Future of Coal and Nuclear Power

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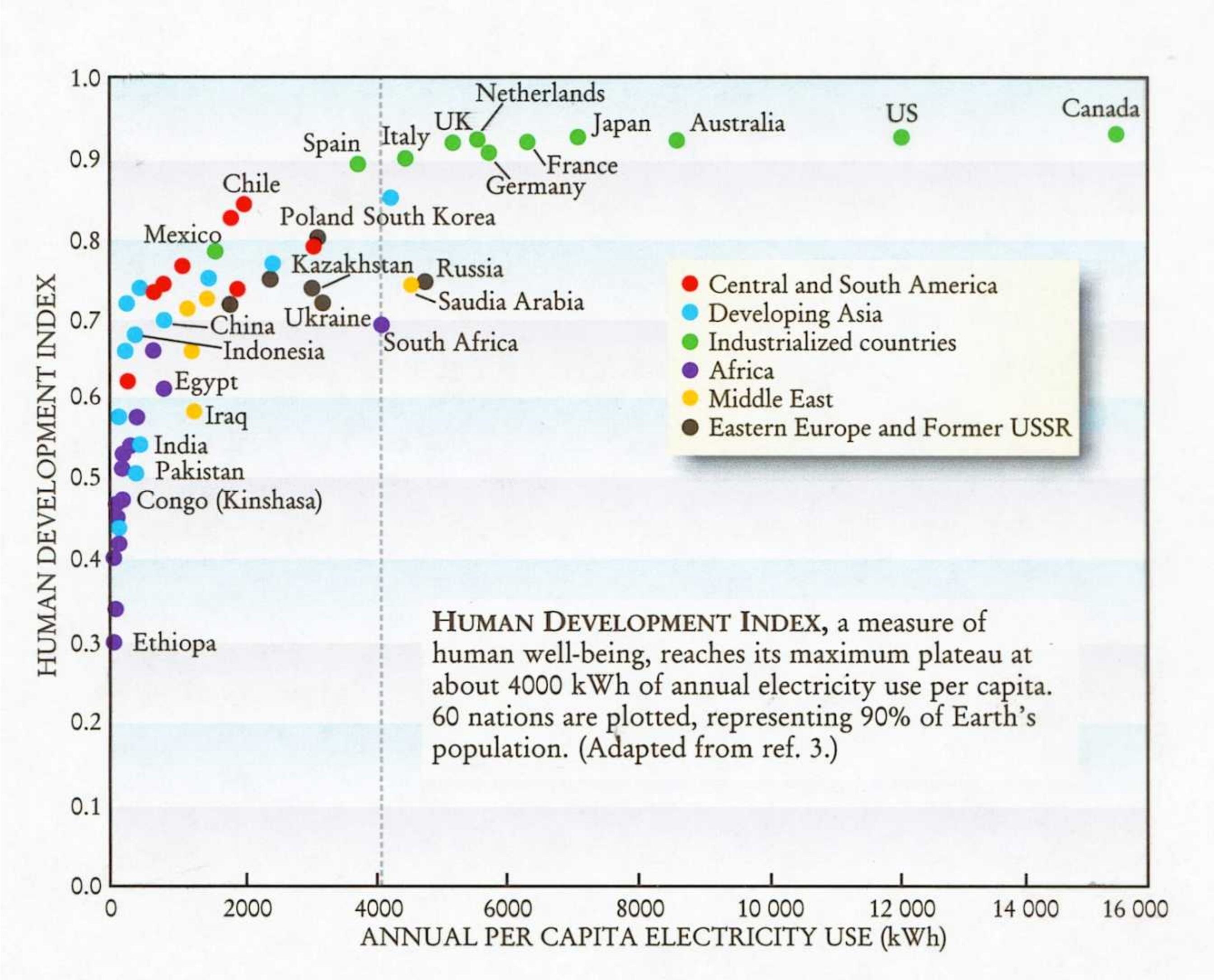
NAE Engineering Achievement of the Twentieth Century

- Electrification
- Reflects both the technological challenge of this continent-scale system and the ubiquitous contribution to quality of life

Annual Per Capita Electricity Use (kWh)



HUMAN DEVELOPMENT INDEX, a measure of human well-being, reaches its maximum plateau at about 4000 kWh of annual electricity use per capita. 60 nations are plotted, representing 90% of Earth's population. (Adapted from ref. 3.)

