Lessons Learned from U.S. Government Support of Clean Coal Technologies

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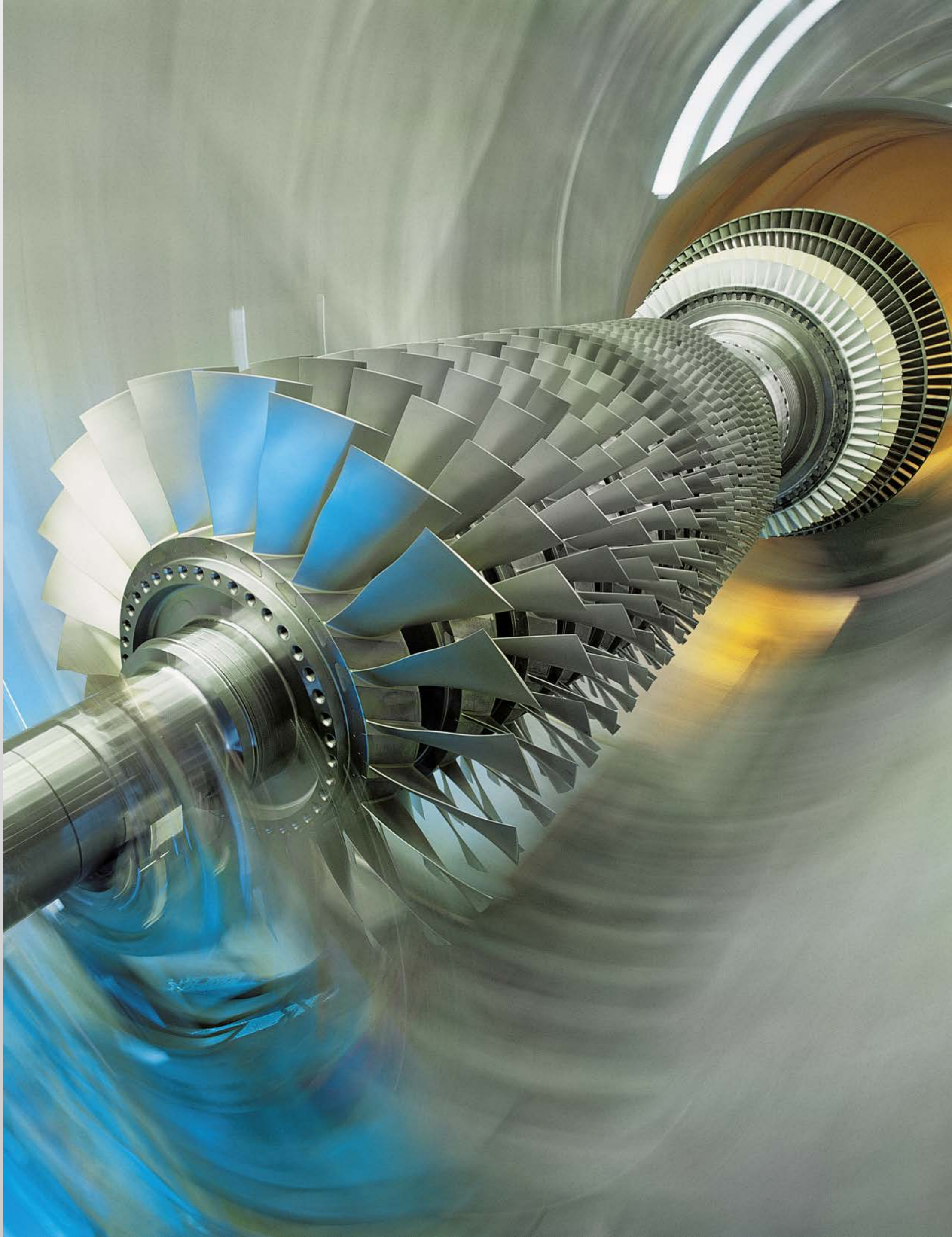
U.S. DEPARTMENT OF ENERGY | National Energy Technology Laboratory



National Energy Technology Laboratory

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MISSION

Advancing energy options to fuel our economy, strengthen our security, & improve our environment

