Assessing Carbon Sequestration Options for Fossil Fuel Power Plants

Edward S. Rubin
Department of Engineering and Public Policy
Carnegie Mellon University
Pittsburgh, Pennsylvania

Presentation to the

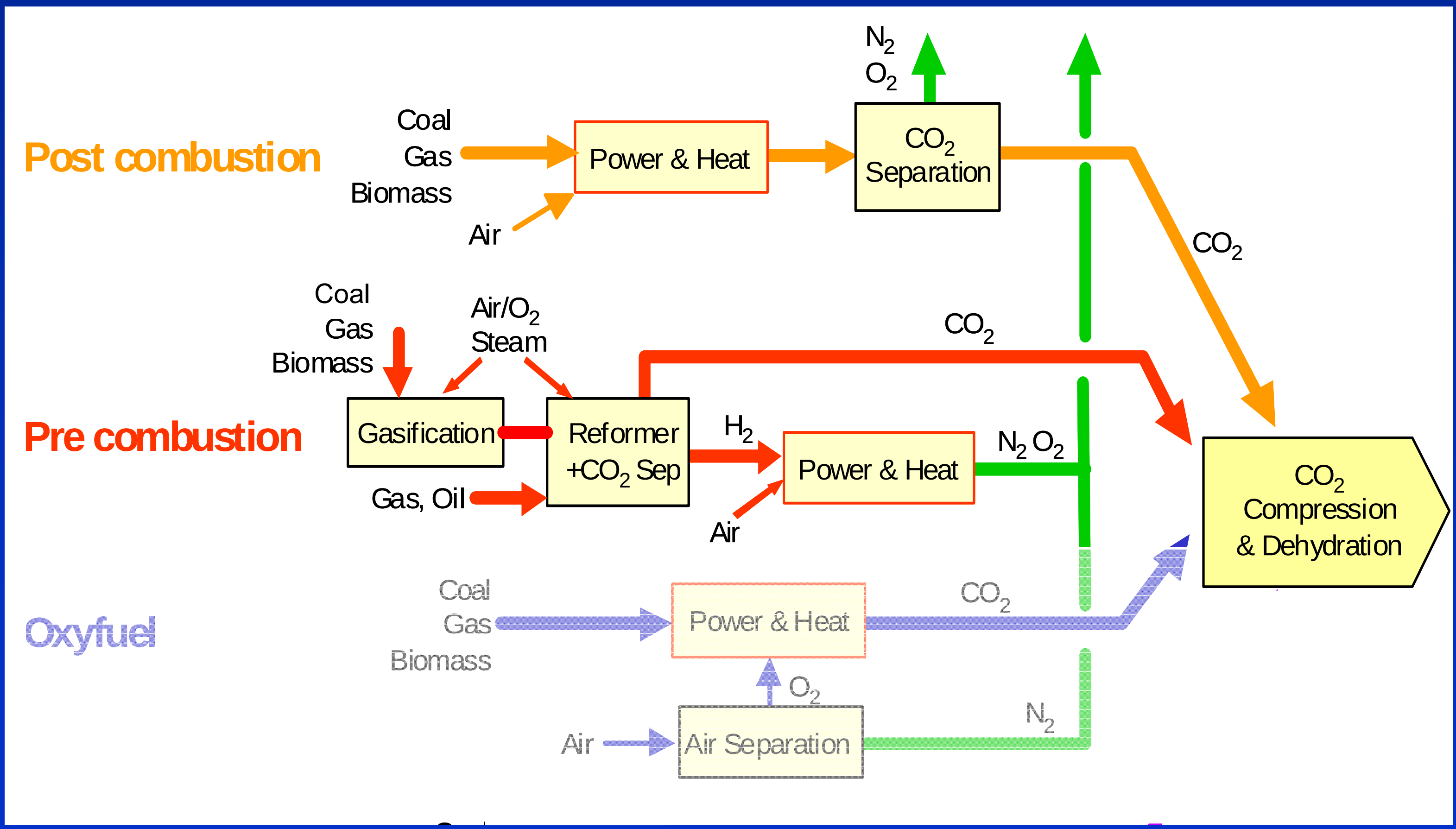
EPRI Advisory Council
Pittsburgh, PA

April 24, 2007

Motivating Questions

- What is the current status of CO_2 capture and storage (CCS) technologies?
- What are the current costs, efficiencies and impacts for power plant options?
- What is the outlook for improved technology?
- What are key needs to realize these improvements?

CO_2 Capture Options for Power Plants



Source: IPCC SRCCS, 2005

What is the current status of CCS technology?

Status of CCS Technology

- Both pre- and post-combustion CO_2 capture technologies are commercial and widely used in industrial processes, mainly in the petroleum and petrochemical industries
- CO_2 capture also has been applied to flue gas streams from gas-fired and coal-fired boilers (to produce CO_2 for sale), but not yet at the scale of a large modern power plant
- Integration of CO_2 capture, transport and geologic sequestration has been demonstrated in several industrial applications, but not yet at an electric power plant
- Several new large-scale power plant projects planned in different countries over the coming decade

Examples of Post-Combustion CO_2 Capture at Coal-Fired Plants

(Source: ABB Lummus)

Shady Point Power Plant
(Panama, Oklahoma, USA)

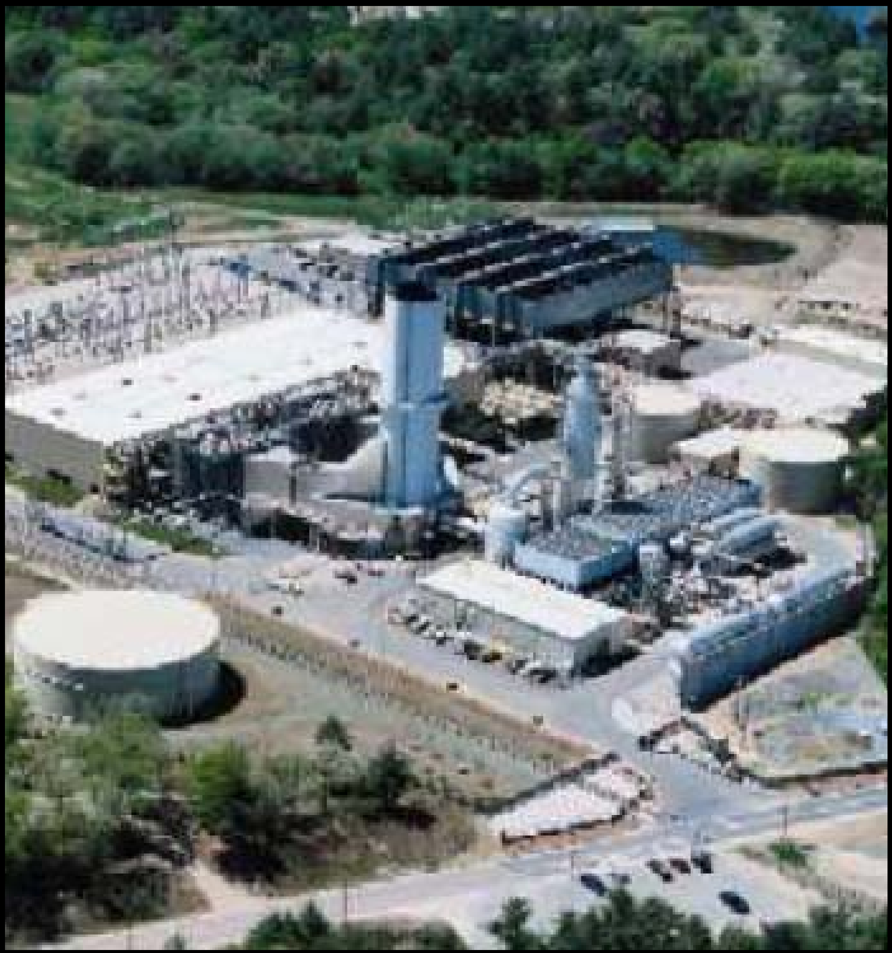
(Source: (IEA GHG)

Warrior Run Power Plant
(Cumberland, Maryland, USA)

E.S. Rubin, Carnegie Mellon

Examples of Post-Combustion CO_2 Capture at Gas-Fired Plants

(Source: Suez Energy Generation))



Bellingham Cogeneration Plant

(Bellingham, Massachusetts, USA)

(Source: Mitsubishi Heavy Industries)

Petronas Urea Plant Flue Gas

(Keda, Malaysia)

Examples of Pre-Combustion CO_2 Capture Systems

(Source: Chevron-Texaco)

Petcoke Gasification to Produce H_2

(Coffeyville, Kansas, USA)

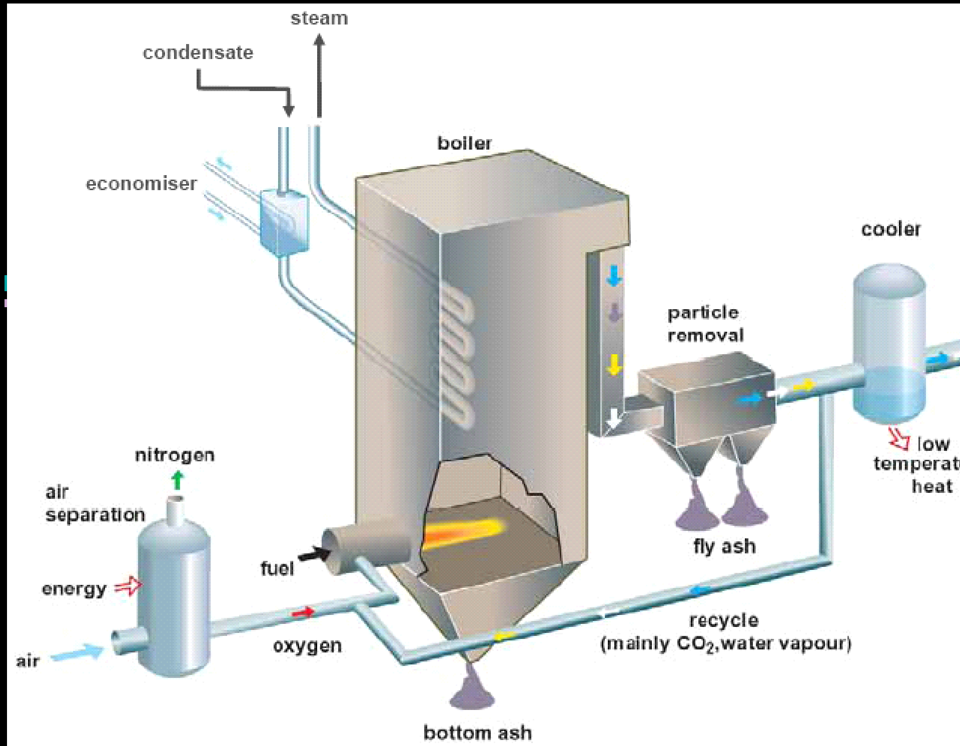
(Source: Dakota Gasfication

Coal Gasification to Produce SNG

(Beulah, North Dakota, USA)

E.S. Rubin, Carnegie Mellon

Example of Oxyfuel Combustion Capture System



The Vattenfall 30 MW_{th} Oxy-Coal Pilot Boiler with CO_2 capture at Schwarze Pumpe (Germany), starting mid-2008

