2007

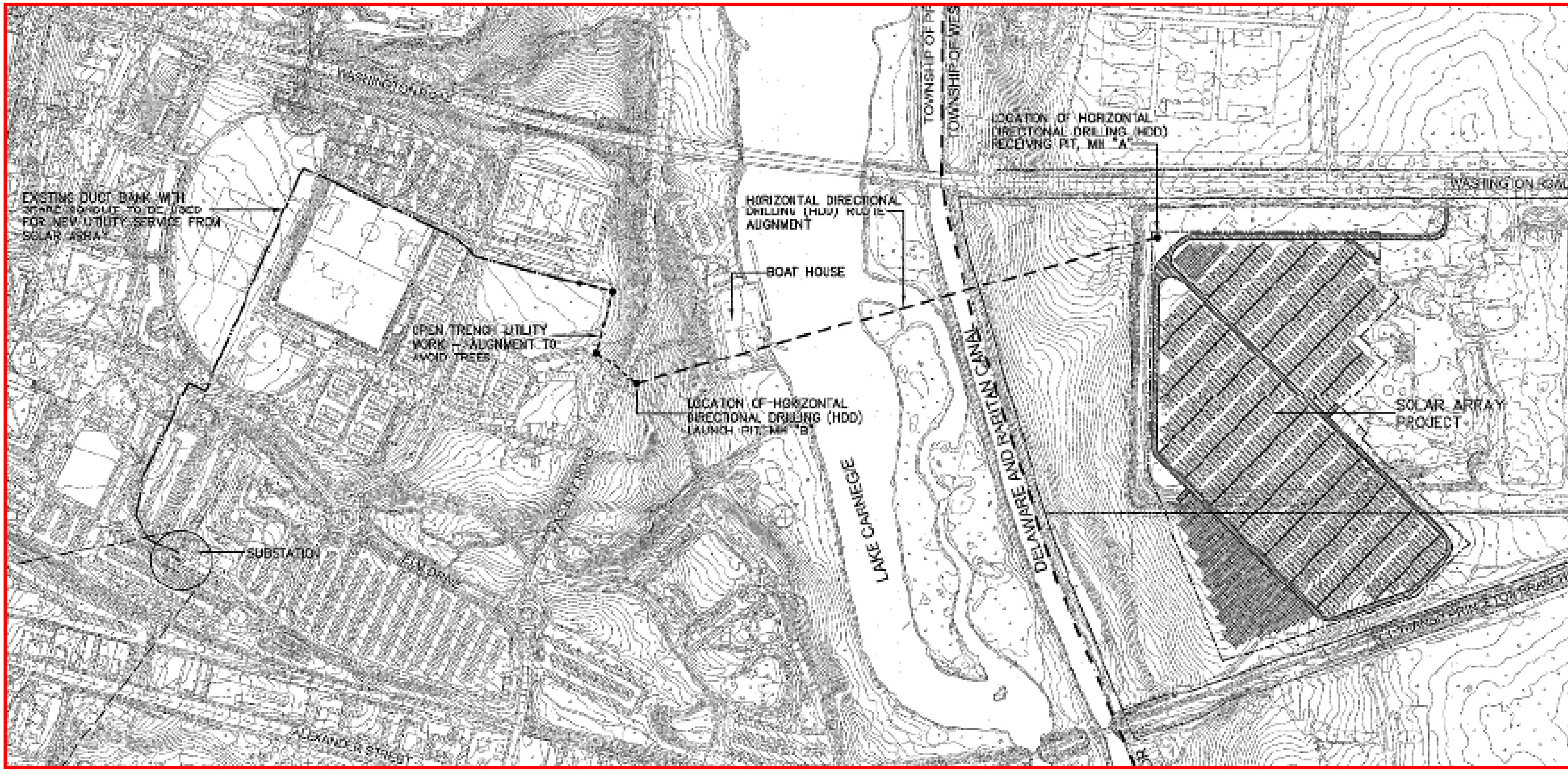
Photovoltaic Power

Graphics courtesy of DOE Photovoltaics Program

Princeton solar field

Princeton's 5.4 MW Solar PV website is now up and running. You can get access to some basic live data about the system and some introductory data about solar PV technology via the facilities energy project web page: http://www.princeton.edu/facilities/info/major_projects/solar_field/. The same website has a photo gallery that tracks the construction.

The PU-PV 5 MW system



Source: Ted Borer, Facilities, Princeton University

The PU-PV system: Capacity factor

Verify that the systems capacity factor is 17%:

Data:

Peak power: 5.4 MW (sometimes written 5.4 MW_p)

Annual output: 8 GWh

Calculation:

The output is about 1500 hrs/yr of peak capacity.

System capacity factor: 1500 hrs/8760 hrs = 17%.

The PU-PV system and the University's CO_2 goals

Verify that the CO_2 savings are 3 $MtCO_2$/yr:

Assumed grid CO2 intensity: 400 gCO_2/kWh
Then 8 GWh annual output produces annual emissions savings of about 3 $MtCO_2$.

(Note: Coal power: 1000 g CO_2/kWh, natural gas: 500 g CO_2/kWh.)

Verify that the project produces 6% of needed 2020 savings to meet Princeton's goal:

The 2020 Princeton goal is 95 $MtCO_2$/yr and projected business-as-usual emissions are heading for 145 $MtCO_2$/yr.

So 3 $MtCO_2$/yr is 6% of the 50 $MtCO_2$/yr of needed 2020 savings.

Panel efficiency and geometry

Verify that the panel efficiency at "rated power" is 19.6%:

Princeton has bought Sunpower's "E19-320" panel. It is a 96-cell (12x8) panel with 320 W rated power (a rated voltage of 54.7 volts times a rated current of 5.86 amps). Rated power (peak power) is power produced for an incident solar flux of 1000 W/m^2 – roughly the flux when the sun hits a panel at right angles, as it does for the *fixed* panels near mid-day on some clear summer days.

The panel frontal area is 1.63 m^2: 1.559 meters long by 1.046 meters wide. Hence, the panel produces $320W/1.63m^2$ = 196 W_p/m^2, when the incident flux is 1000 W/m^2. Thus, the efficiency at peak sunlight is 19.6%.

Most of the panels are *tracking*, not fixed. They are see-saws rotating on a north-south *horizontal* shaft, driven in groups by a common motor . The panels, therefore, are completely flat at noon. A tilted shaft would increase the noon-time incident flux, but it would also increase shading and require one motor per panel

For details about the cells ("all-back-contact monocrystalline") and panels, see: http://us.sunpowercorp.com/downloads/product_pdfs/Panels/sp_e19_320wh_ds_en_ltr_p_223.pdf.

The PU-PV system: land demands

Verify that the peak output per area of land is 50 W_p/m^2:

Peak-power: 5.4 MW-peak
Land required: 27 acres = 10.9 ha (2.47 acres = 1 ha. 1 ha = 10^4 m^2.)
So land intensity is 50 W_p/m^2.

Compare to 196 W_p/m^2 panel output flux in direct sunlight: geometry and land use combine to produce a land intensity that is *four* times less.

The "ground-coverage ratio" is the total area of the panels in a specific configuration divided by the area of land required for a given configuration. The University chose Sunpower's T0 Tracker system. Its ground-coverage ratio is quoted as 0.35 to 0.50. Thus, much of the factor of four can be assigned to the need for space between panels to reduce shading and provide access.

The PU-PV system: choice of two trackers

Sunpower sells two systems, a T0 and a T20 Tracker, using the same panels. They differ in how much one panel casts a shadow on another. The T0 Tracker produces more shading, because its panels are closer together. It therefore has a higher ground coverage ratio (it has a lower land intensity, it uses more land per kWh), but it captures less power per panel.

The T0: the ground-coverage ratio is 0.35 to 0.50.

The T20: the ground-coverage ratio is 0.20 to 0.24.

My guess is that Princeton chose the T0 Tracker, because land is at a premium.

The data sheets for the two trackers are at:
http://us.sunpowercorp.com/downloads/product_pdfs/trackers/SunPower_t0tracker_en_lt_w_ra.pdf

http://us.sunpowercorp.com/downloads/product_pdfs/trackers/SunPower_t20tracker_en_lt_w_ra.pdf.

Do wedge strategies get used up?

For any strategy, is the second wedge easier or harder to achieve than the first? Are the first million two-megawatt wind turbines more expensive or cheaper than the second million two-megawatt wind turbines?

> The first million will be built at the more favorable sites.
>
> But the second million will benefit from the learning acquired building the first million.

The question generalizes to almost all the wedge strategies: Geological storage capacity for CO_2, land for biomass, river valleys for hydropower, uranium ore for nuclear power, semiconductor materials for photovoltaic collectors.

All present the same question: *Will saturation or learning dominate?*

Policy issues

How do we reduce emissions?

Three ways:

Be very smart, so no policy is needed.

“S < C “ (solar is cheaper than coal).

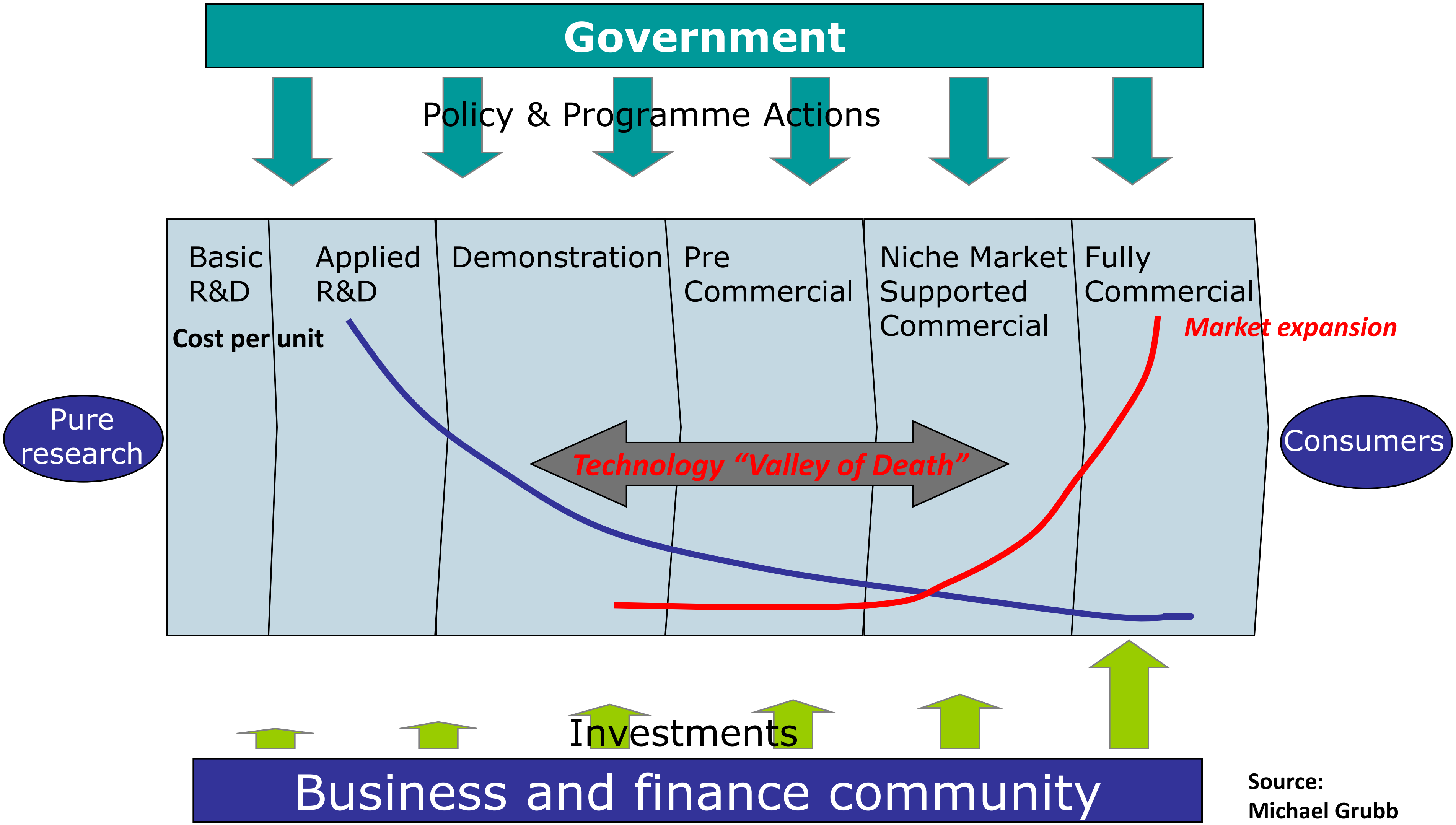
Regulatory policy and referenda: Forbid and require.

Market-based policies: Change relative prices.

Research and development (R&D) is an important and contentious policy arena

How much?
How close to market: “pre-competitive” vs. “picking winners”?
The Valley of Death

The Technology Innovation Chain – from R&D to Market



Source:
Michael Grubb

How do we bend these curves?

Three ways:

Be very smart, so no policy is needed.

“S < C “ (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

Market-based policies: Change relative prices.

Regulatory issues ("Command and Control")

Rules and standards

- Framing (e.g., concentration vs. absolute amount – "the solution to pollution is dilution")
- Timing

Subsidies and penalties

- Fines to automakers and Corporate Average Fuel Economy (CAFE)
- Production tax credit (PTC), Investment tax credit (ITC)

Regulation of electric utilities

- Regulated and deregulated states
- Best available control technology (BACT)
- Public Utilities Regulatory Policy Ace (PURPA) and "avoided cost"
- Dispatch rules
- Net metering

How do we bend these curves?