Albany, Oregon

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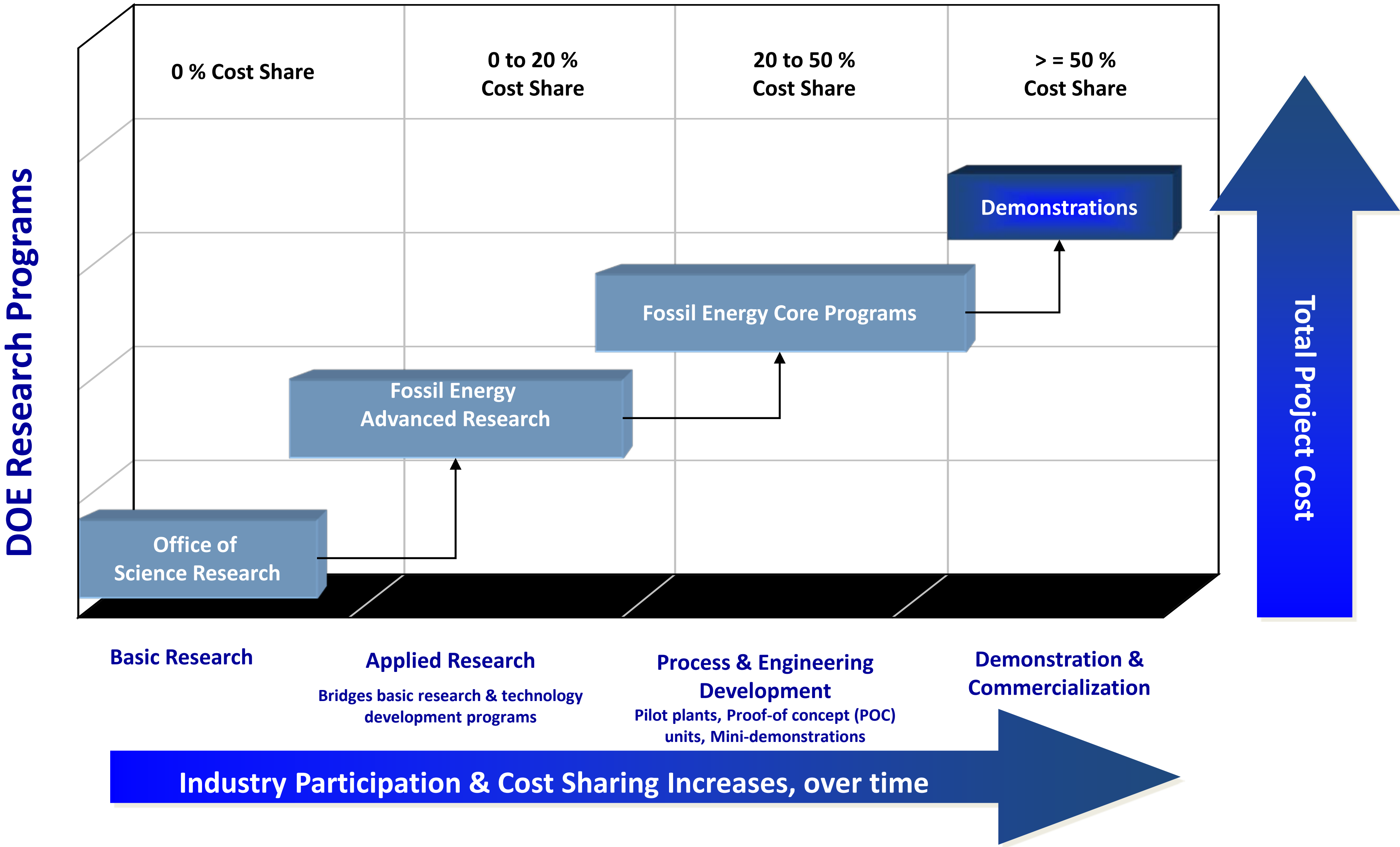
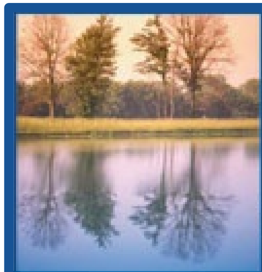
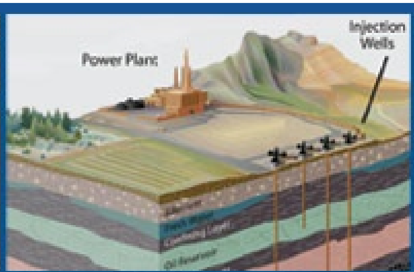
Teach oneself by exploring the old and deducing the new

Cost Share Ensures Commercial Relevance



Return on Investment from Fossil Energy RD&D





FE Research — The Return on Investment

$111 billion in benefits[1] ***$13 return for every $1 invested[3]***	***37 million add'l tons of avoided SO_2, 16 million add'l tons of avoided NO_x[1]***	***1.2 million jobs created[1]*** ***Thousands of researchers trained***	***12-fold increase in shale gas production[2]***	***10-fold increase in EOR using CO_2 injection[3]***	***50–70% cost reduction in mercury control at coal-fired power plants[4]***
2000–2020	**2000–2020**	**2000–2020**	**2000–2011**	**1985–2010**	**2000–2008**
Clean Coal program	***Clean Coal program***	***Clean Coal program***	***Natural Gas & Petroleum Technologies program***	***Natural Gas & Petroleum Technologies program***	***Mercury Control program***

[1]Bezdek, R. (2010). Costs and Benefits of DOE Investments in Clean Coal Technology: Implications for CCS. Presented at the Washington Coal Club, Washington, D.C., retrieved from www.washingtoncoalclub.org/docs/20100720_Bezdek.ppt. [2]Newell, R. (2011). Shale Gas and the Outlook for US Natural Gas Markets and Global Gas Resources. [3]Koottungal, L. (2010). 2010 Worldwide EOR Survey. Oil & Gas Journal, 108(14), 41–53. [4]http://www.netl.doe.gov/technologies/coalpower/ewr/mercury/pubs/NETLHgR_Darticlefuelprocessingnov09.pdf.

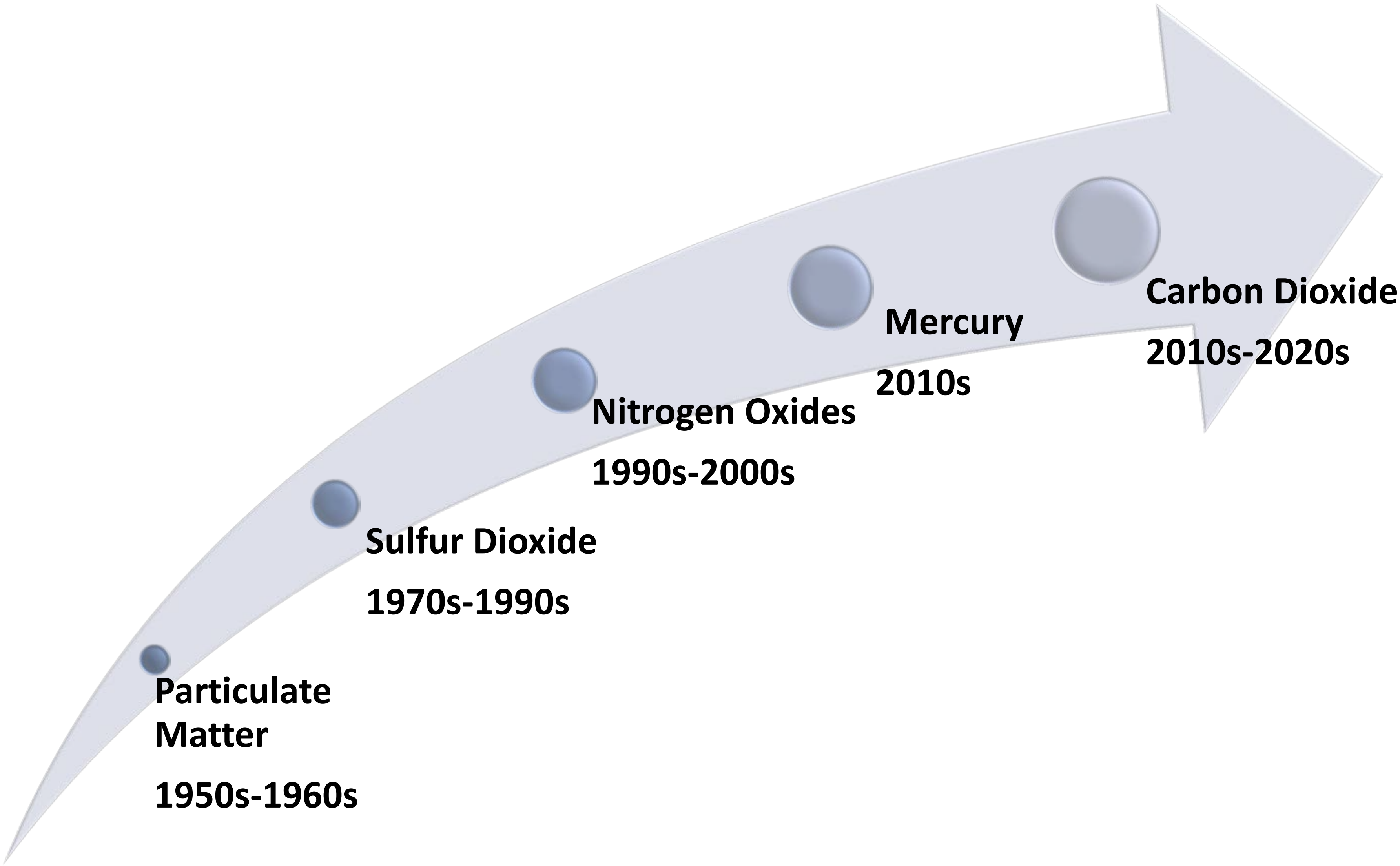
Comparison of Coal-Based Power Generation Platform Technologies