Source: Vattenfall, 2006

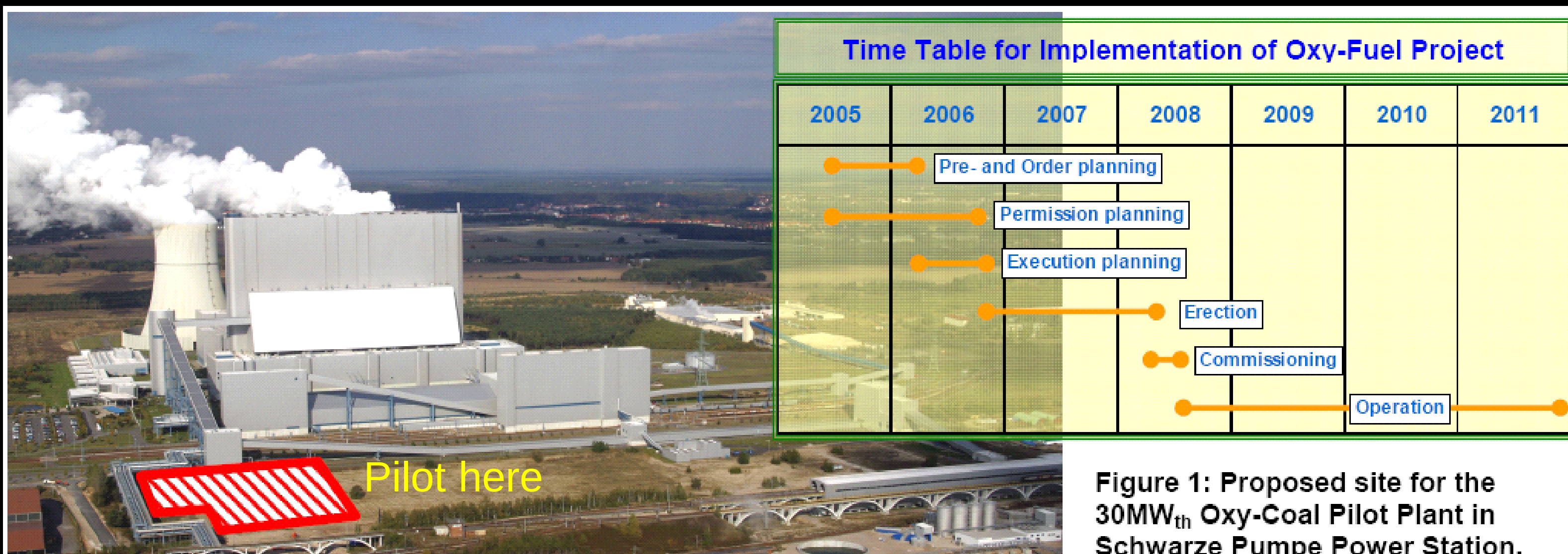
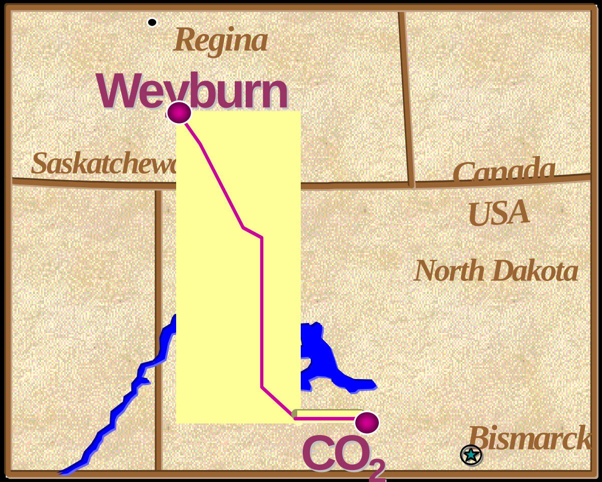


Figure 1: Proposed site for the 30MW_{th} Oxy-Coal Pilot Plant in Schwarze Pumpe Power Station.

E.S. Rubin, Carnegie Mellon

Geological Storage of Captured CO_2 with Enhanced Oil Recovery (EOR)



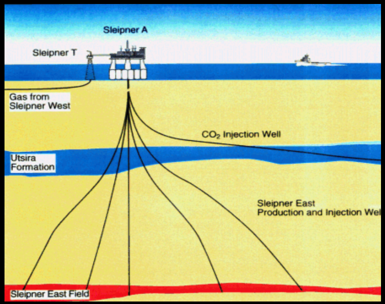
Sources: USDOE; NRDC

E.S. Rubin, Carnegie Mellon

Geological Storage of Captured CO_2 in Deep Saline Aquifers

Source: Statoil

Sleipner *(Norway)*



In Salah /Krechba *(Algeria)*

Source: BP

E.S. Rubin, Carnegie Mellon

What are the current costs, efficiencies and impacts ?

Many Factors Affect Reported Costs of CO_2 Capture & Storage

- Choice of CCS Technology
- Process Design and Operating Variables
- Economic and Financial Parameters
- Choice of System Boundaries; *e.g.*,
  - One facility vs. multi-plant system (regional, national, global)
  - GHG gases considered (CO_2 only vs. all GHGs)
  - Power plant only vs. partial or complete life cycle
- Time Frame of Interest
  - Current technology vs. future (improved) systems
  - Consideration of technological "learning"

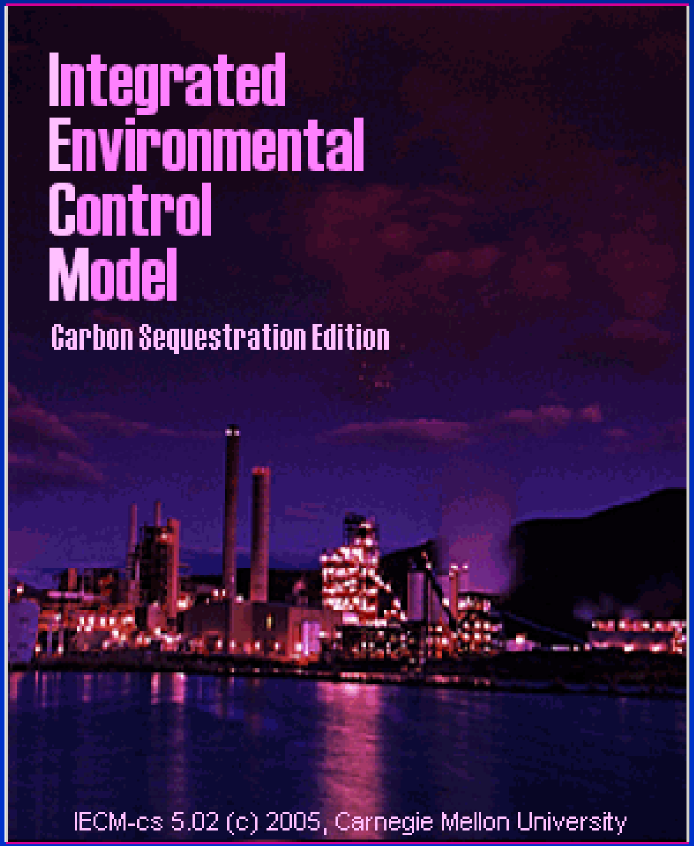
CMU Modeling Approach

- Systems Analysis Approach
- Process Performance Models
- Engineering Economic Models
- Advanced Software Capabilities
  - User-friendly graphical interface
  - Probabilistic analysis capability
  - Easy to add or update models

The IECM

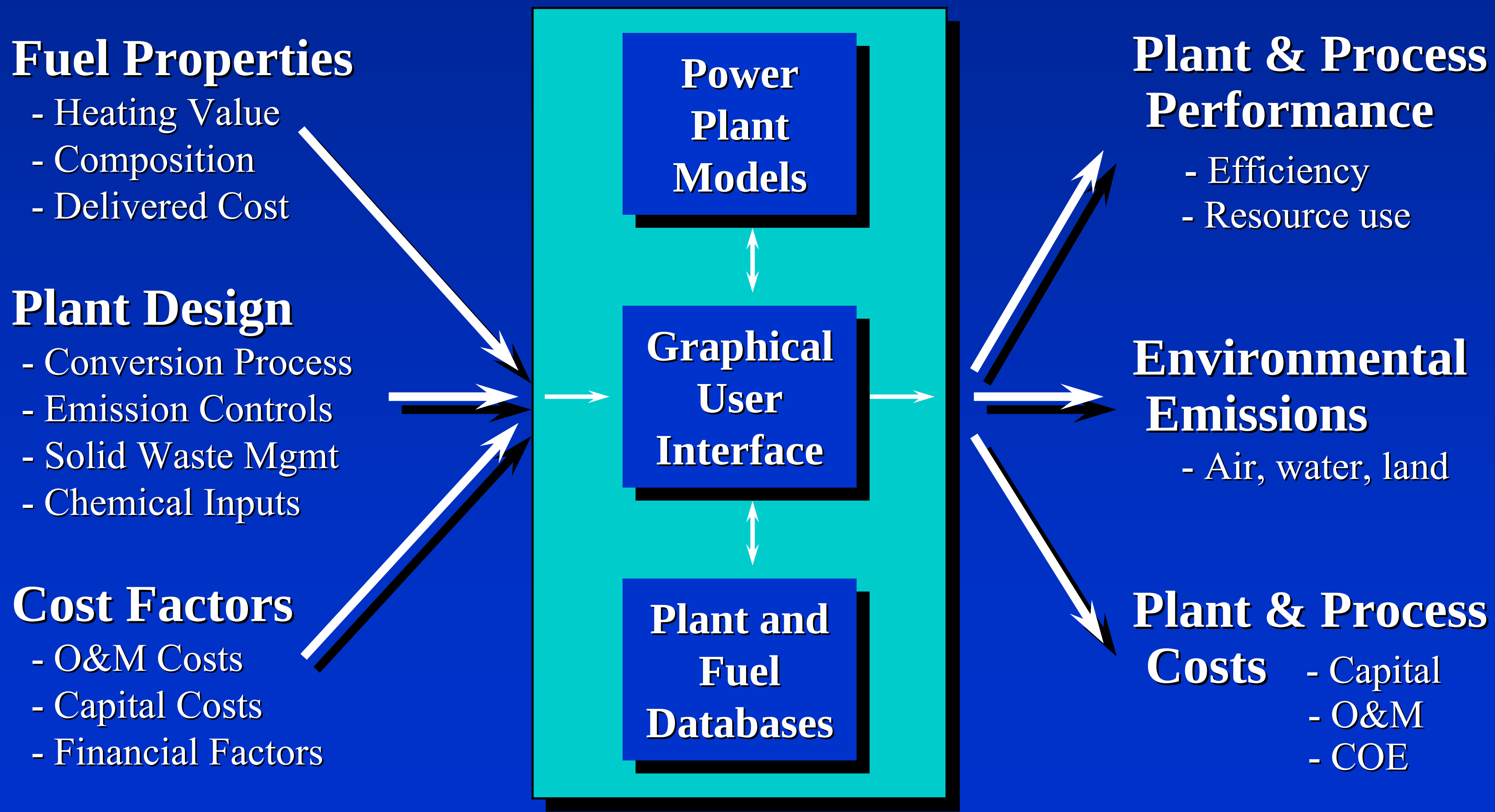
(Integrated Environmental Control Model)

- A desktop computer model developed for DOE/NETL
- Provides preliminary design estimates of performance, emissions, costs and uncertainties:
  - PC, NGCC and IGCC plants
  - Environmental control options (criteria air pollutants, HAPs, CO_2 capture, transport, storage)
- Free and publicly available (www.iecm-online.com)



IECM Software Package

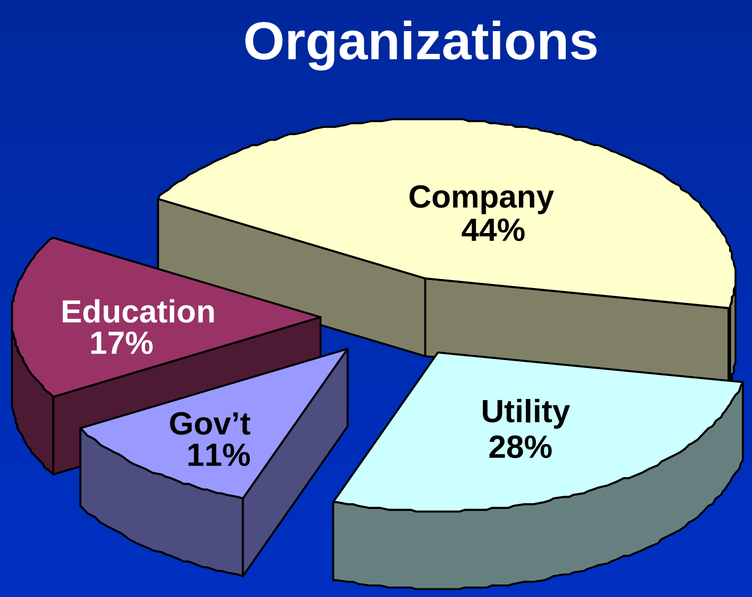
(Free at: www.iecm-online.com)

