NUCLEAR POWER AND ITS ALTERNATIVES FOR A CARBON-CONSTRAINED WORLD

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9 October 2007

Conference on Security and Cooperation in South Asia: a Global Perspective
Berlin, Germany

Massachusetts Institute of Technology,
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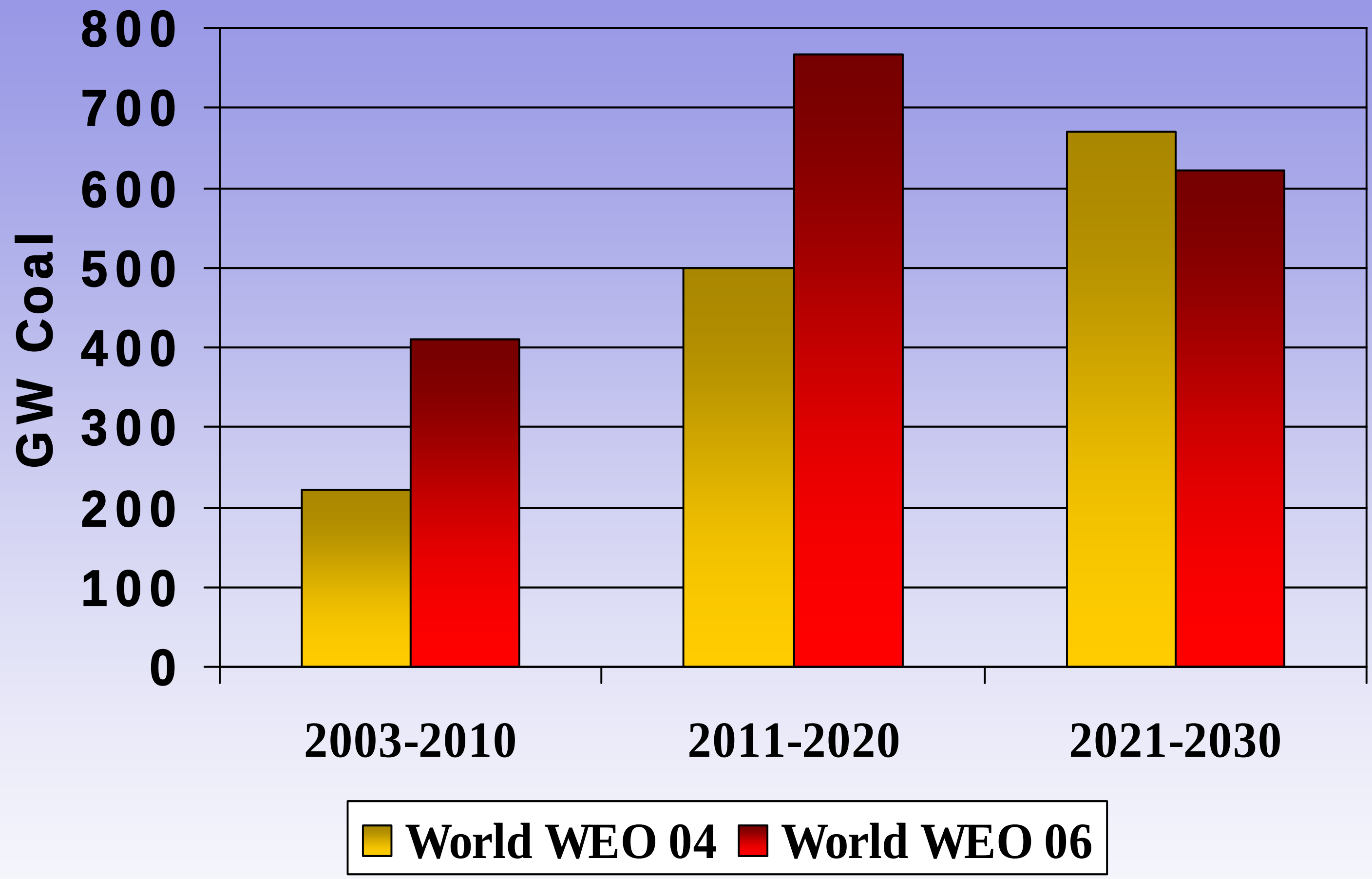
WILL CARBON MITIGATION CONCERNS CATALYZE NUCLEAR POWER RENAISSANCE?

- High priority now given to carbon mitigation in most political circles
  - Europe/Japan action
  - Stern Review
  - US:
    - 22 June 2005 Bipartisan Senate Resolution overturning 1997 Byrd-Hagel Resolution
    - Hurricane Katrina, Gore book
    - US carbon policy likely with Democrat or Republican in White House post 2008
  - Recent G-8 Summit
- Interest in reviving the nuclear power option inspired largely by its carbon mitigation potential
  - Proven zero GHG-emitting technology
  - Large potential contribution to energy supplies

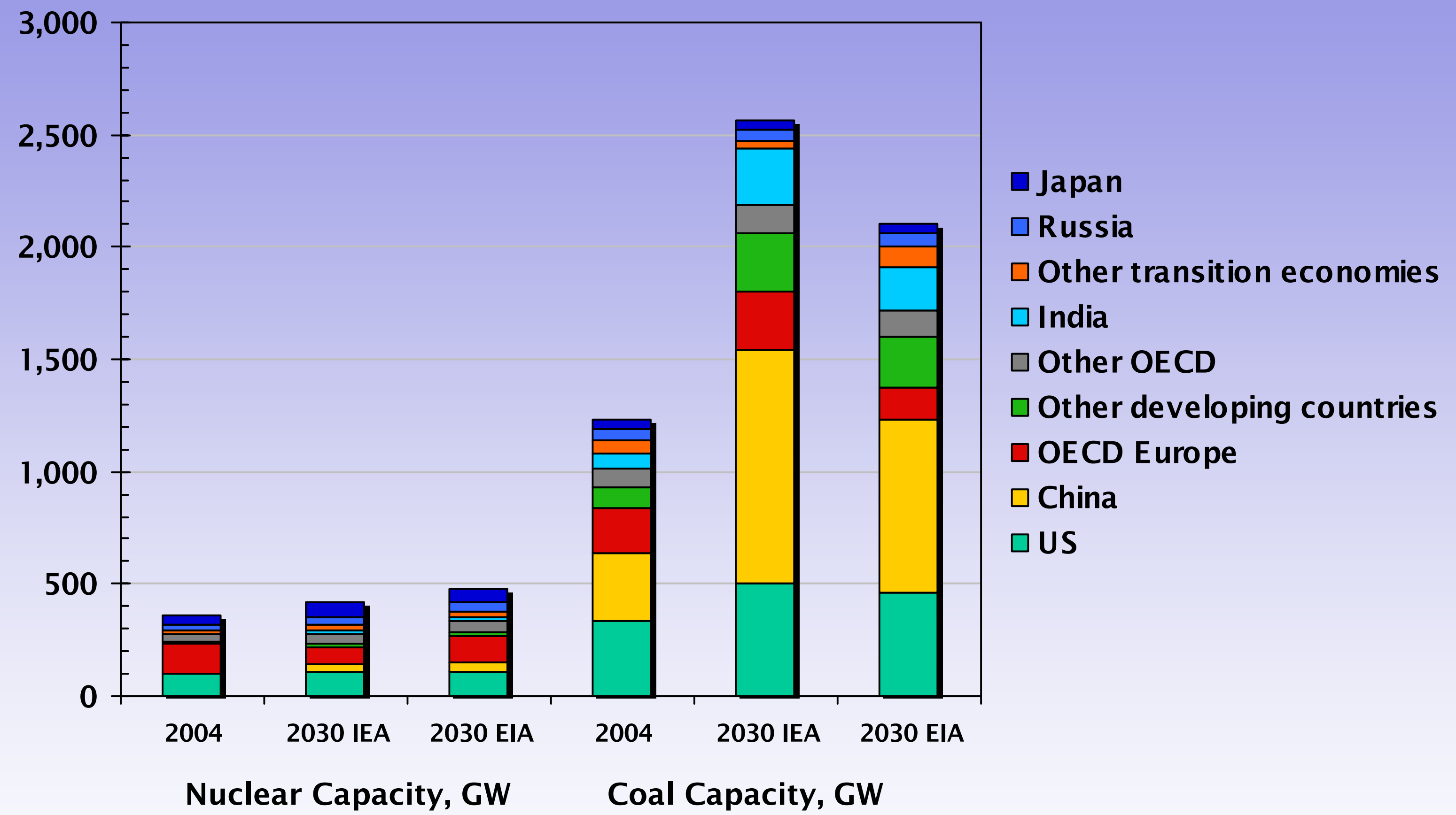
CAN NUCLEAR POWER RENAISSANCE HELP SLOW RUSH TO COAL?



Incremental new coal capacity by decade

WEO 2006 projection ➔ C commitment for 1800 GW_e of new capacity 2003-2030 = 1.2 X total historical CO_2 emissions from all coal burning

IEA & EIA FORECASTS FOR NUCLEAR & COAL



Nuclear Renaissance would require strong *public policy* support because there is now little *real* market interest…*real* action is in coal

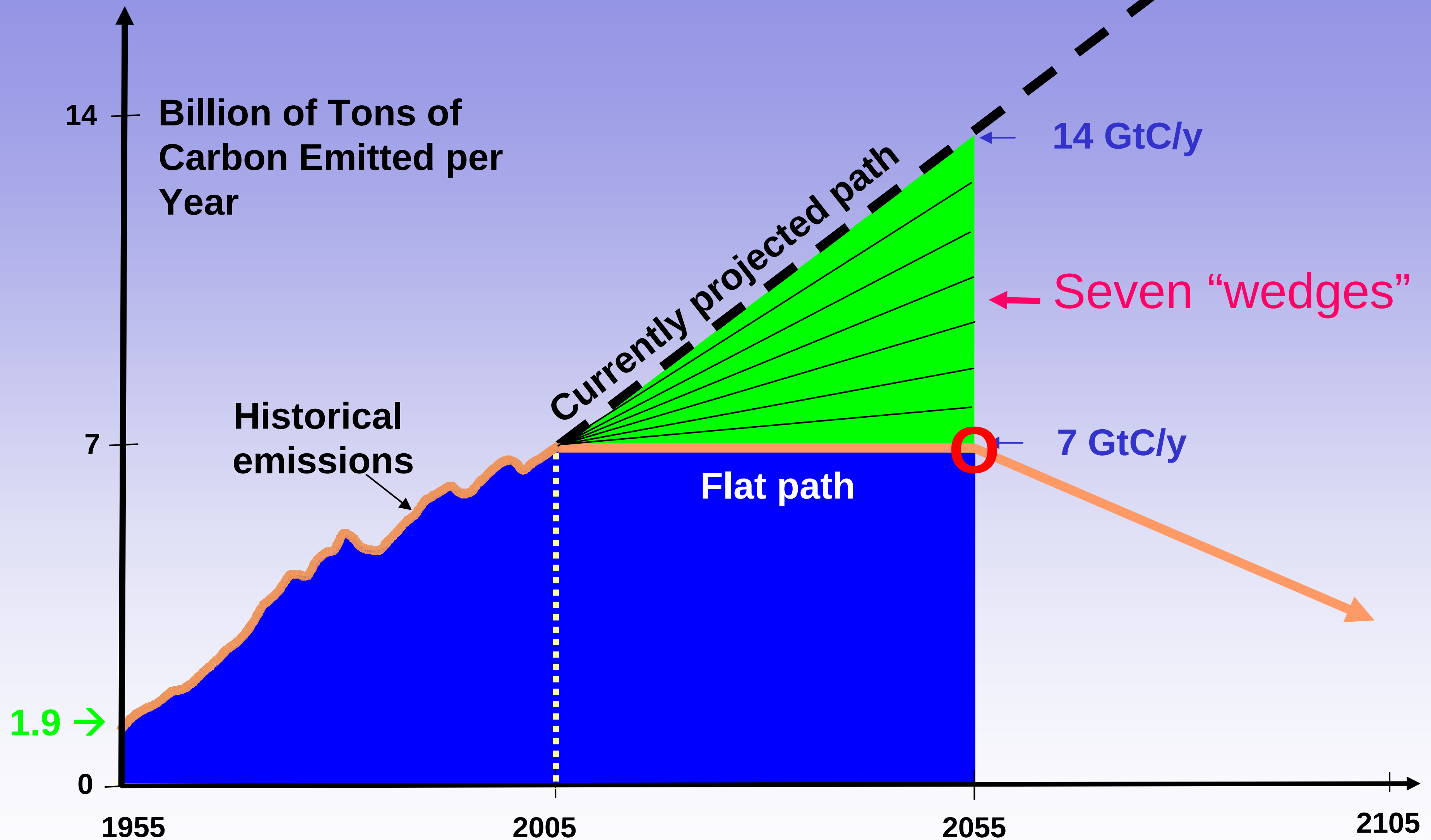
HURDLES TO BE SURMOUNTED

- Loss of public confidence
  - reactor safety
  - radwaste storage
- Loss of investor confidence—financial risks
- Deterioration of non-proliferation regime
  - Iran, North Korea
  - US GNEP has not been helpful:
    - Clouding of separation of peaceful atom/military atom via resurrection of nuclear reprocessing option
    - Stable international regime cannot be realized by creating two classes of global state citizenry (safe countries and unsafe countries)
  - Impatience with progress in implementing Article 6 of NPT
- Spectre of terrorist acquisition of "the bomb"
  - Via "Loose nukes" today
  - Via widespread nuclear power systems tomorrow?