MIT Joint Program on the Science and Policy of Global Change

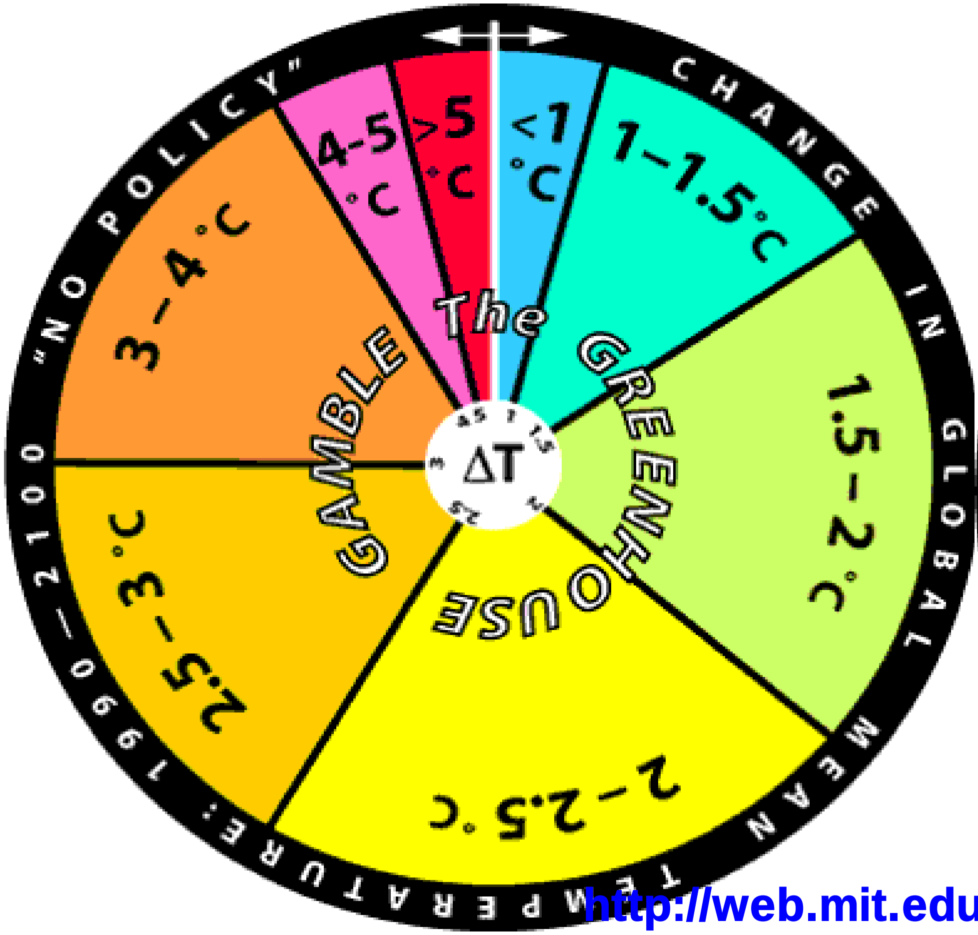
H. Jacoby and R. Prinn, co-directors

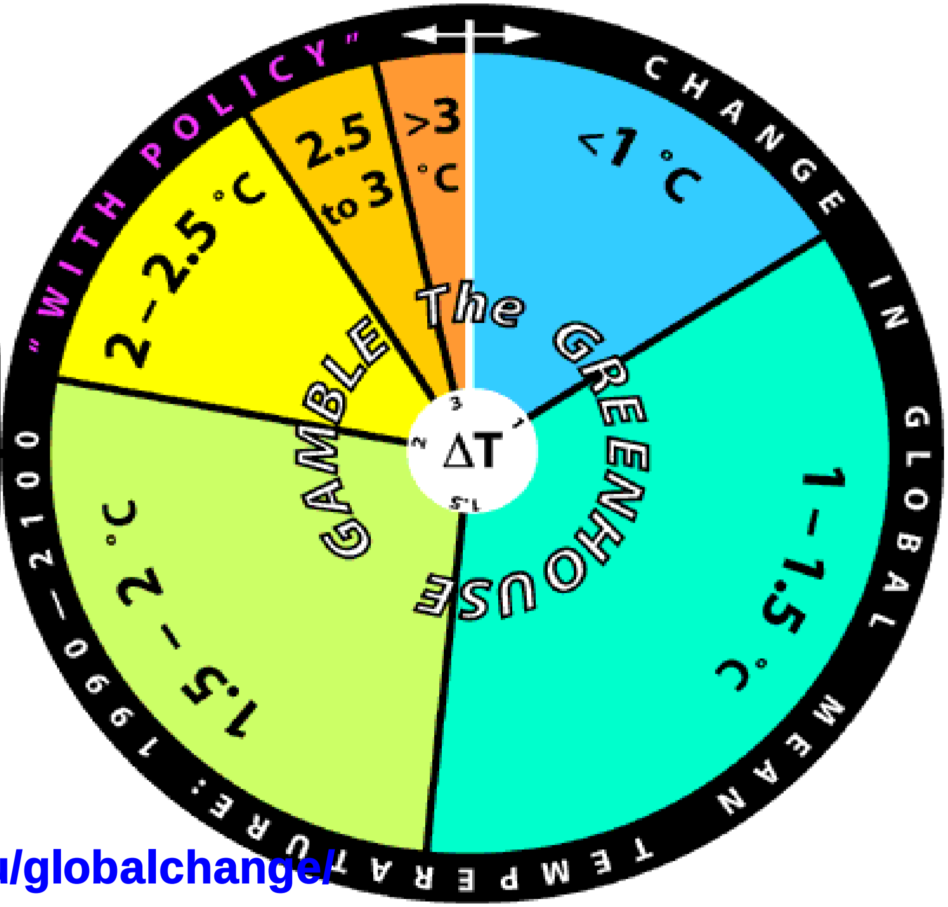
HOW CAN WE EXPRESS THE VALUE OF A CLIMATE POLICY UNDER UNCERTAINTY?

Compared with NO POLICY

What would we buy with STABILIZATION of CO_2 at 550 ppm?

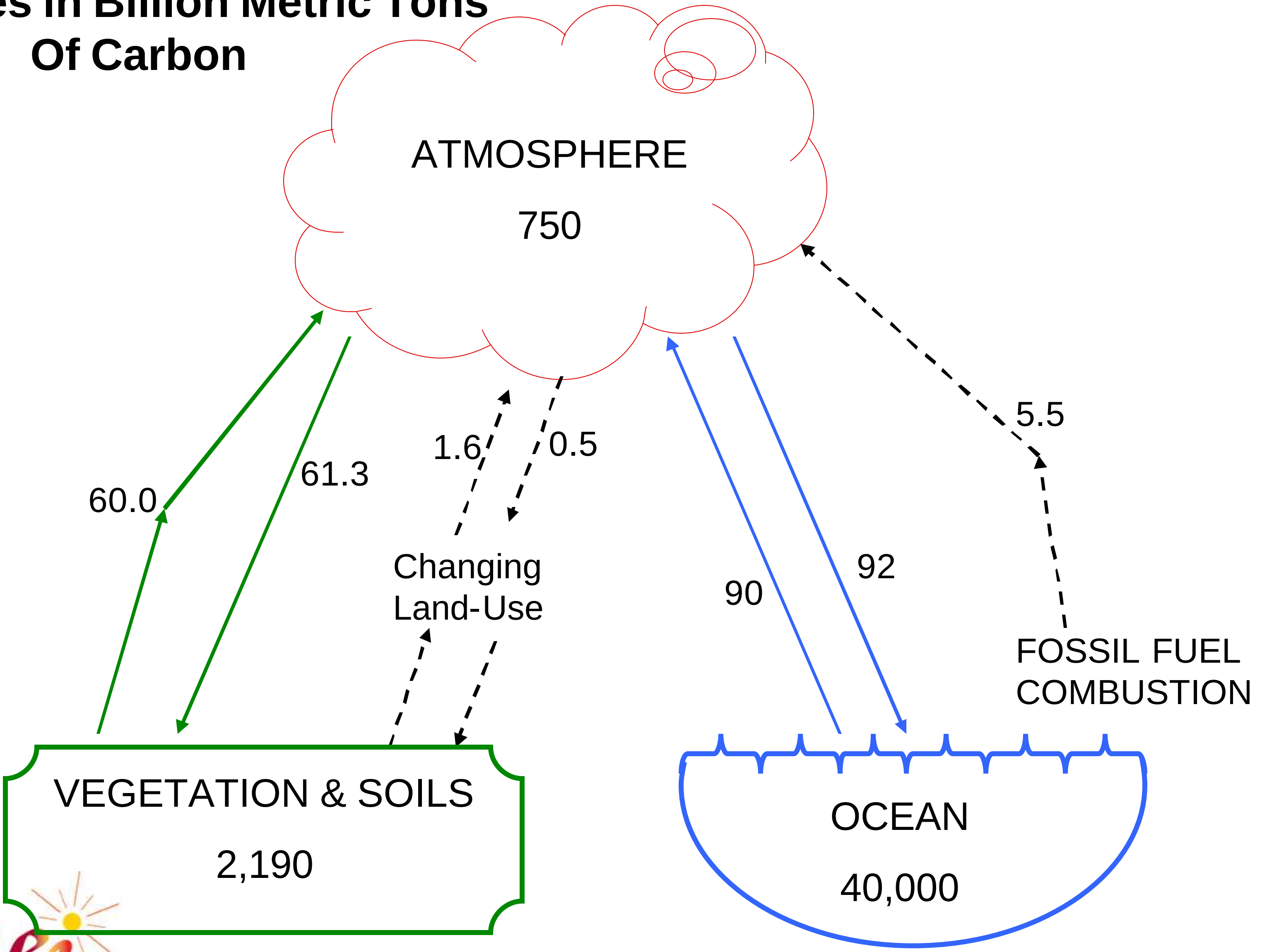
A NEW WHEEL with lower odds of EXTREMES





http://web.mit.edu/globalchange/

Global Carbon Cycle (IPCC/EIA) All Entries in Billion Metric Tons Of Carbon



US Carbon Dioxide Emissions (EIA BAU)