Three ways:

Be very smart, so no policy is needed.

“S < C “ (solar is cheaper than coal).

Regulatory policy and referenda: Forbid and require.

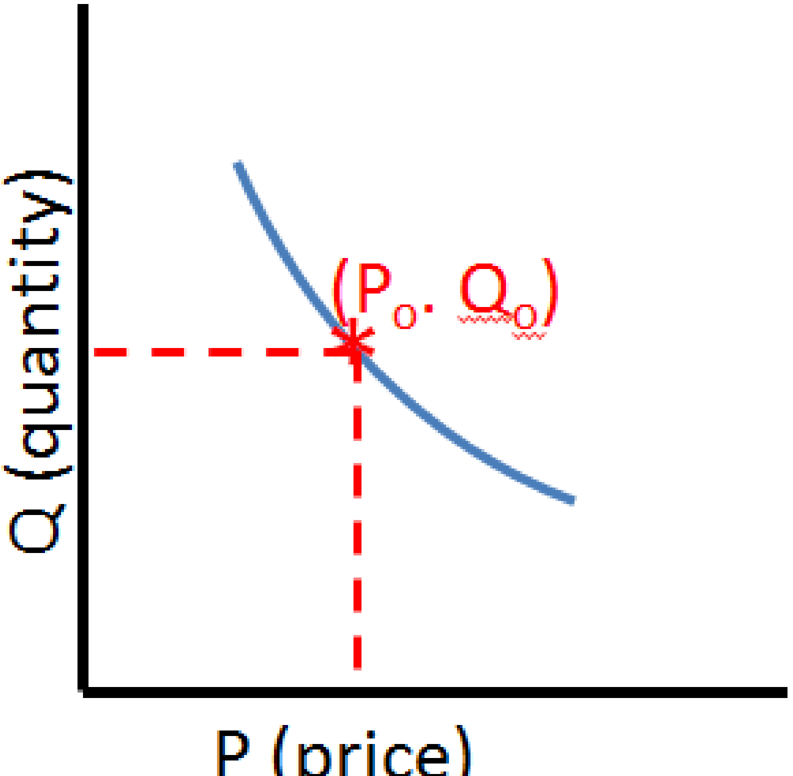
Market-based policies: Change relative prices.

Ideal cap-and-trade = Ideal tax

Cap-and-trade and tax in their pure forms are identical.

Assume Q(P) exists:

- Cap-and-trade: Fix Q_o, then find P_o.
- Tax: Fix P_o, then find Q_o.



Design issues in cap and trade
(and in most other market mechanisms)

System boundary and offsets

Schedule of cap reductions or tax increases

Mixed strategies (the collar)

Fines for non-compliance (the stick)

Auction or give for free? (the carrot)

Iteration: How soon? How often.

Iterative risk management

In another decade we'll know a lot more about the earth, both because of new climate science and because of what the earth tells us about itself.

We’ll also know more about the solutions themselves, thanks to both R&D and field experience.

All this argues for making decisions *iteratively*.

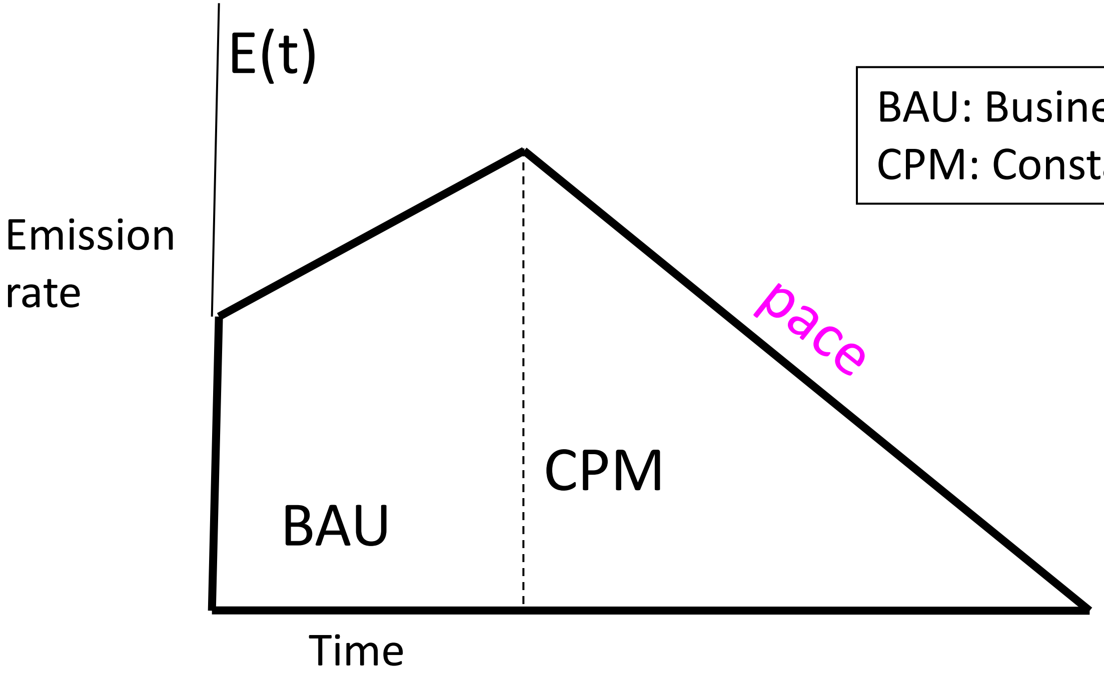
Broad issues behind policy choices

Why act now?

Alliances and surrogate goals.

Getting to Yes. Just saying No.

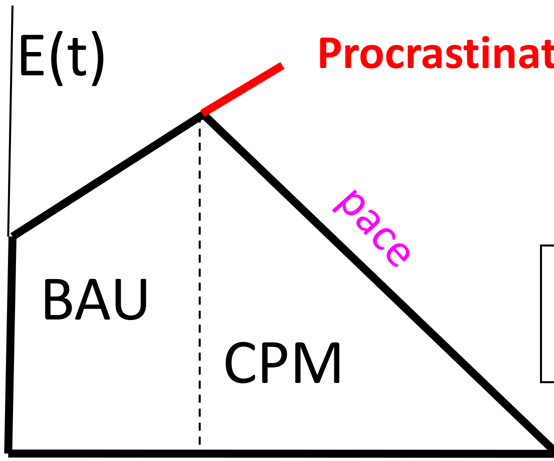
An idealization of mitigation



BAU: Business As Usual
CPM: Constant-Pace Mitigation

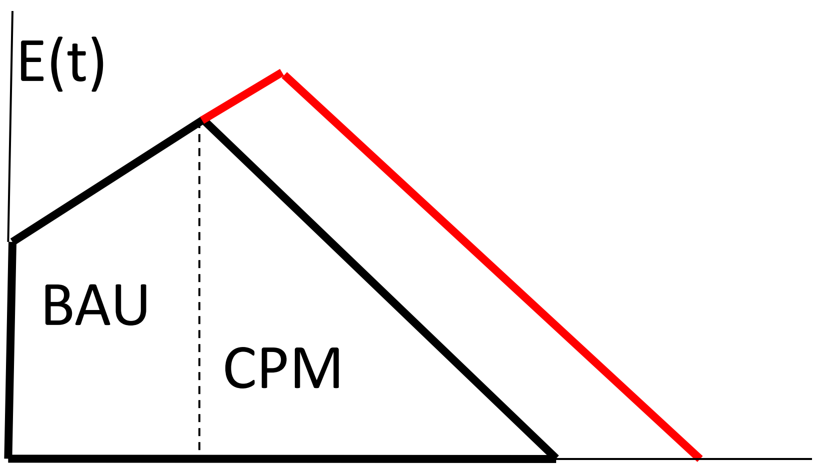
Today, approximately half of emissions are retained in the atmosphere and half move to other reservoirs.

Procrastination and “Pace”

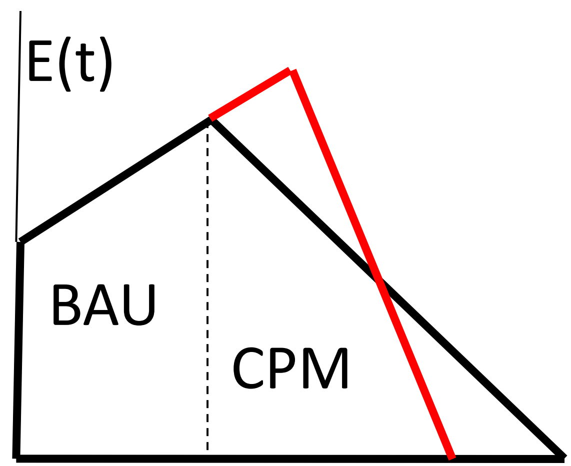


Procrastination can lead to…

BAU: Business As Usual
CPM: Constant-Pace Mitigation



(1) Extra total emissions, because pace cannot be increased,



OR (2) Constant total emissions, with a faster pace.

Arguments for Delay (1 of 2)

SCIENCE

- We don't know the science. Human activity may be having a negligible effect, swamped by natural variation.
- We may be having an effect, but the impacts are, on balance, favorable.

TECHNOLOGY

- We do not yet have the tools to solve the problem.
- The tools to solve the problem that we have are far inferior to the tools we will have if we conduct R&D for a few decades.
- We have tools that could solve the problem, but they are too dangerous. The cures are worse than the disease.

Arguments for Delay (2 of 2)

POLITICS, ECONOMICS

- The costs of mitigation are too high, relative to any willingness to pay.
- Government makes a mess of things when it intervenes in the economy.
- The world has more important things to do, notably to deal with world poverty.
- It is wasteful to engage developing countries in mitigation now, given that they will have much greater capacity for implementation later.
- Mitigation will hurt the poor in every country. Wait till we are richer.
- The net result will be to transfer wealth from rich to poor, not good policy.

PHILOSOPHY

- Government should not run our lives.
- People aren't ready to tackle climate change – the issue is too abstract.
- Whatever the impacts, we can adapt to them.
- We should not play God. We should not control nature.

Adaptation

Adaptation can be organized by:

- Before (preparation), during (coping) and after (resilience)
- The threat (extreme events, chronic change)
- The sector affected (farmers, the elderly, the poor)
- The level of government most appropriately involved
- Structural (dikes) vs. non-structural (land use zoning, evacuation) responses

How should effort be divided between mitigation and adaptation. Adaptation is gaining share. Is this “delay”?

Getting to Yes

The more we fear climate change, the less we can allow ourselves to be squeamish about imperfect “solutions.”

We must remember that we want solutions to work. It can’t be enough to identify what’s wrong with a strategy as it is first proposed. We must ask: With what changes, would this strategy become acceptable? How might we get from here to there?

Getting to No

However, we may decide, in some situations, to forego an option.

This may be the result of a moral judgment. We will prefer enduring some amount of climate change to the compromises required to avoid it.

Surrogate Goals (1 of 3)

Definition of a surrogate goal

A person who holds Goal A strongly and Goal B weakly, but believes that achieving Goal B will also achieve Goal A, can pursue Goal B as a *surrogate* for Goal A.

Usually, Goal A will be revealed only in special circumstances. Recognizing that a multiplicity of surrogate goals is at play has considerable explanatory power.

Surrogate Goals (2 of 3)

Surrogate goals and climate change

In the formulation of policy to deal with climate change, the general objective of slowing the rate of climate change is often a surrogate for more strongly held goals, such as:

- Augmenting financial transfers to developing countries
- Bringing the fossil fuel era to a close
- Curtailing consumerism and human centeredness
- Promoting self-sufficiency, autonomous communities
- Diminishing the power of technological elites
- Promoting environmental science
- Encouraging entrepreneurship

Surrogate Goals (3 of 3)

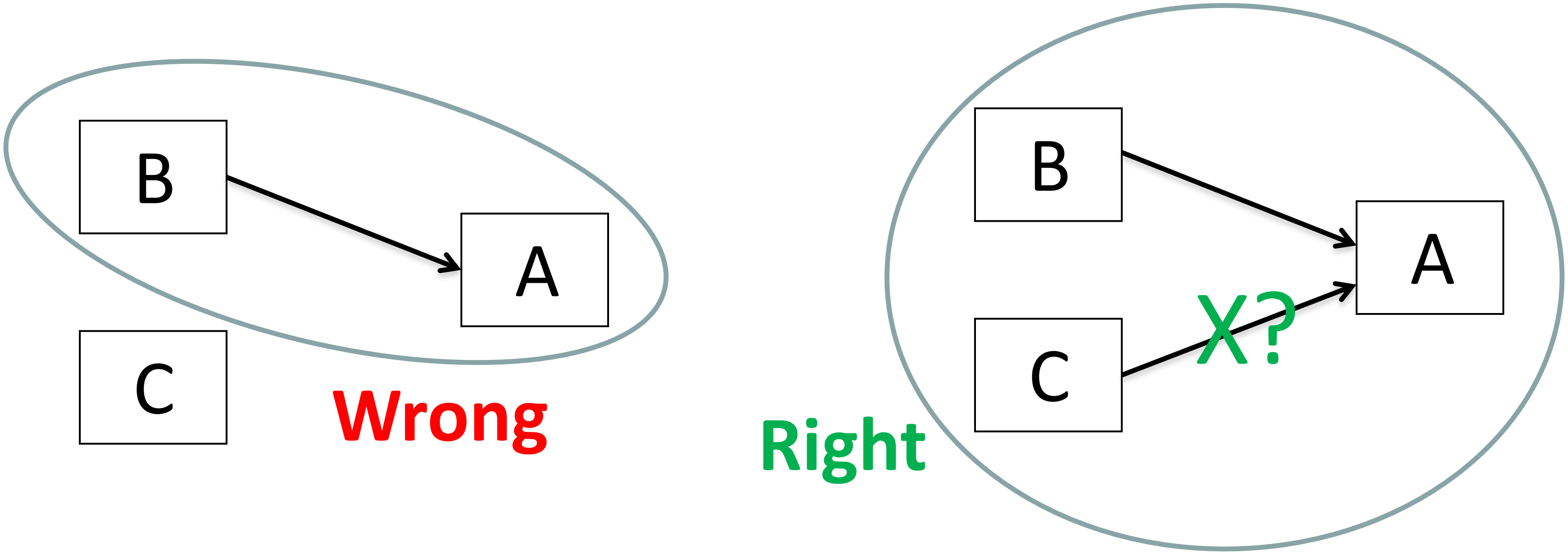
A problem arises when an action in support of the surrogate goal negates the person’s more strongly held goal.