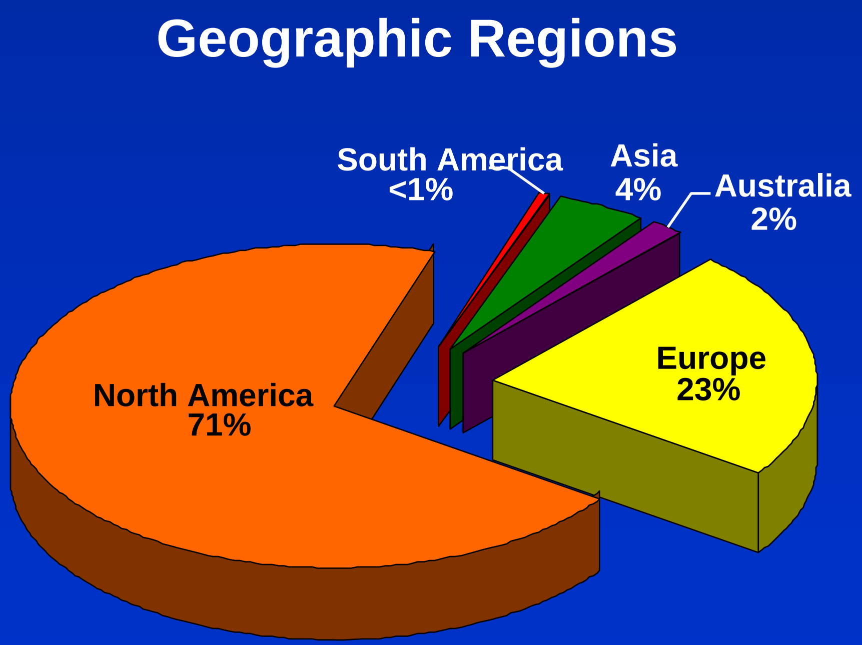


Some Recent IECM Users

ABB Lummus Global, Inc.
AEP-SCR Eng'r
Air Liquide
Air Products plc
Airborne Clean Energy
Akzo Nobel Functional Chem
Alberta Economic Dev.
Alberta Env.
Alberta Res. Council
ALCOA Power Gen., Inc.
Allegheny Energy Supply
Alliant Energy
Alstom (Switzerland)
Alstom Power Boiler GmbH
ALSTOM Power Centrales
Alstom Power Inc.
Alstom Power Plant Lab.
American Electric Power
American Transmission Co.
Ankara University
APAT
Apogee Scientific, Inc.
ARCADIS
Argonne National Lab.
ATCO Power
Balcke-Durr GmbH
Basin Electric Power Coop.
Battelle
Battelle Northwest
Bechtel Power Corp.
Black & Veatch Corp.
BOC Gases
Boiler Systems Eng'r, E.S.O.
BP
BP Int'l Limited
BP Power Ltd.
BP Sunbury
Canada Env.
Canada Natural Resources
Canadian Clean Power Coalition
Carnegie Mellon University
Chalmers University
Chinese Academy of Sci.
Cinergy Power Gen. Services, LLC
Clean Energy Systems Inc.
Coal in Sustainable Dev., Tech Transfer
Coaltek LLC / Jupiter Oxygen Corp.
Cogentrix Energy, Inc.
Columbia University
CONSOL Energy, Inc.
Consumers Energy
Coop. Res. Centre for Greenhouse Gas
COORETEC
CQ, Inc.
Croll-Reynolds
CSEnergy
Dept. of Energy (DOE)
Dept. of Energy, Instituto de Carboquimica
Dept. of Env. and Natural Res. - NC
Dept. of Env. Protection - NJ (DEP)
Dept. of Env. Protection - PA (DEP)
Dept. of Env. Quality - VA (DEQ)
Dept. of Env. Services - NH (DES)
Detroit Edison Co.
DMCR/Dutch Ministry of Env. (VROM)
DONG Energy Gen.
Dont Inc.
Doosan Babcock Energy Ltd.
Dynegy Midwest Gen.
E. On UK
E.ON Energie AG
Edison Mission Energy
Electric Energy, Inc. (EEI)
Electric Power Gen. Assoc.
Electric Power Res. Inst. (EPRI)
Electricite de France (EDF)
Emera Inc.
Enel
AmerenUE
Energetics, Inc.
Energi E2
Energy & Env. Res. Center (EERC)
Energy & Env. Res. Corp.
Energy & Env. Strategies
Energy Res. Centre of the Netherlands
ENSR, Inc.
Env. & Renewable Energy Systems
Env. Defense
Env. Protection Agency - IL (EPA)
Env. Protection Agency (EPA)
First Energy Corp.
FirstEnergy Corp.
Florida Power & Light Co.
FLS Miljo A/S
Fluent, Inc.
Fluor Daniel Canada, Inc.
Ford
Fortum Power and Heat Oy
Fossil Energy Res. Corp.
Foster Wheeler Energia Oy
Friedman, Billings, Ramsey & Co.
Fuel Tech, Inc.
Gas Tech. Inst. (GTI)
Gassnova
GE Global Res.
GE Infra, Energy
General Electric Co.
Generators for Clean Air (GCA)
GM R&D Center
Great River Energy
Gyeongsang National University
H&W Mgmt. Sci. Consultants
Hamon Res. Cottrell, Inc.
Harvard University
Hatch Acres
Holland Board of Public Works
IEA Clean Coal Centre
IEA Env. Projects, Ltd.
IEA Greenhouse Gas R&D
IFP
Illinois Clean Coal Inst.
Illinois Dept. of Natural Resources
Illinois Inst. of Tech.
Imperial College
Indian Inst. of Tech.
Industries Limited
INERCO
Institut Teknologi Bandung (ITB)
Inst. of Applied Energy (IAE)
Inst. of Energy - EC/JRC
Intermountain Power Service Corp.
Ishikawajima-Harima Heavy Industry
Jack R. McDonald, Inc.
Japan Petroleum Exploration Co.
Kanazawa University
Kansas City Power & Light Co.
KEMA Nederland B.V.
Kennecott Energy
Kinectrics
Korea Electric Power Corp.
Korea Inst. of Energy Res.
Korea Western Power Co.
LAB SA
Lehigh University
Lincoln Electric System
Lower Colorado River Authority
MacQuarie University
Massachusetts Inst. of Tech. (MIT)
Michigan State University
MidAmerican Energy Co.
Midwest Gen. EME, LLC
Minnkota Power Coop., Inc.
Nanyang Technological University
National Energy Tech. Lab. (NETL)
National Power Plc.
Neill and Gunter
NESCAUM
New Energy & Ind. Tech. Org. (NEDO)
Nicholson & Hall Corp.
Niksa Energy Associates
NIPSCO
Niro A/S
Norman Plaks Consulting
Norsk Hydro ASA
Norsk Hydro ASA, Oil & Energy Res.
North Carolina State University
Norwegian University of Sci. and Tech.
Nova Scotia Power, Inc.
NRDC Natural Res. Defence Council
NTNU/Statoil
NTPC Limited
Ontario Power Gen.
OREC/Buckeye Power, Inc.
Pace Global Energy Services
Pacific Corp.
Pacific Northwest National Lab. (PNNL)
Pembina Inst.
Pinnacle West Energy
PIRA Energy Group
PowerGen
Powergen Power Tech.
PPL Gen., LLC
Prairie Adaptation Res. Coll.
Praxair Inc.
Princeton University
Reaction Eng'r Inst.
Reaction Eng'r Int'l
Res. Inst. of Innovative Tech. Earth
Res. Triangle Inst.
RMB Consulting & Res., Inc.
RWE Power AG
SAIC
Salt River Project
Salt River Project (SRP)
Sargent & Lundy
SaskPower
Savvy Eng'r, LLC
Sci. Applications Int'l. Corp. (SAIC)
Scientech
SFA Pacific, Inc.
Shell Chemical Co.
Shell Global Solutions Int'l
Siemens
Sierra Pacific Power Co.
Sintef Energy Res.
SNC Lavalin
Southern Co. Gen.
Southern Co. Services, Inc.
Statoil
Steven Coons Consulting
Superior Adsorbents, Inc.
Syncrude
Tampa Electric Co.
Tennessee Valley Authority (TVA)
Terra Humana Clean Tech. Eng'r Ltd.
Tetra Tech EM Inc.
Texas A&M University
Texas Municipal Power Agency
TMommer Consultants
TNO Env., Energy and Process Innov
Toshiba Corp.
TransAlta
TU Dresden
Twenty-First Strategies, LLC
TXU Electric
University of Aberdeen
University of Bath
University of Calgary
University of California
University of Edinburgh
University of Lecce
University of Maine
University of Manchester Inst. Sci. Tech.
University of New Orleans
University of Newcastle
University of North Carolina
University of Pittsburgh
University of Queensland
University of Regina
University of Salvador UNIFACS
University of South Wales
University of Stuttgart
University of Texas
University of Toronto
University of Twente
University of Waterloo
URS Corp
Vattenfall AB
Vattenfall Utveckling AB
W.L. Gore & Associates, Inc.
Washington Power
Wheelabrator Air Poll. Control Inc.
Wisconsin Dept. of Natural Res.
Wisconsin Public Service Corp.
Wolk Integrated Technical Services
World Bank