Millions of Metric Tons

	Residential + Commercial		Industrial		Transportation		Total	
	2006	2030	2006	2030	2006	2030	2006	2030
Petroleum	153	137	421	436	1952	2145	2526	2718
Natural Gas	392	483	399	433	33	43	824	959
Coal	10	9	189	217	0	0	227	198
Electricity	1698	2295	642	647	4	5	2344	2947
TOTAL	2253	2924	1651	1733	1989	2193	5921	6822
		1.1%/yr		0.2%/yr		0.4%/yr		0.6%/yr

Coal and Nuclear Power

Largest contributors to US baseload electricity generation

- Coal: about 50%
- Nuclear: about 20%
- Natural gas: about 17%

CHALLENGES for TW/Gigaton-C SCALE in 2050

3x nuclear; 600 GW coal with CCS

Economics

- Very capital intensive: about \$3500-4000/kWe for nuclear and coal with CO2 capture (Progress Energy \$5000/kWe nuclear???)

“ALL-IN” CAPITAL COSTS ($/kWe)

5000		
4500		
	Solar PV	cost reduction? Interest rates? CF?
4000	SCPC with CC	sequestration? Retrofits?
	Oxyfiring with CC	sequestration?
	IGCC with CC	reliability? Sequestration?
3500	Nuclear	licensing? Waste management? Finance?
	Biomass CFB	co-firing option?
3000	Solar thermal	
2500	IGCC-no CC	why? Retrofit?
2000	SCPC-no CC	licensing? CO2 charges?
	wind	intermittency? 30-40% capacity factor?
1500		
1000		
	NGCC	high/volatile NG prices? Dispatch?
500		
0		

Simple example

Caution : do not try to finance such power plants at home with these formulas!

Nuclear: about 6.75 cents/kWh

Coal without CCS: about {5.5 cents + 4.5 cents [CO2 price/$50 t-CO2]}/kWh

Coal with CCS: about {8.8 cents + 0.9 cents [CO2 price/$50 t-CO2]}/kWh

Crossover prices:

- Nuclear - coal without CCS: about $15/t-CO2
- Coal with and without CCS: about $45/t-CO2

Risk management/options???

Challenges cont'd

Back end

- Nuclear waste system not implemented
- Scale of CO2 sequestration huge: order of billion barrels of compressed CO2 for lifetime of a modest utility-scale coal plant

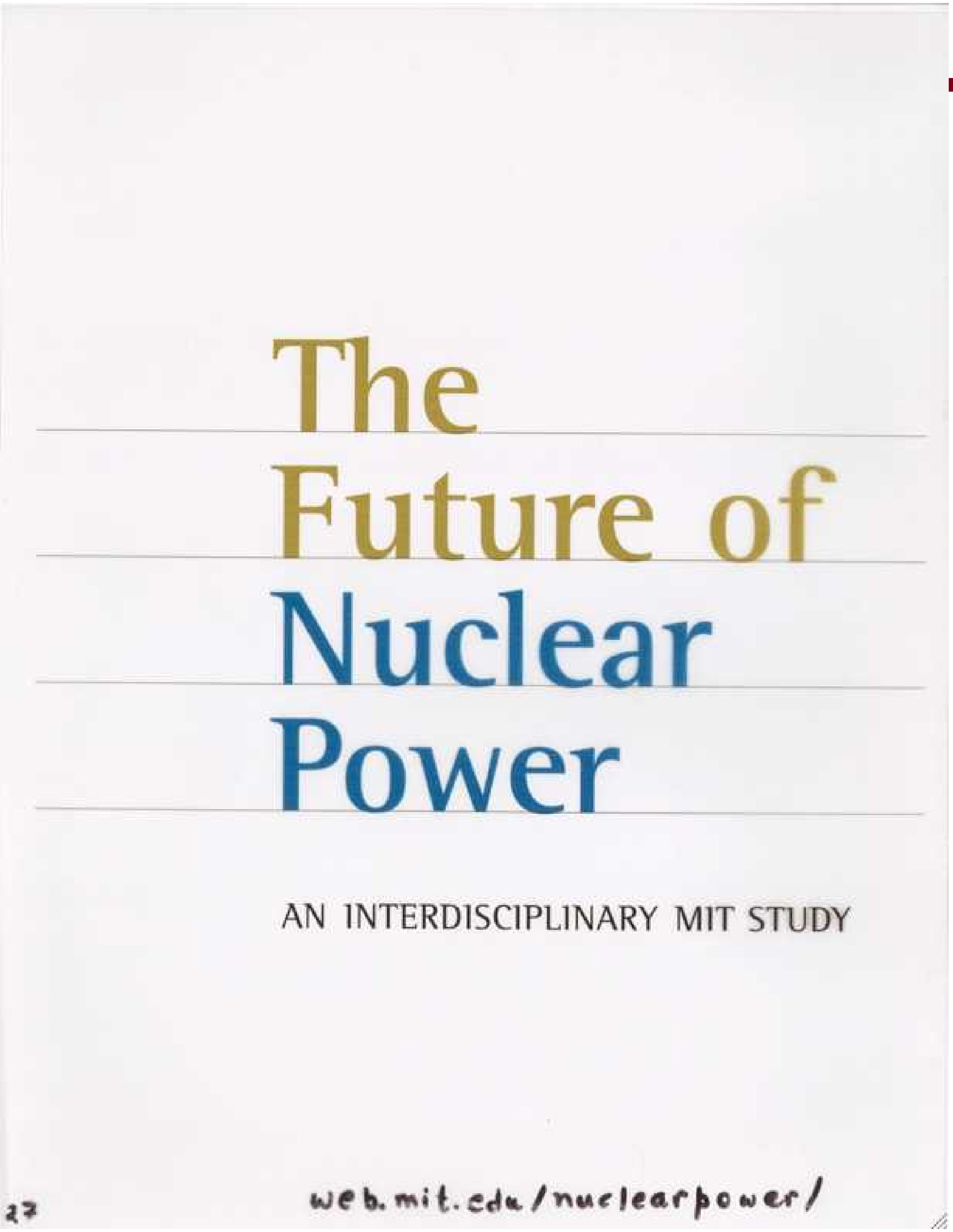
"Proliferation"

- Risks of creating nuclear weapons threshold states through nuclear fuel cycle development (e.g. Iran) and of enabling nuclear terrorism through separated plutonium diversion/theft
- Climate risk through proliferation of coal plants (e.g. 100 GW in China in 2006!)