- **Pulverized Coal (PC) Boilers**
  - Commercialized in 1920s-1930s
  - Approximately 5000 units operating world-wide; 1100 in US
  - Unit sizes up to ~ 1300 MWe
- **Fluidized Bed Combustion (FBC) Boilers**
  - Commercialized in 1970s-1980s
  - Approximately 500 units operating world-wide; 150 in US (most small)
  - Unit sizes up to ~ 600 MWe
- **Integrated Gasification Combined-Cycle Power Plants**
  - Commercialized in 1980s-1990s
  - 9 coal-based units operating world-wide; 4 in US
  - Unit sizes up to ~ 300 MWe

Some Demonstration Program Successes

- **Advanced SO_2 Scrubbers (or Flue Gas Desulfurization, FGD)**
  - Pure Air (Bailly), CT-121 (Yates) & S-H-U (Milliken/Cayuga)
- **NO_x Control Technologies**
  - SCR, SNCR, Low-NO_x burners (consider UBC), Reburning
- **Hazardous Air Pollutants (HAPs)**
  - HAPs testing on 10 projects; led to R&D focus on Hg emissions
- **Fluidized Bed Combustion (FBC)**
  - Fuel flexibility; can handle even waste coal
- **Integrated Gasification Combined-Cycle (IGCC)**
  - Wabash River, Tampa/Polk & Kemper (in construction)
- **Carbon Capture & Geologic Storage (currently in progress)**
  - 8 active major demonstration projects currently in progress

Evolution of Air Pollution Controls



DOE Fossil Energy Demonstration Programs

Clean Coal Technology (CCT)

- 5 funding rounds, 1986-93
- 211 proposals → 60 selected → 50 agreements awarded → 33 projects completed
- \$3.26B; 40% DOE/60% Industry

Power Plant Improvement Initiative (PPII)

- 1 funding round, 2001
- 24 proposals → 8 selected → 5 agreements awarded →4 projects completed
- \$68M; 43% DOE/57% Industry

Clean Coal Power Initiative(CCPI)

- 3 funding rounds, 2002-09
- 98 proposals → 18 selected → 12 agreements awarded → 4 completed + 4 active projects
- \$8.2B ; 16% DOE/84% Industry

FutureGen 2.0

- \$1.65B; 64% DOE/36% Industry

Industrial Carbon Capture & Storage (ICCS) Area 1

- 1 funding round, 2009
- 36 proposals → 13 selected → 11 Phase 1 agreements awarded → 3 active Phase 2 projects
- \$1.08B; 64% DOE/36% Industry

Emissions Control & Efficiency Improvements

Notable CCT Program Successes

Advanced Pollution Controls

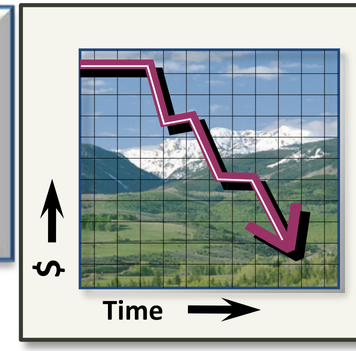
- Installed on 75% of U.S. coal plants
- 1/2 to 1/10 cost of older systems

Flue Gas Desulfurization (FGD) Scrubbers

Low-NO_x Burners

HAPS & Hg Data

- Quantified Hazardous Air Pollutant (HAPs) Levels
- Basis for Mercury (Hg) Regulations



Advanced Coal Power Systems

- First large (265 MW) Circulating Fluidized Bed Combustion (CFBC) power plant
- Two "super-clean" Integrated Gasification Combined Cycle (IGCC) power plants

Jacksonville CFBC

Wabash IGCC

Tampa IGCC

Some Lessons Learned

- Technology performance often degrades, with scale-up
- Baseline technologies usually improve, over time
- Project finance, cost, schedule ≈ Technical considerations
- "Build a better mousetrap, and the world will beat a path to your door" – not necessarily true!
- Coal usage & environmental protection are not mutually exclusive

Technological Carbon Management Options

Pathways for Reducing GHGs -CO_2

Reduce Carbon Intensity

- Renewables
- Nuclear
- Fuel Switching

Improve Efficiency

- Demand Side
- Supply Side

Sequester Carbon

- Enhance Natural Sinks
- Capture & Store

All options needed to:

- Affordably meet energy demand
- Address environmental objectives

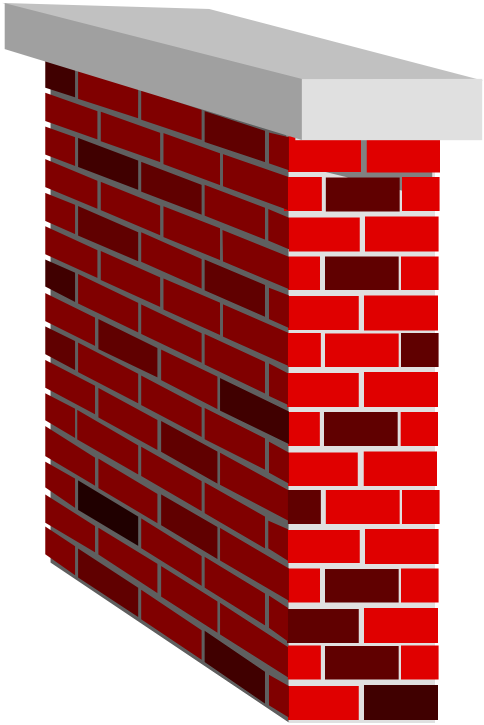
Key Challenges to Carbon Capture and Storage

Technical Issues

- **Capture Technology**
  - Existing Plants
  - New Plants
  - PCC, IGCC, Oxy-comb., Chemical looping, etc.
- **Cost of CCS**
- **Sufficient Storage Capacity**
- **Permanence**
- **Best Practices**
  - Storage Site Characterization
  - Monitoring/Verification
  - Site Closure
  - Etc., etc.

Legal/Social Issues

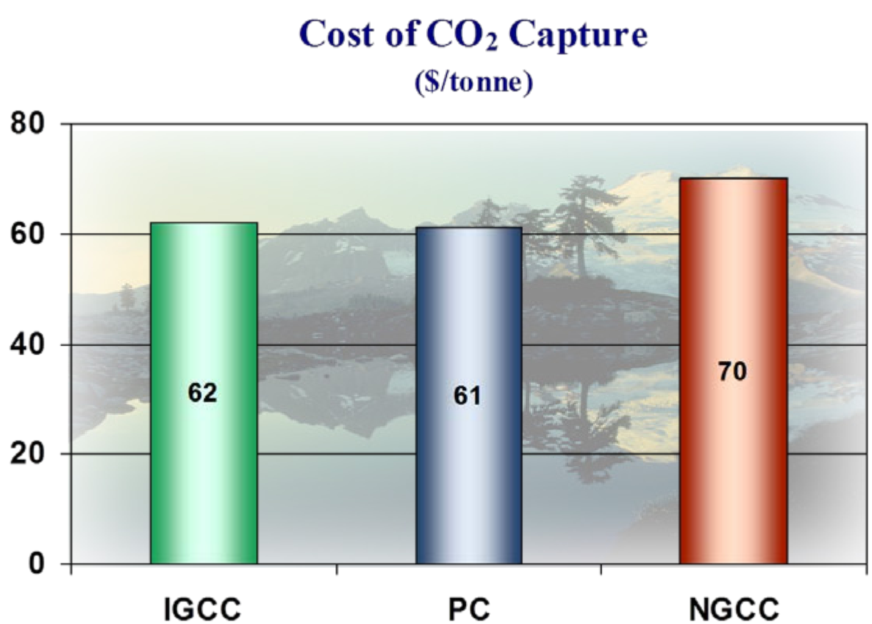
- **Regulatory Framework**
  - Permitting
  - Treatment of CO_2
- **Infrastructure**
- **Human Capital**
- **Legal Framework**
  - Liability
  - Ownership
    - pore space
    - CO_2
- **Public Acceptance (NIMBY → NUMBY)**

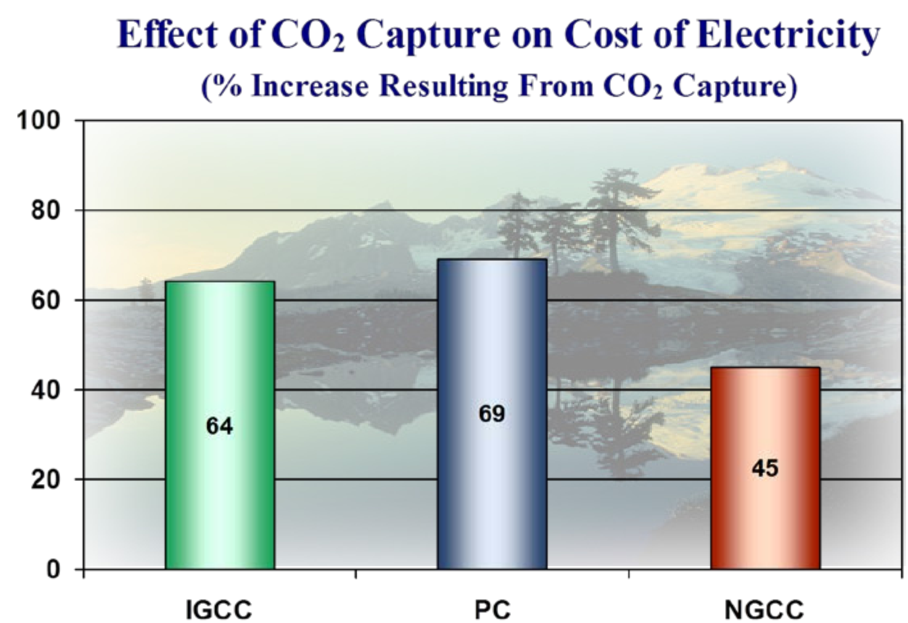


Projects helping to address both categories of issues

CCS Is Expensive (…but RD&D can reduce costs)

- 45–70% increase in cost of electricity
- 35–110% increase in capital cost
- 15-21% decrease in plant output per lb of coal feed





Source: *Cost and Performance Baseline for Fossil Energy Power Plants study, Volume 1: Bituminous Coal and Natural Gas to Electricity – Rev3 Draft*