Capturing and storing CO_2 prolongs the fossil fuel era.

Large and distant solar arrays and windfarms do not promote local self-reliance.

Be careful how you wish for what you wish for.

Principle: You want A. You figure out that B will get us to A, and you like B. You foster B. But *there is always a C that someone else likes and you don't like at all*, which also gets us to A. Unless you are alert, your efforts enable C.



Message: Add conditionality; bargain or walk away.

EXTRA SLIDES

Archived readings for Week 11 Nuclear Power

The Report of the President's Commission on the Accident at Three Mile Island

Mathew Wald, 2003, Dismantling Nuclear Reactors. *Scientific American* May 2003.

John Holdren, 1992, Radioactive-Waste Management in the United States: Evolving Policy Prospects and Dilemmas. *Annual Review of Energy and the Environment* Vol. 17 pp. 235-59

Congressional Quarterly inc., *The Nuclear Age: Power, Proliferation, and the Arms Race* (Congressional Quarterly, Washington, D.C., 1984) Chapter 1: How Reactors Work.

Robert H. Socolow, remarks. In *Proceedings of the 2nd MIT International Conference on the Next Generation of Nuclear Power Technology*, Oct. 25-26, 1993. Massachusetts Institute of Technology, Cambridge, MA 02139.

EXTRA SLIDES – POLICY

Setting goals

Targets

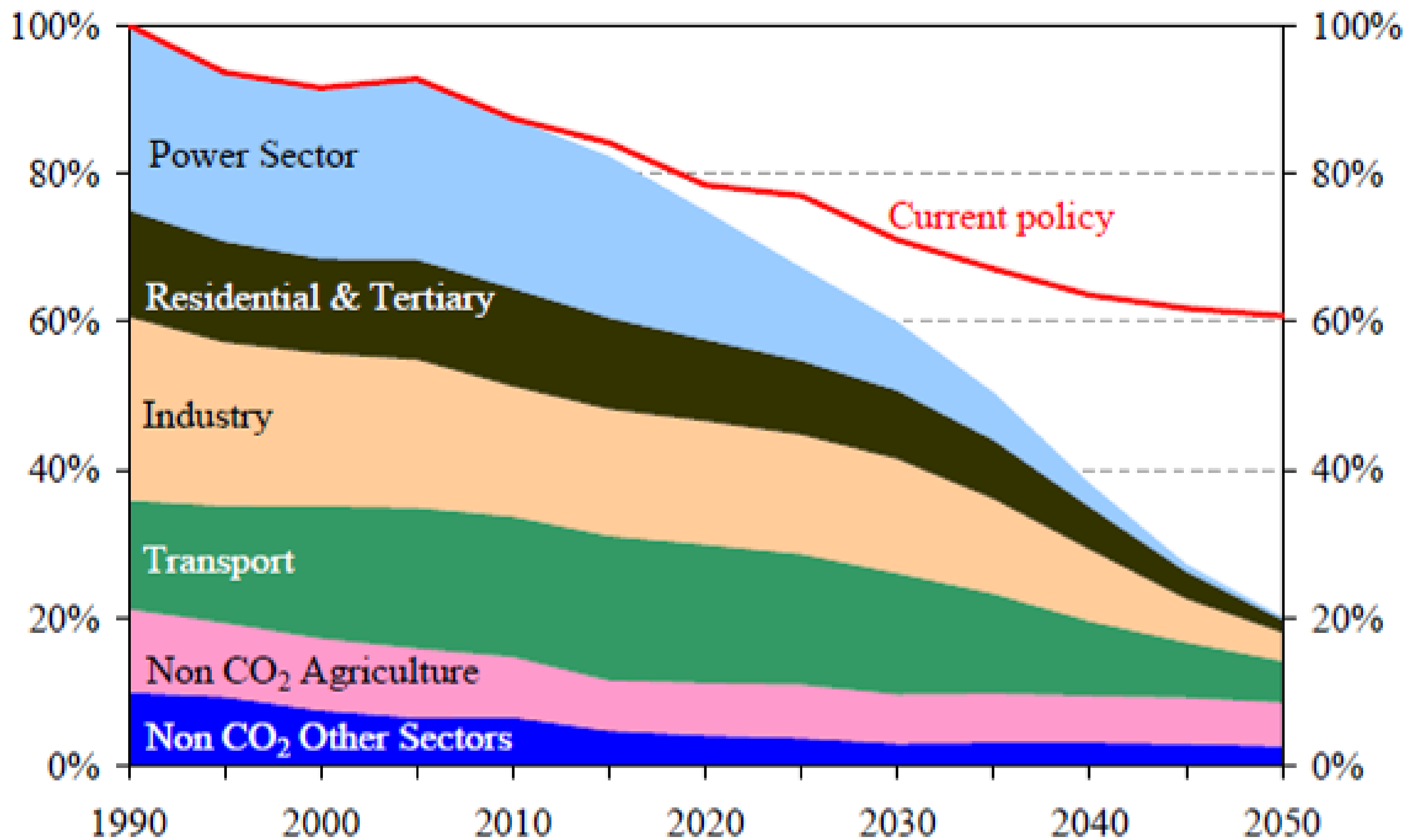
Long-term or interim?

“Aspirational” or with compelling carrots and sticks?

Conditional on the behavior of others?

Scenarios and road maps are important tools for exploring self-consistency.

Figure 1: EU GHG emissions towards an 80% domestic reduction (100% =1990)



Fonte: Roadmap for moving to a low-carbon economy in 2050
http://ec.europa.eu/clima/policies/roadmap/index_en.htm

America's Climate Choices

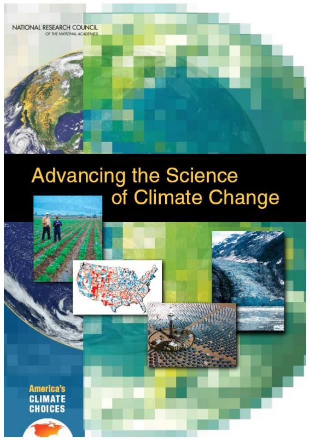
A congressional initiative in 2008 to:

> **"…investigate and study the serious and sweeping issues relating to global climate change and make recommendations regarding what steps must be taken and what strategies must be adopted in response to global climate change, including the science and technology challenges thereof."**

***Products already*: A summit (March 2009), four reports from "panels," and a Final Report from the overarching "*Committee on America's Climate Choices"* (of which I was a member).**

Information at http://americasclimatechoices.org

Four panel reports

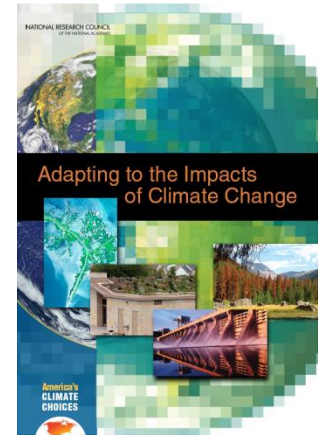


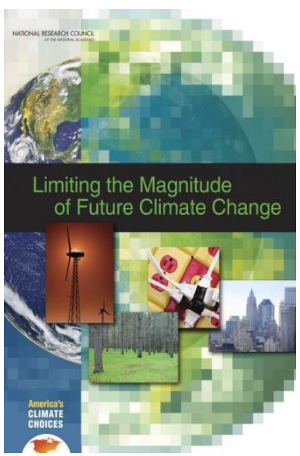
Advancing the Science of Climate Change

"Science panel"

Adapting to the Impacts of Climate Change

"Adapting panel"



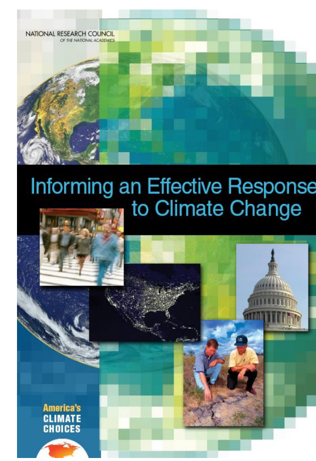


Limiting the Magnitude of Future Climate Change

"Limiting panel"

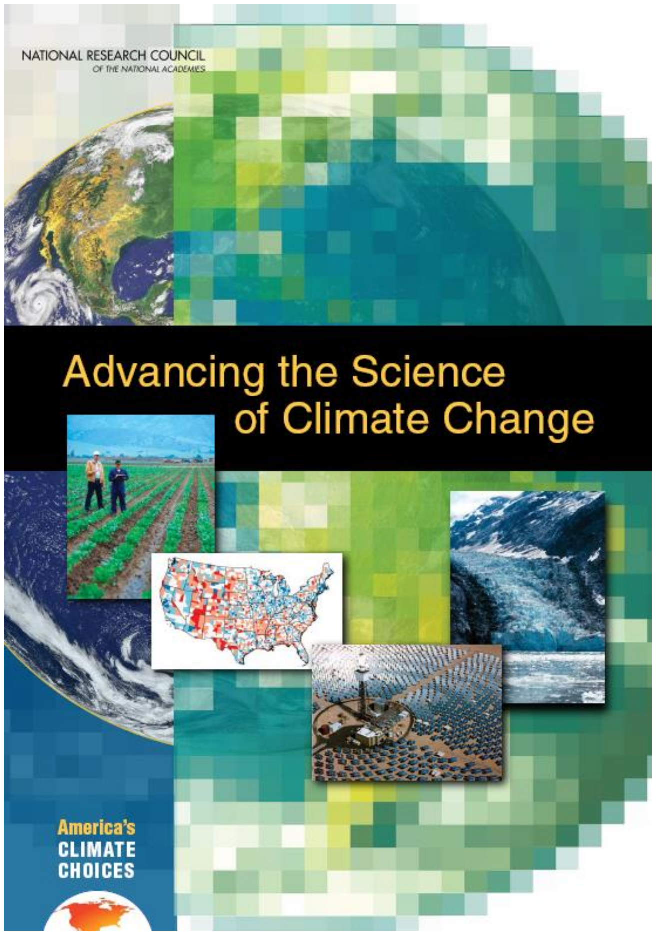
Informing an Effective Response to Climate Change

"Informing panel"



Available at http://www.nap.edu

Science Panel: Sorry, it's real.



CONCLUSION #1: Climate change is occurring, is caused largely by human activities, and poses significant risks for a broad range of human and natural systems.

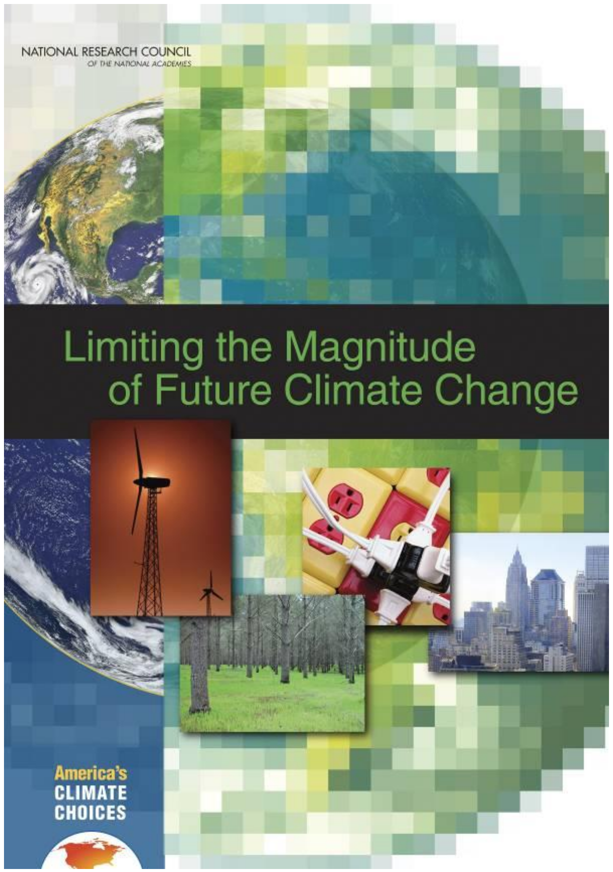
Science Panel: "A new era of climate research"

The nation needs a comprehensive and integrative climate change science enterprise that not only contributes fundamental understanding but also informs and expands America's climate choices.

Scientists need to engage stakeholders/citizens in order to build trust, access local knowledge, and learn about priorities.

The federal climate change research program should develop, deploy, and maintain a comprehensive observing system that supports all aspects of understanding and responding to climate change.