OUTLOOK FOR SURMOUNTING HURDLES

- Under strong carbon mitigation policy financial risks are likely to be much less than at present
- Technical solutions are available for addressing historical issues
  - High degree of intrinsic safety with new reactor designs
  - Interim retrievable spent fuel storage in dry casks while long-term storage systems are evolved
- Industry understands well that nuclear accident anywhere would cripple industry everwhere
- But can public confidence be restored?
- Proliferation/terrorist risks
  - More challenging
  - Consider in context of implications of a successful nuclear renaissance

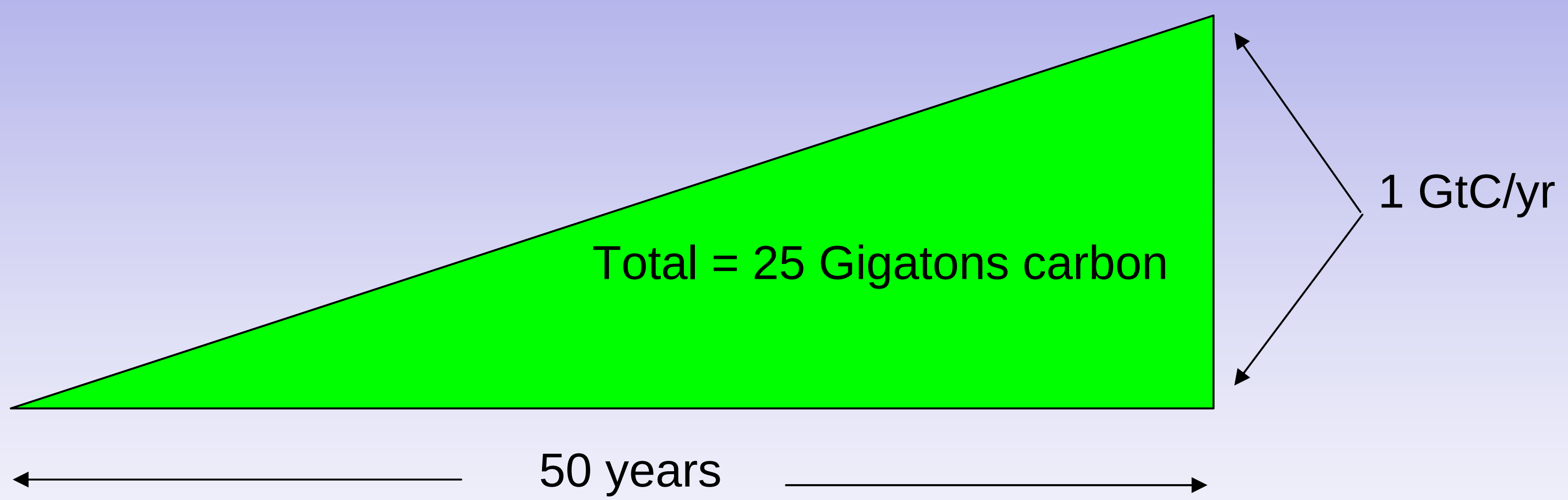
GLOBAL "WEDGES" STRATEGY



After Pacala and Socolow (2004)…S**table emissions needed until 2050**

WHAT IS A "WEDGE"?

A "wedge" is a strategy to reduce carbon emissions that grows in 50 years from zero to 1.0 GtC/yr. The strategy has already been commercialized at scale somewhere.



Cumulatively, a wedge redirects the flow of 25 GtC in its first 50 years. This is 2.5 trillion dollars at $100/tC.

A "solution" to the CO_2 problem should provide at least one wedge.

How much new nuclear electricity for 1 wedge?

Graphic courtesy of NRC

Over 50 years, add 700 GW (twice current capacity)…fourteen 1-GW plants/year…to displace coal capacity.

Cumulative plutonium (Pu) in spent fuel by 2054 if all nuclear power via once-through fuel cycles: 4000 t Pu (+ another 4000 t Pu if current capacity is continued).

Compare with ~ 1000 t Pu in all current spent fuel, ~ 100 t Pu in all U.S. weapons.

5 kg ~ Pu critical mass.

Potential Pitfalls:
Nuclear waste
Nuclear proliferation and terrorism

ADDRESSING WEAPONS THREATS TO ENABLE LARGE NUCLEAR POWER ROLE

- Repairing non-proliferation regime is necessary but not sufficient
- Much stronger non-proliferation regime needed to enable major role for nuclear power in carbon mitigation
- Reasons for cautious optimism:
  - Widespread recognition of:
    - "Latent proliferation" threat (*Iran*)
    - Risk of terrorists acquiring nuclear weapons
  - Growing recognition of uselessness of nuclear weaponry
    - 1986 Reagan/Gorbachev meeting at Reykjavik
    - "A World Free of Nuclear Weapons"—8 January 2007 *Wall Street Journal* Op Ed by George Shultz, William Perry, Henry Kissinger, Sam Nunn
    - September 2007: Barak Obama embraces Shultz, Perry, Kissinger, Nunn proposal
- But political challenges are daunting
- Effort needed to manage large-scale nuclear power has been known since Dawn of Nuclear Era (*Acheson-Lilienthal Report*):

…there is no prospect of security against atomic warfare in a system of international agreements to outlaw such weapons controlled *only* by a system which relies on inspection and similar police-like methods. The reasons supporting this conclusion are not merely technical but primarily the inseparable political, social, and organizational problems involved in enforcing agreements between nations, each free to develop atomic energy but only pledged not to use bombs. So long as intrinsically dangerous activities may be carried out by nations, rivalries are inevitable and fears are engendered that place so great a pressure on a system of enforcement by police methods that no degree of ingenuity or technical competence could possibly cope with them.

Report on International Control of Atomic Energy prepared for the Secretary of State's Committee on Atomic Energy by a Board of Consultants (David E. Lilienthal, Chairman), 1946

NUCLEAR RENAISSANCE VS MAJOR ALTERNATIVES FOR LOW CARBON POWER

- "Fixing" non-proliferation regime warrants top priority
  - Feasible…but
  - Politically challenging
- Intensity of effort will depend on alternative low C options for power
  - Their viability
  - Public attitudes toward them vis a vis nuclear
- In spirit of "wedges" approach to addresssing climate change mitigation in this ½ century, focus here is on near-commercial alternatives that offer wedge-scale potentials
  - Carbon capture and storage (CCS) for coal power
  - "Baseload" wind power (*wind + compressed air energy storage*)

Carbon Capture*

The Wabash River
Coal Gasification Repowering Project

Graphics courtesy of DOE Office of Fossil Energy

*Step One of Carbon Capture and Storage (CCS)

Source: Robert Socolow

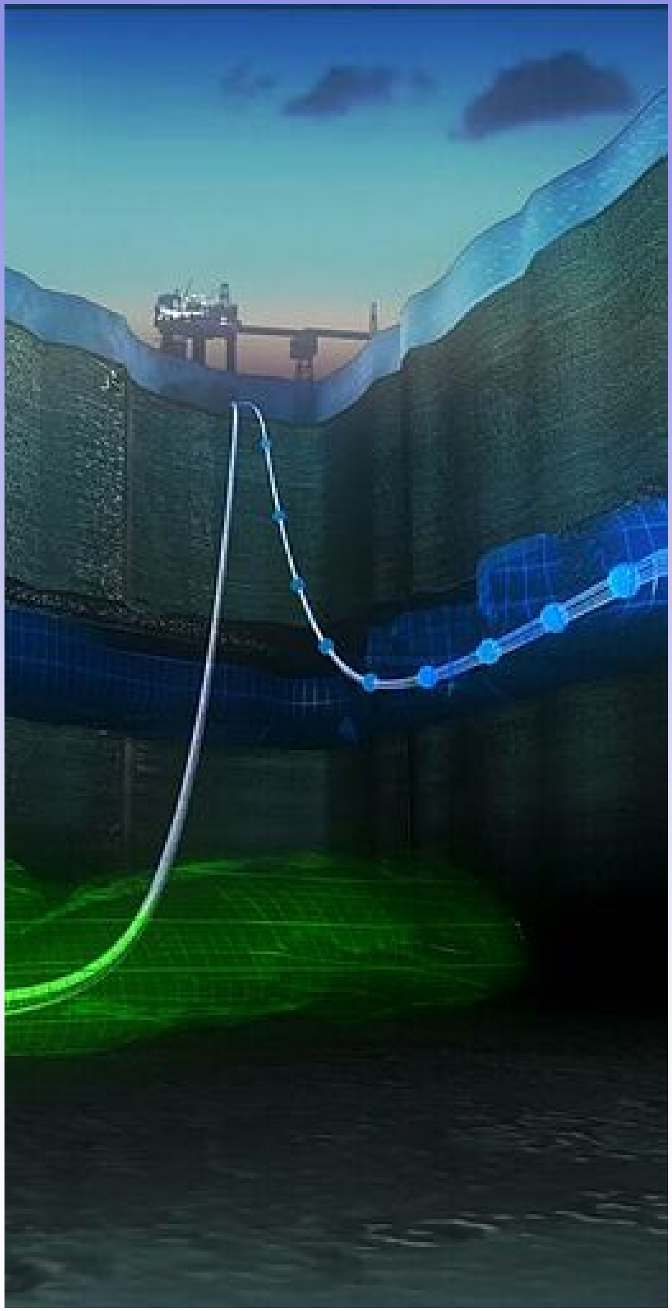
Effort needed for 1 wedge:

CCS for 800 GW coal

Potential Pitfalls:

Second step, carbon storage, founders.

Carbon storage



Graphic courtesy of Statoil ASA

Effort needed for 1 wedge:

70 Sleipner equivalents installed every year and maintained until 2054

A volumetric flow of supercritical CO_2 somewhat greater than the flow of oil today

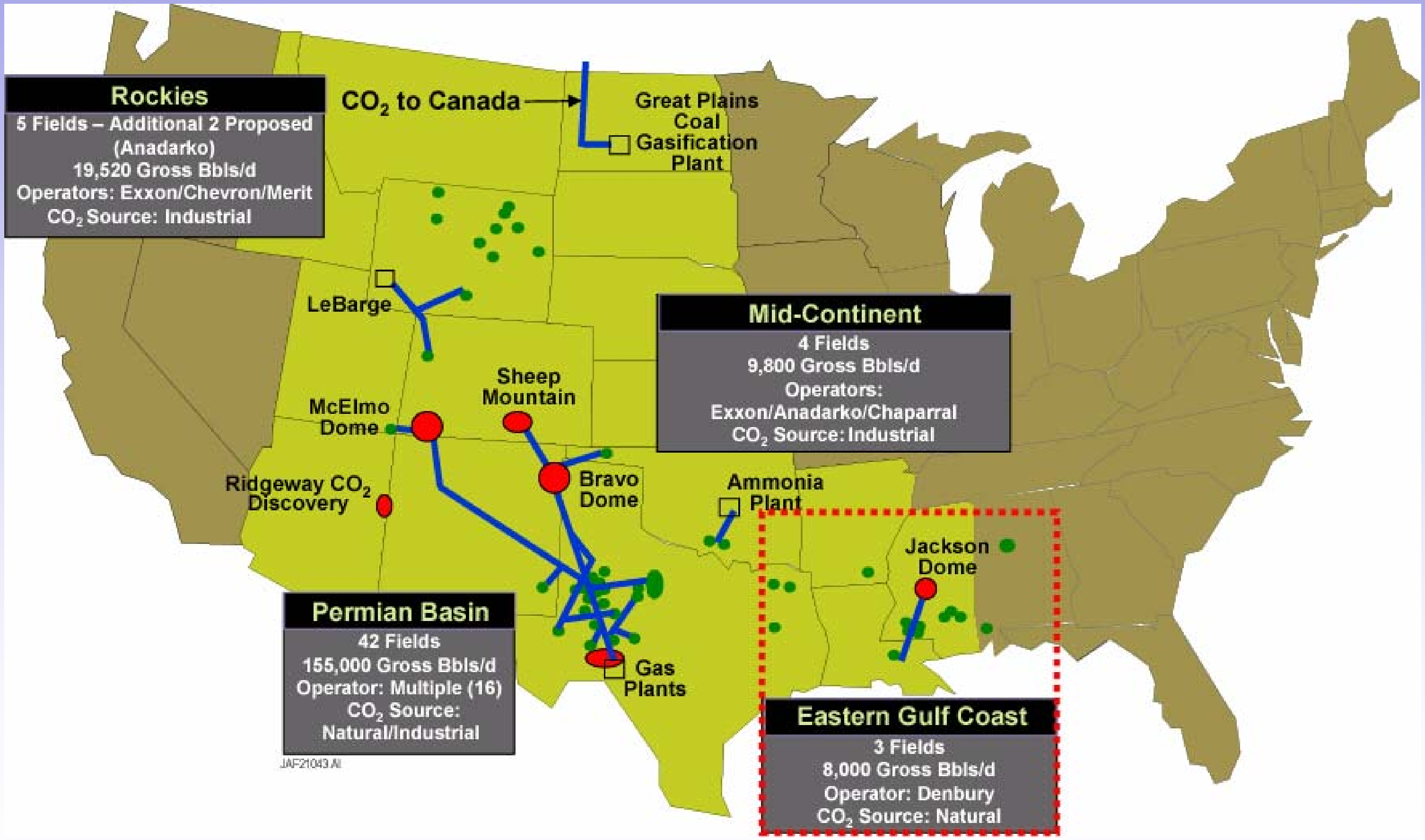
Potential Pitfalls:
Public acceptance
Global and local CO_2 leakage

Source:
Robert Socolow

OPTIONS FOR CO_2 STORAGE

- Goal: store 100s to 1000s of Gt CO_2 for 100s to 1000s of years
- Major options, disposal in:
  - Deep ocean (*concerns about storage effectiveness, environmental impacts, legal issues, difficult access*)
  - Carbonate rocks [*100% safe, costly (huge rock volumes), embryonic*]
  - Disposal in geological media (*focus of current interest*)
    - Enhanced oil recovery
    - Depleted oil and gas fields (*geographically limited*)
    - Deep saline formations
      - Huge potential, ubiquitous (*at least 800 m down*)
      - Such formations underly land area ≡ ½ area of inhabited continents (*2/3 onshore, 1/3 offshore*)
  - Most large anthropogenic CO_2 sources within 0-200 km of prospective geological storage sites
  - Already some experience [*e.g.*, Sleipner (*saline formation under North Sea*); In Salah, Algeria (*water leg of natural gas field*) and CO_2-EOR (*30 million tonnes CO_2/y—4% of US oil production*)]