Challenges cont'd

RD&D

- Relatively little advanced concept research for a long time (lots of "hand-me-downs")
- Very expensive commercial viability demonstrations associated with high capital costs and with absence of a suitable CO2 emissions price signal
- "First mover" issue for nuclear plants
- Lack of experience for coal conversion with CO2 capture and sequestration
- Promising new EFRCs initiative at DOE/Science to pursue fundamental enabling research



The Future of Nuclear Power

AN INTERDISCIPLINARY MIT STUDY

web.mit.edu/nuclearpower/

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Nuclear power future?

- Economics ?
- Nuclear spent fuel management?
- Proliferation risks/enrichment and reprocessing?

Reference frame

- GHG emissions and nuclear “renaissance”?
  - TW scale is a tripling
  - Inevitably a spread to new regions, some of proliferation risk

- Long term geological isolation of SNF/HLW appears to be scientifically sound in well chosen sites with good project execution
  - Once through fuel cycle is a viable economically-favored option for some time

- Storage of SNF for a century or so should be implemented

Reference frame cont'd

- APS POPA: "There is no urgent need for the US to initiate reprocessing or to develop additional national repositories…there is time to determine the best path for the next phase of the expansion of nuclear power…It Is important, however, to use that time effectively to explore the options more thoroughly than has been done to date."

Drivers of reconsideration of spent fuel management in US

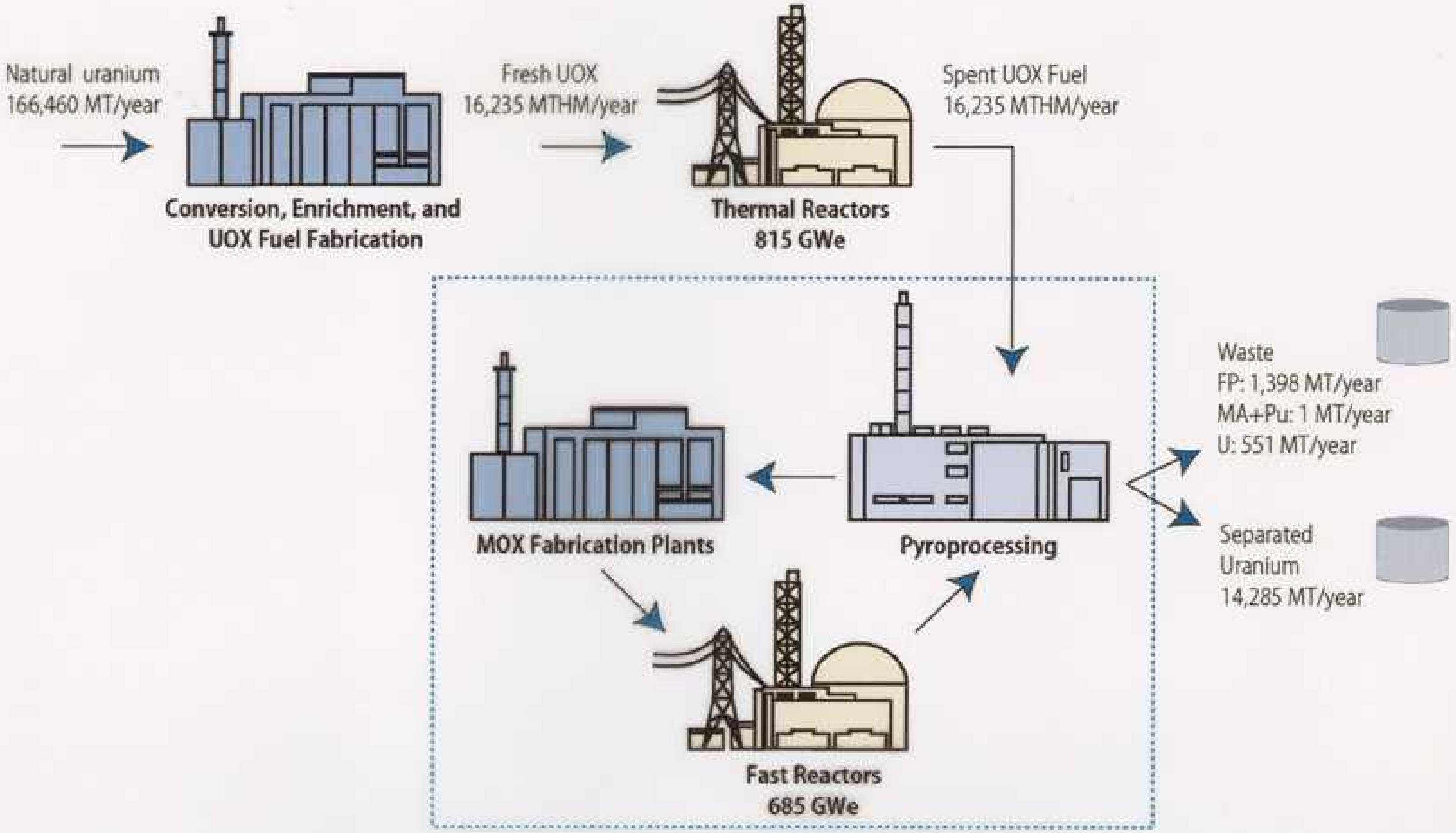
1. Renewed interest in nuclear power plant construction
2. Licensability of Yucca Mountain up in the air
3. Failure of government to begin acceptance of spent fuel, and implications for first mover initiative
4. Global expansion of nuclear power creats challenges for nonproliferation treaty regime
5. Administration proposed Global Nuclear Energy Partnership, entailing advanced fuel cycles that reprocess spent fuel and recycle all actinides

MITei

Spent fuel reprocessing

- Links waste and nonproliferation considerations
  - Long term heating from actinides and weapons usability
  - Risk primarily with enrichment and reprocessing
  - Today about 250 tons of separated plutonium globally
  - Exaggerated claims for waste management benefits of PUREX/MOX fuel cycle
  - New technologies may address these concerns and provide significant waste management benefits

Figure 4.3 Closed Fuel Cycle: Full Actinide Recycle — Projected to 2050



Nuclear fuel leasing

- Fresh fuel supply, used fuel return
- “supplier” states and “user” states
  - Marketplace reality today
  - “stay-put” period of 10 to 15 years
  - R&D participation
  - Fresh fuel incentives
    - E.g., CO2 emissions credits
    - Candidate user states in Mideast?