Limiting Panel: Prompt, sustained efforts



A robust U.S. response requires:

- **An inclusive national framework for aligning the goals and efforts of actors at all levels**
- **Aggressive pursuit of all major near-term emission reduction opportunities *and* R&D to create new options**
- **Iterative management of policy responses**

Limiting Panel: Recommendations*

1. **Adopt a mechanism for setting an economy-wide price on carbon.**

2. **Complement the carbon price with policies to:**
   - Realize the practical potential for energy efficiency and low-emission energy sources;
   - Establish the feasibility of carbon capture and storage and new nuclear technologies;
   - Accelerate the retirement, retrofitting or replacement of GHG emission-intensive infrastructure.

3. **Create new technology choices by investing heavily in research and crafting policies to stimulate innovation.**

***first three of seven recommendations**

Limiting Panel: Recommendations

4. Consider potential equity implications when designing and implementing climate-change policies, with special attention to disadvantaged populations.

5. Establish the United States as a leader to stimulate other countries to adopt GHG reduction targets.

6. Enable flexibility and experimentation with policies to reduce GHG emissions at regional, state, and local levels.

7. Design policies that balance durability and consistency with flexibility and capacity for modification as we learn from experience.

The logic of national targets

Target: limiting global mean temperature increase
(e.g., 2 deg, 3 deg)

What is a 'safe' amount of climate change?
Depends on impacts associated with given temp targets; willingness of society to tolerate risks

----

Target: limiting global atmospheric GHG concentrations
(e.g., 450 ppm, 550 ppm)

How does GHG concentration translate into global temp change (and other impacts)?
Depends on climate sensitivity and the strength of other forcing factors (e.g., aerosols)

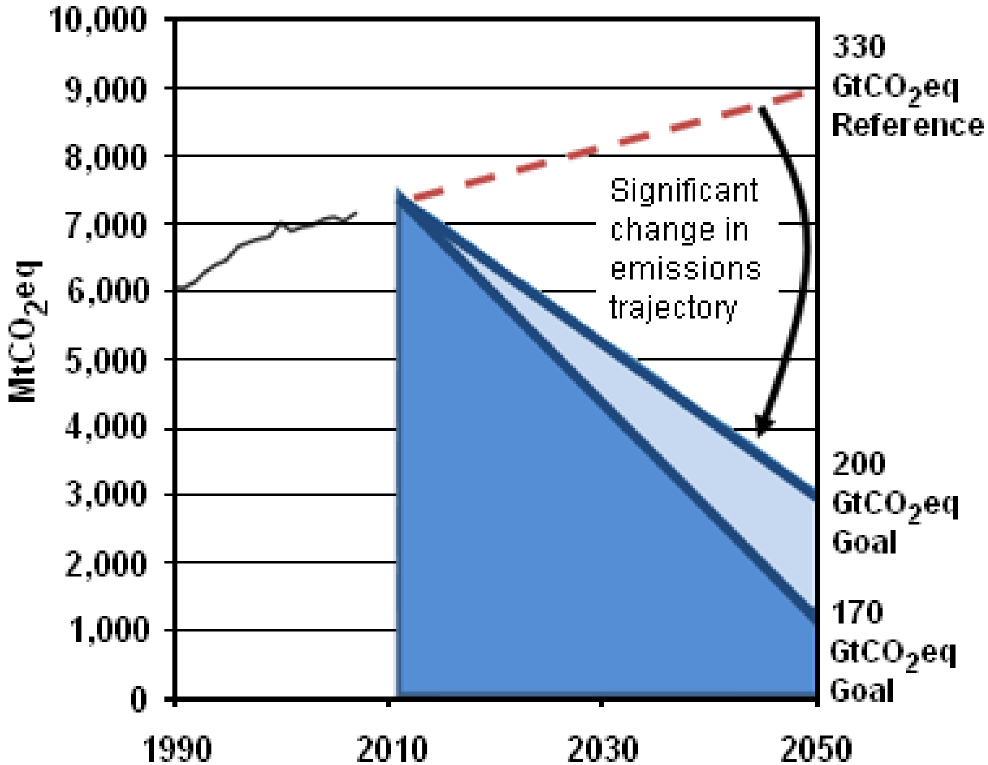
Target: limiting global GHG emissions
(e.g. global emission budget, or percent reduction)

How does a given level of emissions translate into atmospheric GHG concentrations?
Depends on carbon cycle dynamics and timing of emissions (e.g., are overshoots allowed?)

Target: limiting U.S. GHG emissions
(e.g. national emission budget, or percent reduction)

What is a 'reasonable' share of U.S. emission reductions relative to the global targets?
Depends on political, practical, economic, and ethical considerations

Limiting Panel: U.S. budget to 2050



‘Representative’ budget: 170–200 Gt $CO_{2\text{-eq}}$, 2012–2050.

Business-as-usual consumes this budget well before 2050.

AR5 WG1 (global) and ACC (US) budgets

AR5 WG1: 1000, 1200, 1500 GtC ever = 33%, 50%, 66% chance of not exceeding “2^{o}C” (the average surface temperature excess relative to “pre-industrial times.”

500 GtC emitted already.
Note: non-CO_2 greenhouse gases must be included.
700 GtC = 2600 $GtCO_2$

America’s Climate Choices: 170-200 $GtCO_{2e}$ between 2012 and 2050.

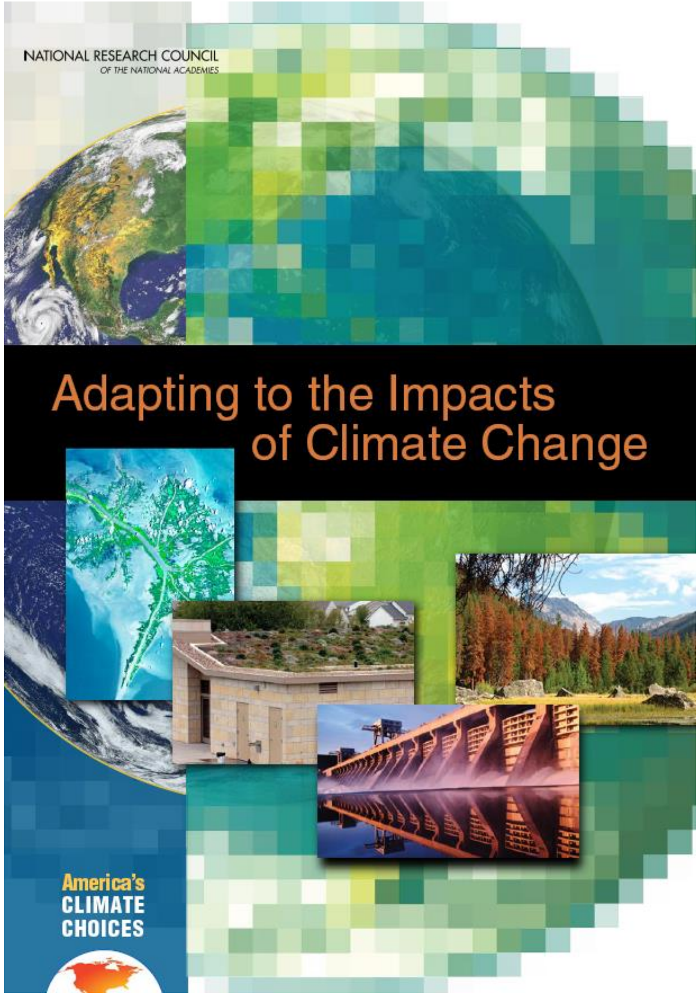
So, non-CO_2 greenhouse gases are included.

Limiting Panel cautionary note

Meeting an emissions budget in the 170–200 Gt CO_2-eq range could be technically possible, but it is very difficult.

Essentially all available options (e.g. efficiency, renewables, CCS, nuclear, biofuels) would need to be deployed at levels close to what is estimated as technically possible; and these estimates are based on very optimistic assumptions.

Adaptation: A U.S. perspective



There is a real risk that impacts could emerge rapidly and powerfully. Mobilizing now to increase the nation's adaptive capacity can be viewed as an insurance policy against an uncertain future.

Key sectors: ecosystems, agriculture and forestry, water, health, transportation, energy, and coastal regions.

Adaptation to extreme events

Example: The Hot Weather–Health Watch/Warning System, Philadelphia, 1995

Whenever the National Weather Service issues a heat wave warning, local media are required to provide information on how to avoid heat-related illnesses and how to help elderly persons.

Those involved include

- Philadelphia Corporation for the Aging
- Department of Public Health
- Local utility company and water department (halt service suspensions)
- Fire Department Emergency Medical Service (increase staffing)
- Senior centers (extend hours of operation of air-conditioned facilities)

Adaptation to the new normal

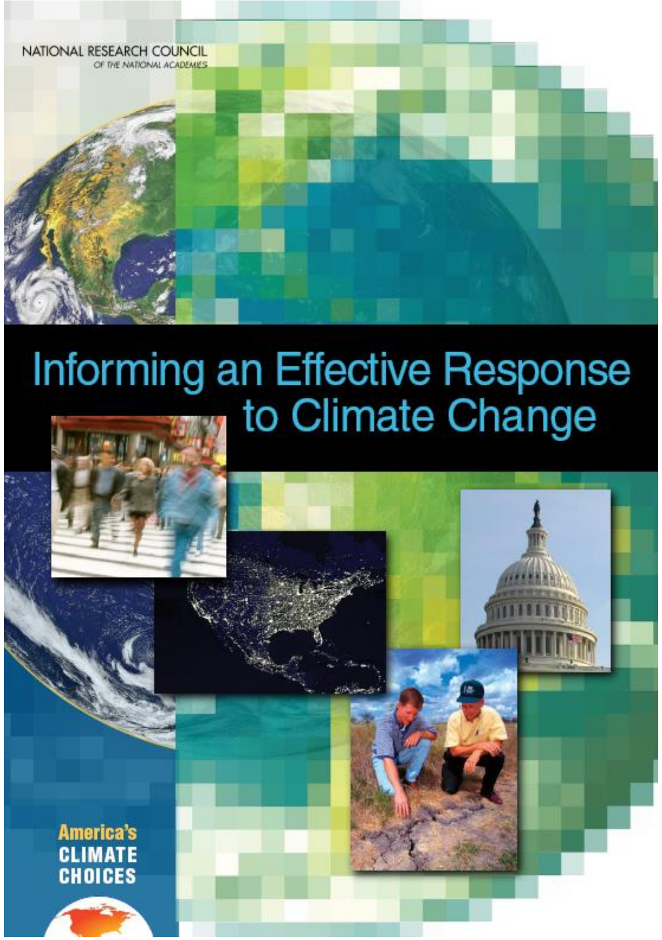
A “new normal” requires transformational adaptations:

- Movement of people and facilities away from vulnerable areas
- Changes in ecosystem and land management objectives
- Revisions of water-rights law

Contingency planning for high-impact/low-probability outcomes requires vigilant monitoring to detect early signals and continuous assessment of the adequacy of responses.

Adaptation needs to be adaptable.

Informing Panel: Improved information systems



- Federal coordination of diverse decision-making
- Institutions that will produce improved tools

Informing Panel: All sorts of decisionmakers

Climate response is and will always be decentralized.

Federal roles include:

- **clear leadership**
- **regular evaluation and assessment**
- **aggregation and dissemination of “best practices”**
- **development and diffusion of decision-support tools**
- **training of researchers and practitioners.**

The federal government must avoid preemption that discourages productive decisions by other actors.

Policy slides from Phil Hannam
October 15, 2013

General Policy Design Principles

1. Every independent policy goal requires at least one independent policy instrument
2. Policies should strive to attain the necessary degree of macro-control with the *minimum* sacrifice of micro-level freedom and variability
3. Policies should leave a margin of error because of biological uncertainties *[spaceship earth]*
4. Policies must recognize that we must always start from historically given initial conditions *[e.g. the market is here to stay; owners of private property will not relinquish it, etc]*
5. Policies must be able to adapt to changing conditions
6. Design policies at the scale of their effects *[e.g. local problems need local solutions; global problems need global solutions]*

[Adopted from Daly and Farley 2003]

Policy Tools

Direct Regulation >>>Command-and-Control regulations

Positive Features

- Limits pollution/ harvest to acceptable level
- Directly addressed biological limits
- Can be tailored to all, or some, individuals
- Familiar to most policy makers and easy/cheap to monitor and administer

Negative Features

- Low allocative efficiency
- No incentive to surpass the goal (mercury example)
- Does not allow micro-flexibility (violates our policy principles)

General Policy Design Principles
Property Rights

Coase theorem:

As long as property rights are assigned (and there are negligible transaction costs) the market can efficiently allocate resources

Three types of property rights:

- Property Rule: One person is free to interfere with another, or free to prevent interference
- Liability Rule: One person is free to "interfere" with another or prevent interference, but must pay compensation
- Inalienability Rule: If a person is entitled to the presence or absence of something, then no one can legally take that right away for any reason.

Policy Tools

- Direct Regulation
- Pigouvian Taxes
- Pigouvian Subsidies
- Tradable Permits

Policy Tools

Pigouvian Taxes >>> LIABILITY RULE (polluter pays principle)

Positive Features

- Ideally, the tax operates at the marginal external cost (effectively a market correction)
- Cost effectively reduces environmental costs
- Tax per unit of pollution creates an incentive for further reductions!
- If a firm is driven out of business, it implies it the social benefit was lower than the social cost

Negative Features

- If economy grows, more firms come online, who can still increase pollution/ extraction
- Assumes that revenue from the tax is used to remedy the environmental/ social harm
- Incentivizes outsourcing of the pollution

Policy Tools

Pigouvian Subsidies >>>Assume polluter has right to pollute!
(but society pays him/her not to)

Positive Features

- If the abatement costs are lower than the subsidy, the firm reduces pollution
- Useful as an incentive for ecosystem restoration (paying you to reforest your land)
- Useful as an international mechanism to get sovereign nations to

Negative Features

- The subsidy might attract new entrants, thus increasing pollution (Example: HFC’s in China)
- Reward goes to the polluter!