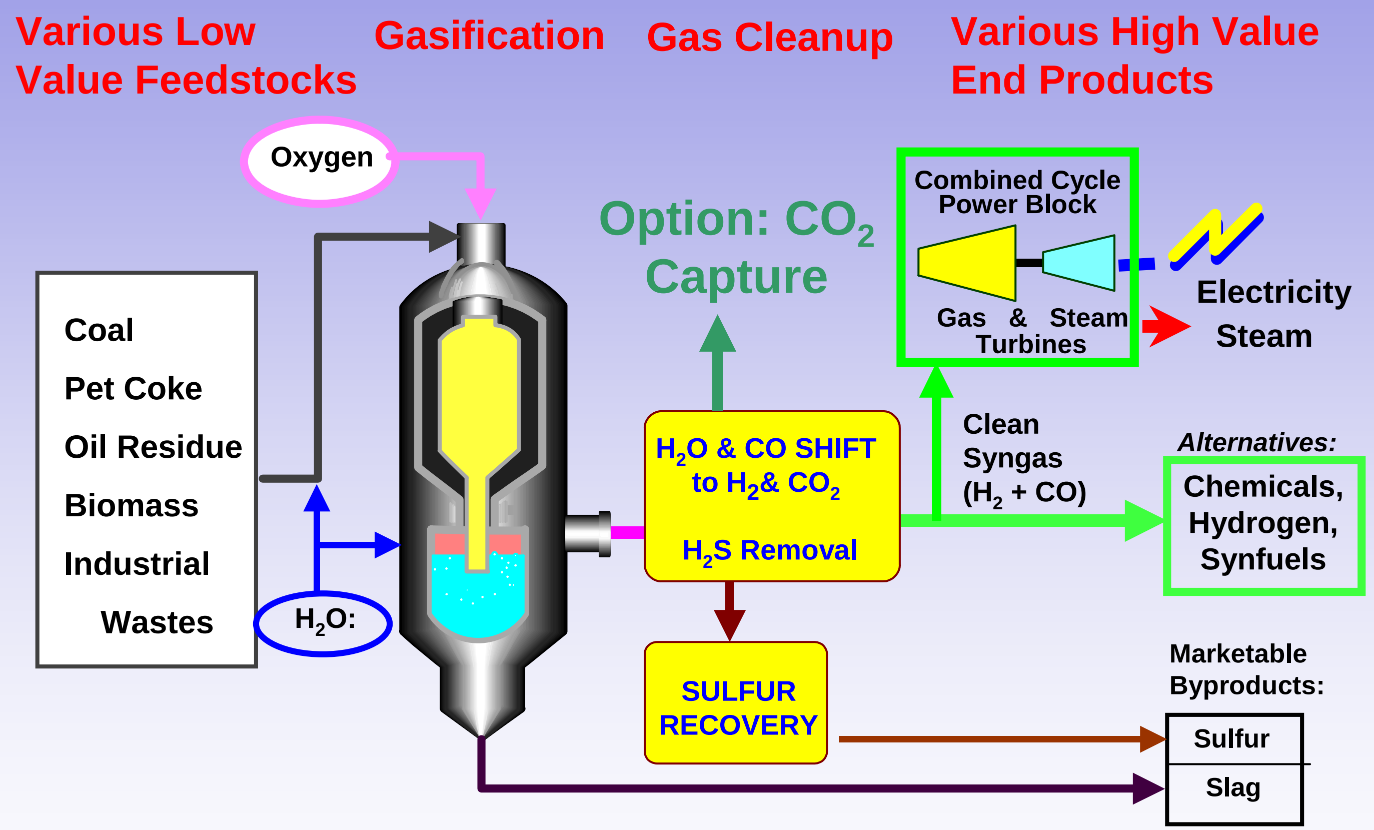
EXTENSIVE US EXPERIENCE WITH CO_2 TRANSPORT FOR ENHANCED OIL RECOVERY …SOME CO_2 IS ANTHROPOGENIC



IPCC SPECIAL REPORT ON CCS (2005)

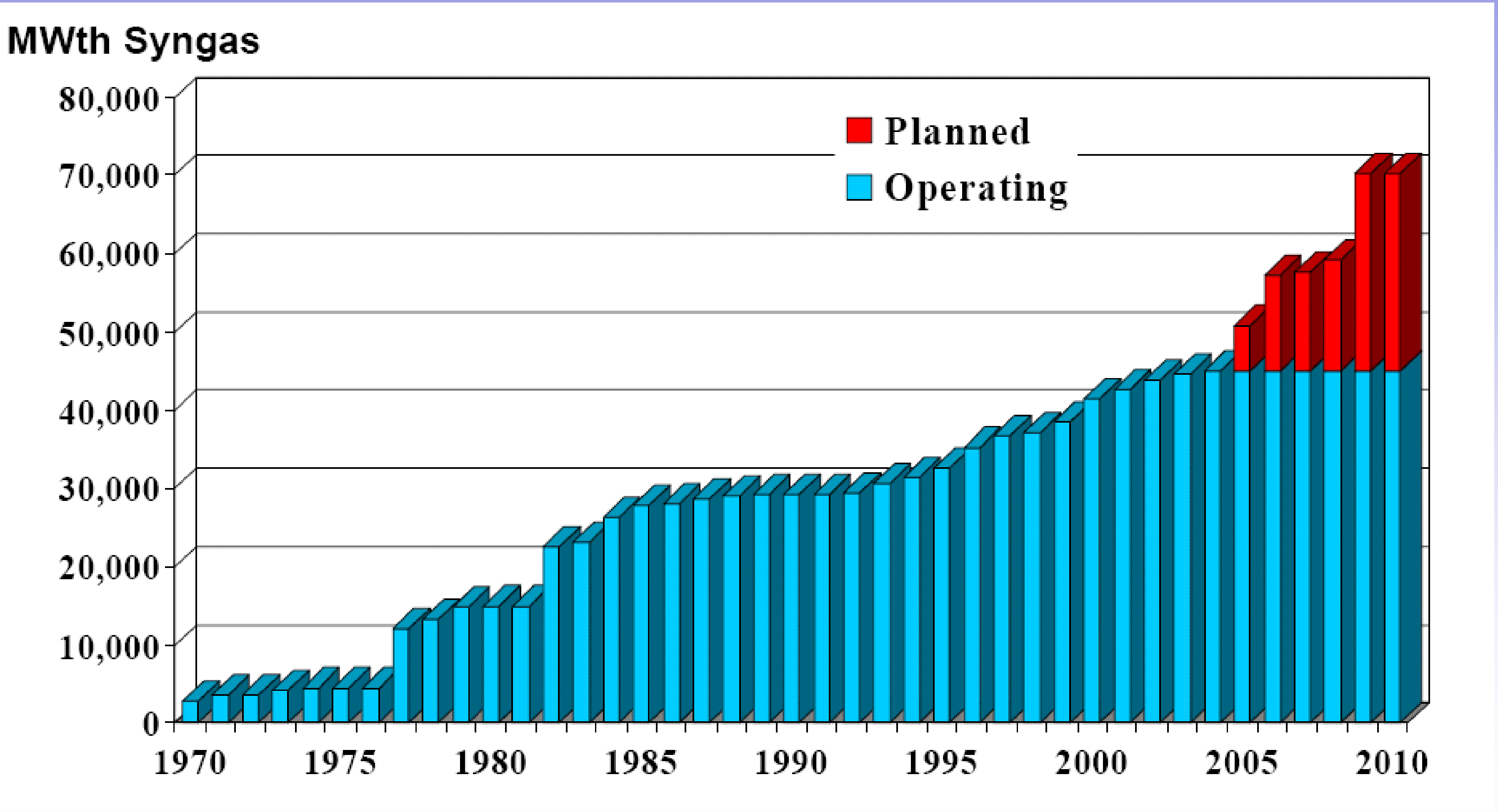
- IPCC is:
  - positive on geological storage,
  - not so positive on ocean storage or mineralization
- CO_2 capture and storage (*CCS*) can:
  - contribute 15% to 55% in mitigating climate change
  - reduce climate mitigation cost 30% or more
  - reduce emissions 80-90% compared to plant w/o CCS
- CCS plants require 10-40% more energy than plants w/o CCS
- 66-90% probability that worldwide geo-storage capacity at least 2000 Gt CO_2 (*fossil fuel emissions = 24 Gt CO_2 in 2002*)
- On CO_2 retention in *appropriately selected and managed* reservoirs :
  - 90-99% probability that retained fraction will exceed 99% over 100 y
  - 66-90% probability that retained fraction will exceed 99% over 1000 y
- CO_2 pipeline risk ~ to or < than for HC pipelines in operation

GASIFICATION TO CONVERT LOW-VALUE FEEDSTOCKS INTO HIGH-VALUE PRODUCTS

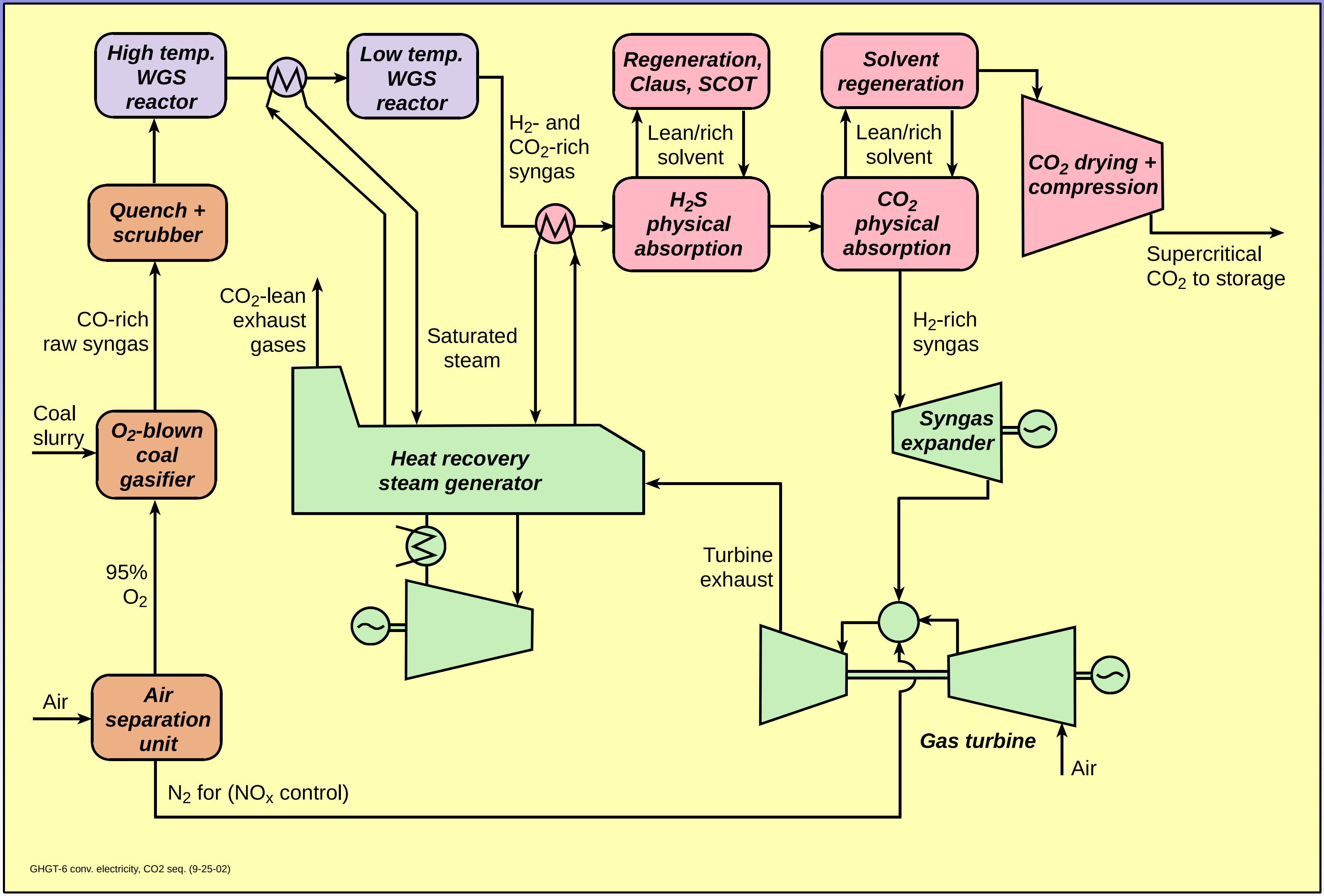


Gasification in O_2/steam of coal and other carbonaceous materials: key enabling technology for making clean energy (*electricity and synthetic fuels*) and for low-cost CO_2 capture & storage (*CCS*)

CUMULATIVE WORLDWIDE GASIFICATION CAPACITY AND GROWTH



COAL IGCC WITH PRECOMBUSTION CO_2 CAPTURE



Key to low CO_2 capture cost via IGCC: recovery of CO_2 at high partial pressure

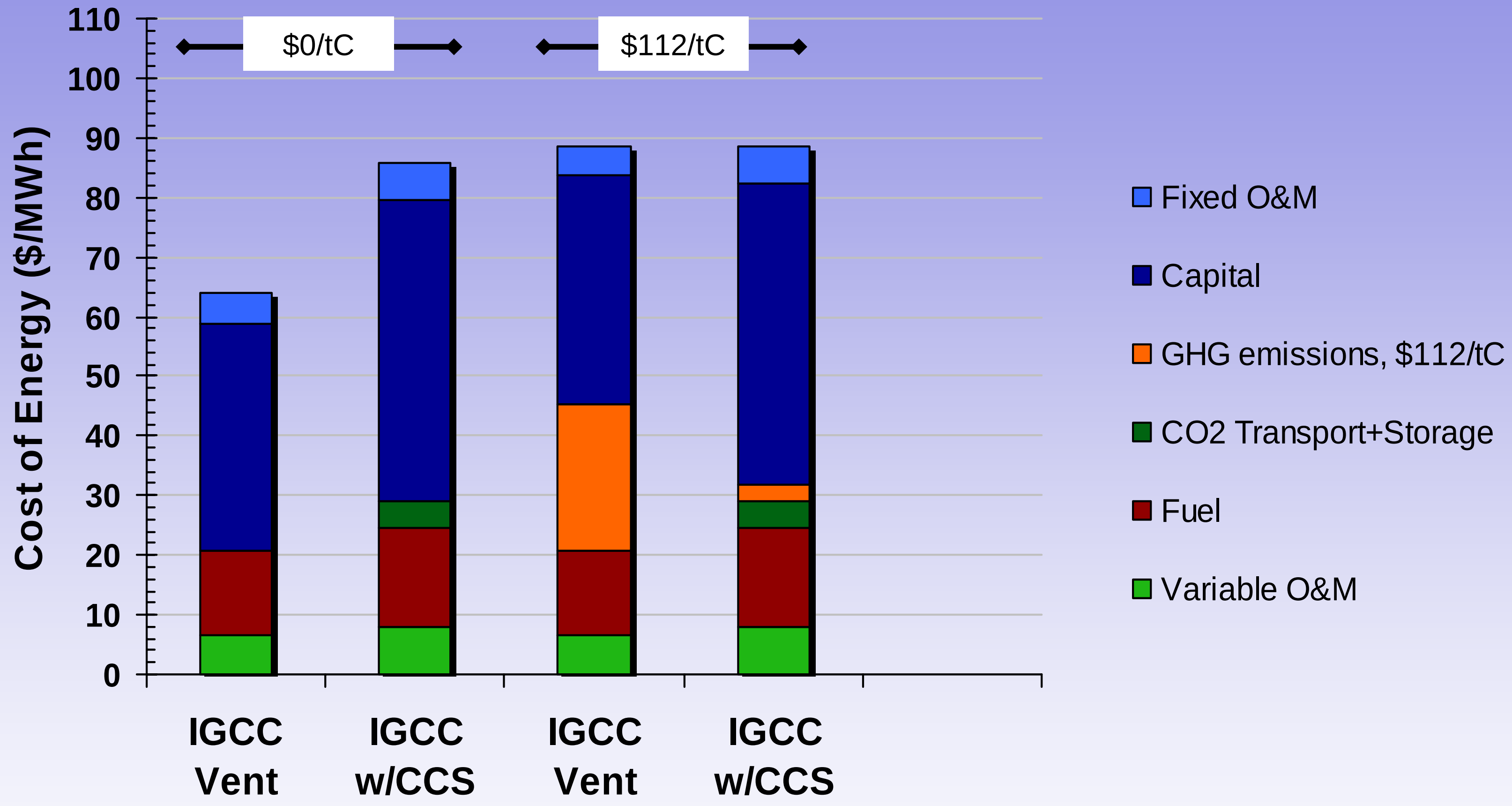
PLANNED IGCC WITH CCS PROJECTS

Project	CO_2 storage	Feedstock	Capacity (MW_e)	Online
E.ON—Killingholme, UK	Gas fields, North Sea	Coal	450	2011
Goldman Sachs—Lockwood, Texas, US	EOR	Petcoke	600 + 600	2011 /2013
BP—Carson, California, US	EOR	Petcoke	500	2012
Powerfuel—Hatfield Colliery, UK	EOR	Coal	900	2012
Centrica/Progressive Energy—Teesside, UK	EOR	Coal/ Petcoke	800	2012-2013
BP/Rio Tinto—Kwinana, Perth, Australia	Offshore saline formation	Coal	500	2014
RWE—Germany	Saline formation	Coal	450	2014