Near-term priorities

- Realize NPP “first mover” initiative/exercise EPACT05
- Establish process and program plan for moving SNF as soon as possible from reactor sites to one or more Federal locations for interim storage and security
    - Satisfy NWPA requirements and “decouple” Federal and private sector imperatives
- Implement robust R&D program for both open and closed fuel cycles
- Pursue international fuel cycle arrangements based on “fuel leasing” concept of assured nuclear fuel supply and spent fuel return

The Future of Coal

OPTIONS FOR A
CARBON-CONSTRAINED WORLD

- Under most scenarios, coal use will grow even with a carbon tax.
    - Cheap, abundant, supply and demand well correlated (but most carbon intensive)

- The development of “competing” base load technologies, such as nuclear and natural gas, will affect coal use.

- The long term future of coal use, and an associated abatement of CO2 emissions, are sensitive to the development and public acceptance of Carbon Capture and Sequestration (CCS) technology and the timely provision of incentives to its commercial application.

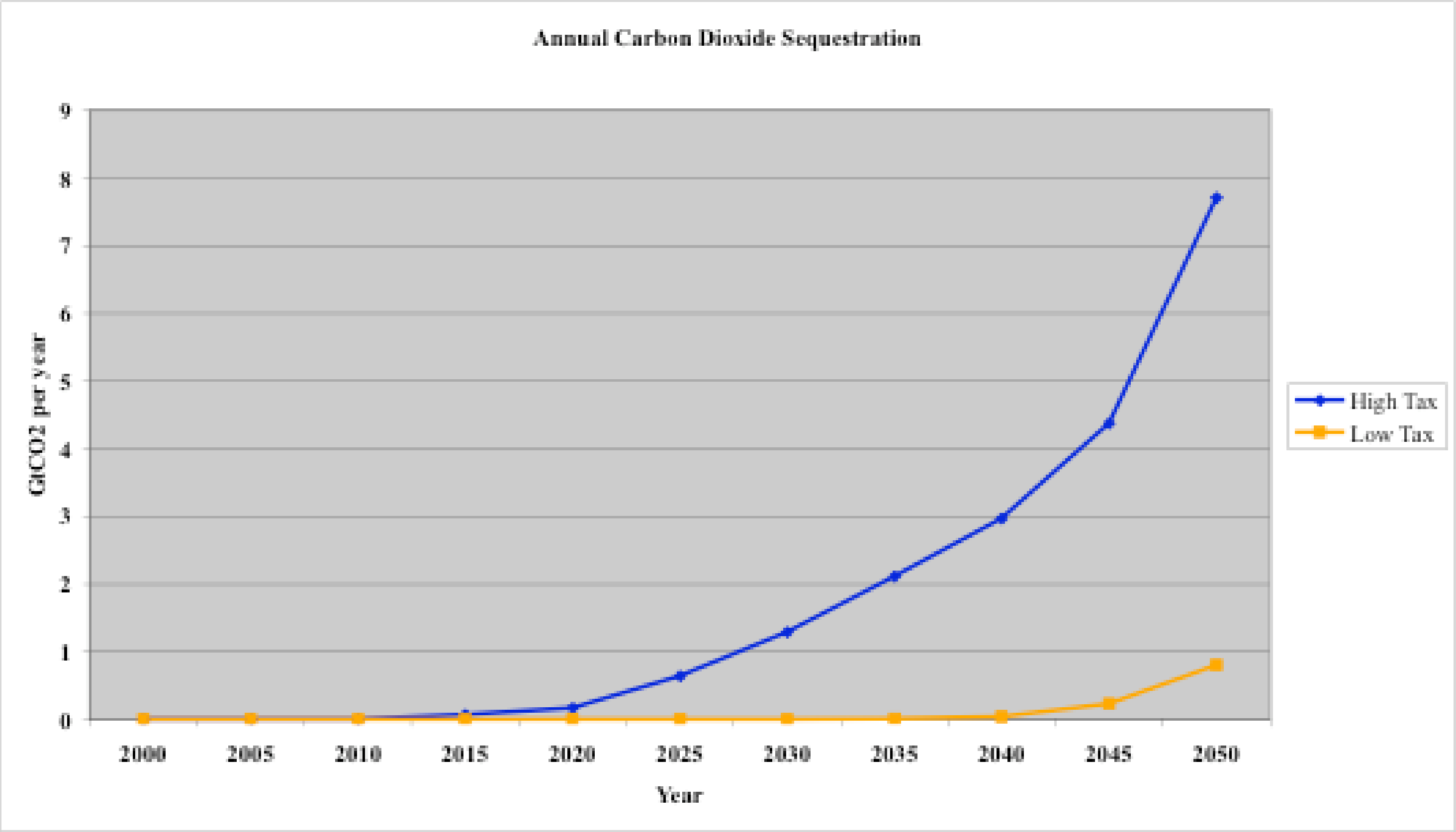
- Scale is a major issue.
    - Megatonne/year for plant
    - Hundred megatonne/plant lifetime (Billion barrels)
    - Gigatonne/year global to significantly mitigate climate risks.

	China	India	USA	% of	World
Population (B)	1.3	1.1	0.3	42	6.4
GDP[PPP] (T$)	1.7[7.0]	0.6[3.1]	10.7	37[40]	35[52.5]
Electricity (TWh)	2.1	0.5	3.9	41	16.0
CO2* (Bt-CO2)	4.7	1.1	5.8	44	26.6
Coal (Bt)	2.2	0.4	1.0	61	5.9