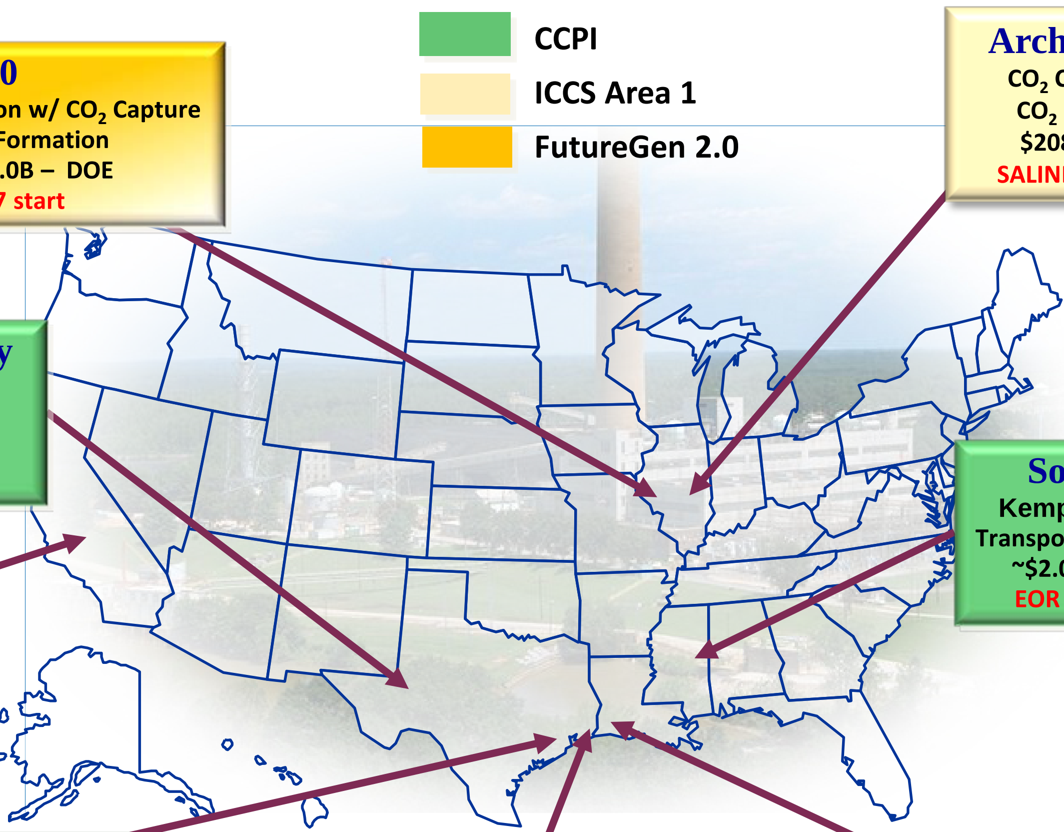
Notes:
- Reference non-capture plants are Supercritical PC for coal cases and NGCC for natural gas cases.
- Above values exclude CO_2 transport and storage costs

List of Active DOE/Fossil Energy Major Projects

Program/Project	Technology	CO_2, tpy	Cost/DOE Share	Status/Start-Up
Clean Coal Power Initiative (CCPI) Demonstrations				
Kemper County	IGCC, 67% CO_2 Cap.	3 million	$2.01B/$270M (10%)	Construction/2014
Summit Texas	IGCC/Poly, 90% "	2.2 "	$1.73B/$450M (26%)	Proj. Financing/2017
H_2 Energy California	IGCC/Poly, 90% "	2.6 "	$4B/$408M (10%)	Proj. Financing/2019
NRG Parish	Post-Comb., 90% "	1.4 "	$775M/$167M (22%)	Proj. Financing/2016
Industrial Carbon Capture & Sequestration (ICCS) Demonstrations				
Archer Daniels Midland	EtOH, 90% CO_2 Cap.	0.9 million	$208M/$141M (68%)	Construction/2014
Air Products Port Arthur	SMR, 90% "	0.9 "	$431M/$284M (66%)	Operations/2013
Leucadia Lake Charles	MeOH, 90% "	4.5 "	$436M/$261M (60%)	FEED/2015
FutureGen 2.0				
Oxy-Fuel/CO_2 Capture	Oxy-Comb., 90% Cap.	1 million	$1.2B/$590M (49%)	FEED/2017
CO_2 Pipeline & Storage	Geol. Storage (saline)	---	$572M/$459M (80%)	---
Total	**8 Projects**	**Various**	**$11.4B/$3B (26%)**	**Start-Ups 2013-2018**

Major CCS Demonstration Projects

Project Locations & Cost Share



FutureGen 2.0
Large-scale Testing of Oxy-Combustion w/ CO_2 Capture and Sequestration in Saline Formation
Project: ~$1.78B – Total; ~$1.0B – DOE
SALINE – 1 MM TPY 2017 start

Archer Daniels Midland
CO_2 Capture from Ethanol Plant
CO_2 Stored in Saline Reservoir
$208M – Total, $141M – DOE
SALINE – ~0.9 MM TPY 2014 start

Summit TX Clean Energy
Commercial Demo of Advanced IGCC w/ Full Carbon Capture
~$1.73B – Total, $450M – DOE
EOR – ~2.2 MMTPY 2017 start

HECA
Commercial Demo of Advanced IGCC w/ Full Carbon Capture
~$4B – Total, $408M – DOE
EOR – ~2.6 MM TPY 2019 start

Southern Company
Kemper County IGCC Project
Transport Gasifier w/ Carbon Capture
~$2.01B – Total, $270M – -DOE
EOR – ~3.0 MM TPY 2014 start

NRG
W.A. Parish Generating Station
Post Combustion CO_2 Capture
$775 M – Total
$167M – DOE
EOR – ~1.4 MM TPY 2016 start

Air Products and Chemicals, Inc.
CO_2 Capture from Steam Methane Reformers
EOR in Eastern TX Oilfields
$431M – Total, $284M – DOE
EOR – ~0.93 MM TPY 2012 start

Leucadia Energy
CO_2 Capture from Methanol Plant
EOR in Eastern TX Oilfields
$436M - Total, $261M – DOE
EOR – ~4.5 MM TPY 2017 start