Policy Tools

Tradeable Permits >>> Impose a property right to the entity owning the quote (rights to absorptive capacity of a medium)

Positive Features

- Assigns rights to a rival good made excludable by quotas
- Distribution of the quotas can be designed to achieve other social goals
- If the economy grows, the quota does not
- Allows micro-level freedom: Harnesses power of markets

Negative Features

- Determination of the proper quota level is difficult and contentious
- If demand rises, or the quota is reduced, prices can spike (supply/ demand), creating political pressure.

EXTRA SLIDES
SOLAR ELECTRICITY

Flux estimates for renewables

TABLE 7.2 Average Energy Flux in Renewable Energy Systems

Source	Area	Heat (W/m^2)	Work (W/m^2)
Solar	Collector	150	20
Photovoltaic	Cell		30
Hydropower	Drainage basin		0.01
Wind	Turbine disk		40
Geothermal	Field	0.1	0.02
Biomass	Field	0.5	0.1
Ocean tidal	Tidal pond		1
Ocean thermal	Surface area		
Ocean wave	Frontal area		10,000

Average solar flux at earth's surface

Once more: solar energy strikes a surface perpendicular to the sun at the earth's surface at a rate: ~ [0.69 x 1368 W/m^2] = 944 W/m^2

As seen from the sun, the earth is a disk with radius, R_E, so the solar input is πR_E^2 times 944 W/m^2.

This energy lands on an area of $4\pi R_E^2$, so the average solar flux on a horizontal surface at the Earth's surface is:

(1/4)*944 W/m^2, or about **240 W/m^2.**

Hydropower

By far the largest renewable energy resource currently deployed.

Confrontation:

Symbol of making nature work for people: TVA.

Symbol of people overwhelming natural systems.

Huge variation in unit scale. Largest dams are world's largest point concentrations of electric power generation.

Relation to rainfall: Power out divided by area of drainage basin (W/m^2).

Relation to environmental impact: Power out divided by area of land flooded by reservoir (W/m^2). Steep valleys score well (good – depending on the valley!), Amazon dams score poorly.

Geothermal power

Effort needed by 2055 for 1 wedge: 700 GW displacing coal power.

Geothermal power

TABLE I. World-wide geothermal installed capacity in the year 2000 in MWe.

United States	2,228	Kenya	57
The Philippines	1,909	Guatemala	33
Mexico	855	China	29
Italy	785	Russia	23
Indonesia	589	Turkey	20
Japan	547	Portugal (Azores)	16
New Zealand	437	Ethiopia	9
Iceland	170	France (Guadalupe)	4
El Salvador	161	Thailand	0.3
Costa Rica	142	Australia	0.17
Nicaragua	70	Total	8154

8 GW are installed, 1% of a wedge.

The “potential” geothermal resource

A silly calculation shows how very high estimates for the potential of geothermal energy can emerge: *How much thermal energy flows when the first 1.0 km of the Earth’s crust cools by 1.0 K?*

Assumptions:
Density of rock (ρ) = 2500 kg/m^3; specific heat of rock (C) = 1.0 kJ/kg-K. Then, volumetric specific heat (ρC) = 2500 kJ/m^3-K

Answer: (5 x 10^14m^2)x(1.0 km)x(2500 kJ/m^3-K)x(1.0K)
= **1.2x10^{24}J**.

This is 3000 years of supply of 400 EJ/yr primary energy. The calculation ignores the inefficiency of conversion when one starts with low-grade heat

Wind Power

The costs of wind power have fallen dramatically.

Vocabulary choices reveal lack of consensus regarding whether wind machines are attractive: “Windmill,” “wind turbine,” “aerogenerator”; “windfarm.”

Intermittency and the Capacity Factor

The *capacity*, measured in watts, is the maximum (“peak”) designed rate of production of power. The *capacity factor* is actual annual power production divided by what would be produced from a power plant producing at capacity for the whole year.

The capacity factor of an intermittent renewable energy source, for both wind and direct solar collection (photovoltaic or thermal), is about 30%. For a baseload coal or nuclear plant it is about 85% to 90%.

So a wedge requires the substitution of about 2000 GW_{peak} of intermittent renewable power for 700 GW of baseload coal.

What instantaneous wind speed corresponds to a flux of 400 W/m^2?

Power/area = $\frac{1}{2} \rho v_a^3$. Here, the density of air, $\rho = 1.2\ kg/m^3$, and v_a is the freestream velocity.

Answer, v_a = 8.7 m/s (19.5 mph).

At 400 W/m^2, 1 MW crosses a disk with a 30m radius.

The area here is transverse to the wind direction. It is not a land area. (Land area calculations require minimum windmill spacing.)

Table 9: World wind energy resource densities[a]

Region	Class 5–7		Class 4		Class 3	
	1,000km²	*percent*	*1,000km²*	*percent*	*1,000km²*	*percent*
Africa	200	1	3,350	11	3,750	12
Australia	550	5	400	4	850	8
North America	3,350	15	1,750	8	2,550	12
Latin America	950	5	850	5	1,400	8
Western Europe	371	22	416	10	345	8.6
Eastern Europe & former USSR	1,146	5	2,260	10	3,377	15
Rest of Asia	200	5	450	2	1,550	6
Total	**8,350**	**6**	**9,550**	**7**	**13,650**	**10**

1365 Mha

a. Source: [62] and personal communication. The wind classes correspond to the notation used in the U.S. wind atlas [26] (see table 4). The areas corresponding to the different wind classes are given in thousands km² for the six continents.

North America Class 5-7 winds must be mostly in Canada, since (previous slide) 1.2% of U.S. land area has Class 5-7 winds.

Wind Hydrogen

Prototype of 80 m tall Nordex 2,5 MW wind turbine located in Grevenbroich, Germany
(Danish Wind Industry Association)

Effort needed by 2055 for 1 wedge:

2 billion 100 mpg_e cars running on hydrogen instead of 60 mpg cars running on gasoline or diesel. *Requirement*: 200 MtH_2/yr.

To produce this hydrogen: two million 2 MW windmills

Twice as many windmills as for a wedge of wind electricity

2010: 200,000 MW (10 %)

Solar Thermal Energy

Source of heat

solar water heating

active space heating

passive solar heating

Source of cooling (solar heat sink): Passive air conditioning

Source of drying (wood, crops, clothes)

Source of electricity – Carnot limits put emphasis on collection of at high temperatures, therefore on concentrators (troughs, dishes). With concentration comes a loss of diffuse radiation.

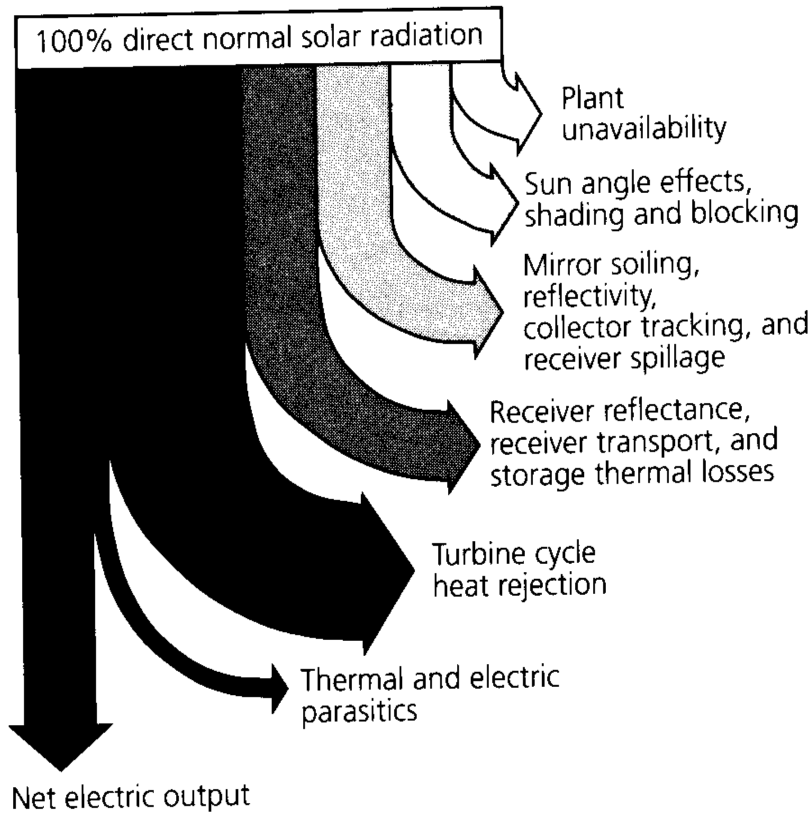


FIGURE 2: Efficiency with which a solar-thermal system converts sunlight to electricity is charted. From 10 to 30 percent of direct sunlight reaching a system is converted into electricity.

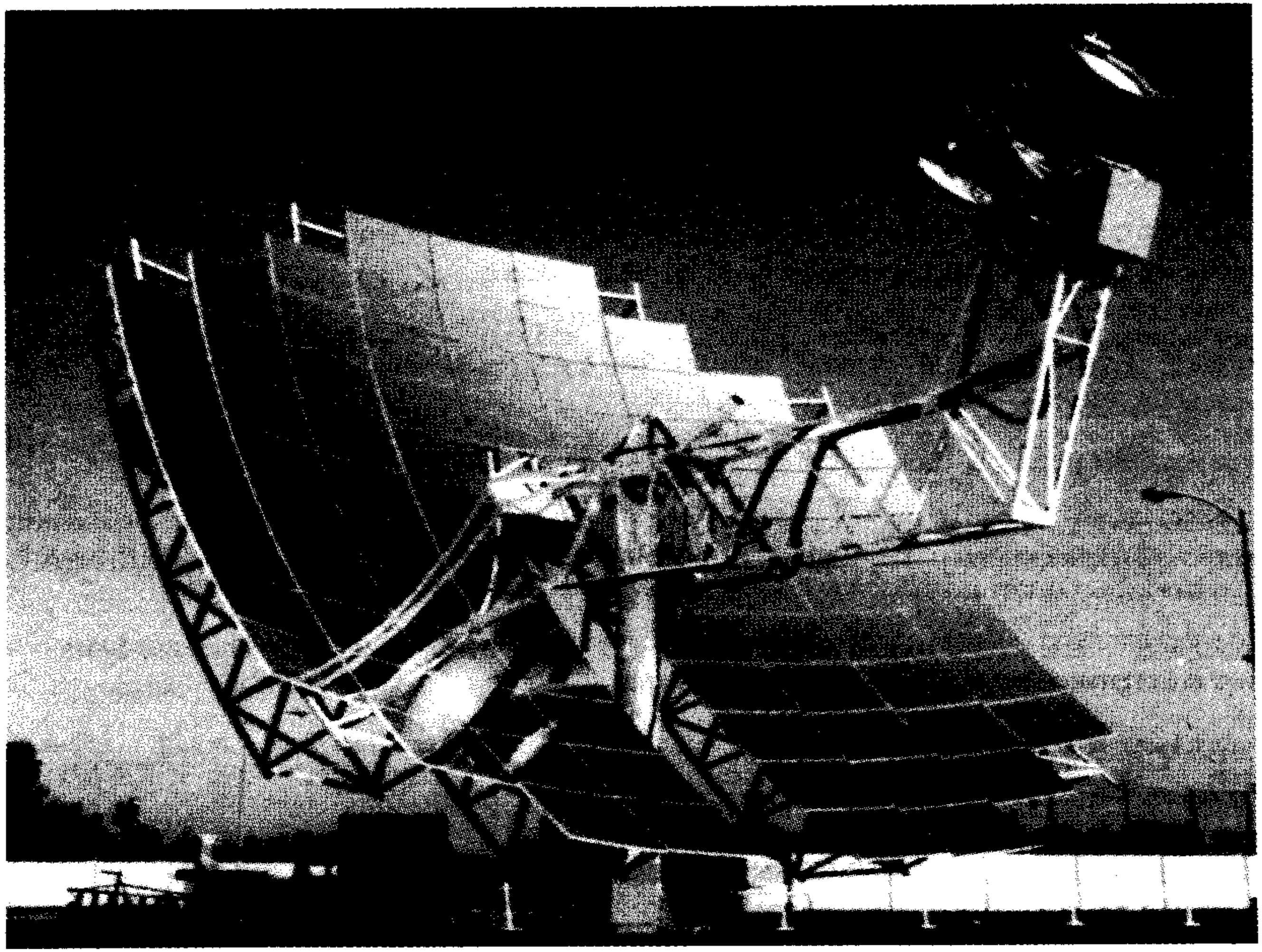


FIGURE 30: The McDonnell Douglas/United Stirling dish–Stirling module is shown.