IEA 2006

* Fossil fuel combustion only

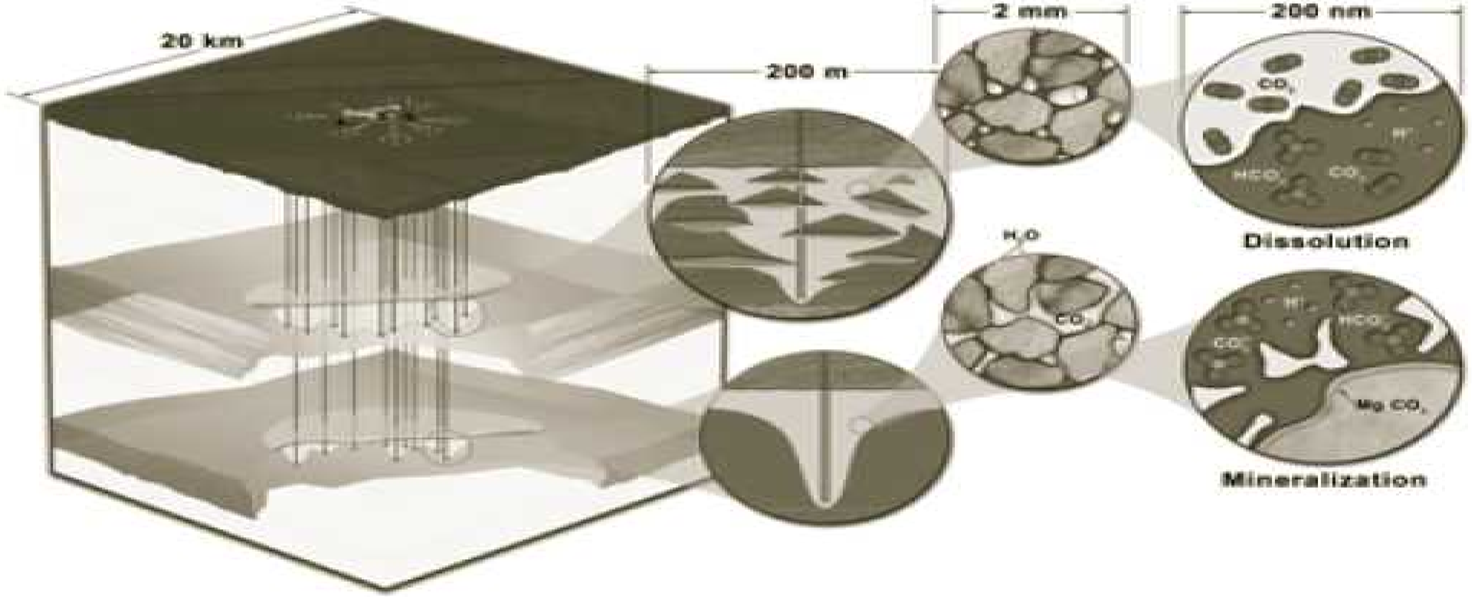
PPP = purchasing power parity


Annual Carbon Dioxide Sequestration
GtCO2 per year
0
1
2
3
4
5
6
7
8
9
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Year
High Tax
Low Tax

CO2 capture and geologic sequestration

- CO2 capture proven, but basic research needed to improve cost/performance
- Extensive technical program needed to resolve scientific issues for storage of Gigatonne quantities annually
- Immense infrastructure requirements need study
- Broad range of regulatory issues to be resolved (permitting, liability, monitoring,…)
- Urgently need to put 10-15 year research and demonstration program in place; it must operate at large scale to resolve issues

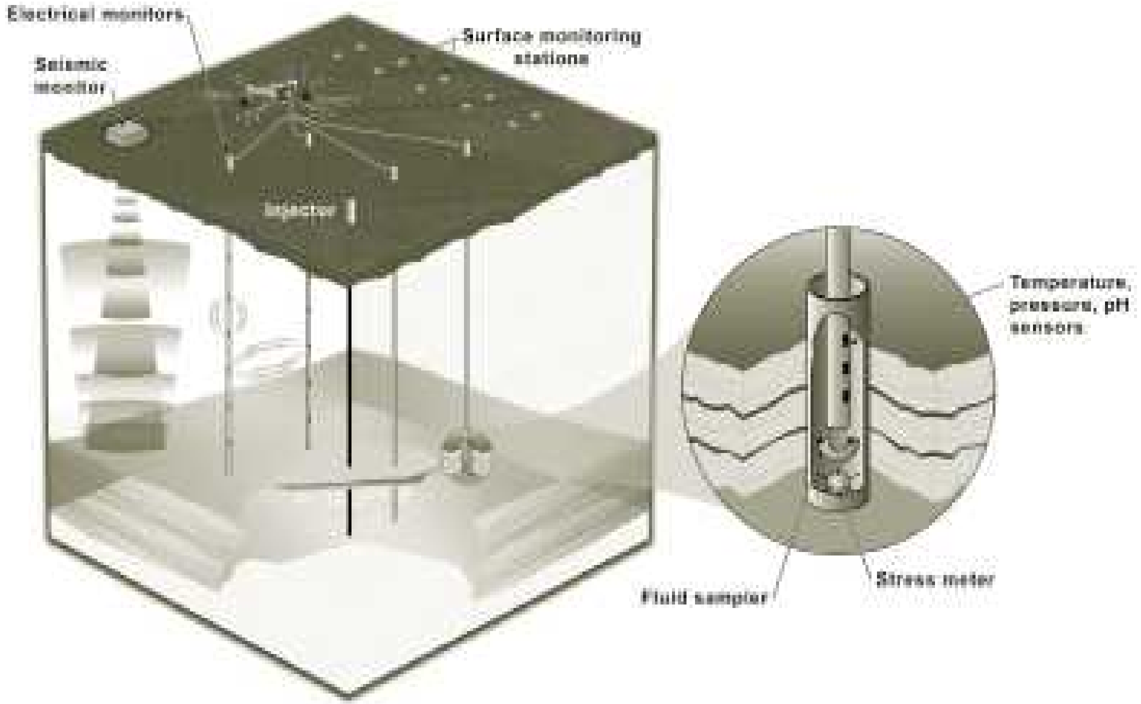
Figure 4.1 Schematic of Sequestration Trapping Mechanisms



Schematic diagram of large injection at 10 years time illustrating the main storage mechanisms. All CO_2 plumes are trapped beneath impermeable shales (not shown) The upper unit is heterogeneous with a low net percent usable, the lower unit is homogeneous. Central insets show CO_2 as a mobile phase (lower) and as a trapped residual phase (upper). Right insets show CO_2 dissolution (upper) and CO_2 mineralization (lower)

Monitored experiments essential

Figure 4.3 Hypothetical Site Monitoring Array



Schematic diagram a monitoring array providing insight into all key parameters. Note both surface and subsurface surveys and down-hole sampling and tool deployment. A commercial monitoring array would probably be much larger.

Technology alternatives for coal plants

- Pulverised coal - air driven and oxy-fired
- Integrated gasification combined cycle (IGCC)
- Advanced concepts, e.g. chemical looping

- Optimized capture plant always quite different from non-capture plant
  - Retrofit complicated and capture ready not very convincing
- Coal quality matters a lot
- No clear technology winner

Efficiency loss for CO_2 Capture

Figure 3.11 Parasitic Energy Requirement for Oxy-Fuel Pulverized Coal Generation with CO_2 Capture Vs. Supercritical PC without CO_2 Capture