Profile of IECM Users



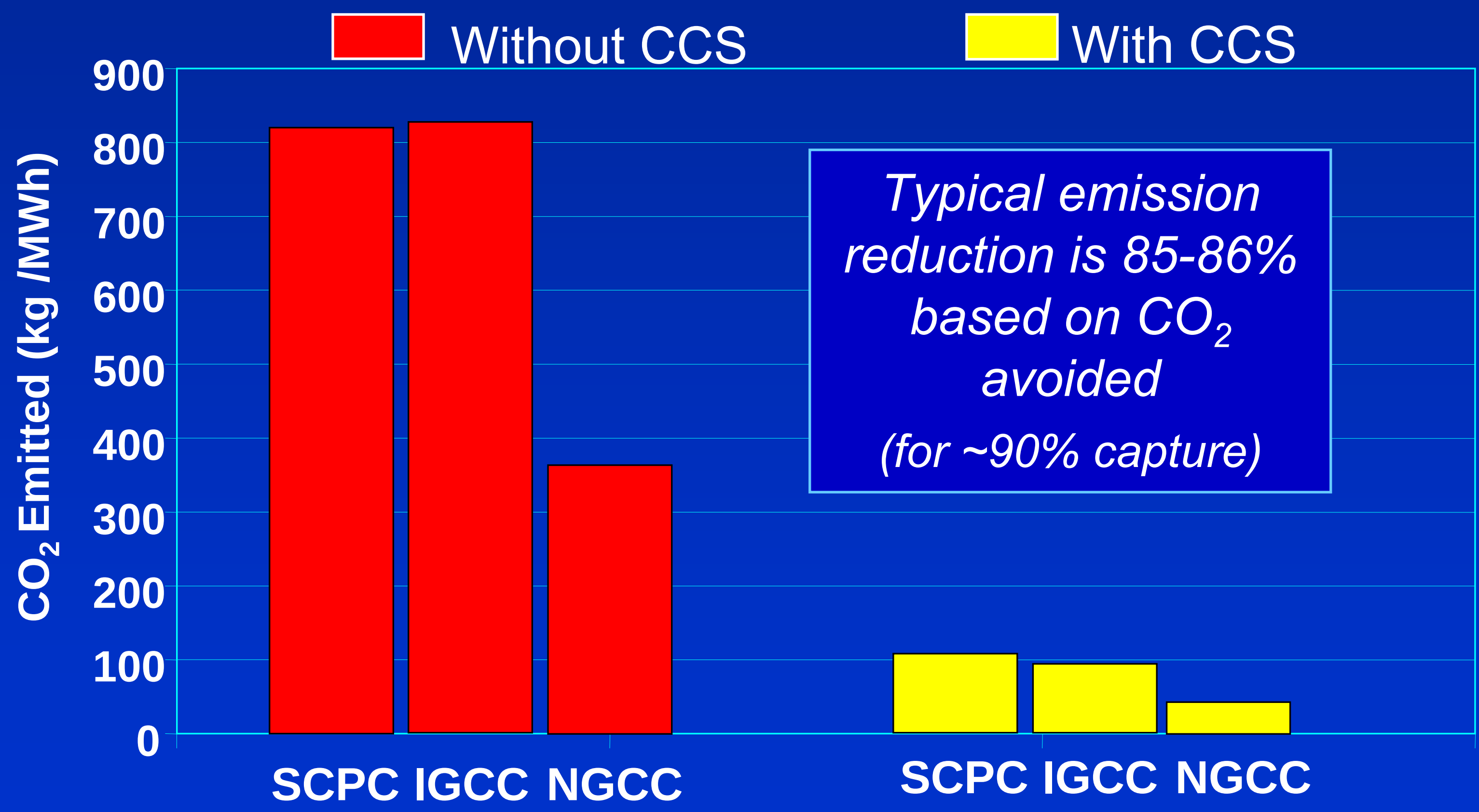


- *Over 500 organizations*
- *Over 1000 users worldwide*

Model Applications

- Process design
- Technology evaluation
- Cost estimation
- R&D management
- Risk analysis
- Environmental compliance
- Marketing studies
- Strategic planning

Illustrative CO_2 Emission Rates for New Power Plants (kg CO_2/MWh)



E.S. Rubin, Carnegie Mellon

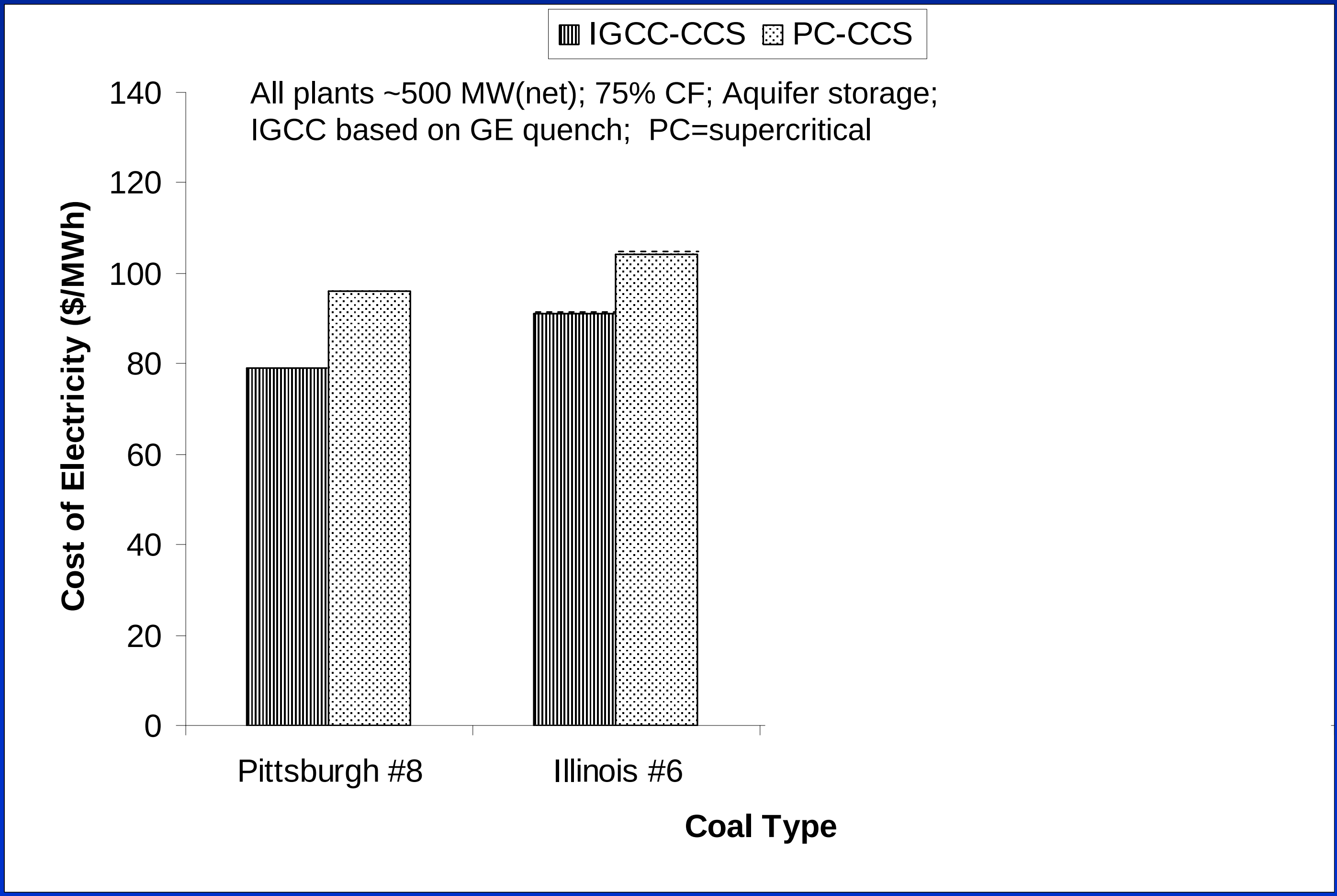
Representative CCS Costs for New Power Plants Using Current Technology

Incremental Cost of CCS Relative to Similar Plant without CCS	Natural Gas Combined Cycle Plant	Supercritical Pulverized Coal Plant*	Integrated Gasification Combined Cycle Plant*
Increase in plant capital cost for capture & compression	*~76%*	*~63%*	*~37%*
Increase in levelized COE (capture & compression only)	*~46%*	*~57%*	*~33%*
Added cost of CCS with aquifer storage ($/MWh)	**10–30**	**20–50**	**10–30**
Added cost of CCS with EOR storage ($/MWh)	10–20	10–30	0–10

**Based on bituminous coals. Source: IPCC, 2005*

Costs for New PC and IGCC Power Plants Using Current CCS Technology

(2005 $/MWh; dashed lines based on constant $/GJ for all coals)

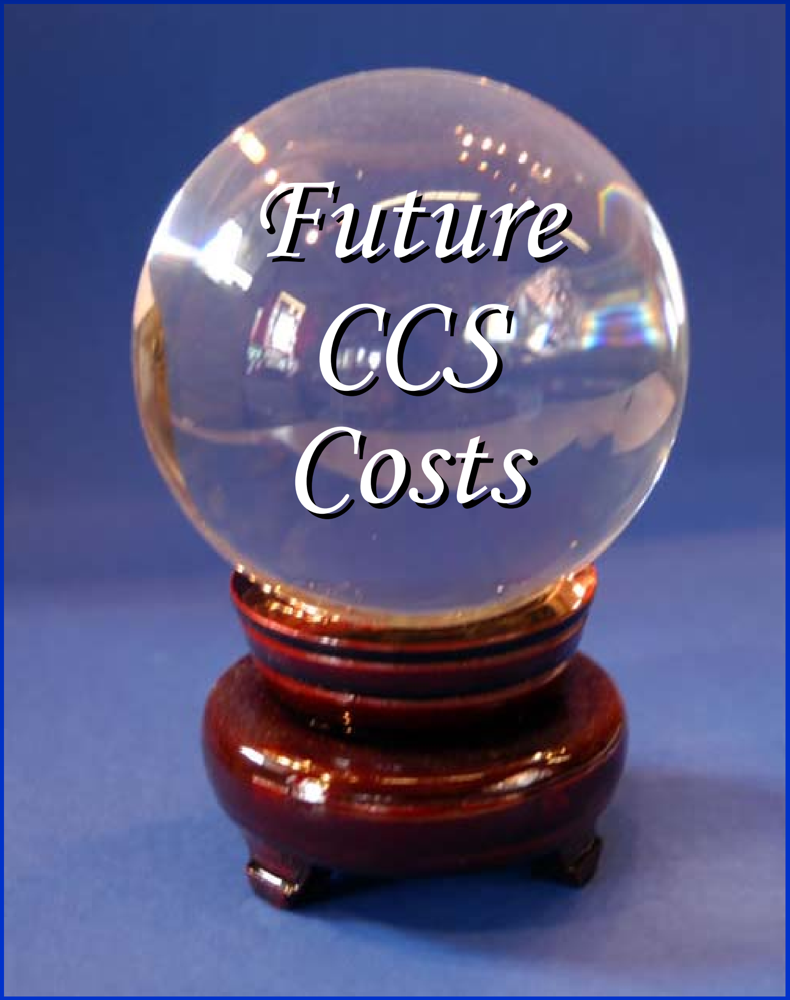


Importance of the CCS "Energy Penalty"

- CCS energy penalty defined as the *increase in fuel energy input per unit of net electrical output* (relative to a similar plant without CCS)
- Additional energy/MWh for representative plants:
  - SCPC = 31%; IGCC = 16%; NGCC = 17%
- This directly increases plant-level resource requirements and emissions per MWh of:
  - Fuel and reagent use
  - Solid and liquid wastes
  - Non-sulfur air pollutants
  - Upstream (life cycle) impacts

What is the outlook for improved capture technology?

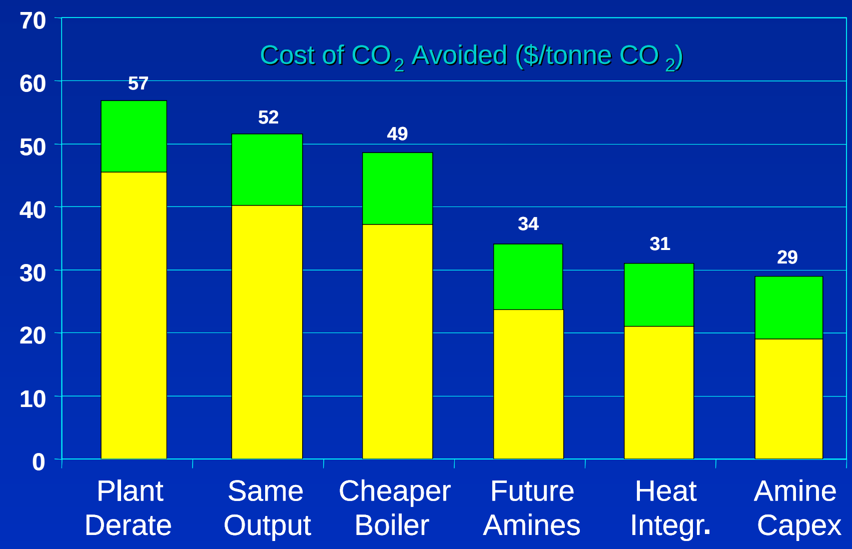
Use Powerful Analytical Methods



Two Approaches to Estimating Future Technology Costs

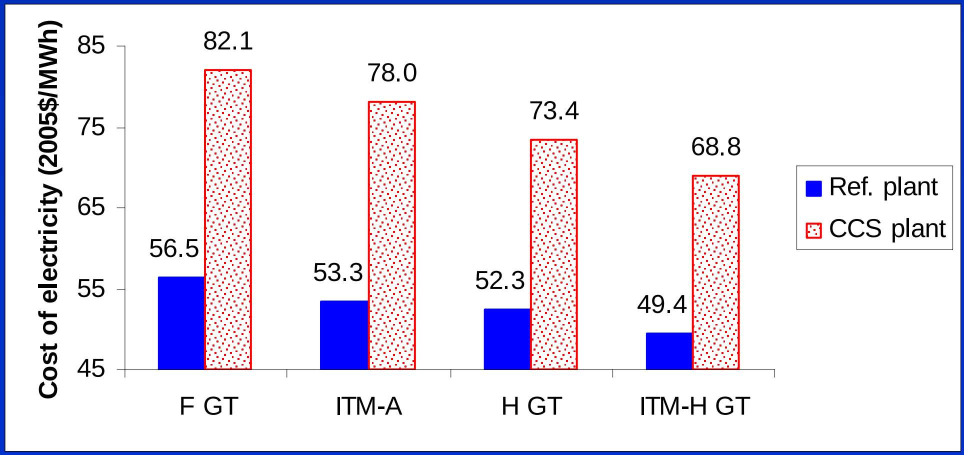
- *Method 1:* Engineering-Economic Analysis
  - A "bottom up" approach based on engineering process models, informed by judgments regarding potential improvements in key process parameters