Flat-plate thermal energy provider

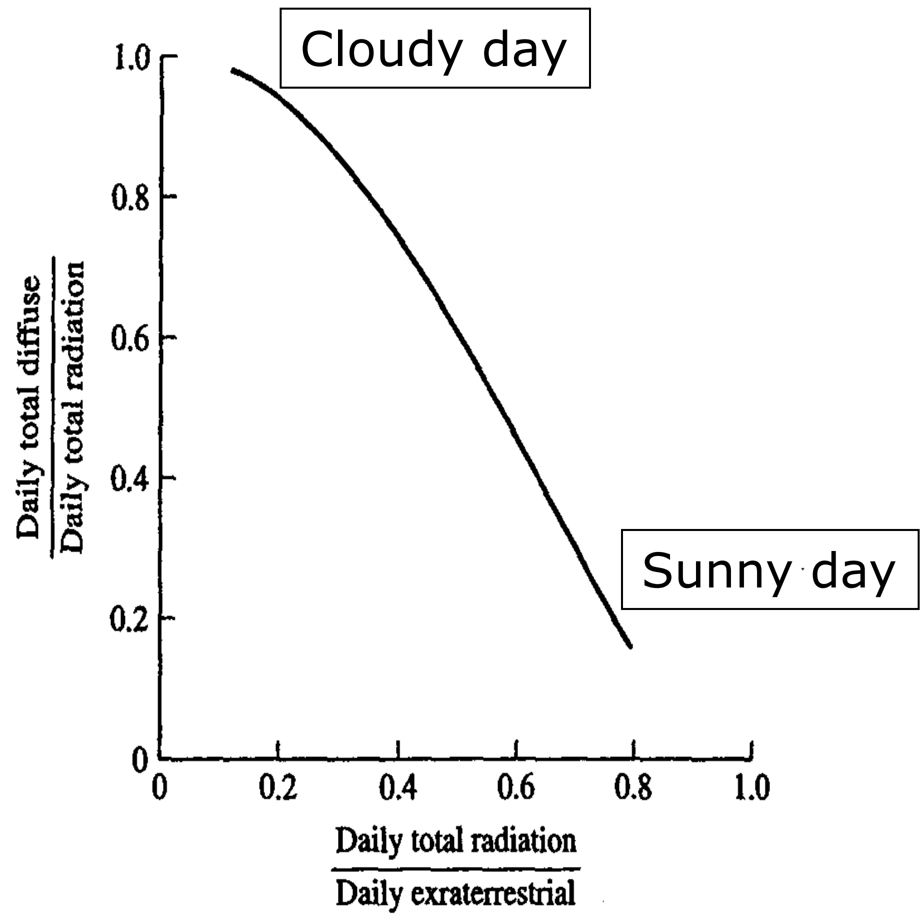


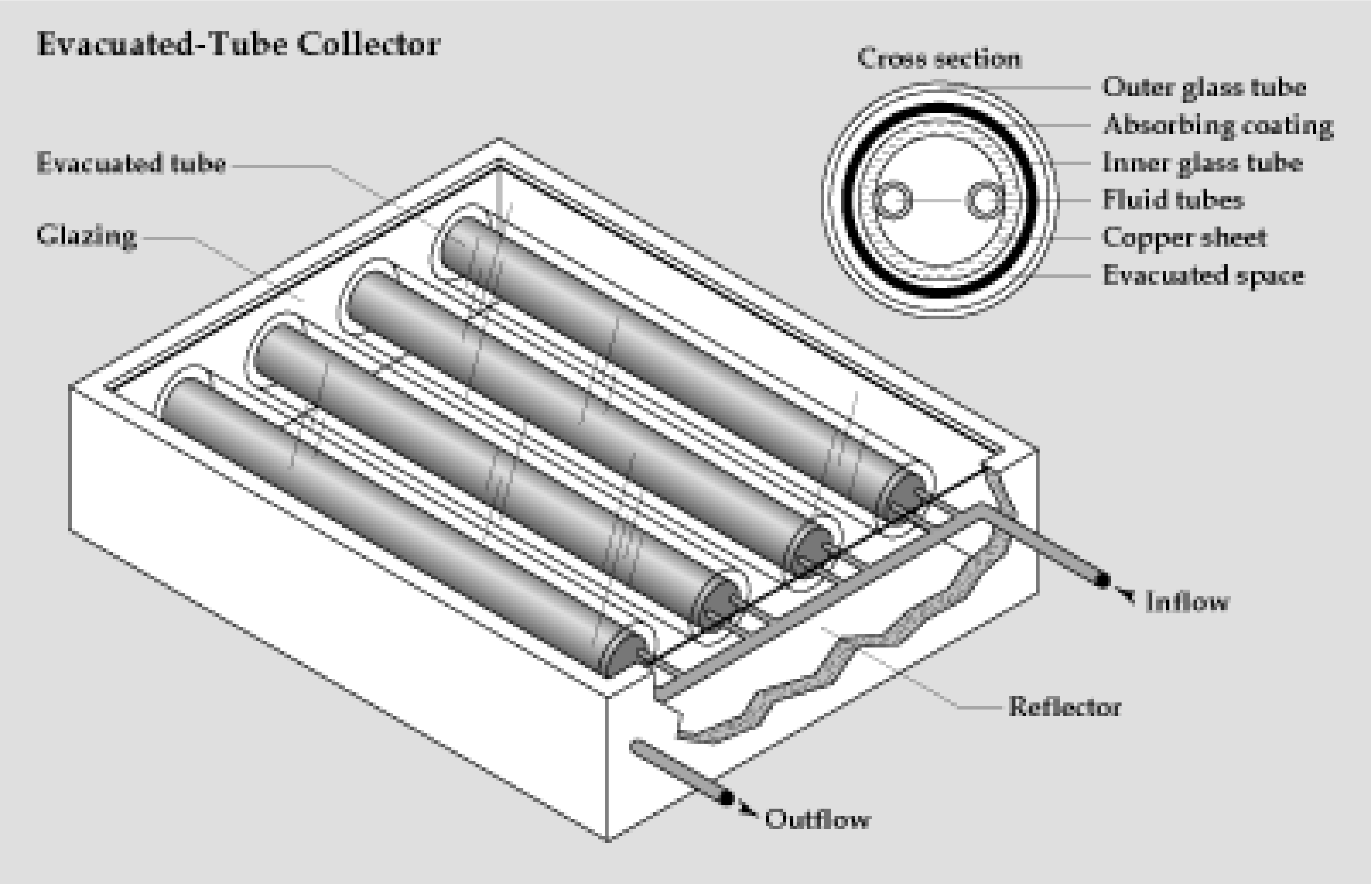
Figure 7.6 The ratio of daily diffuse to total radiation as a function of the ratio of daily total to extraterrestrial radiation, showing that cloudiness increases the diffuse portion of total radiation.

Flat-plate collector system

Jerusalem
(warm climate)

Source: http://en.wikipedia.org/wiki/Image:Solarboiler.jpg, accessed 4-12-07

Evacuated-tube flat-plate collectors



Source: U.S. Dept. Energy, http://upload.wikimedia.org/wikipedia/en/4/47/Evacuated_tube_collector.gif

Available solar energy for focusing vs. flat-plate collection

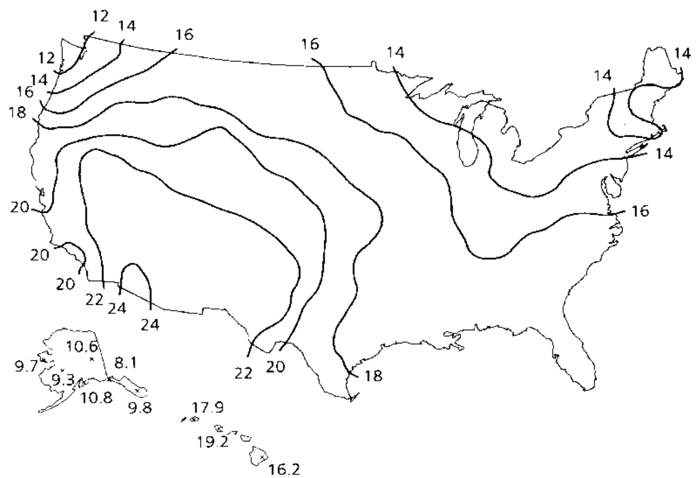


FIGURE 2a: Average daily solar energy in megajoules reaching a 1 m² flat-plate collector facing south and tilted at the latitude angle. The energy includes sunlight received directly from the sun's disk and diffuse sunlight scattered from clouds and particles in the air.

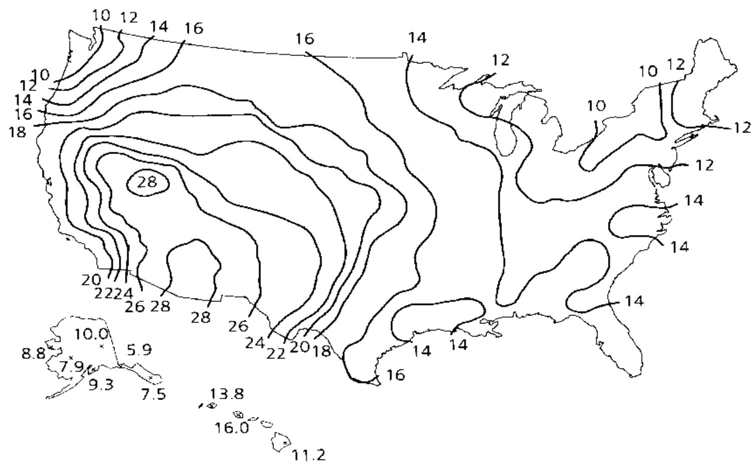


FIGURE 2b: Average daily solar energy in megajoules reaching a 1 m² surface directly from the sun's disk. It is assumed that the surface is rotated continuously through the day so that it is pointed directly at the sun (collector surface is always perpendicular to a line connecting the site with the sun). Sunlight reaching the surface from scattered sunlight is not included.

Flat, fixed, optimally tilted: collects total sunlight, including scattered light.

Concentrating, continuously tracking: collects direct sunlight but not scattered light. Collects more in SW, less in NE.

Flux units: (MJ/m^2-day). 1 MJ/m^2-day = 11.6 W/m^2

Annual storage of heat and cold

Thermal storage of heat

Thermal storage of coolth

The Enerplex Ice Pond at Forrestal Center

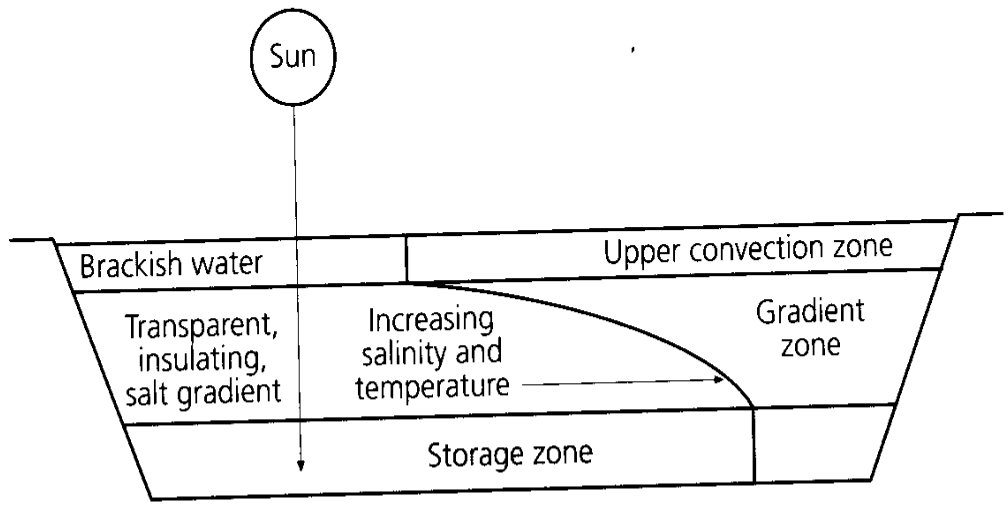


FIGURE 4: Solar pond with its characteristic salt gradient, is shown.

The Ice Ponds at Forrestal (1980-84)

A Princeton University research project at the Center for Energy and Environmental Study (Ted Taylor, Don Kirkpatrick, Rob Socolow).

Ice ponds were built to investigate seasonal storage of ice for air conditioning.

Ice production and retention combines two technologies: ice houses (18^{th} c.) and snow machines for ski slopes (20^{th} c.).

Project, funded by Prudential Insurance Co., coupled the ice pond to one of two experimental office buildings demonstrating solar architecture.

Someday every office building will be built like this.

Right now, Enerplex is unique.

ENERPLEX, in Princeton Forrestal Center, uses the natural elements to set new standards for energy efficiency and first class office space: A winter-frozen ice pond for summer cooling. An underground stream's constant temperature for year-round climate control. Enormous skylighted atriums and corridors for 75 percent daylighting. Meticulously sized and shaped windows that admit winter sun and block summer heat, and one of the most impressive, tenant improvement packages ever offered.

The results: An anticipated reduction by almost two-thirds in the use of purchased energy for our tenants over conventional new buildings.

ENERPLEX contains 260,000 square feet of superb office space that is now leasing. For information, please contact our exclusive Agent.