ENERGY ECONOMICS MUST REFLECT RECENT HUGE CONSTRUCTION COST ESCALATION

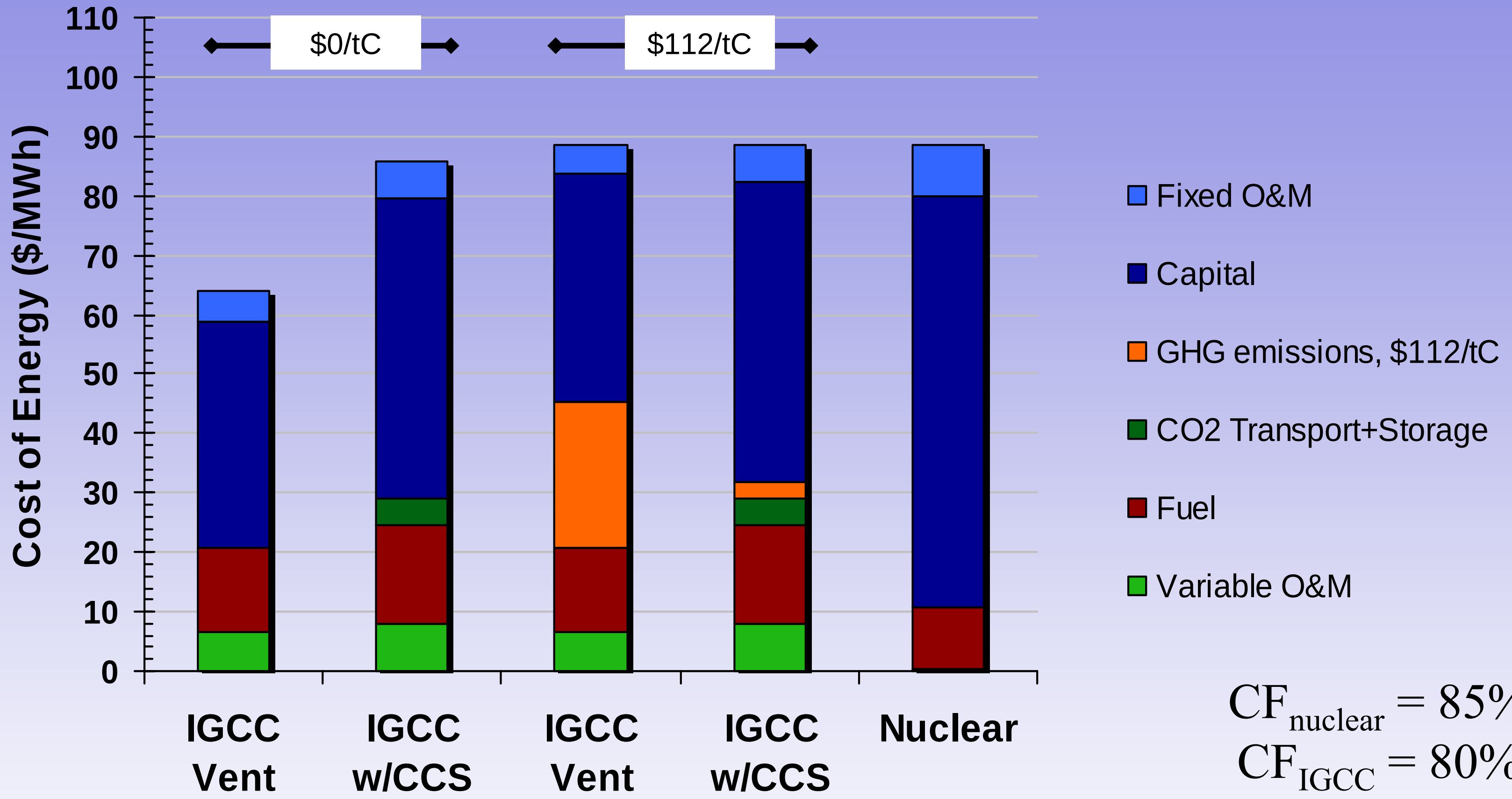
- Even for “tried & true” supercritical pulverized coal steam electric plants, real capital cost ($\$/kW_e$) up at least 35% compared to 2002
- Real construction-related costs in 2006 relative to 2002:
  - Steel mill products up 1.4 X
  - Copper up 3.8 X
  - Aluminum up 1.7 X
  - Nickel up 3.4 X
  - Tungsten up 3.3 X
  - Cement up 1.2 X
  - Construction labor up 1.1 X
- Annual backlog at major Engineering, Procurement, and Construction (EPC) firms up 2 X, 2002-2006
- Cause: Demand/supply shortfalls a result of stellar construction growth—especially in Asia (*e.g.*, *China added almost 100 GW_e of new coal generating capacity in 2006*)

COAL IGCC POWER COST (CO_2 VENTED vs CCS)



Recent construction cost escalations have been taken into account. Assumed coal price = $1.5/GJ (HHV). Assumed cost of CO_2 transport and storage = $5/t CO_2. When CO_2 emissions value = $112/tC ($30.5/t CO_2), generation costs are equal for CO_2 vented and CCS cases.

NUCLEAR CAPITAL COST FOR BREAKEVEN

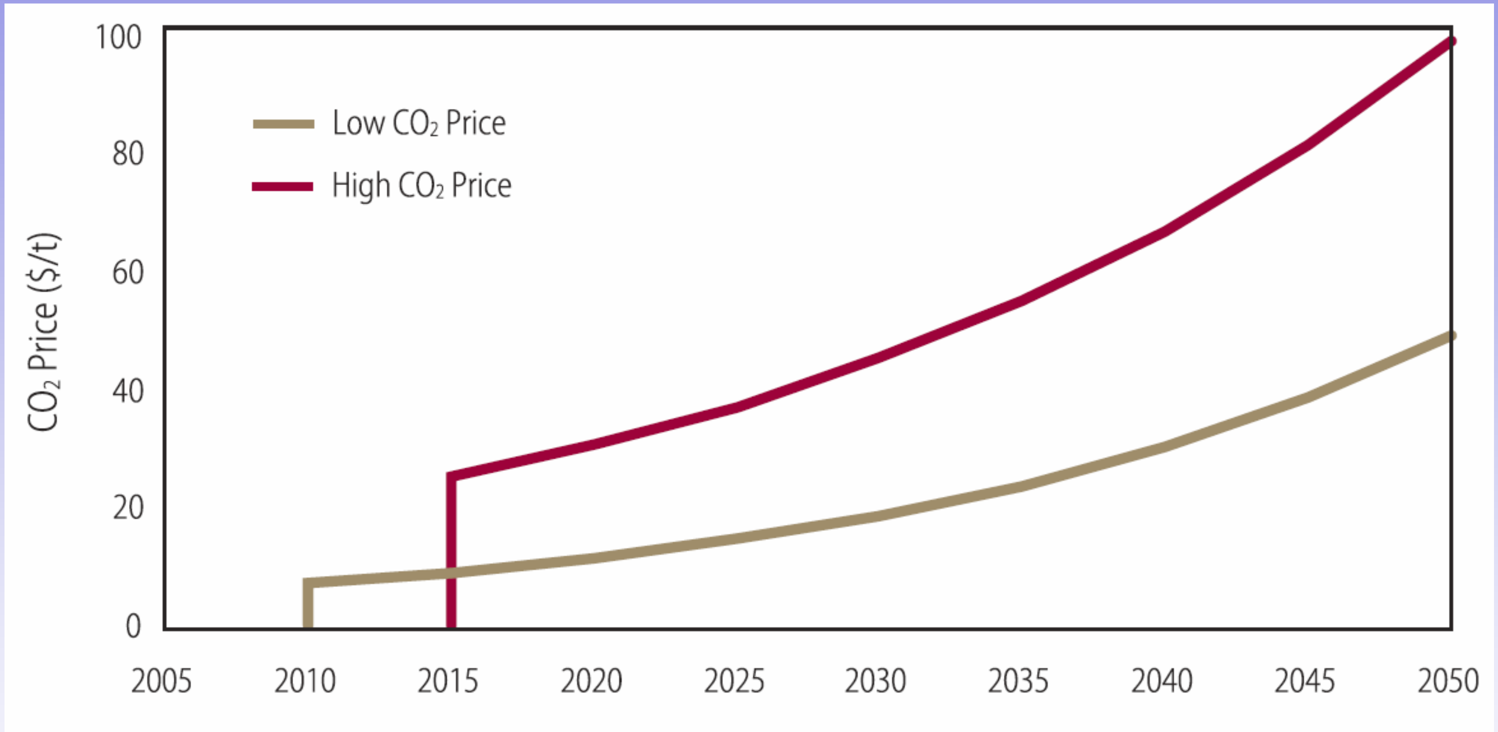


$CF_{nuclear} = 85\%$
$CF_{IGCC} = 80\%$

Breakeven nuclear capital cost = $3100/kW$_e$ (U @ $188/kg, enrichment @ $135/SWU)

Estimated cost, Olkiluoto-3 reactor under construction in Finland = $2500-$3000/kW$_e$ (Source: "Further delay in construction of the Olkiluoto-3 nuclear reactor," *Professional Reactor Operator Society*, www.nucpros.com/?q=node/212, accessed 2 August 2007). New plants probably more costly (*because of recent escalation of construction costs*).

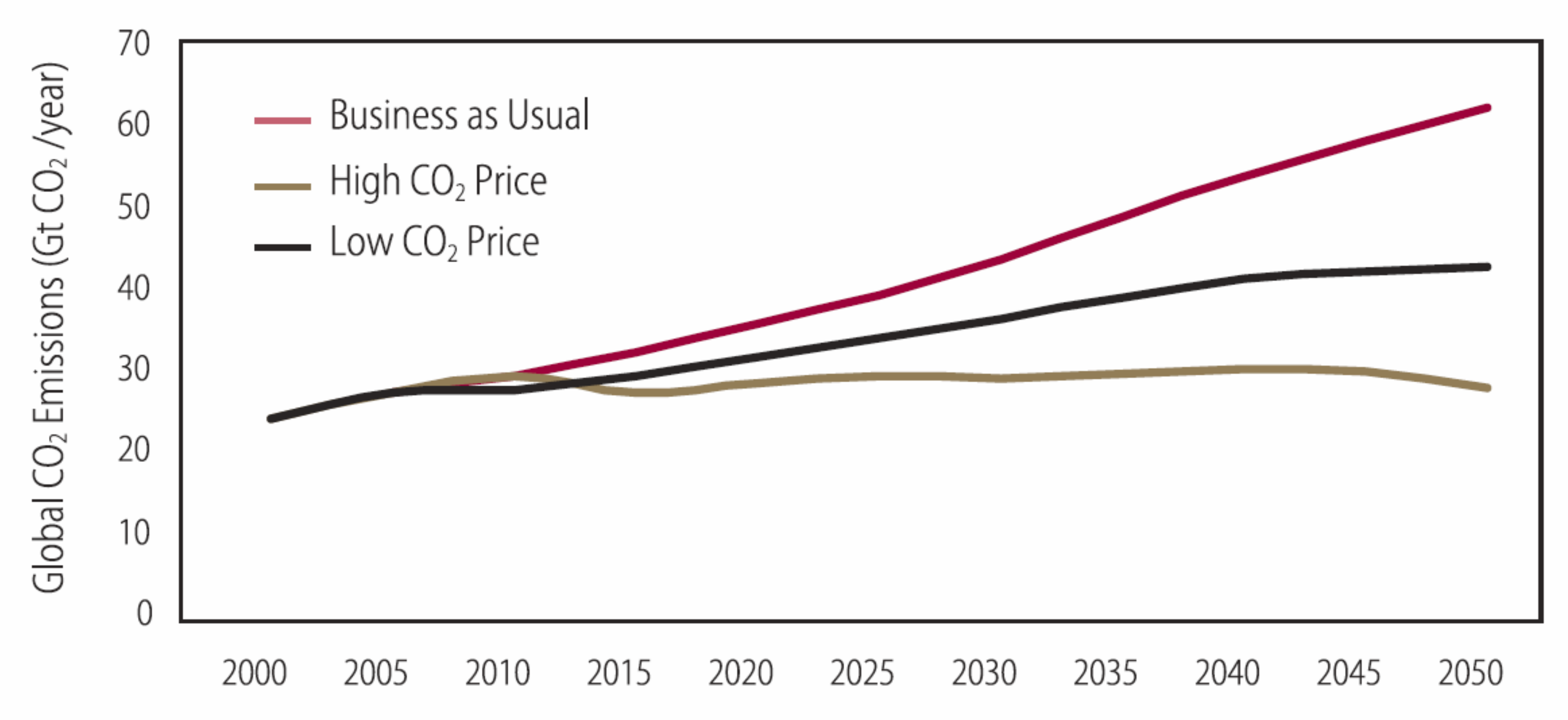
MODELING OF WORLD ENERGY IN MIT FUTURE OF COAL STUDY



Modeling exercise explored impacts of:

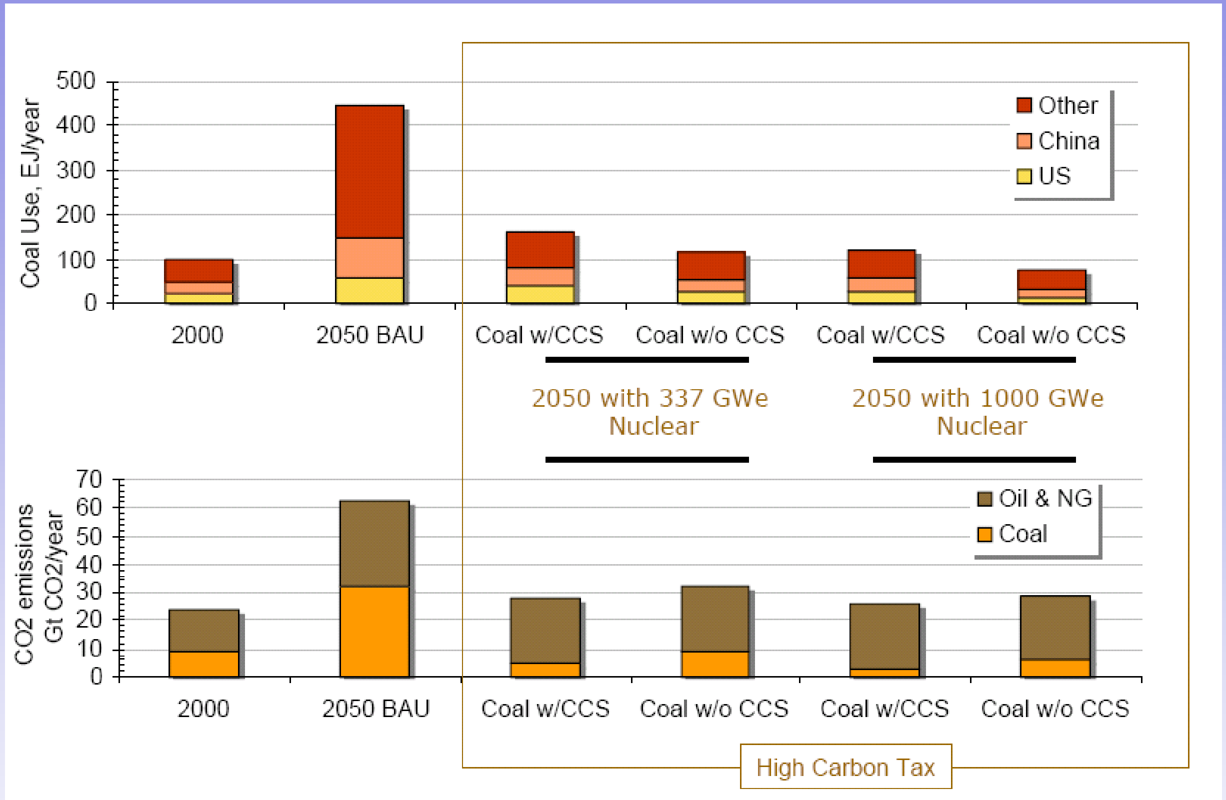
- Low & high CO_2 prices
- Low nuclear & high nuclear cases (327 GW_e & 1000 GW_e in 2050)

RESULTS OF MIT COAL STUDY MODELING



Stabilization of global CO_2 emissions through mid-century (*goal of wedges strategy*) is feasible with high but not low CO_2 price trajectory

RESULTS OF MIT COAL STUDY MODELING



- CO_2 price has huge impact in reducing mid-century coal use
- Coal's role in mid-century energy economy is much greater with CCS
- Emissions only marginally lower for high nuclear scenario than for low nuclear scenario, but coal use is markedly lower in high nuclear cases
- Modeling effort did not consider serious expansion of renewable power as response to high CO_2 price

PRIORITIES FOR CO_2 CAPTURE AND STORAGE

- Carry out on region-by-region basis:
  - Detailed assessments of geological storage capacity
  - Development of "supply curves" for CO_2 storage (*$/tonne vs tonnes*)
- Establish as major fields of scientific/engineering endeavor:
  - CO_2 leakage science
  - CO_2 leakage mitigation technology
- To understand better prospects for "gigascale" CO_2 storage & to establish scientific/engineering basis for regulating long-term CO_2 storage:
  - Carry out over next decade many "megascale" CO_2 storage projects—with emphasis on storage in alternative deep saline aquifer geologies
  - Make these projects major scientific/engineering laboratories for modeling, monitoring, and verification (*MMV*)
- If these activities are carried out worldwide, we will have a high degree of understanding of the gigascale prospects for CO_2 storage at the end of a 10-15 year period

Wind Electricity

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

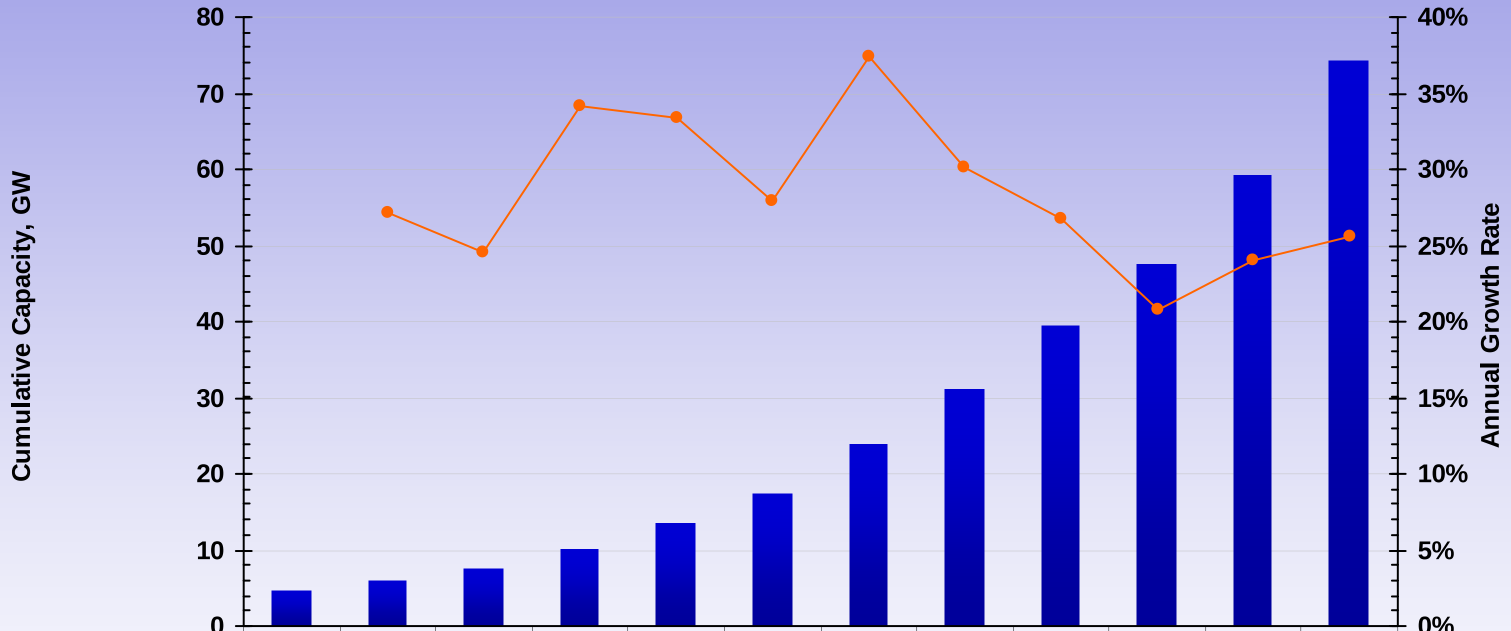
Effort needed for 1 wedge:

One million 2-MW windmills displacing coal power.

Today: 70,000 MW (1/30)

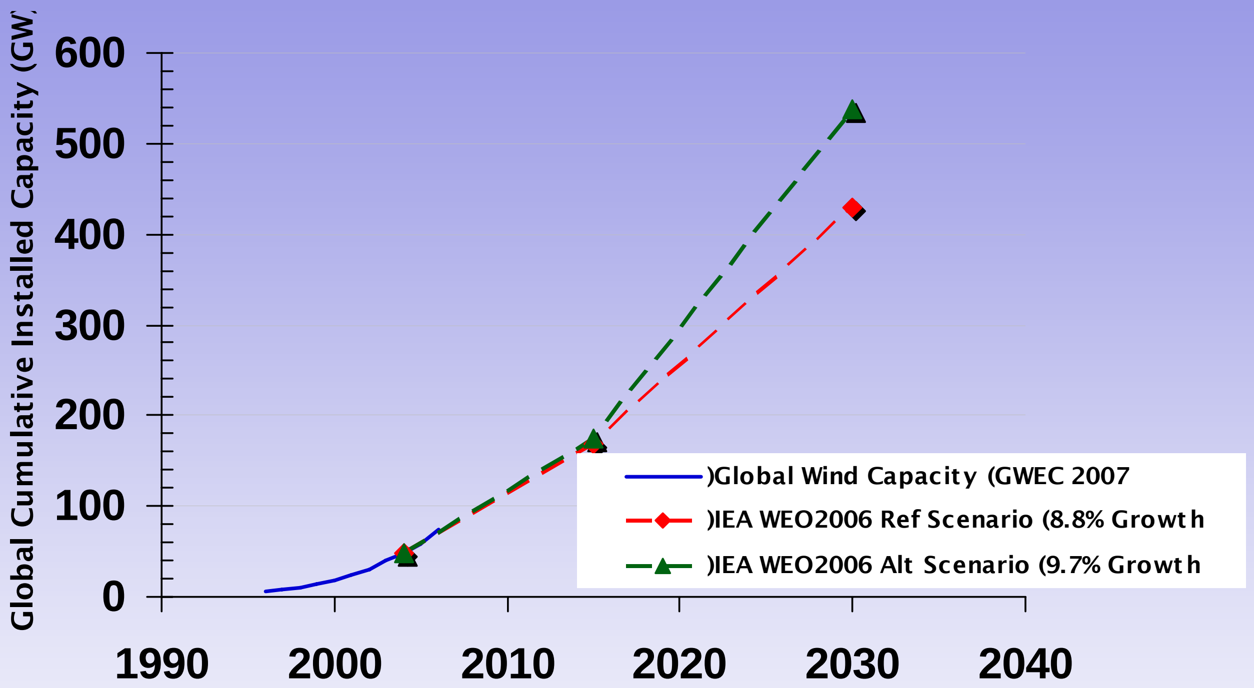
Potential Pitfalls:
NIMBY, bird kills
Changes in regional climate?

EVOLUTION OF GLOBAL WIND CAPACITY



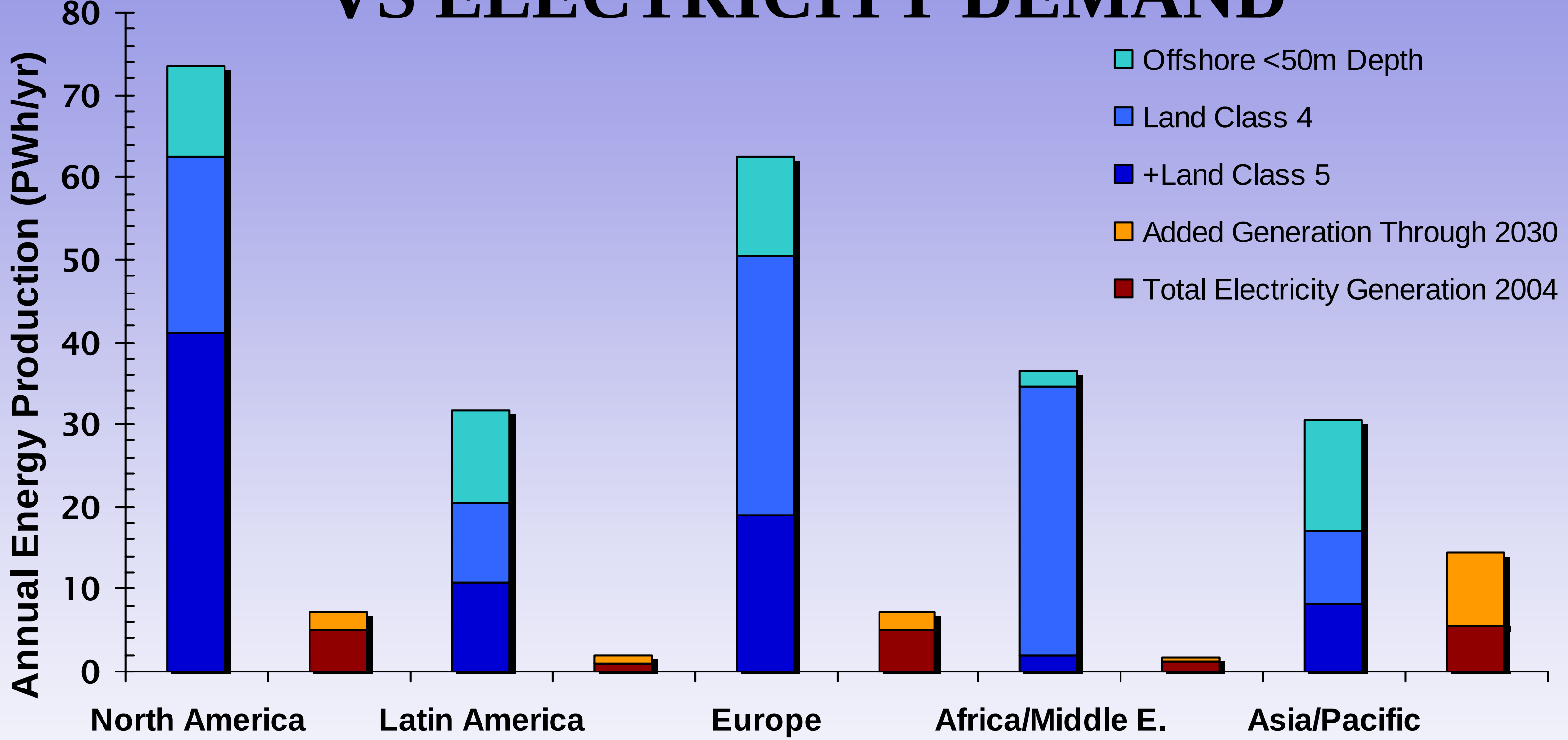
	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
GW	4.8	6.1	7.6	10.2	13.6	17.4	23.9	31.1	39.431	47.62	59.091	74.223
% Growth		27.1%	24.6%	34.2%	33.3%	27.9%	37.4%	30.1%	26.8%	20.8%	24.1%	25.6%

GLOBAL WIND CAPACITY PROJECTIONS



The Global Wind Energy Council expects much more rapid growth for wind power than is projected in *WEO 2006* by the IEA —to the range 1130-2100 GW_e by 2030