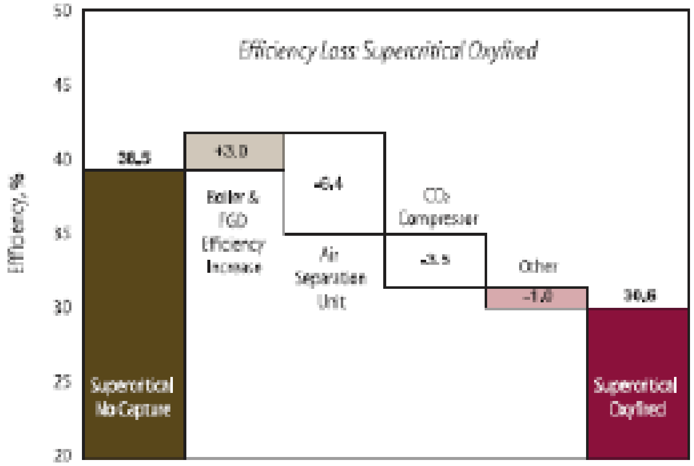
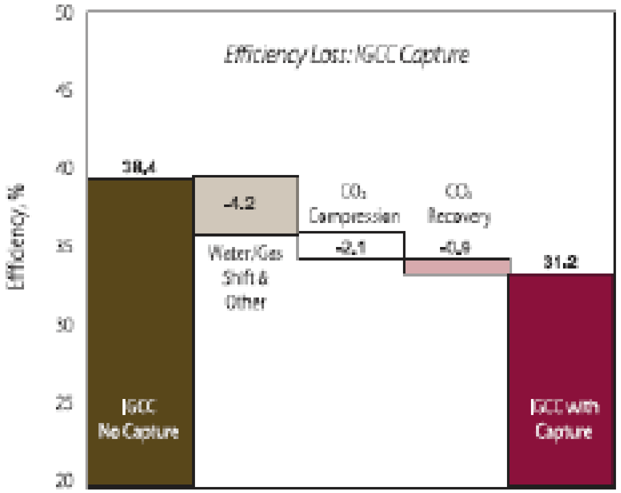
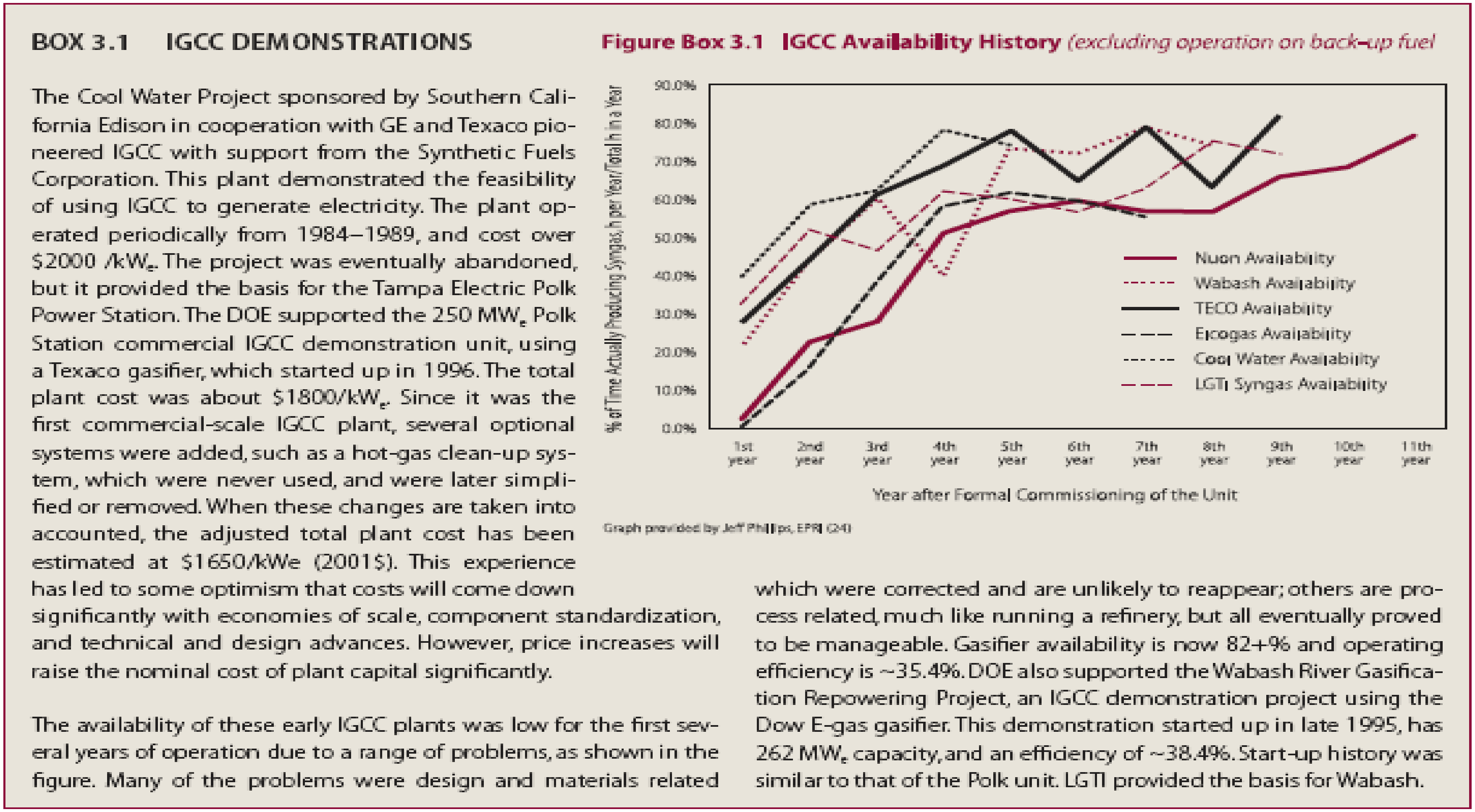


Figure 3.14 Parasitic Energy Requirement for IGCC with Pre-Combustion CO_2 Capture



Capture technology based on old, proprietary technologies from Oil industry, e.g RECTICSOL, SELEXOL, Amine scrub.



BOX 3.1 IGCC DEMONSTRATIONS

The Cool Water Project sponsored by Southern California Edison in cooperation with GE and Texaco pioneered IGCC with support from the Synthetic Fuels Corporation. This plant demonstrated the feasibility of using IGCC to generate electricity. The plant operated periodically from 1984–1989, and cost over \$2000 /kW$_e$. The project was eventually abandoned, but it provided the basis for the Tampa Electric Polk Power Station. The DOE supported the 250 MW$_e$ Polk Station commercial IGCC demonstration unit, using a Texaco gasifier, which started up in 1996. The total plant cost was about \$1800/kW$_e$. Since it was the first commercial-scale IGCC plant, several optional systems were added, such as a hot-gas clean-up system, which were never used, and were later simplified or removed. When these changes are taken into accounted, the adjusted total plant cost has been estimated at \$1650/kWe (2001\$). This experience has led to some optimism that costs will come down significantly with economies of scale, component standardization, and technical and design advances. However, price increases will raise the nominal cost of plant capital significantly.

Figure Box 3.1 IGCC Availability History *(excluding operation on back-up fuel*

Graph provided by Jeff Phillips, EPRI (24)

The availability of these early IGCC plants was low for the first several years of operation due to a range of problems, as shown in the figure. Many of the problems were design and materials related which were corrected and are unlikely to reappear; others are process related, much like running a refinery, but all eventually proved to be manageable. Gasifier availability is now 82+% and operating efficiency is ~35.4%. DOE also supported the Wabash River Gasification Repowering Project, an IGCC demonstration project using the Dow E-gas gasifier. This demonstration started up in late 1995, has 262 MW$_e$ capacity, and an efficiency of ~38.4%. Start-up history was similar to that of the Polk unit. LGTI provided the basis for Wabash.