Oliver Realty Inc. of New Jersey (609) 987-0004

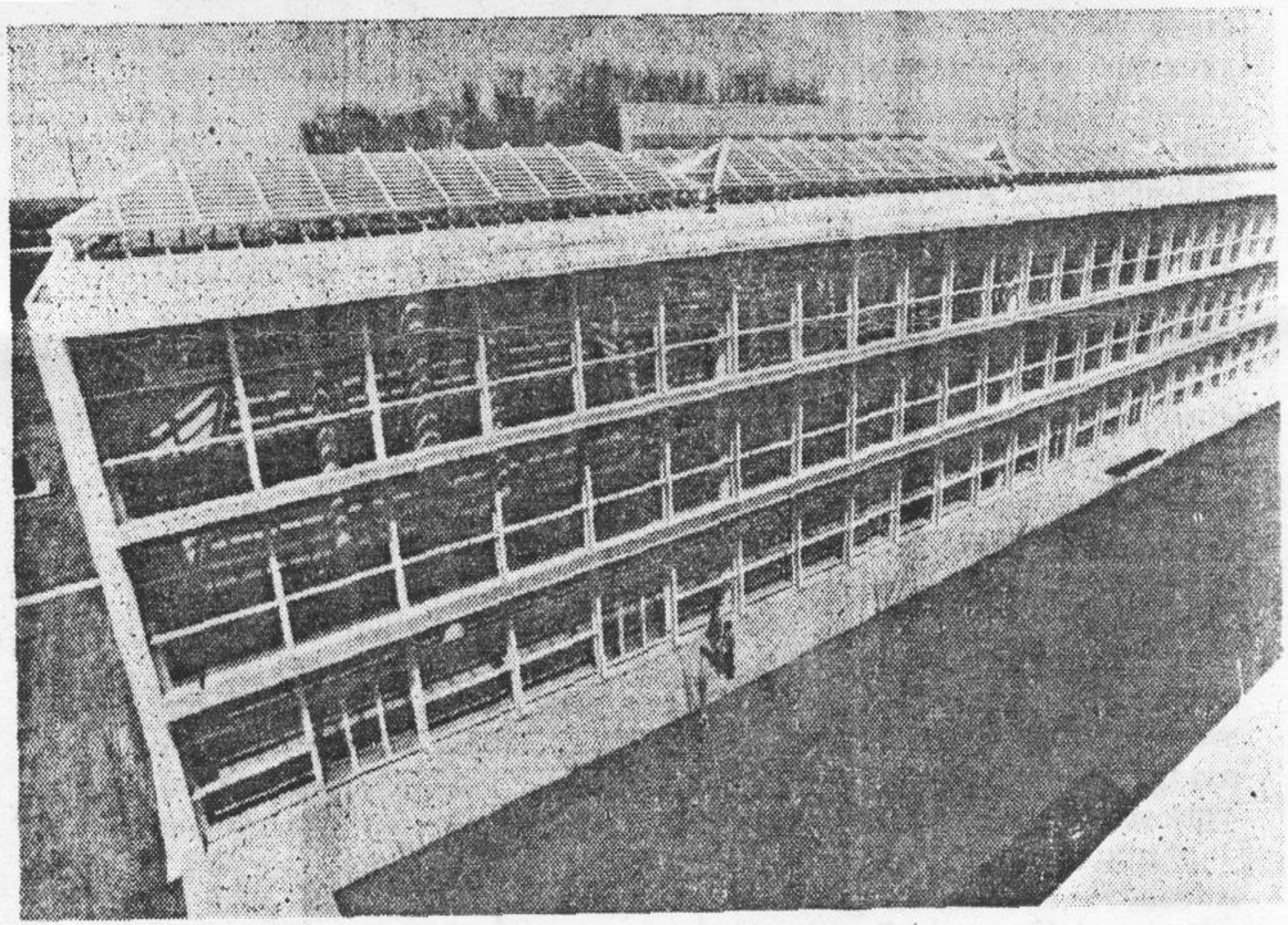
At Princeton Forrestal Center

ENERPLEX

THE NATURAL CORPORATE ENVIRONMENT

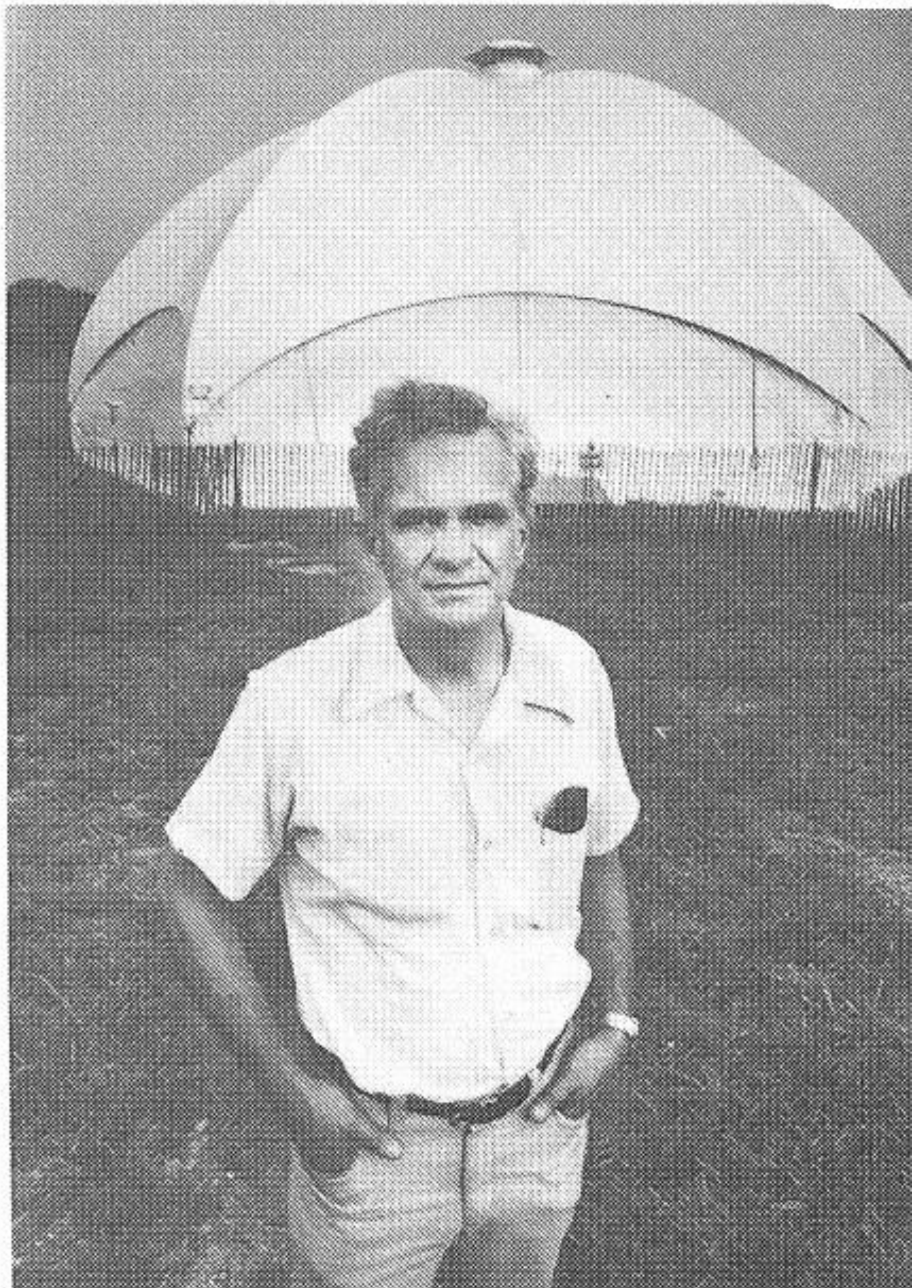
Prudential

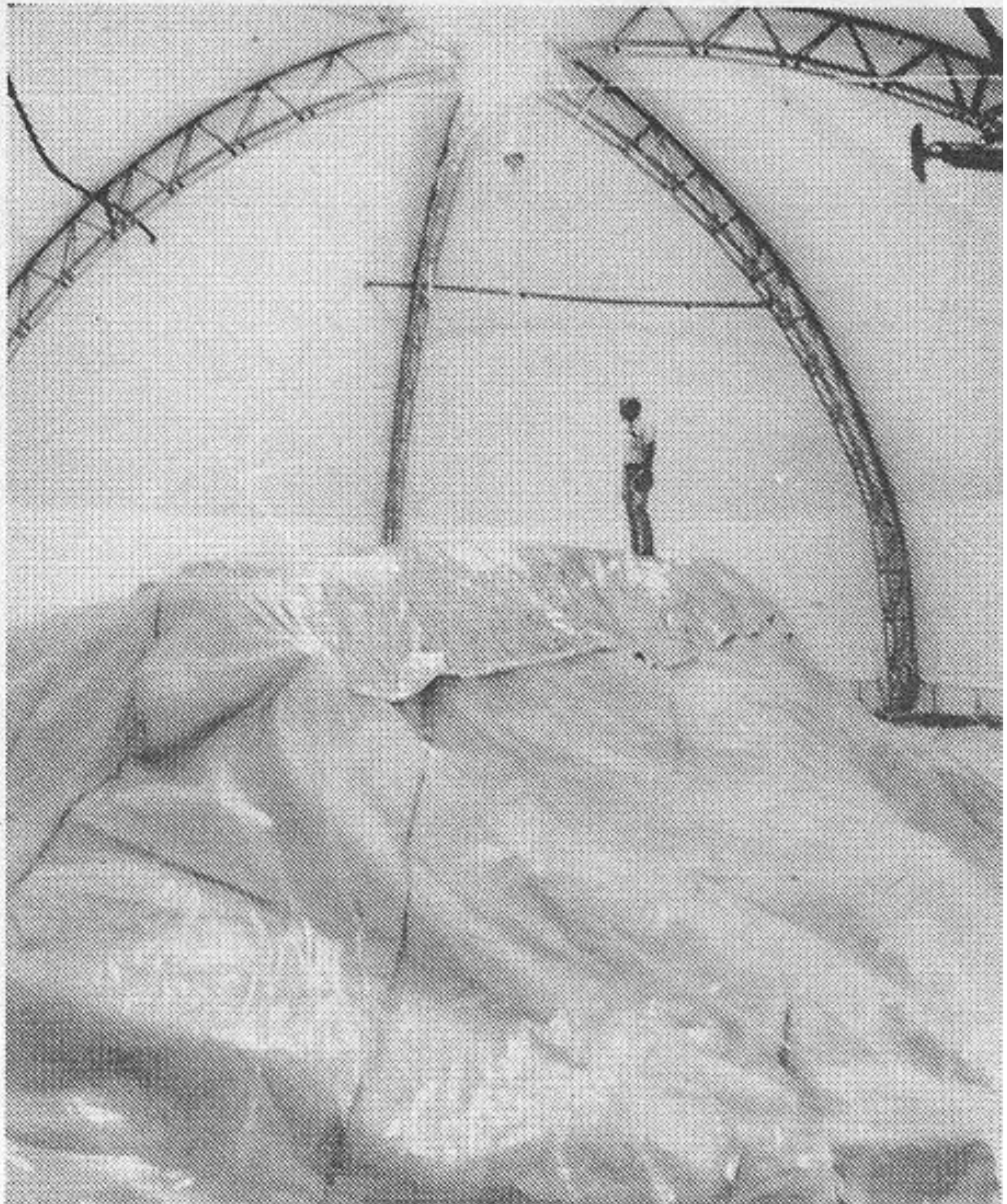
OR
OLIVER
REALTY



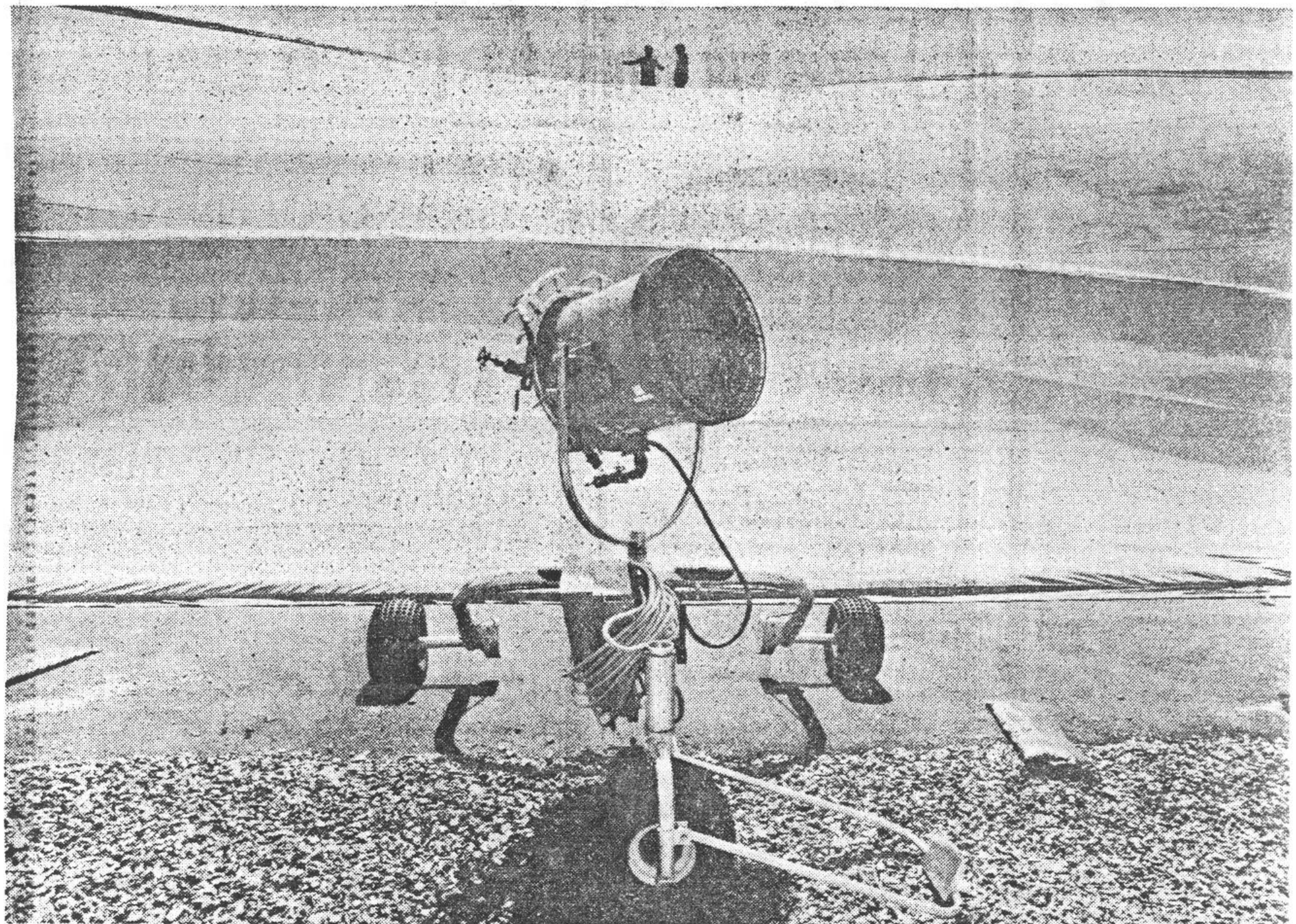
AT ENERPLEX NORTH, a large, glass-enclosed atrium extends across the south facade and acts as a giant passive solar collector.