EXPLOITABLE WIND RESOURCE VS ELECTRICITY DEMAND

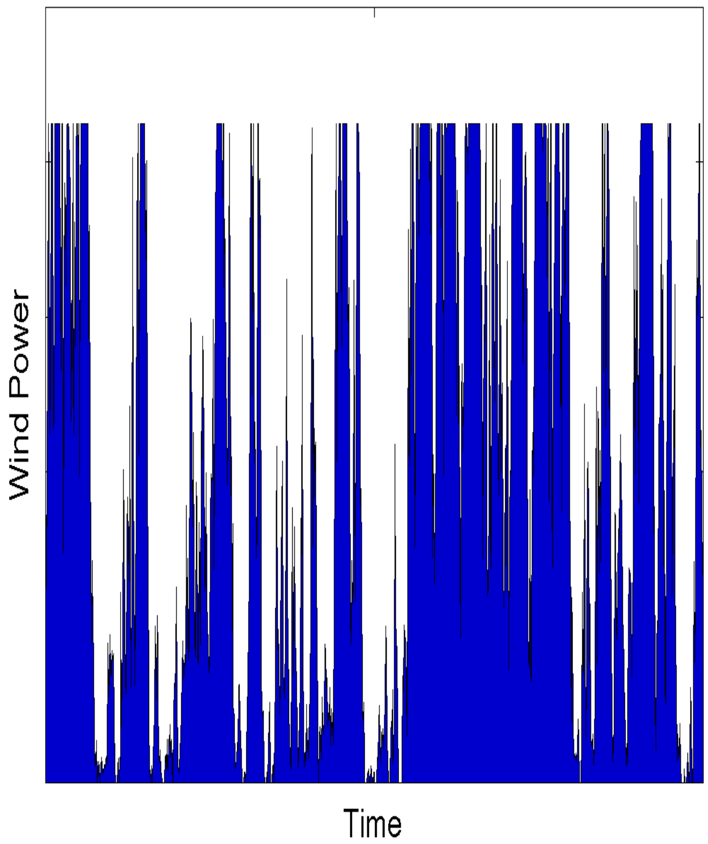


Wind Class Designations
(50m Hub Height)
Class 4: 7-7.5 m/s
Class 5+: >7.5 m/s

Source: Greenblatt 2005; IEA, *World Energy Outlook 2006*

Resource estimates assume 50% of the available resource are excluded due to competing commercial, recreational or environmental land uses.

ADDRESSING INTERMITTENCY/REMOTENESS CHALLENGES FOR WIND POWER

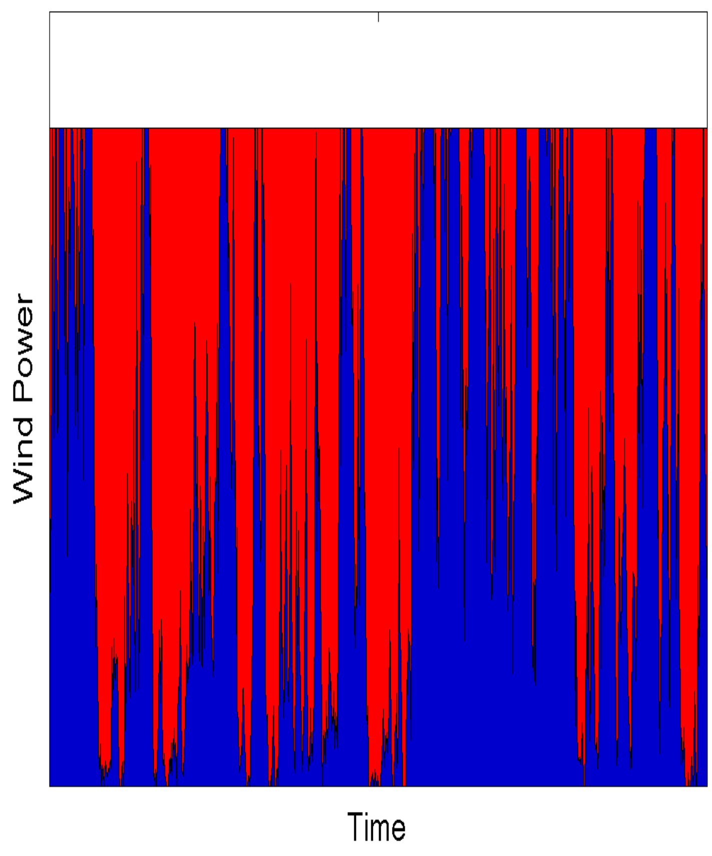


- At high electric grid penetration rates, wind cannot displace baseload capacity (*coal*, *nuclear*) cost-effectively because it is not dispatchable

- Backup capacity needed to balance wind's fluctuations so as to make wind power more valuable

- If wind can be combined with local storage so as to provide baseload power, the remoteness challenge could also be addressed by making long-distance, high-voltage transmission more affordable

OPTIONS FOR BASELOADING WIND POWER TO ENABLE COMPETITION WITH COAL POWER



Options for Baseloading Wind

- Backup:Natural Gas (SC/CC)
  - Low Capital Cost
  - Fast Ramping
- Storage via CAES
  - Low-cost bulk storage
  - Potential widespread availability in wind-rich regions
  - Fast ramping
  - Low heat rate
  - High part-load efficiency

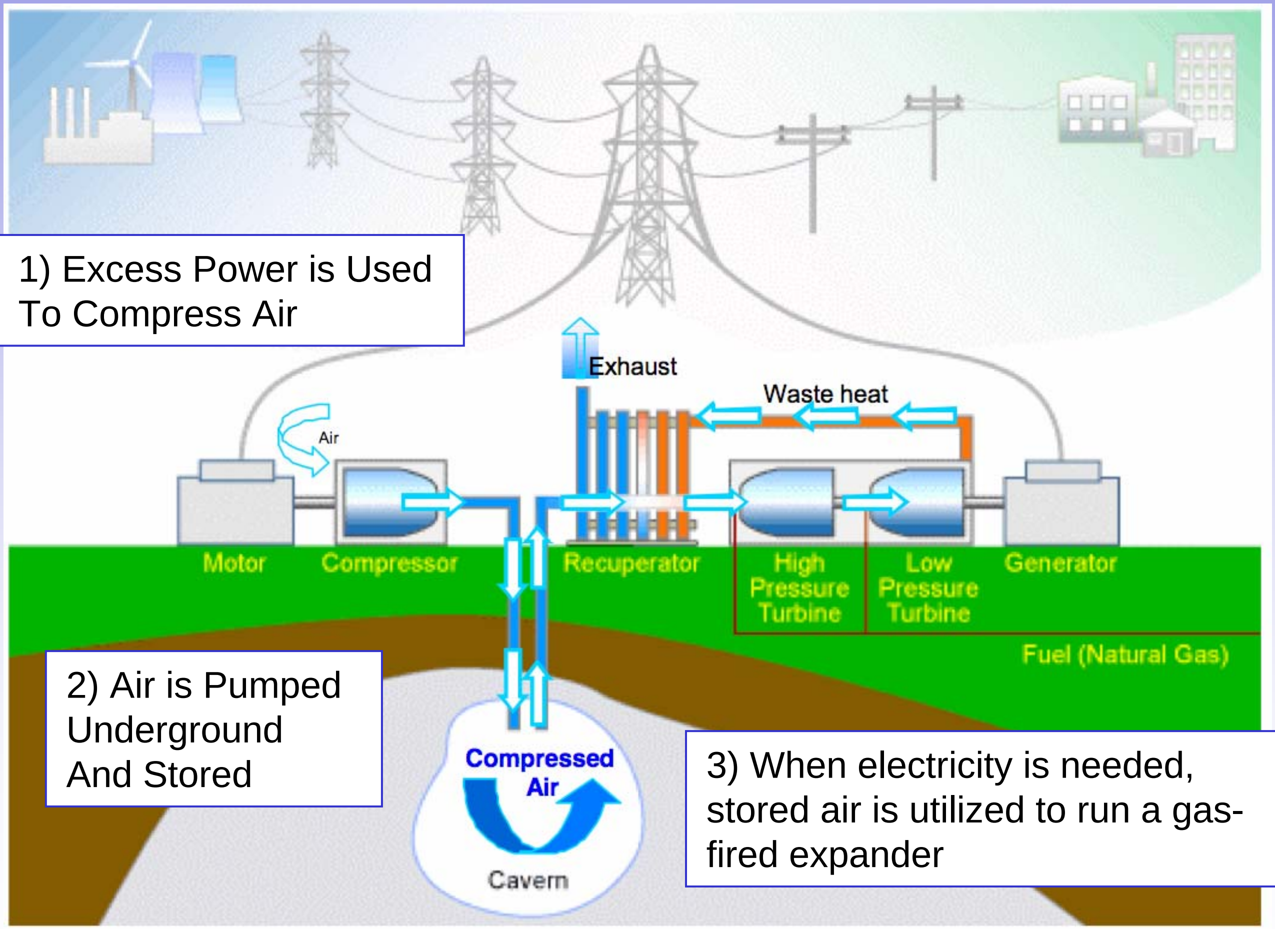
CAPITAL COSTS FOR ENERGY STORAGE OPTIONS

Source: PCAST, 1999 and EPRI/DOE, 2003

Technology	Capacity ($/kW)	Storage ($/kWh)	**Cost of 20 hrs. storage ($/kW)**
Compressed Air Energy Storage (CAES) (300 MW)	**440**	**1**	**460**
Pumped hydroelectric	900	10	**1100**
Advanced battery (10 MW)	120	100	**2100**
Flywheel (100 MW)	150	300	**6200**
Superconductor (100 MW)	120	300	**6100**

CAES is clear choice for:
Several hours (or more) of storage
Large capacity (> ~100 MW)

COMPRESSED AIR ENERGY STORAGE (CAES)



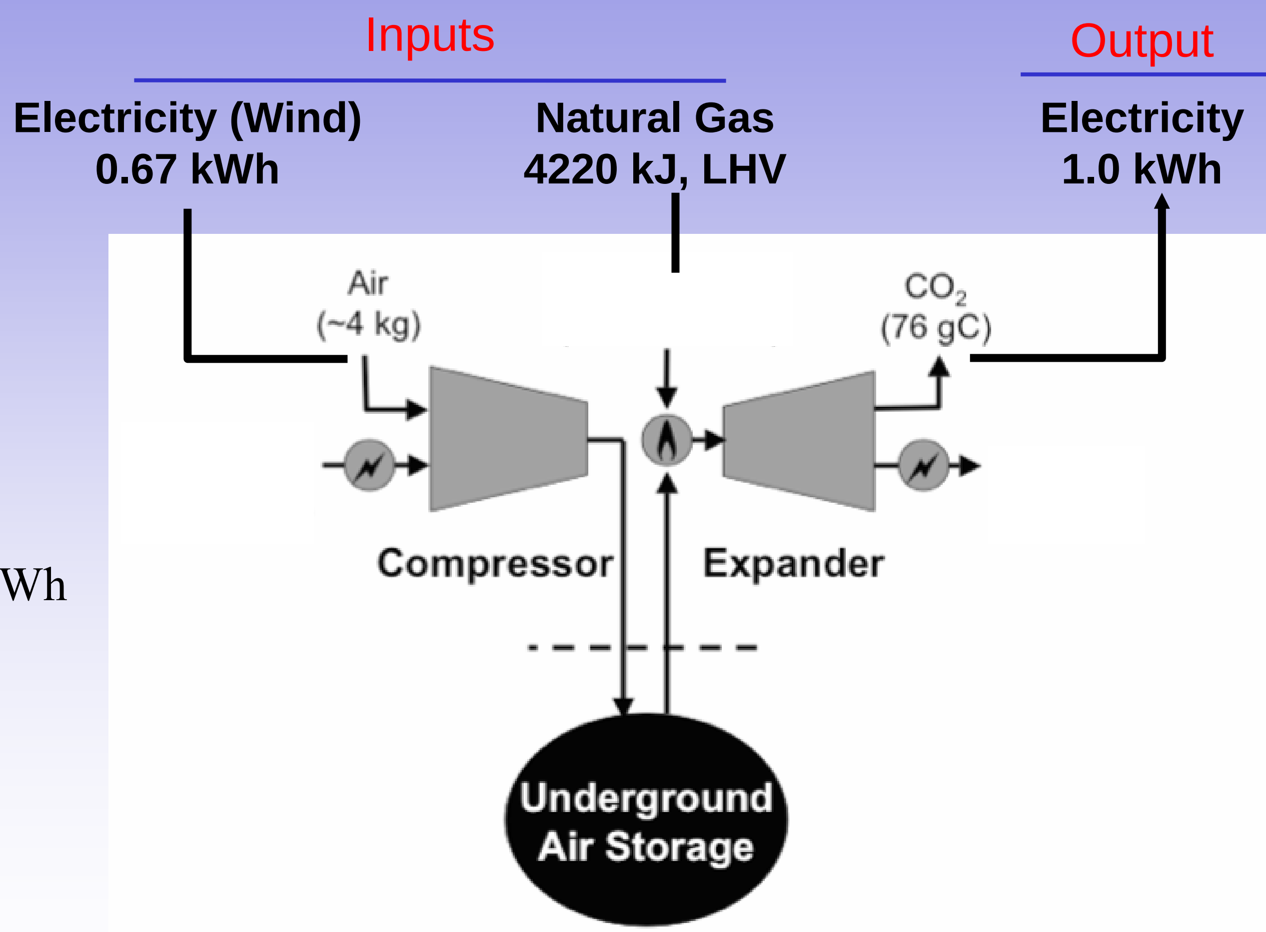
1) Excess Power is Used To Compress Air

2) Air is Pumped Underground And Stored

3) When electricity is needed, stored air is utilized to run a gas-fired expander

CAES EFFICIENCY

Round-Trip Efficiency: ~ 77%



$E_o/E_i = 1.0/0.67 = 1.5$

Heat Rate = 4220 kJ/kWh

STORAGE RESERVOIR OPTIONS FOR CAES

- Capital Costs for Storage ($2002)
  - Mined Hard Rock
    - $10/kWh (*Existing Mine*)
    - $30/kWh (*New Cavern*)
  - Solution Mined Salt Dome
    - $1.75/kWh
  - Porous Rock (*Aquifer*)
    - $0.10/kWh
- Commercial CAES plants use solution-mined salt domes:
  - Huntorf, Germany 290 MW, 2 h (1978)
  - McIntosh, Alabama 110 MW, 26 h (1991)

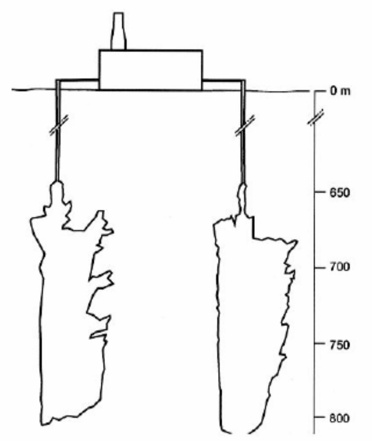


Figure 5 Structure of Huntorf CAES plant salt dome storage with caverns and plant on same scale