Potential Cost Reductions from Advanced Technologies



Improved post-combustion capture for SCPC plants

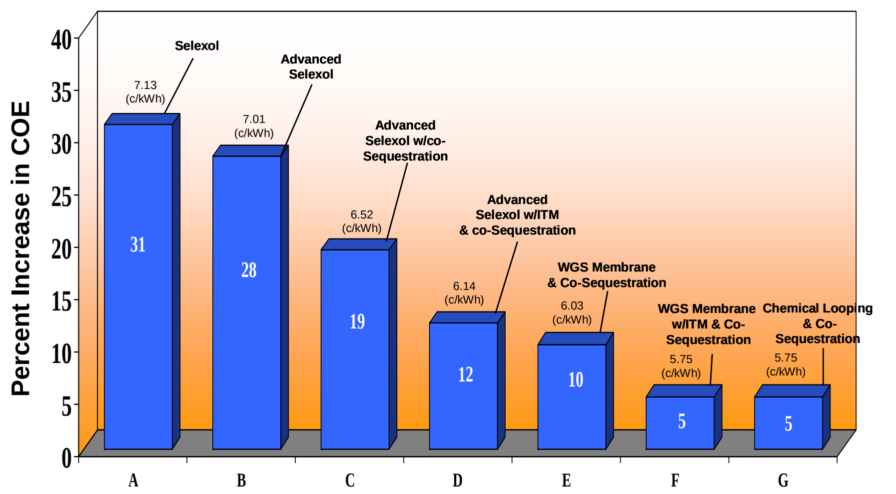
Advanced IGCC plants with pre-combustion capture



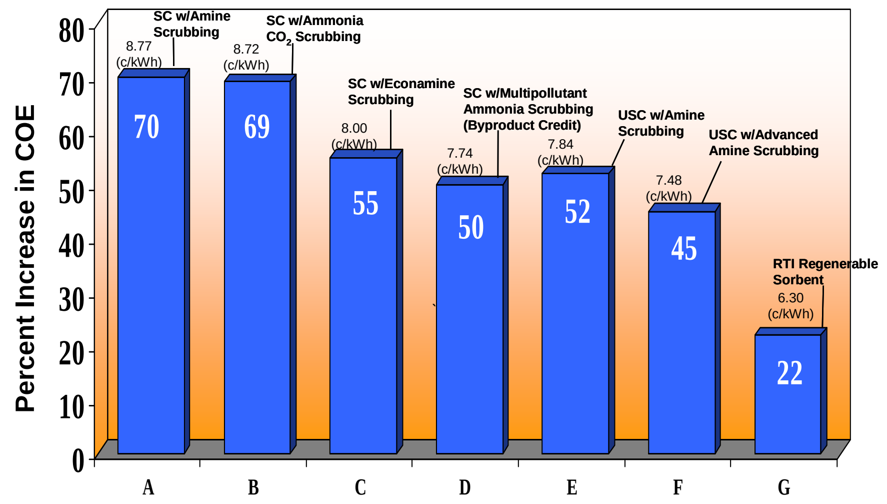
E.S. Rubin, Carnegie Mellon

Cost Projections by DOE/NETL

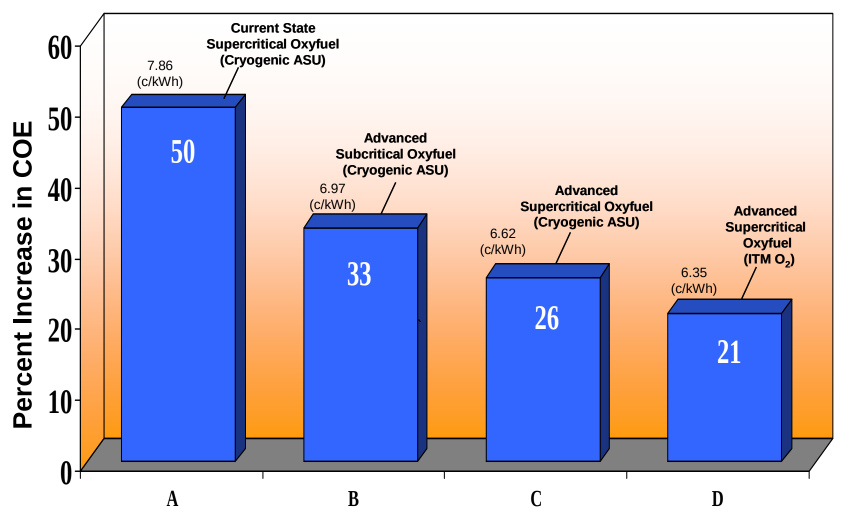
Latest Analyses for IGCC



Latest Analyses for PC Plants



Latest Analyses for Oxy-Combustion



Source: DOE NETL, 2006

E.S. Rubin, Carnegie Mellon

Two Approaches to Estimating Future Technology Costs

- *Method 2:* Use of Historical Experience Curves
  - A “top down” approach based on applications of mathematical “learning curves” or “experience curves” that reflect historical trends for analogous technologies or systems

Retrospective Case Studies

- Flue gas desulfurization systems (FGD)
- Selective catalytic reduction systems (SCR)
- Gas turbine combined cycle system (GTCC)
- Pulverized coal-fired boilers (PC)
- Liquefied natural gas plants (LNG)
- Oxygen production plants (ASU)
- Hydrogen production plants (SMR)

Learning Curve Formulation

General equation:

$$y_i = a x_i^{-b}$$

where,

y_i = time or cost to produce i^{th} unit

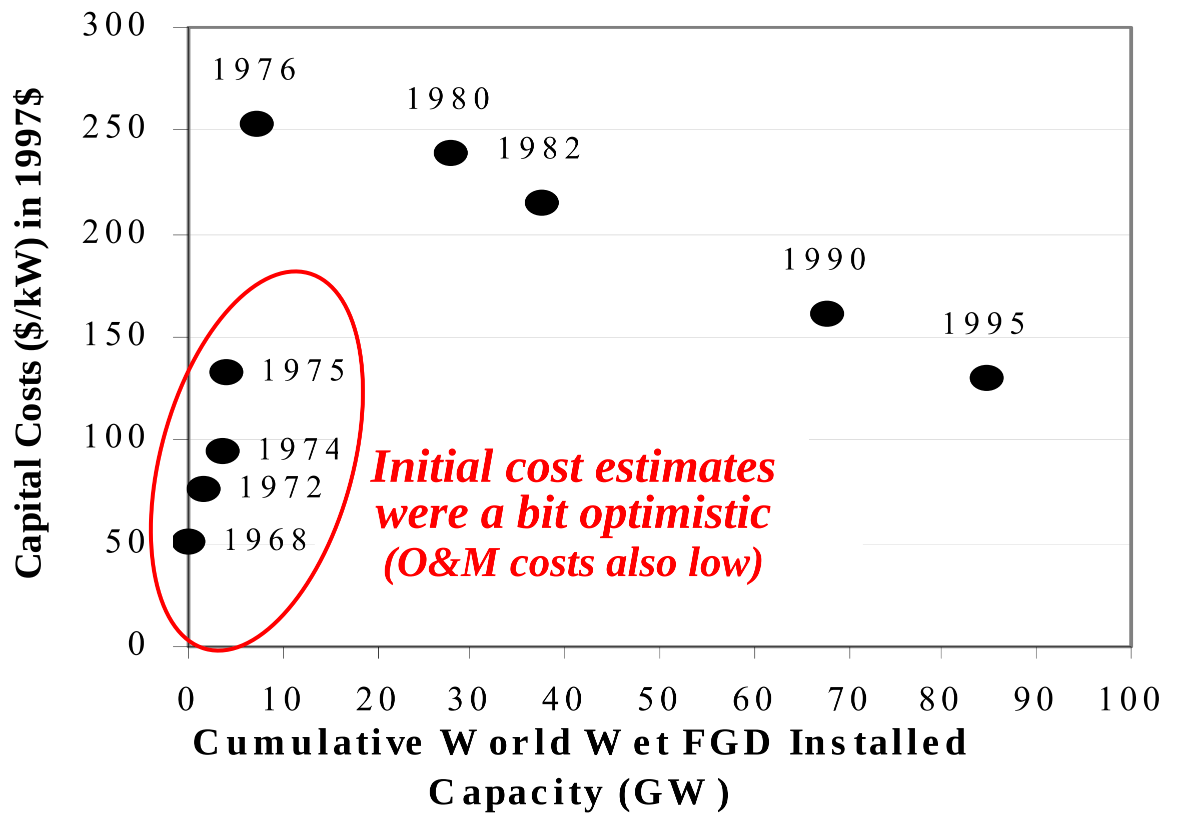
x_i = cumulative production thru period i