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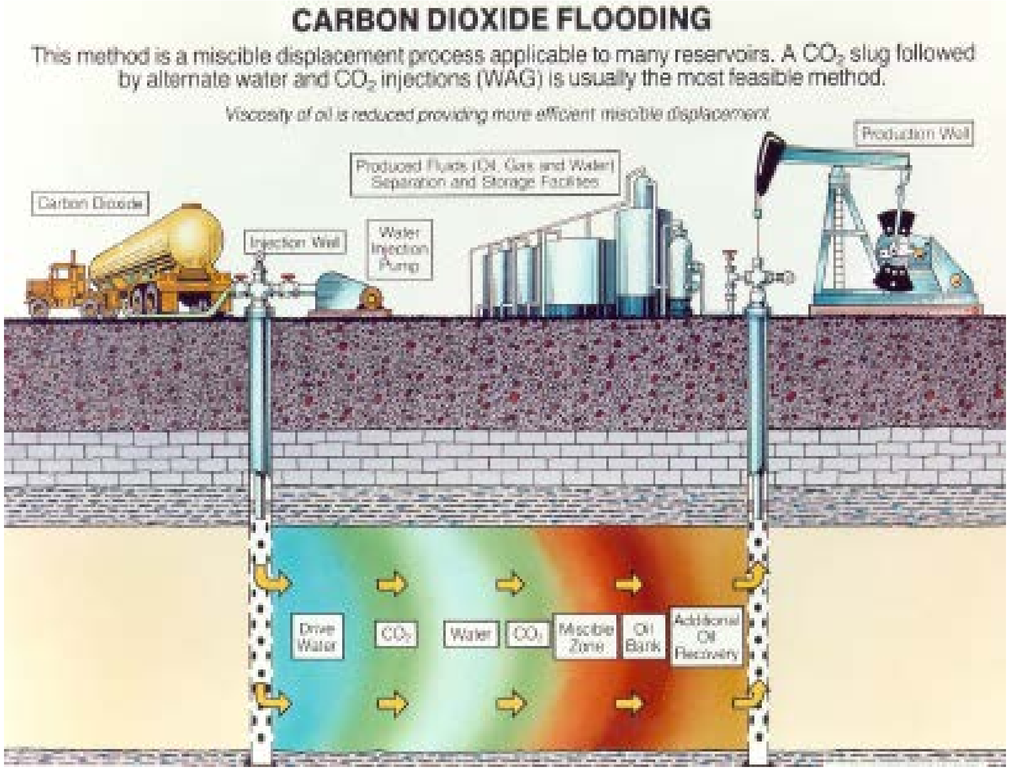
Enhanced Oil Recovery – Beneficial Use of CO_2

- **EOR increasing its role in domestic oil production**
  - EOR: 650,000 bbls/day
    → 13% of domestic production
  - CO_2-EOR: 237,000 bbls/day & growing
  - 90 billion barrels of light oil can yet be recovered in the U.S. using EOR
- **Reduces cost of CCS**
- **Lowers carbon footprint of transportation sector**
  - Oil produced with "next generation" CO_2-EOR may be well-better than carbon neutral
- **Increases energy security**



Strategic Center for Coal

Critical R&D Challenges to Near-Zero Emissions from Coal

Near-Term Plants

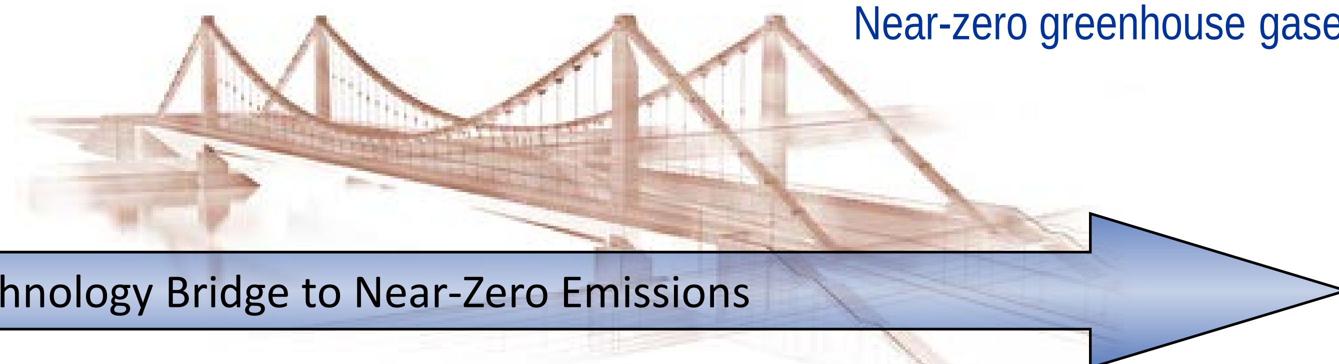
Pulverized Coal

- Power generation
- Improve efficiencies
- Minimize criteria pollutants
- Minimize water usage
- Minimize greenhouse gases

Future Plants

Advanced Coal

- Power and multiple products
- Improve reliability
- Maximize efficiencies
- Near-zero criteria pollutants
- Near-zero water usage
- Near-zero greenhouse gases