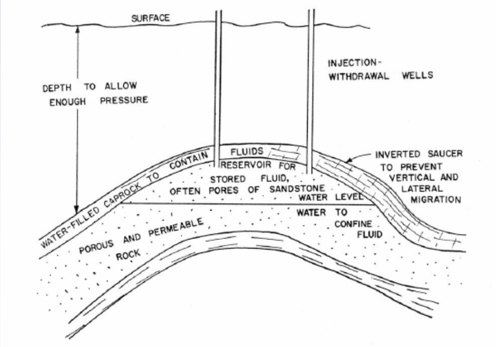
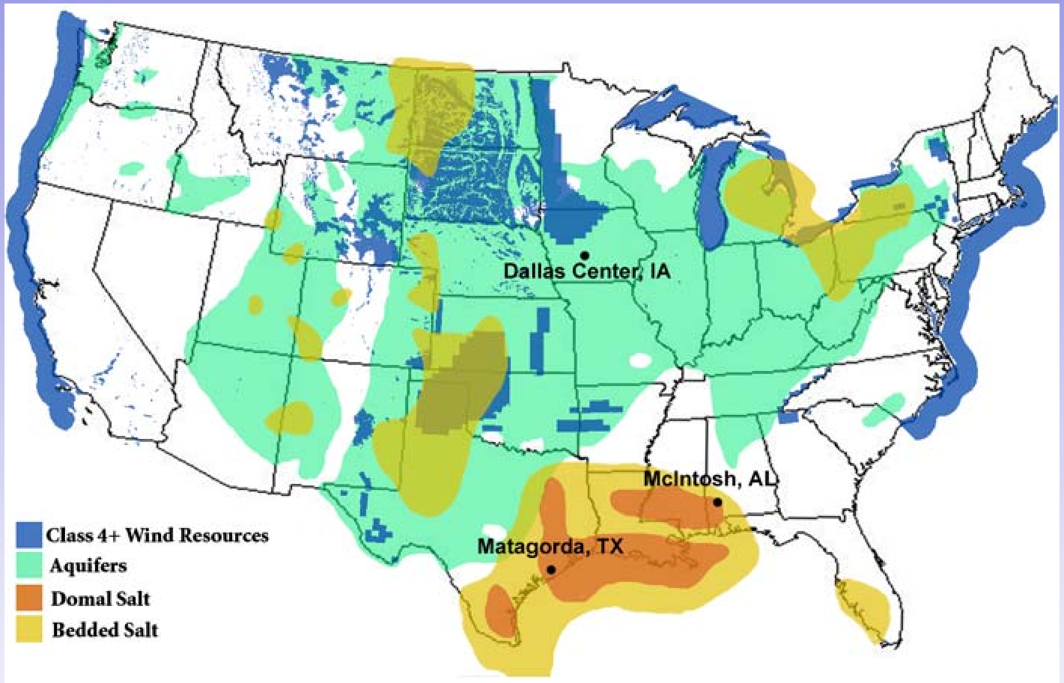
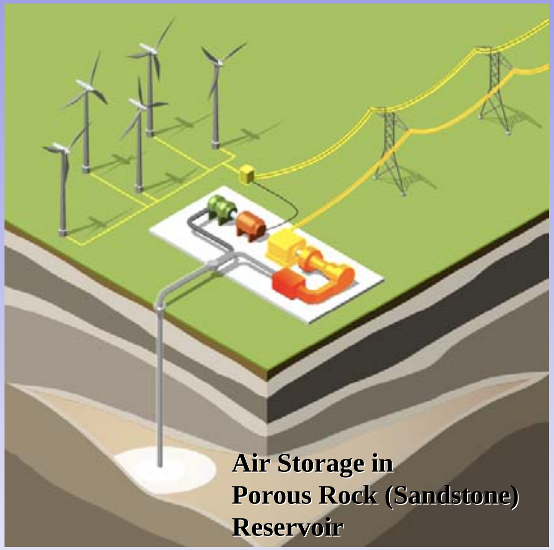


Figure 18 Porous Rock CAES Storage Volume (Katz and Lady 1976)

CAES PROSPECTS FOR WIND BALANCING IN US

Class 4 + Wind Resources & Geology Suitable for CAES

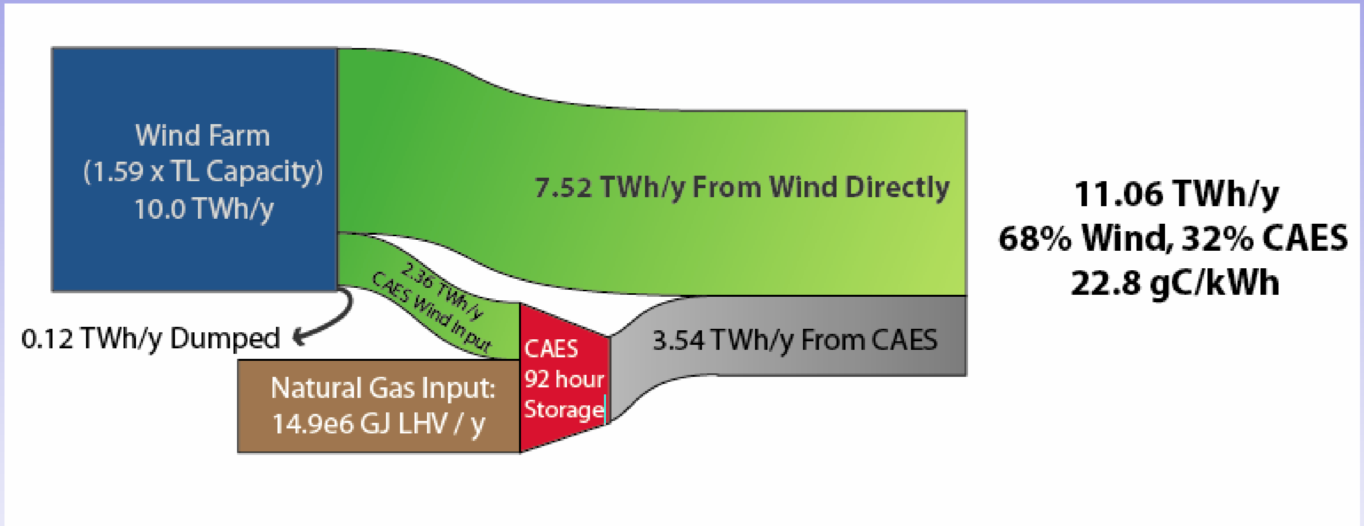




Planned 2011 Iowa Wind/CAES Plant
75 MW Wind + 268 MW CAES

- Deploying CAES in a large scale for wind balancing ➔ a substantial role for aquifers
- Natural gas storage experience provides relevant tools for analyzing site suitability
- Care must be taken to address potential impacts of mineralogical reactions arising from introducing O_2 into reservoir
- Footprint of aquifer needed to “baseload” wind is ~2% of wind farm land area

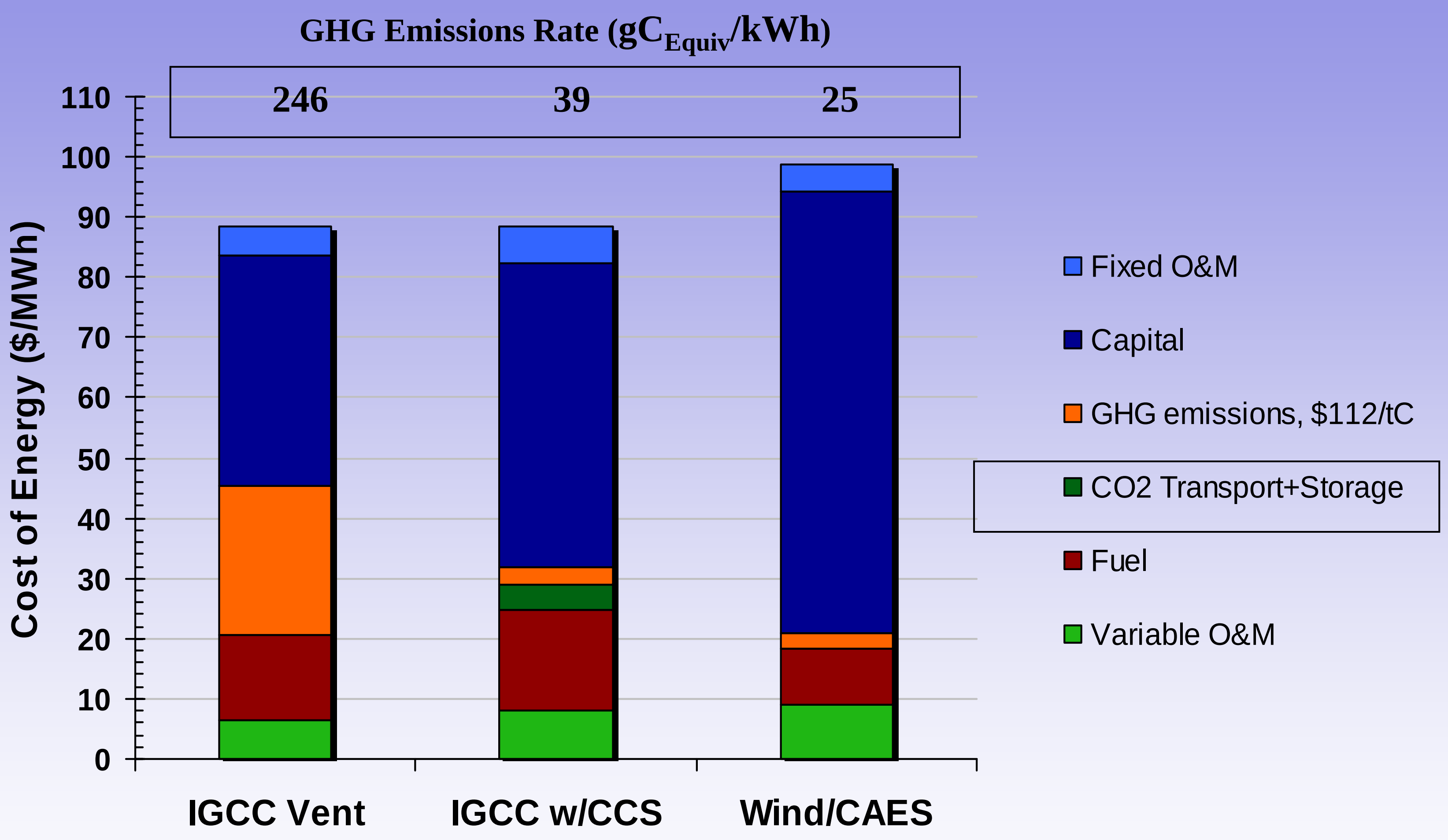
ANNUAL ENERGY FLOWS FOR WIND/CAES



System designed to "baseload" a 2 GW_e transmission line @ 85% capacity factor

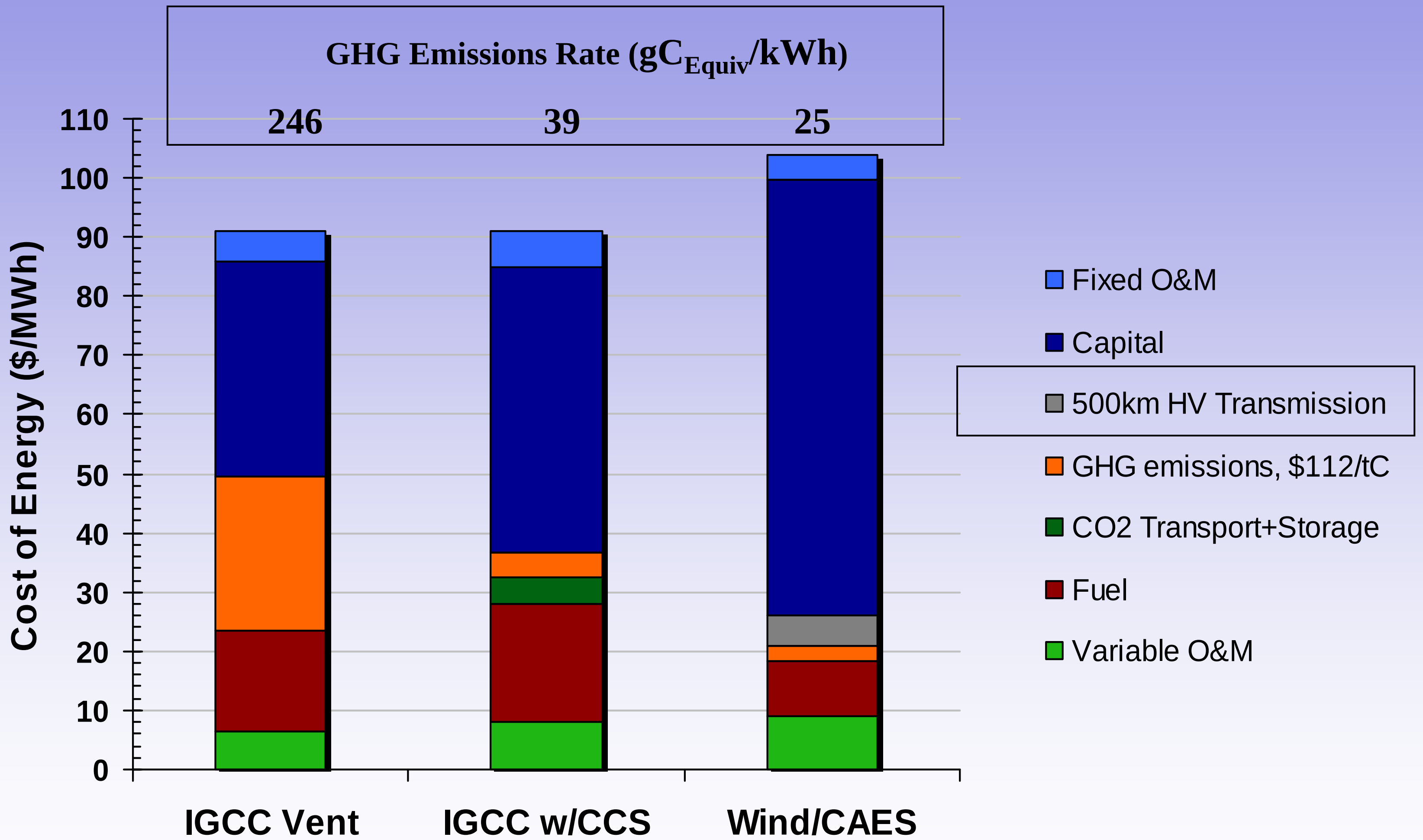
Transmission losses not reflected

GENERATION COSTS FOR BASELOAD OPTIONS



These systems are designed to have capacity factors of 80% for coal IGCC and 85% for wind/CAES