b = learning rate exponent

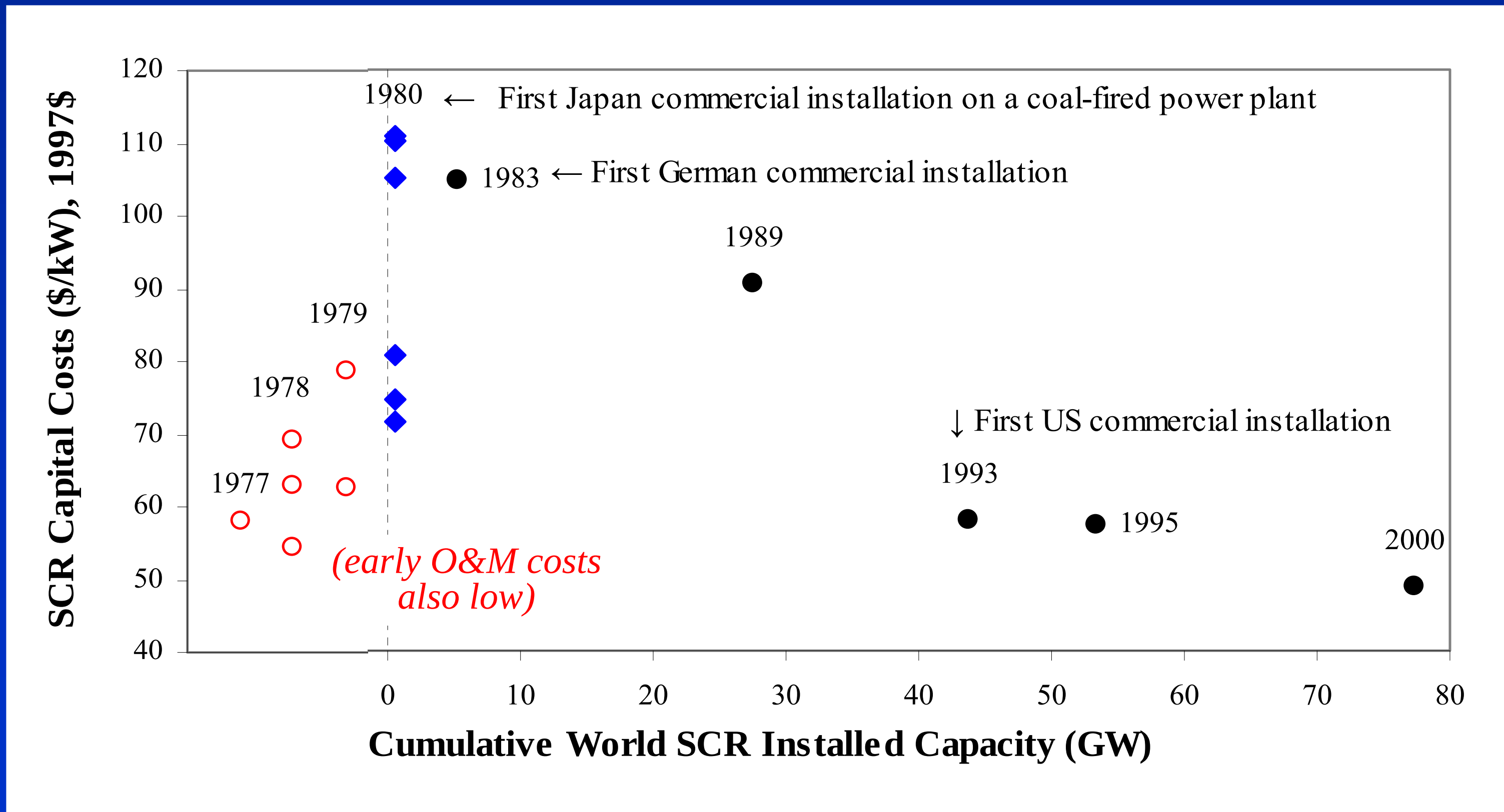
a = coefficient (constant)

Percent cost reduction for a doubling of cumulative output is called the "learning rate" (LR) = $(1 - 2^{-b})$