“FutureGen”

- Need commercial viability demonstration of utility-scale coal combustion/conversion plants with CO_2 capture
  - with URGENCY
- Estimated cost $4B over 10-15 years for three projects, with sequestration
  - if CO_2 supplied by demo plants
- FutureGen = integrated IGCC+CCS “restructured” by Administration
- In principle, new funding approach sensible for commercial viability demonstration
  - but need to move forward with the FutureGen project to avoid loss of another 3-5 years
  - Might also consider separating out sequestration demo as government project

Highest priority

- Move aggressively to demonstrate sequestration at scale, including development of regulatory regime

- Demonstrate integrated systems with CCS
  - Need a portfolio of projects (power, synthetic gas,…)
  - As close to commercial practice as possible (outside approps, govt procurement,…)
  - Consider quasi-government corporation

- Rule out grandfathering

- Reestablish as strong research program at PDU scale (e.g., new capture technologies,…), as well as basic research (EFRCs)

Energy Frontier Research Centers (EFRCs)

* proposed by DOE/Science/BES for FY09 initiation

* accelerate rate of scientific breakthroughs needed for future advanced energy technologies

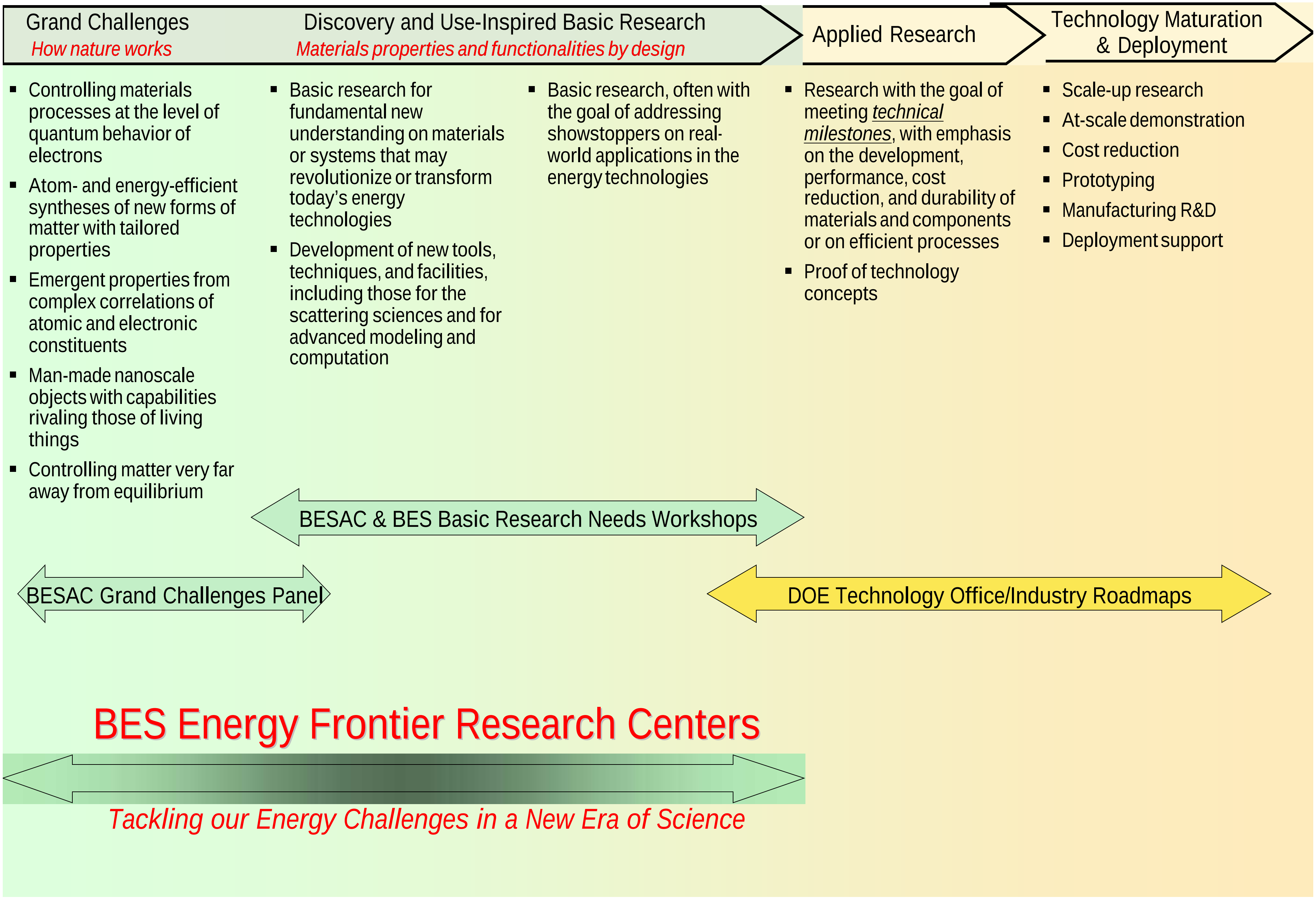
* developed through multi-year portfolio development and multiple well-attended workshops

* research focus areas of direct relevance to nuclear and coal are
    * new generation of radiation-tolerant materials and chemical separation processes for fission applications
    * science-based geological carbon sequestration

Dr. Harriet Kung

2/21/08 Presentation to BESAC

How Nature Works … to … Materials by Design … to … Technologies for the 21st Century



Grand Challenges
How nature works

Discovery and Use-Inspired Basic Research
Materials properties and functionalities by design

Applied Research

Technology Maturation & Deployment

- Controlling materials processes at the level of quantum behavior of electrons
- Atom- and energy-efficient syntheses of new forms of matter with tailored properties
- Emergent properties from complex correlations of atomic and electronic constituents
- Man-made nanoscale objects with capabilities rivaling those of living things
- Controlling matter very far away from equilibrium

- Basic research for fundamental new understanding on materials or systems that may revolutionize or transform today's energy technologies
- Development of new tools, techniques, and facilities, including those for the scattering sciences and for advanced modeling and computation

- Basic research, often with the goal of addressing showstoppers on real-world applications in the energy technologies

- Research with the goal of meeting *technical milestones*, with emphasis on the development, performance, cost reduction, and durability of materials and components or on efficient processes
- Proof of technology concepts

- Scale-up research
- At-scale demonstration
- Cost reduction
- Prototyping
- Manufacturing R&D
- Deployment support

BESAC & BES Basic Research Needs Workshops

BESAC Grand Challenges Panel

DOE Technology Office/Industry Roadmaps

BES Energy Frontier Research Centers

Tackling our Energy Challenges in a New Era of Science

Observations

- We are very likely to need substantial contributions from nuclear power and from coal with CCS in order to meet marginally prudent goals such as doubling of pre-industrial CO2 concentrations
    - This is in addition to improved efficiency, more natural gas, and renewables
- We do not seem able to generate the sense of urgency called for when one considers the train wreck of a “ticking climate clock” and a highly inertial energy supply system
    - The “experts” are more concerned than the public!
- The building blocks for enabling nuclear power and coal with CCS to be viable options for the energy marketplace when CO2 pricing is substantial are clear and largely in place, but the commitment to utilize them remains inadequate