GENERATION COSTS FOR BASELOAD OPTIONS WHEN WIND IS REMOTE

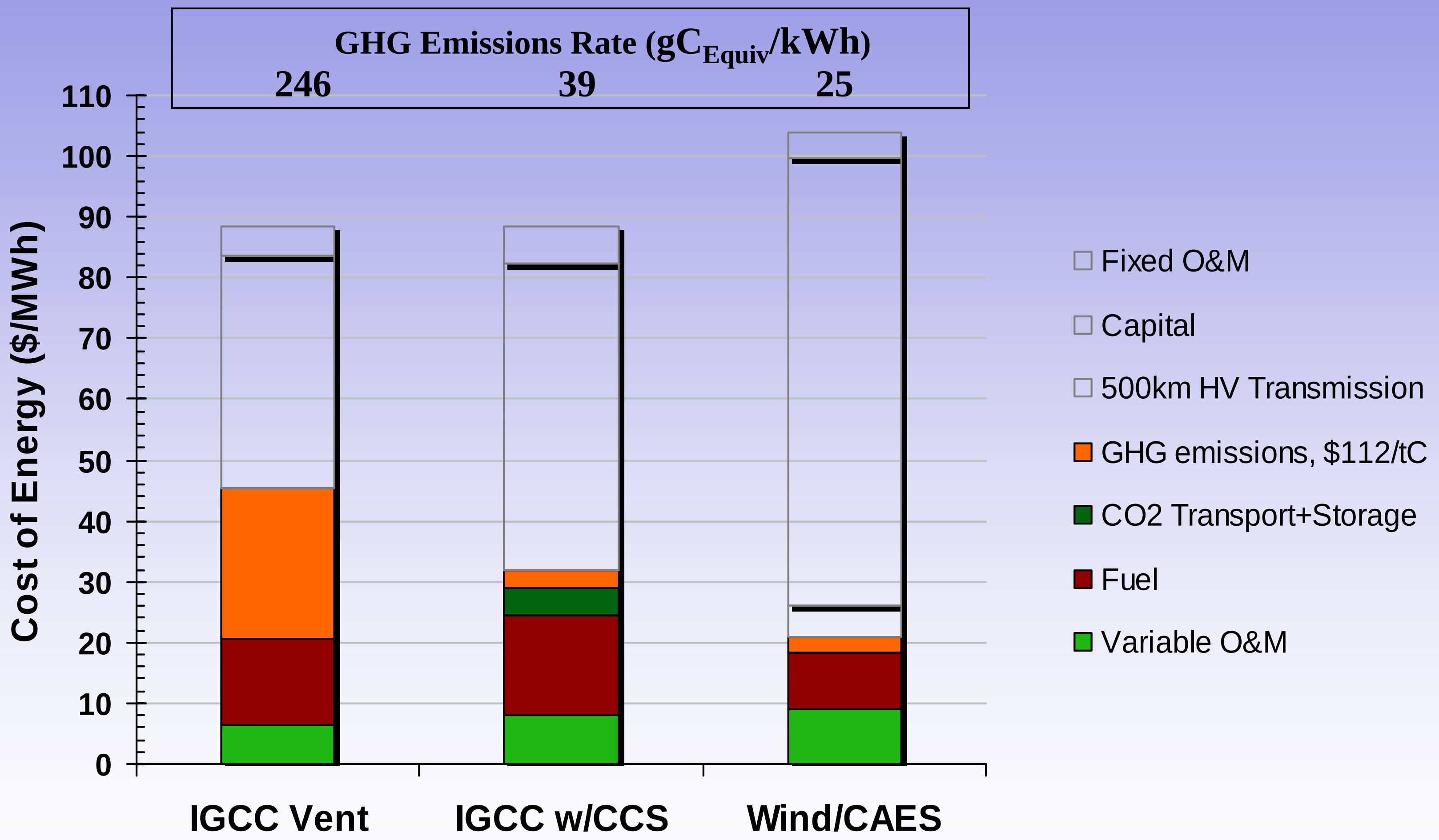


These systems are designed to have capacity factors of 80% for coal IGCC and 85% for wind/CAES

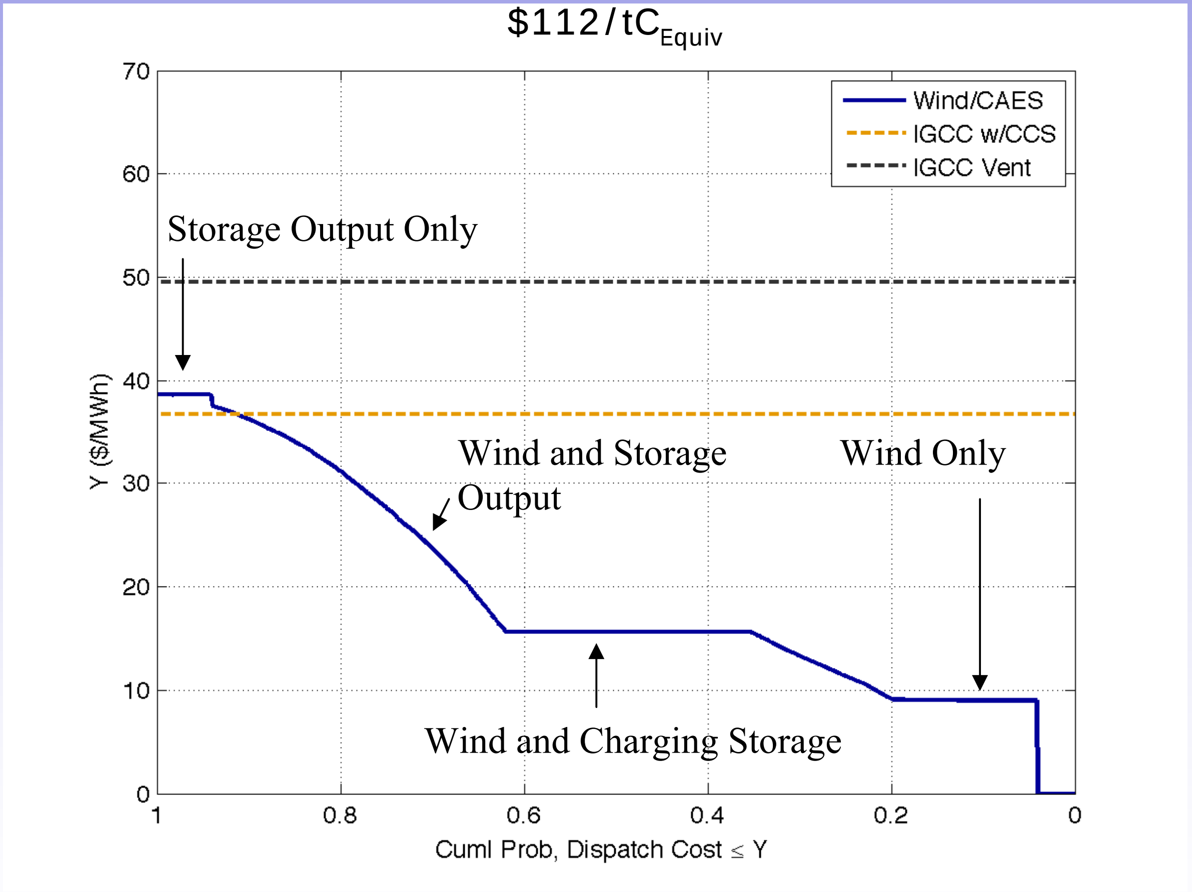
DISPATCH COST ISSUES

- Capacity factors cannot be specified—rather, they are determined in economic dispatch
- **Dispatch Cost**: fuel + variable operations and maintenance + greenhouse gas emissions price + CO_2 transport + storage = short-run marginal cost
- The ordering of power systems called upon to provide power to grid is based on dispatch cost
- Baseload viability requires competitive dispatch costs to sustain large capacity factors

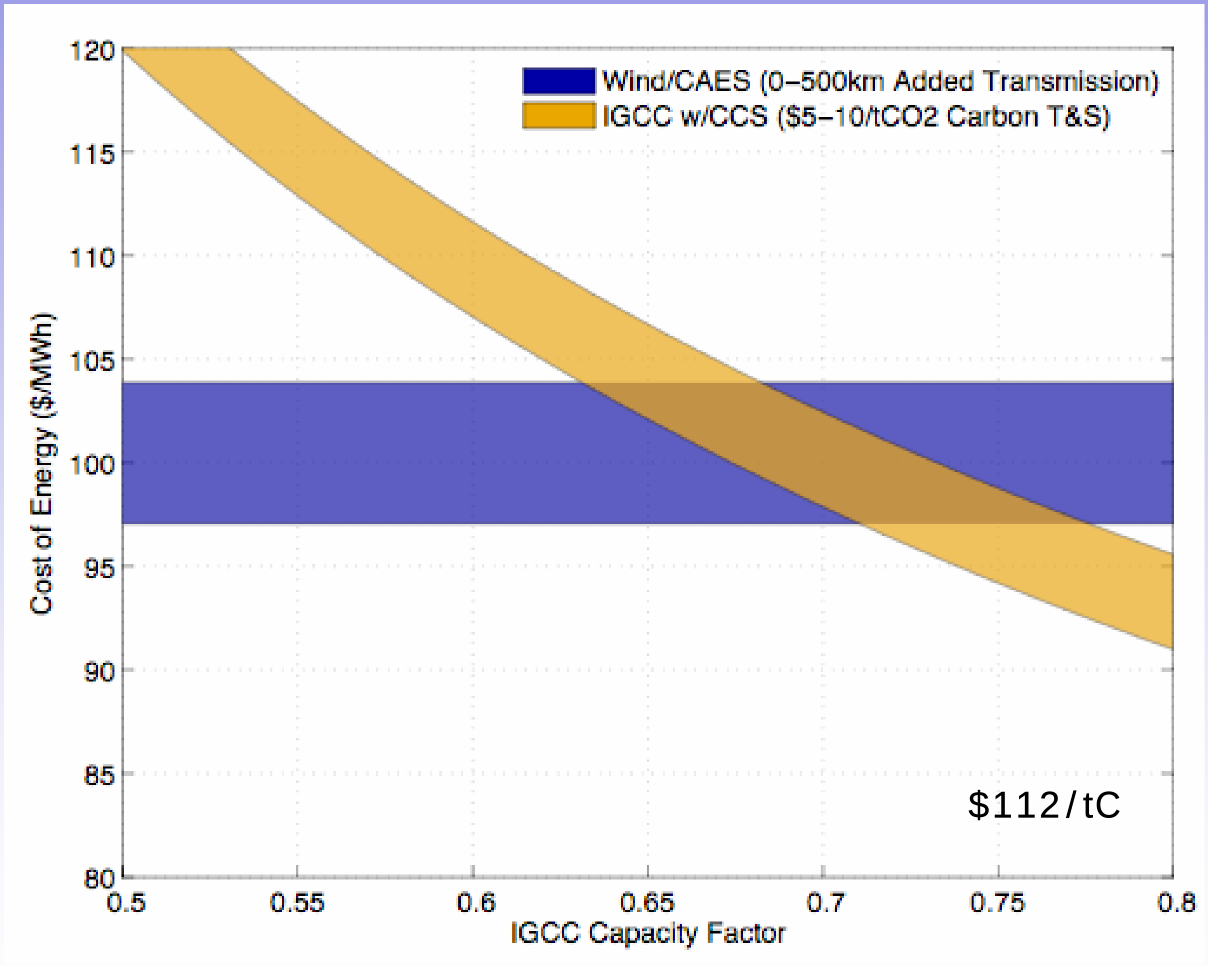
AVERAGE SHORT-RUN MARGINAL COSTS FOR BASELOAD OPTIONS



DISPATCH COST FOR BASELOAD OPTIONS



DISPATCH COMPETITION WOULD FORCE DOWN IGCC CAPACITY FACTOR AND INCREASE ITS GENERATION COST



PRIORITIES FOR WIND/CAES DEVELOPMENT

- Detailed assessments—region-by-region basis—of:
  - Geologies suitable for CAES
  - Wind/CAES coupling opportunities
  - Economic assessments of wind/CAES systems
- R&D on aquifer CAES—e.g., addressing chemical and biological implications of introducing O_2 underground
- Commercial-scale wind/CAES projects in various geologies
- Concerted effort could lead to good understanding of true wind/CAES potential over a 10-15 year period

SUMMARY

- A high priority for carbon mitigation for power:
  - sharply curb CO_2 emissions from coal power generation
  - Commence effort immediately
- Nuclear, coal power with CCS, and wind/CAES are major alternative options for addressing this challenge:
  - None probably supply constrained
  - All roughly cost-competitive
  - None are "squeaky clean"—tradeoffs

SUMMARY (continued)

- Public policy priorities:
  - Megascale experience ASAP with CO_2 storage and wind/CAES to have confidence in gigascale viability of these technologies
  - Repair/strenghthening of non-proliferation regime before encouraging more rapid deployment of nuclear power
- With concerted efforts, prospective gigascale roles of all three options should be clear by 2020
- Non-climate considerations will probably determine technology mix under climate-change-mitigation policy

DIVERSION-RESISTANCE CRITERIA FOR FUTURE NUCLEAR POWER

R.H. Williams and H.A. Feiveson,

Energy Policy, **18** (6): 543-549, 1990

- Restrictions on sensitive nuclear technologies shall be non-descriminatory among nations
- Fissionable weapons-usable material that is not contained in spent fuel and facilities to enrich uranium or to separate plutonium shall not exist outside international centers
- As far as possible, fissionable material that is not contained in spent fuel shall not be produced even in international centers
- Spent fuel shall be stored and disposed of in international centers
- Reactors under national authority shall be designed to reduce to very low levels the production of weapons usable materials in spent fuel (*of the order of a critical mass or less per year per* GW_e *of capacity*)

Extra Slides

FINANCIAL PARAMETERS FOR LEVELIZED COST CALCULATIONS

Construction period (years)	1: wind, 2: transmssion lines, 3: CAES, 4: coal power, 7: nuclear power
Inflation rate (%/year)	2.3
Book/tax life (years)	30/20
Depreciation (for tax purposes)	MACRS
Corporate income tax rate (%)	38.2
Property taxes & insurance (%/year)	2
Nominal (real) return on equity (%/year)	12 (9.4)
Nominal (real) return on debt (%/year)	9 (6.5)
Equity/Debt ratio	50/50