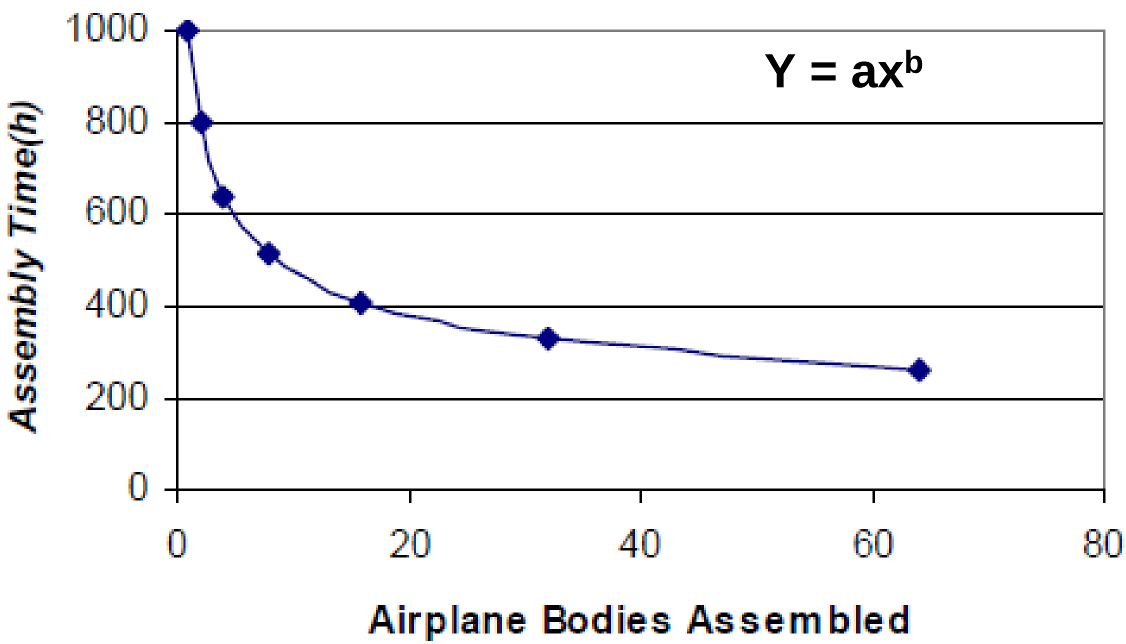


2005 – 2020

2020 – 2050

Background – Learning Curves

Sample Learning Curve Function



a = Cost of first unit

x = Number of units produced

b = Learning rate exponent

$1 - 2^{-b}$ = Learning Rate, reduction in capital cost for doubling of capacity

- Developed by Wright in 1936 after observing labor time reductions to assemble airplanes.
- In 1998 Mackay & Probert showed that a similar rule could be applied to capital cost reductions in renewable energy.
- Models including NEMS rely on this curve to predict future capital costs.

Source: "Learning and Cost Reductions for Generating Technologies in the National Energy Modeling System (NEMS)" E.Gumerman and C.Marnay. Lawrence Berkeley National Laboratory. University of

Large Variation in Learning Curves for Energy Technologies

Technology	Region of Study	Time Period of Study	Estimated Learning Rate	Reference
Coal Power Plants	USA	1960 – 1980	1.0% – 6.4%	Joskow & Rose (1985)
Coal for Electric Utilities	USA	1948 – 1969	25%	Fisher (1974)
Crude Oil at the Well	USA	1869 – 1971	5%	Fisher (1974)
Solar PV Modules	World	1976 – 1992	18%	IEA (2000)
Wind Power	USA	1985 - 1994	32%	IEA (2000)
Wind Power	EU	1980 – 1995	18%	IEA (2000)

Data Source: McDonald and Schrattenholzer, 2001

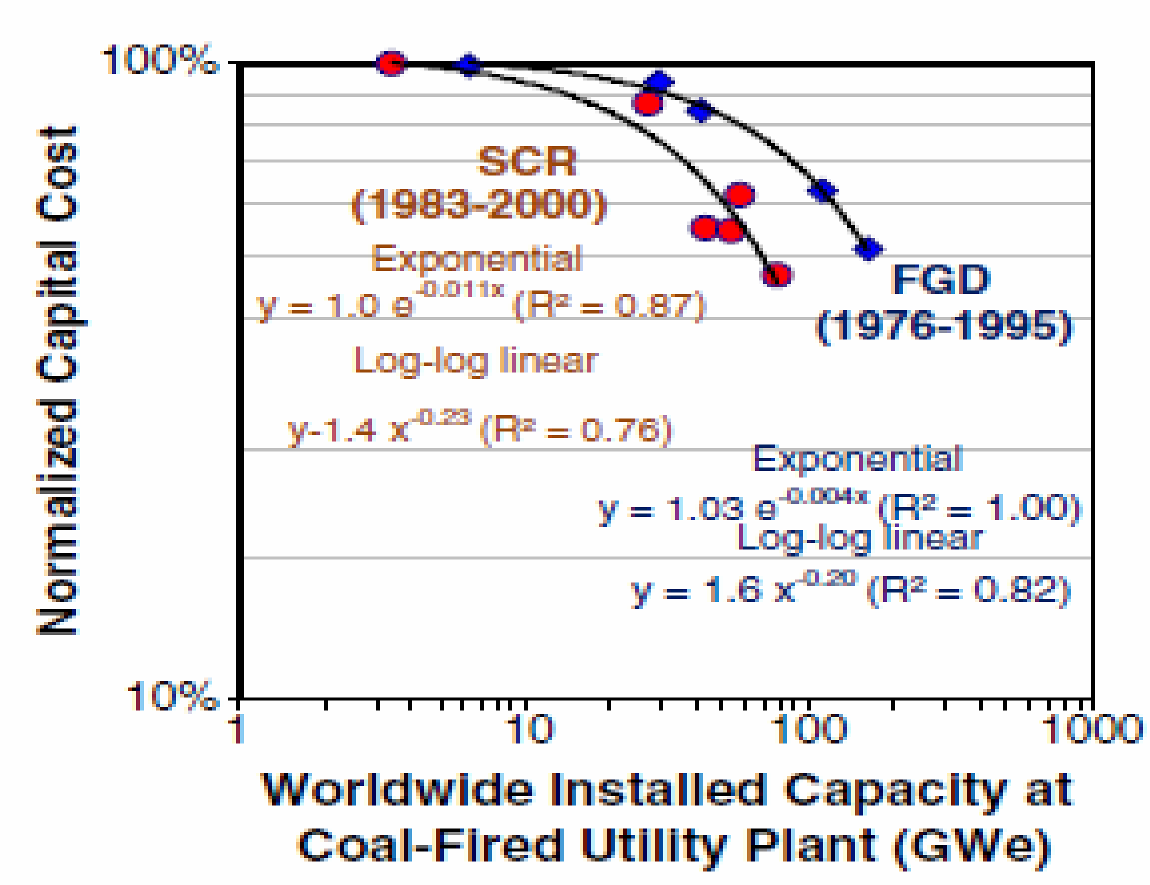
Explanations for Learning Curve Variability

- Experience depreciation
- Short-term pricing behavior
- Differences in performance measures
- Definitional differences
- Varying intensities of Research & Development (R&D)
- Economies of scale
- Cost variability for factors such as land costs, wages & interest payments

Source: "Learning Rates for Energy Technologies" by Alan McDonald & Leo Schrattenholzer, Energy Policy 29, 255-261 (2000).