Taylor and his dome: Let nature do it



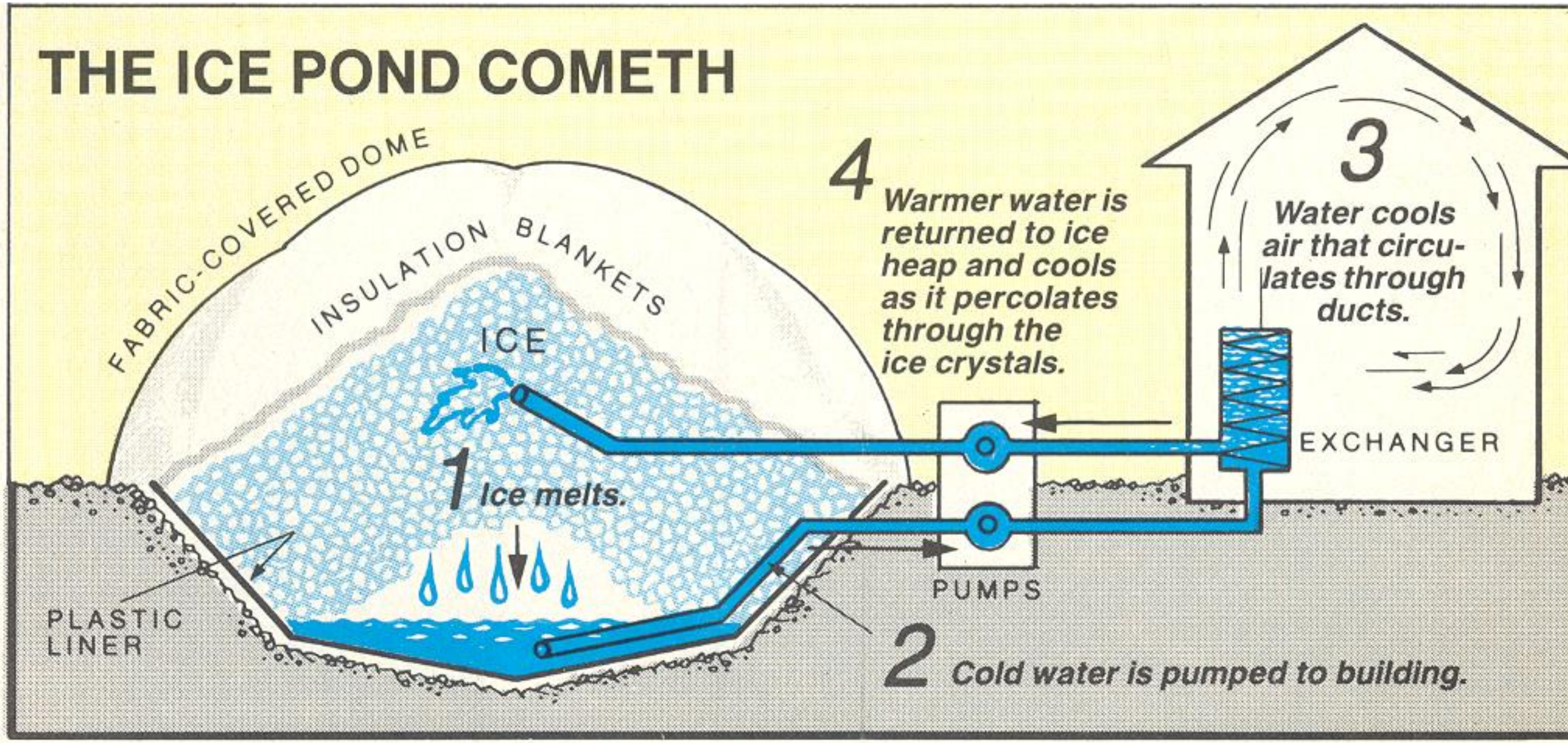


Taylor standing atop his mountain of ice



Philadelphia Inquirer / BRYAN GRIGSBY

A SNOW-MAKER rests outside an enclosed ice pond at Enerplex. Machines like this one create snow, which turn into ice slush and is stored as coolant. Two figures stand atop the dome.



THE ICE POND COMETH
FABRIC-COVERED DOME
INSULATION BLANKETS
ICE
1 Ice melts.
PLASTIC LINER
2 Cold water is pumped to building.
PUMPS
EXCHANGER
3 Water cools air that circulates through ducts.
4 Warmer water is returned to ice heap and cools as it percolates through the ice crystals.

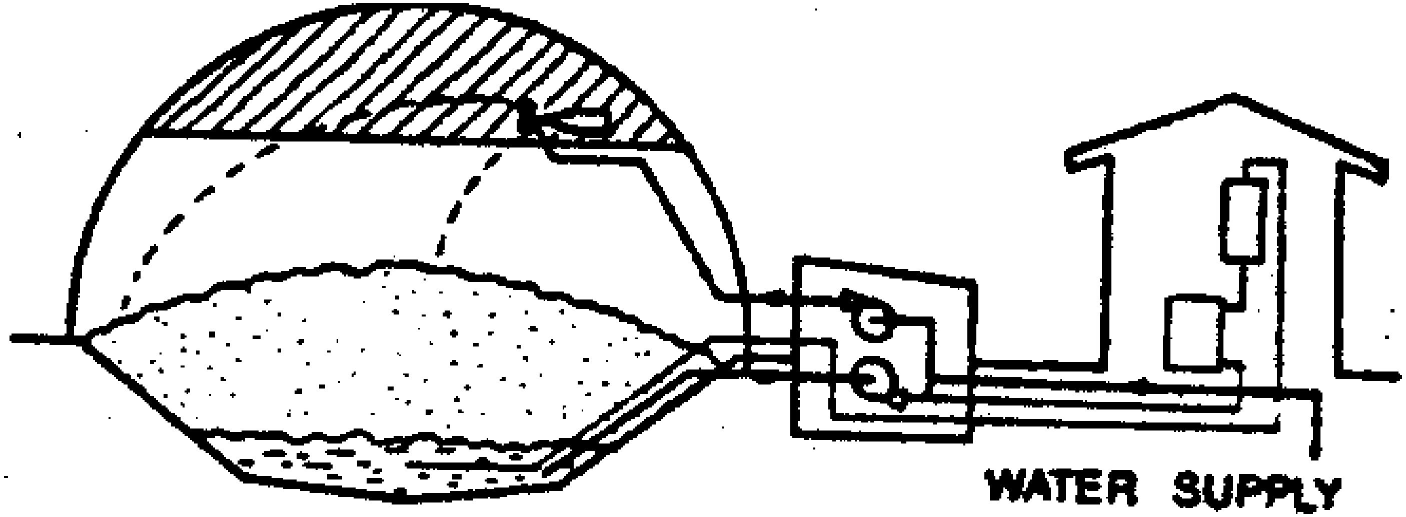


Fig. 3a. Phase II facility winter operation.

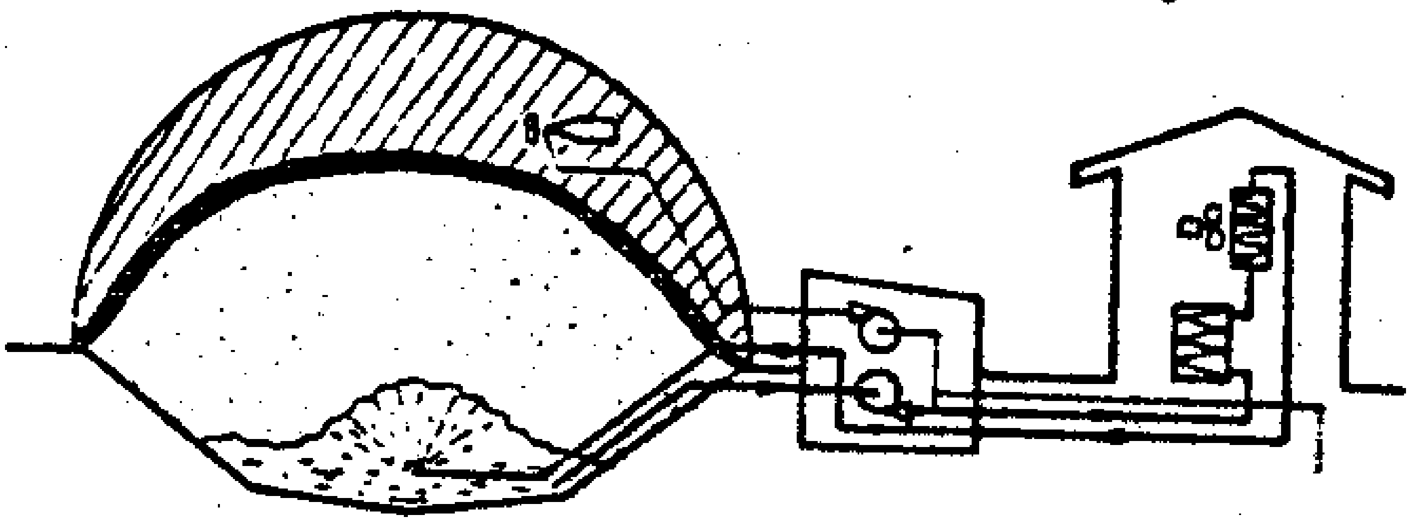


Fig. 3b. Phase II facility summer operation.

Ice production by a snow machine increases linearly with outside temperature.

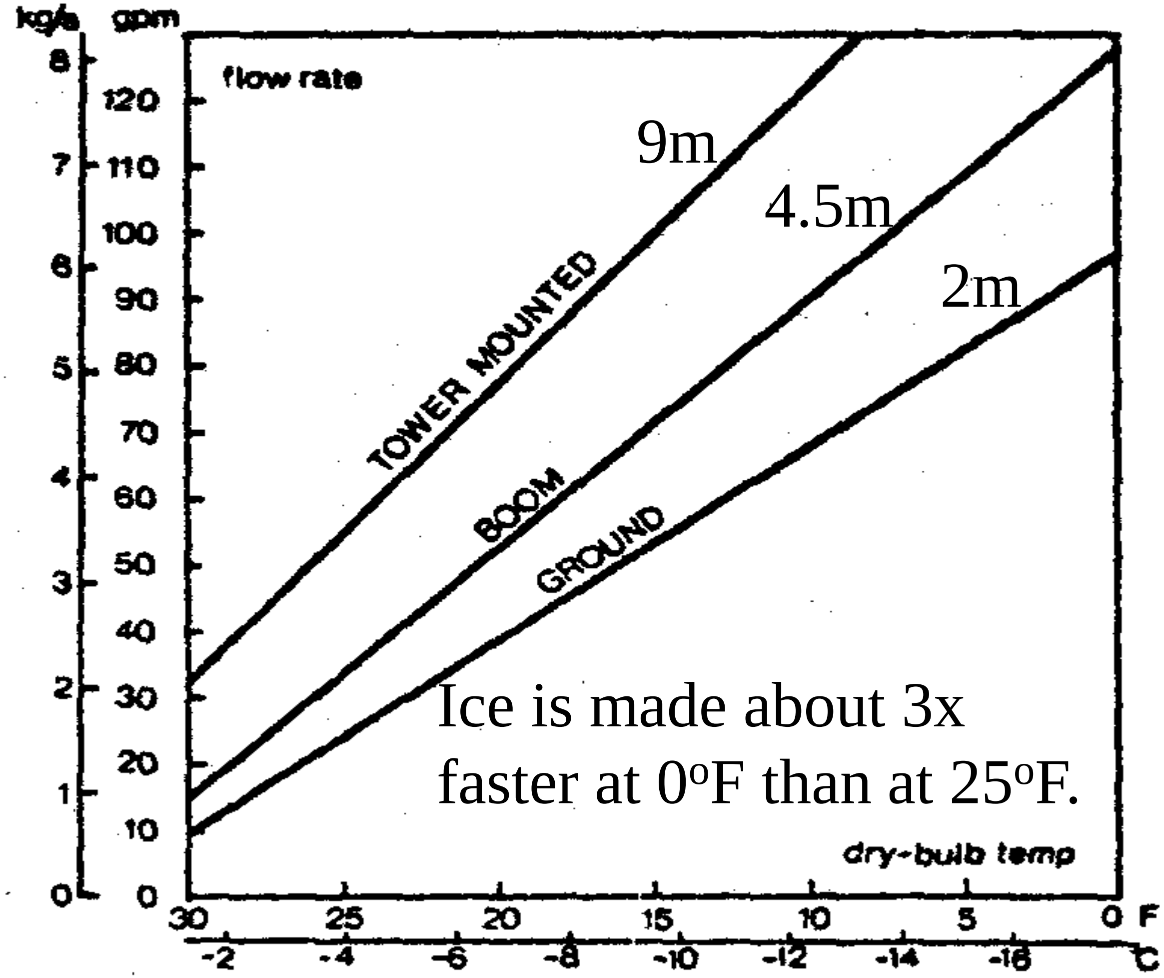


Fig. 1. Snow machine performance curves.