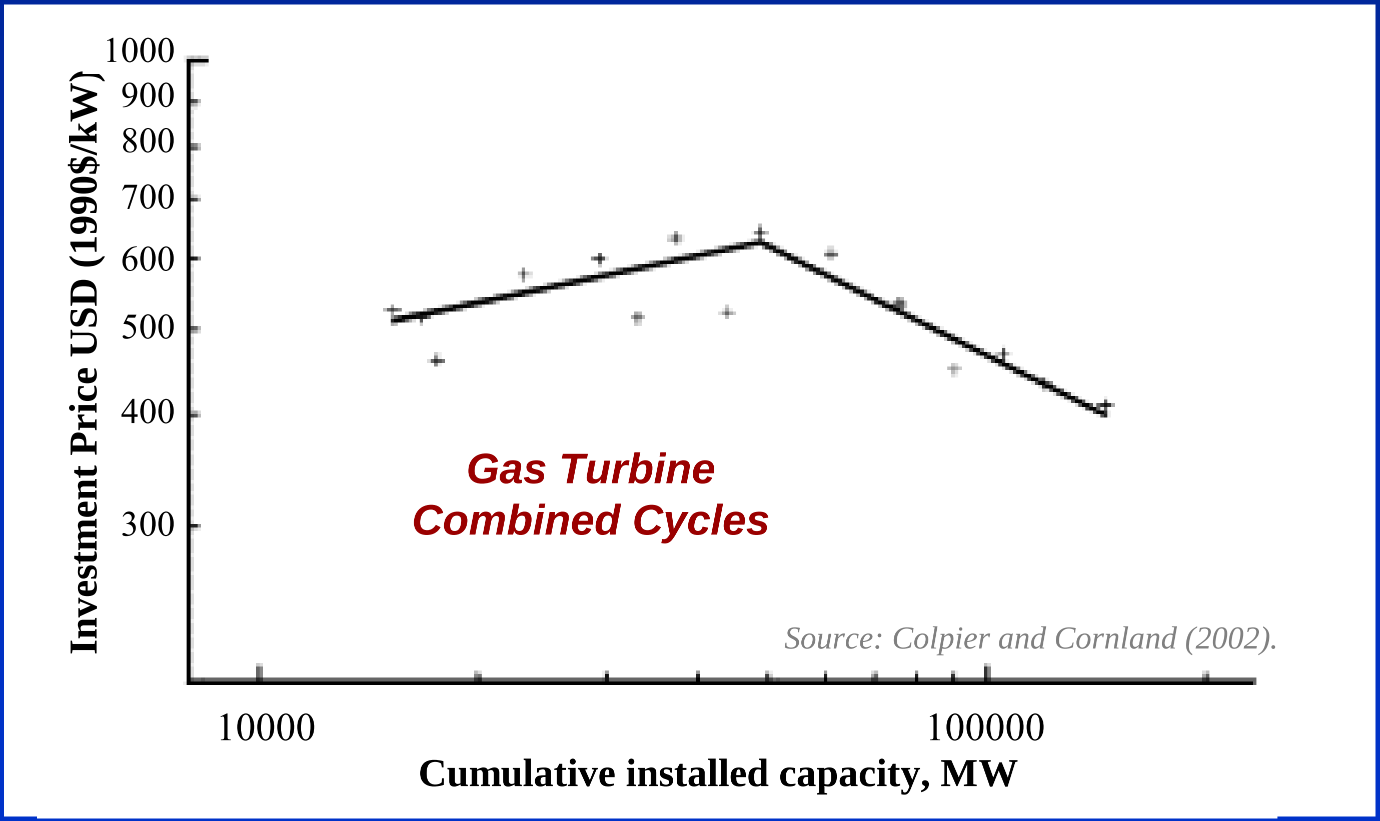
Historical Trend of FGD Capital Cost



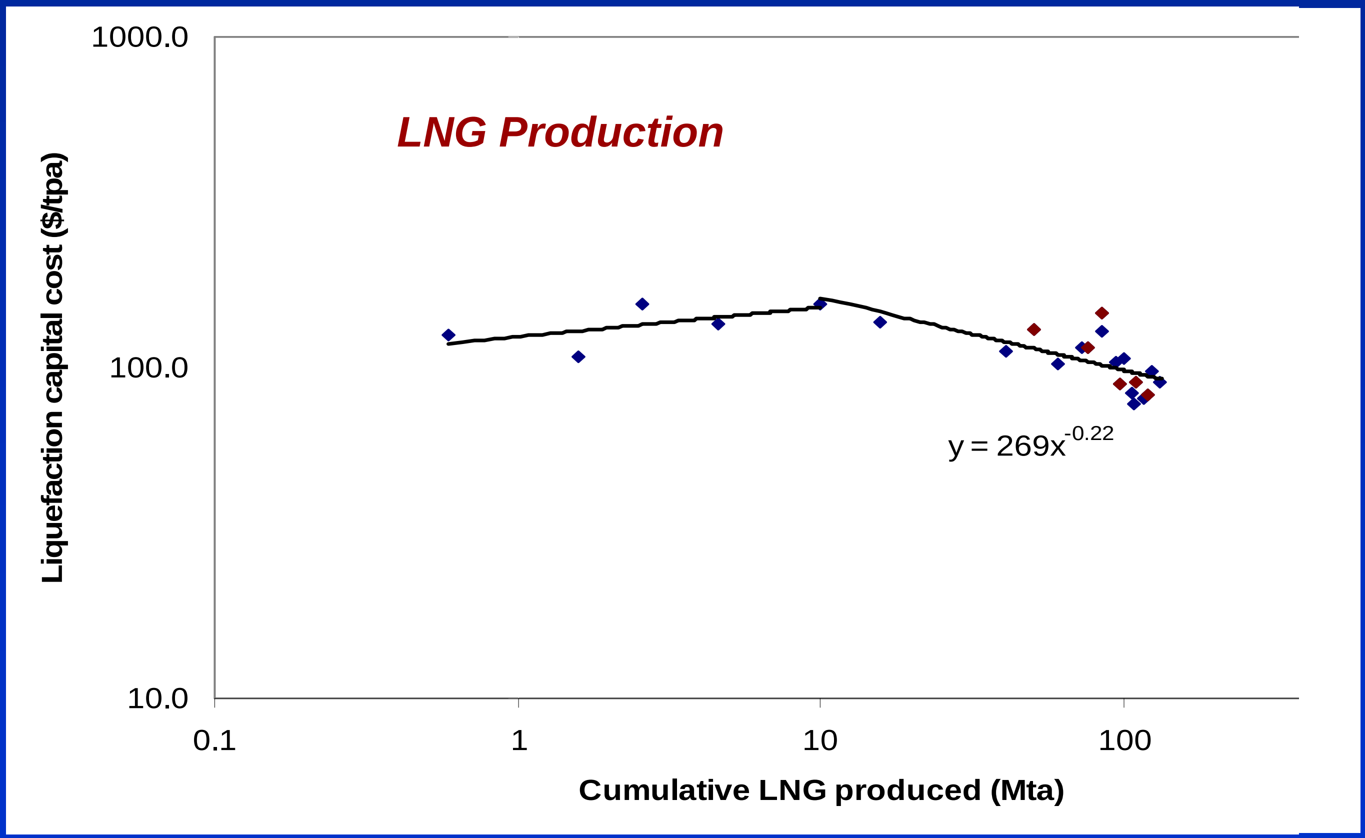
Trend of SCR Cost Estimates



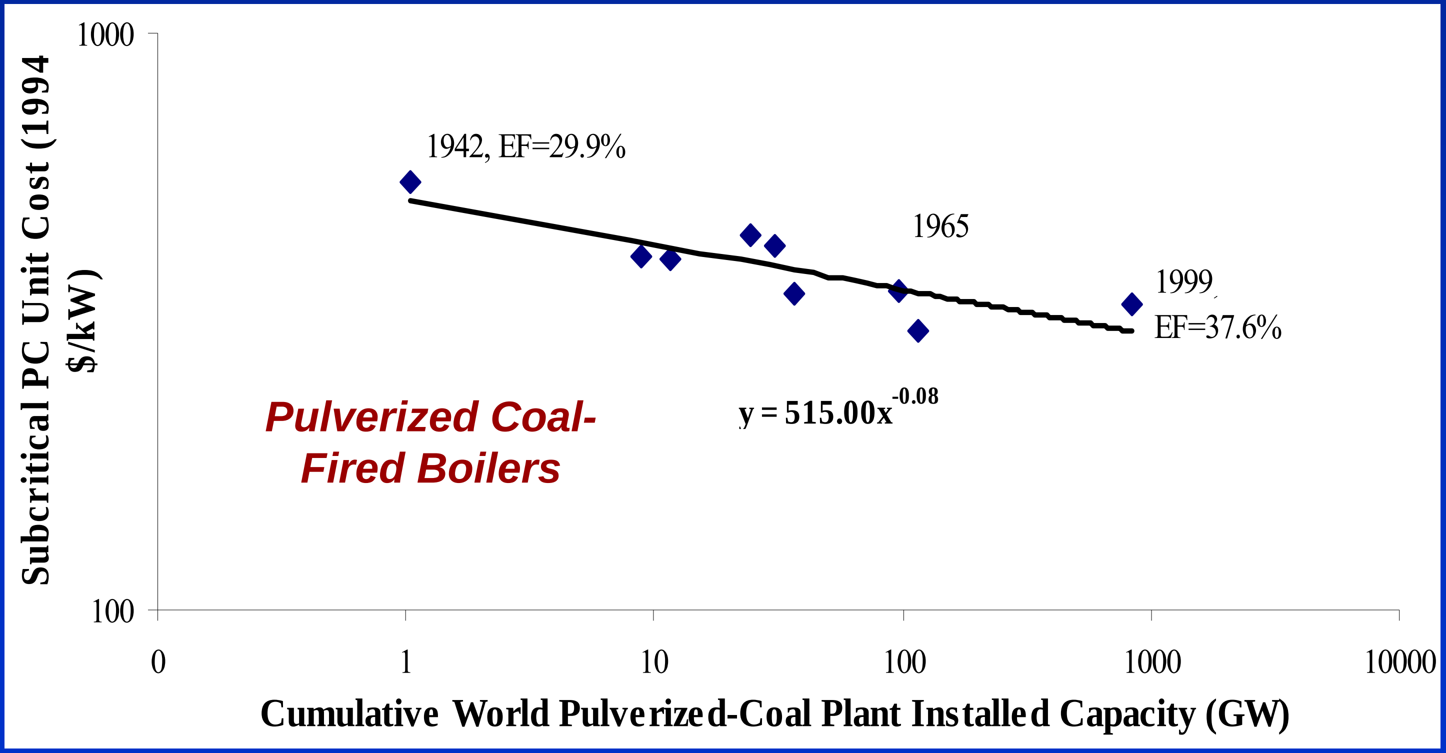
GTCC Capital Costs



LNG Plant Capital Costs



PC Boiler Capital Costs



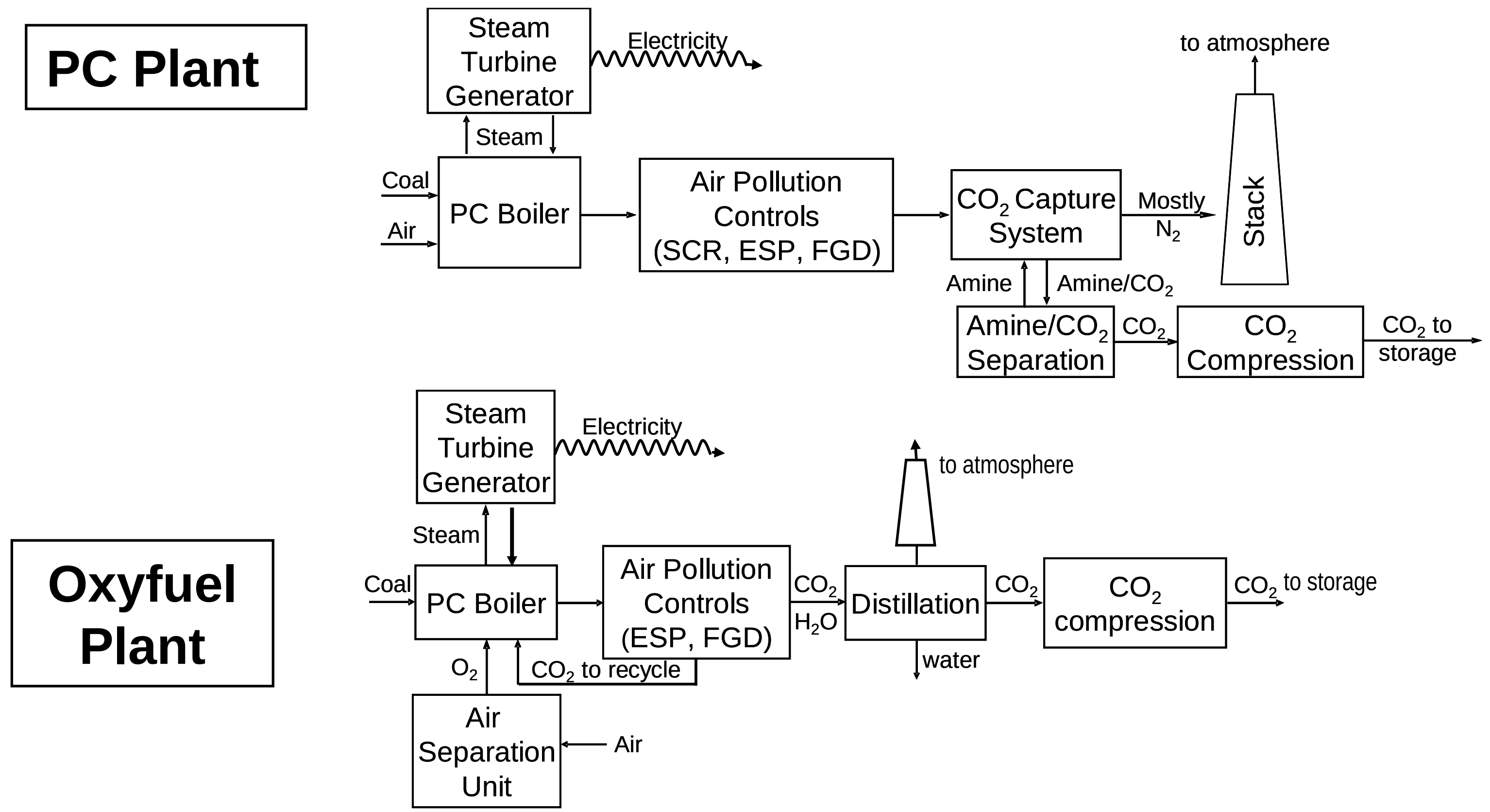
E.S. Rubin, Carnegie Mellon

Case Study Learning Rates

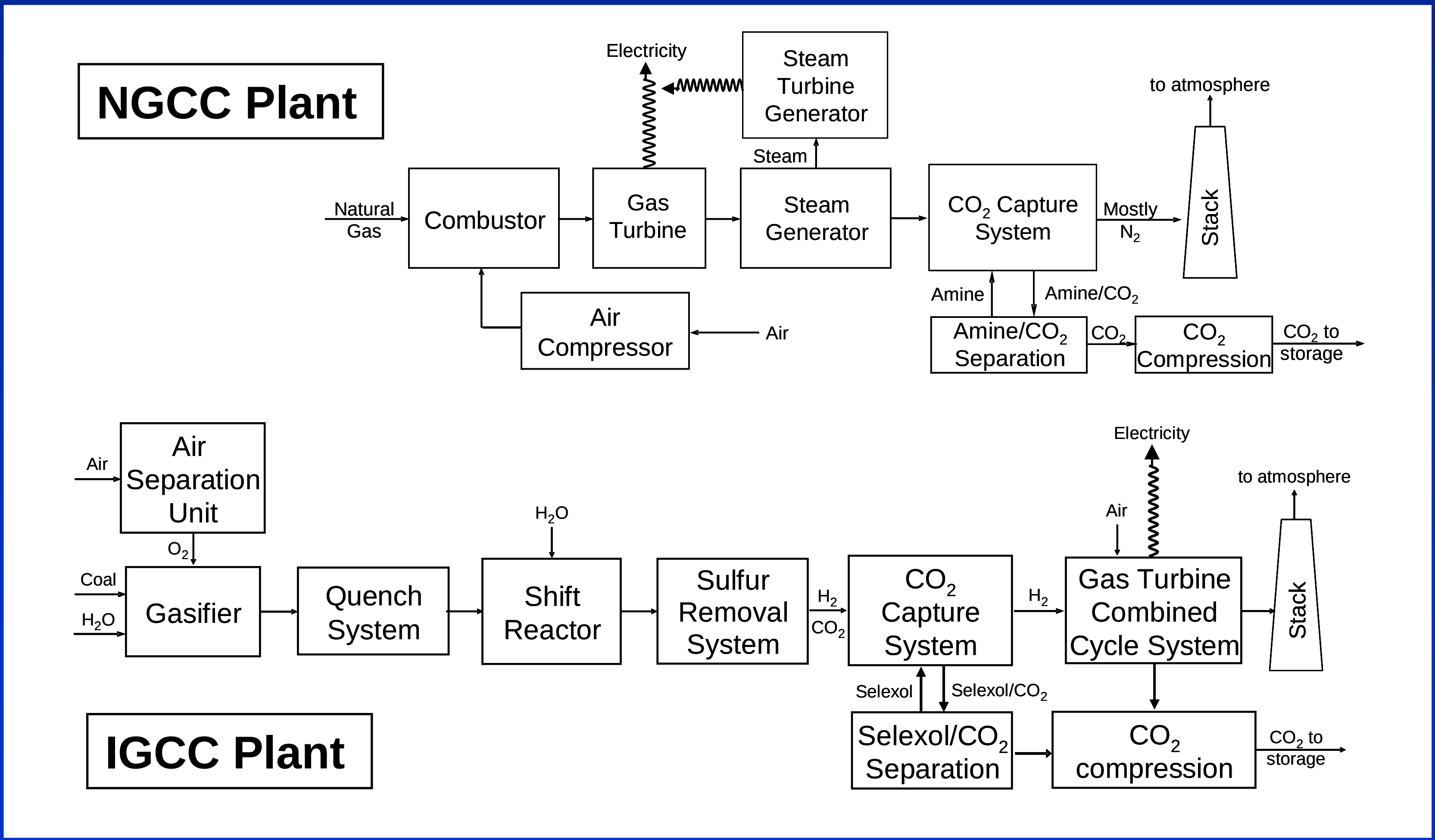
Technology	"Best Estimate" Learning Rates: Capital Cost	O&M Cost
Flue gas desulfurization (FGD)	0.11	0.22
Selective catalytic reduction (SCR)	0.12	0.13
Gas turbine combined cycle (GTCC)	0.10	0.06
Pulverized coal (PC) boilers	0.05	0.18
LNG production	0.14	0.12
Oxygen production (ASU)	0.10	0.05
Hydrogen production (SMR)	0.27	0.27

Results are within ranges reported for other energy-related technologies

Baseline CCS Plant Designs *(1)*



Baseline CCS Plant Designs (2)



E.S. Rubin, Carnegie Mellon

Step 1: Disaggregate each plant into major sub-sections

For example:

- IGCC Plant Components
  - Air separation unit
  - Gasifier area
  - Sulfur removal/recovery system
  - CO_2 capture system (WGS+Selexol)
  - CO_2 compression
  - GTCC (power block)
  - Fuel cost

Step 2: Estimate current plant costs and contribution of each sub-section

Levelized costs in constant $2002

Plant Type & Technology	Capital Cost	Annual O&M Cost*	Cost of Electricity*
IGCC Plant w/ Capture	**1,831** $/kW	**21.3** $/MWh	**62.6** $/MWh
Air separation unit	18 %	8 %	14 %
Gasifier area	27 %	17 %	24 %
Sulfur removal/recovery	6 %	3 %	5 %
CO_2 capture system*	13 %	7 %	11 %
CO_2 compression	2%	2 %	2 %
GTCC (power block)	34 %	9 %	25 %
Fuel cost**	--	54%	19 %

*Excludes costs of CO_2 transport and storage **Based on Pittsburgh #8 coal @ $1.0/GJ

Step 3: Select learning rate analogues for each plant component

Plant Type & Technology	FGD	SCR	GTCC	PC boiler	LNG prod	O_2 prod
IGCC Plant						
Air separation unit						X
Gasifier area					X	
Sulfur removal/recovery	X	X				
CO_2 capture system	X	X				
CO_2 compression						
GTCC (power block)			X			

Step 4: Estimate current capacity of major plant components

Plant Type &Technology	Current MW_{net} Equiv.
IGCC Plant Components	
Air separation units	50,000
Gasifier area	10,000
Sulfur removal/recovery	50,000
CO_2 capture system	10,000
CO_2 compression	10,000
GTCC (power block)	240,000