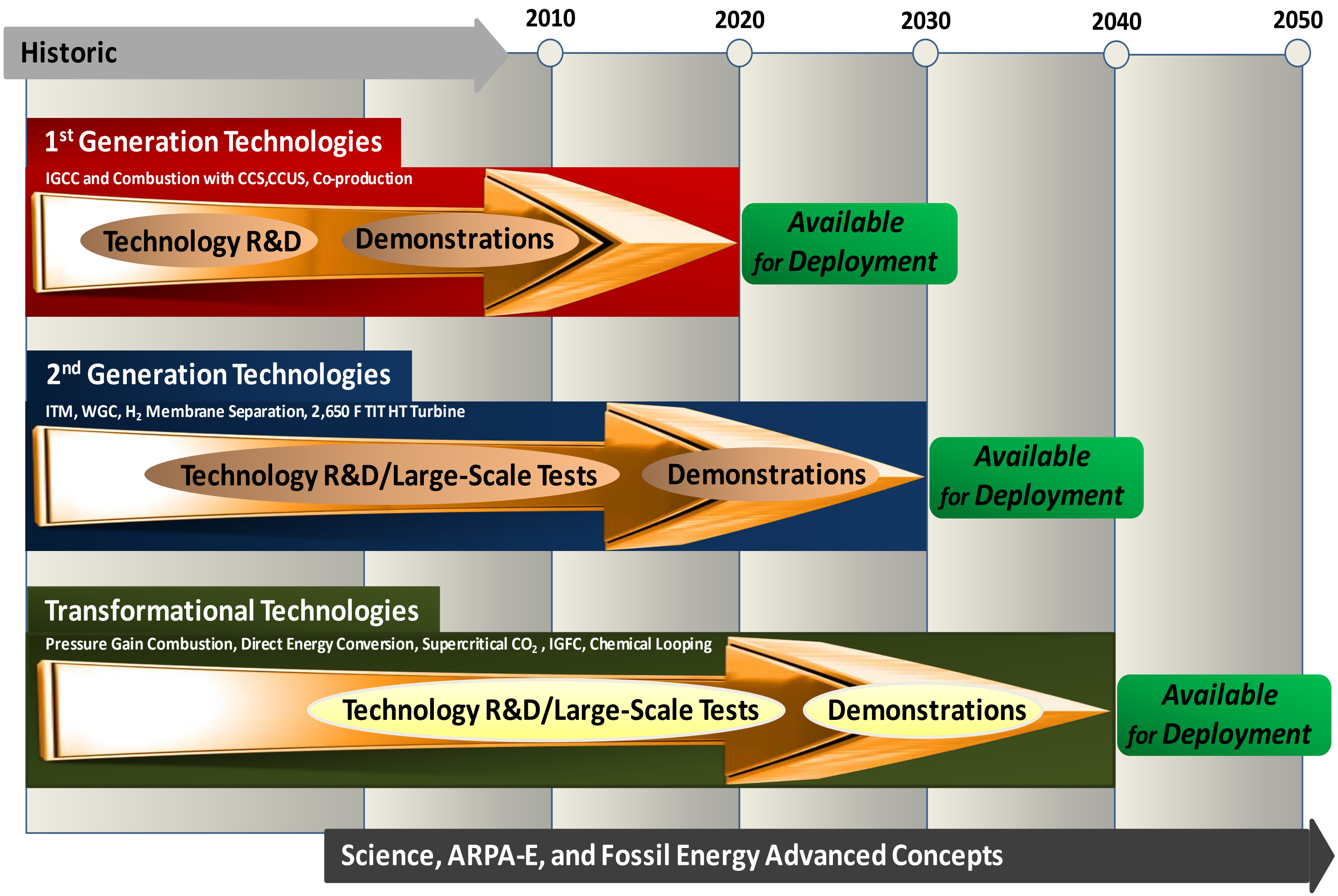
SO_2 & NO_x Control Learning Curves

Non-linear learning curves are prevalent in power plant emission control technologies.



Yeh, S., Rubin, E.S., Hounshell, D.A., and Taylor, M.R. (2009) Uncertainties in Technology Experience Curves, for Integrated Assessment Models, Environmental Sci. and Technol. **43** (18), 6907-14.

CCRP Technology Development Timeline



Some Next Steps for Coal-Based Power Generation Platform Technologies

- **Pulverized Coal Combustion**
  - Tightened emissions controls (e.g., HG)
  - Post-combustion CO2 capture
  - ↑ Temperature, ↑ Pressure (e.g., USC)
  - Oxy-combustion
- **Fluidized Bed Combustion**
  - Oxy-CFB combustion
  - Post-combustion CO2 capture
  - Pressurized CFB (possibly oxy-PFBC)

- **IGCC**
  - ↓ Cost, ↑ Efficiency (e.g., larger combustion turbines)
  - Higher-H_2 syngas, with water-gas shift to enable CCS
  - Polygeneration of electricity, CO_2 and…fertilizers, chemicals and/or fuels
  - Natural gas back-up, low-rank coals, advanced gasifier designs
  - H_2 separation membranes, low cost O_2 supply, warm-gas cleanup

Some Additional Lessons Learned
incl. the 'soft side' of project management

- **Be passionate about job & career, but also be kind to the people you work with…**
- **Be patient and polite, yet persistent…**
- **Be frank and open…**
- **Are there really two sides to every issue?**
  - Complex issues can have more than two 'sides' to consider
- **Dig deep!**
  - Scratch well beneath the surface, to see/understand better
- **Do the math!**
- **Look beyond the % signs…**
  - Seek to understand absolute number stats, as well as percentages
- **Develop good people skills…**
  - Especially, good listening skills
- **Read…**
  - And, strive to become a better writer in the process
- **Imagine. Dream. Explore. Discover. Create.**
- **Make today a good one!**

For More Information

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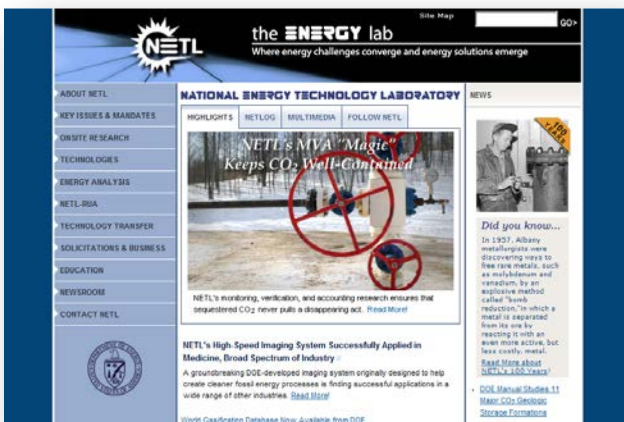

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