Step 5: Set projection period and start of learning

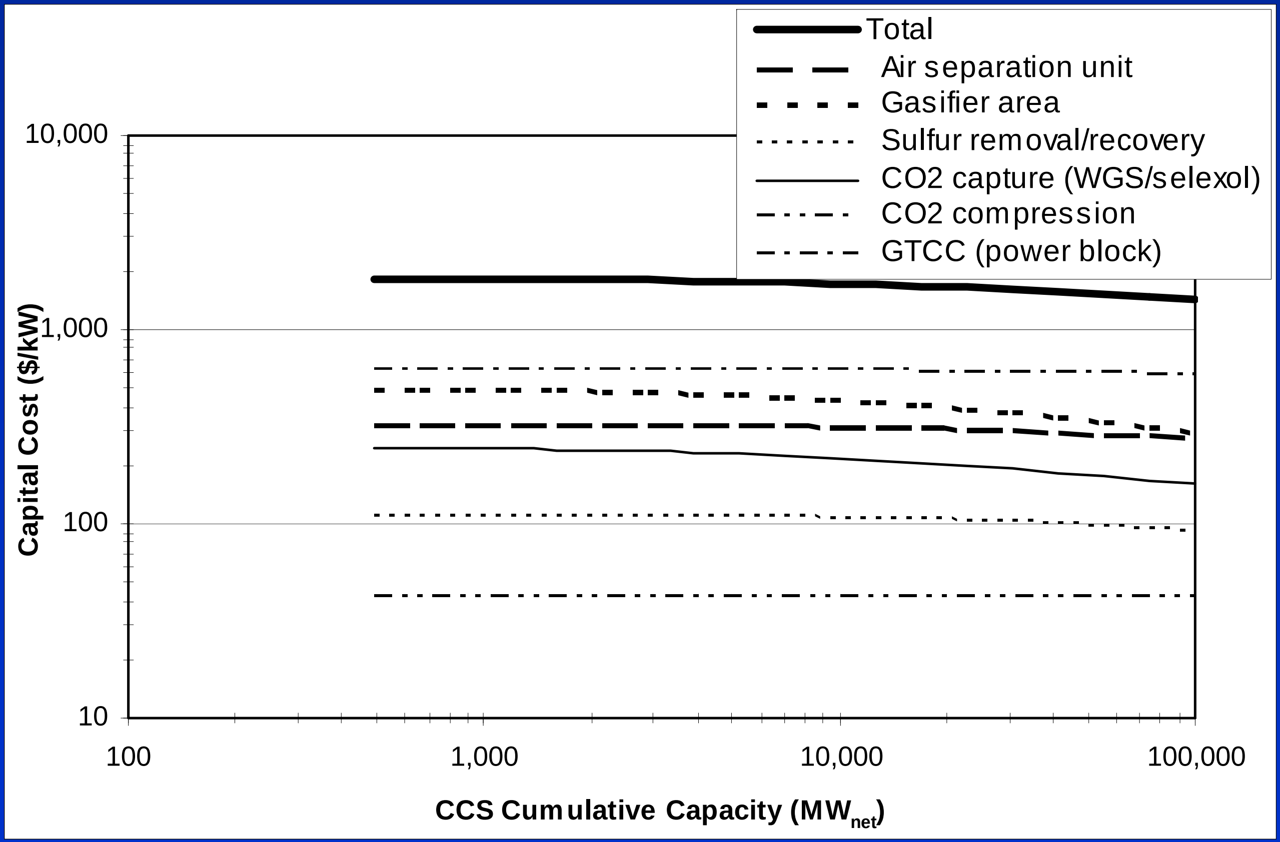
Plant Type	Cumulative CCS Capacity (MW)		
	Learning Begins at:		Learning Projected to:
	1^{st} Plant	n^{th} Plant	
NGCC Plant	432	3,000	100,000
PC Plant	500	5,000	100,000
IGCC Plant	490	7,000	100,000
Oxyfuel Plant	500	10,000	100,000

Step 6: Sensitivity Analysis

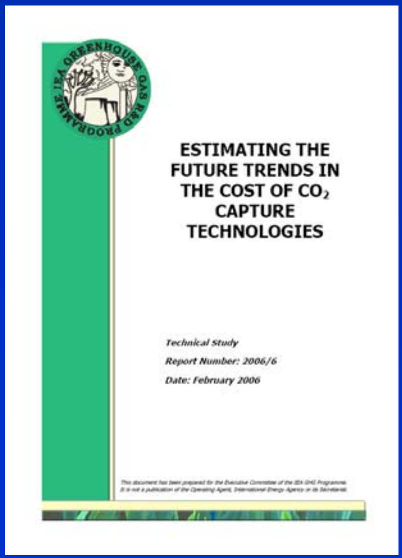
- Learning starts at either first or n^{th} plant
- Range of component learning rates
- Projection to 50 GW of worldwide capacity
- Lower estimates of current component capacity
- Effect of additional non-CCS experience
- Higher fuel prices for coal and natural gas
- Lower financing costs + higher plant utilization

Results for IGCC Capital Cost
(Assuming learning begins at first capture plant)

Based on nominal case study assumptions



Detailed results available in papers and reports



NGCC Sensitivity Case	Capital Cost ($/kW)				COE ($/MWh)			
	Learning Rate	Initial Value	Final Value	% Change	Learning Rate	Initial Value	Final Value	% Change
Nominal Base Case Assumptions	0.022	916	817	10.8%	0.033	59.1	49.9	15.5%
Learning Starts with First Plant	0.014	916	811	11.5%	0.028	59.1	47.0	20.4%
Learning up to 50 GW	0.018	916	849	7.3%	0.031	59.1	52.0	12.0%
Current Capture Capacity = 0 GW	0.029	916	786	14.2%	0.037	59.1	48.8	17.4%
Non-CSS Exp. Multipliers = 2.0	0.030	916	783	14.4%	0.036	59.1	49.0	17.1%
Natural Gas Price = $6.0/GJ	0.022	925	826	10.7%	0.033	76.1	64.2	15.7%
FCF = 11%, CF = 85%	0.022	918	820	10.7%	0.034	51.6	43.3	16.1%

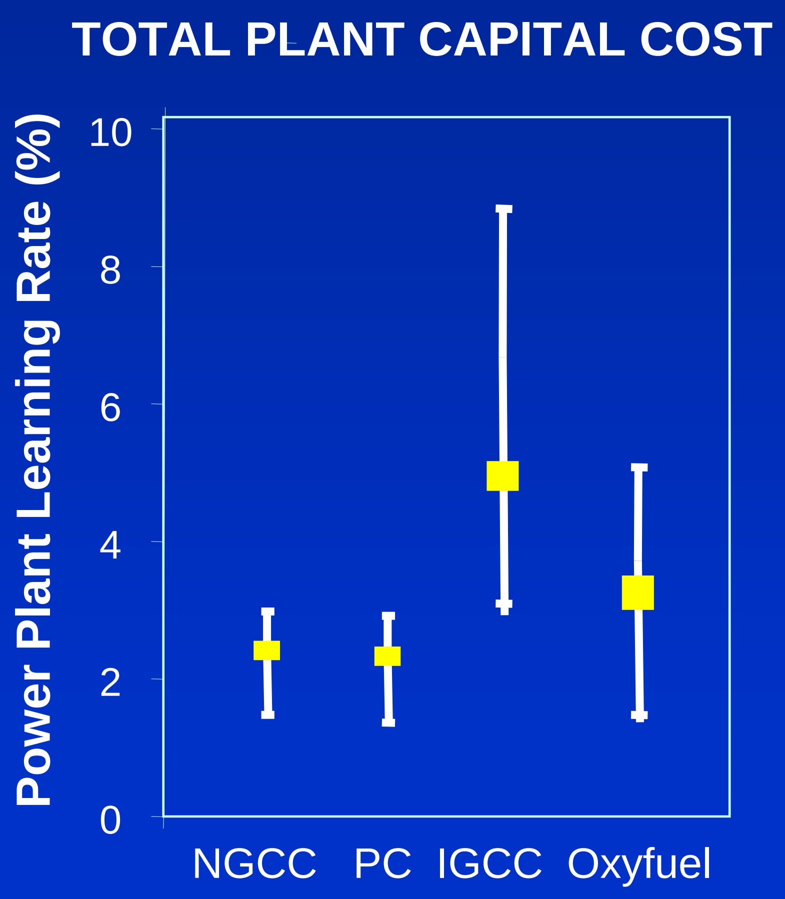
PC Sensitivity Case	Capital Cost ($/kW)				COE ($/MWh)			
	Learning Rate	Initial Value	Final Value	% Change	Learning Rate	Initial Value	Final Value	% Change
Nominal Base Case Assumptions	0.021	1,962	1,783	9.1%	0.035	73.4	62.8	14.4%
Learning Starts with First Plant	0.013	1,962	1,764	10.1%	0.024	73.4	60.8	17.2%
Learning up to 50 GW	0.018	1,962	1,846	5.9%	0.031	73.4	66.0	10.1%
Current Capture Capacity = 0 GW	0.026	1,962	1,744	11.1%	0.042	73.4	60.9	17.1%
Non-CSS Exp. Multipliers = 2.0	0.029	1,962	1,723	12.2%	0.068	73.4	60.4	17.8%
Coal Price = $1.5/GJ	0.021	1,965	1,786	9.1%	0.035	79.6	68.2	14.3%
FCF = 11%, CF = 85%	0.021	1,963	1,785	9.1%	0.039	57.2	48.2	15.7%

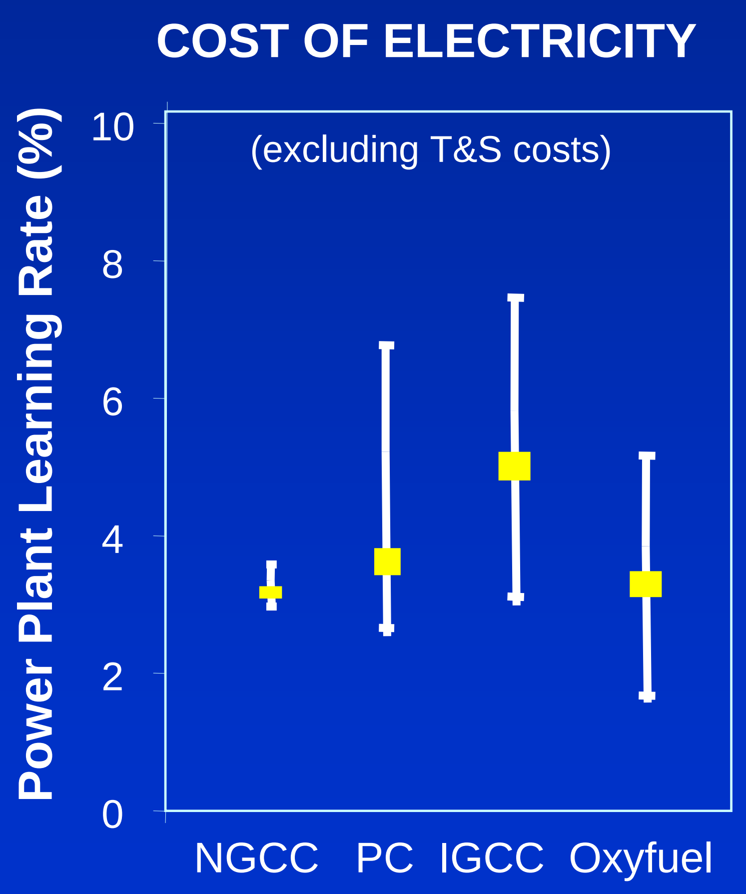
IGCC Sensitivity Case	Capital Cost ($/kW)				COE ($/MWh)			
	Learning Rate	Initial Value	Final Value	% Change	Learning Rate	Initial Value	Final Value	% Change
Nominal Base Case Assumptions	0.050	1,831	1,505	17.8%	0.049	62.6	51.5	17.7%
Learning Starts with First Plant	0.029	1,831	1,448	20.9%	0.032	62.6	48.6	22.4%
Learning up to 50 GW	0.044	1,831	1,610	12.1%	0.045	62.6	54.9	12.2%
Current Gasifier Capacity = 1 GW	0.057	1,831	1,460	20.3%	0.055	62.6	50.2	19.7%
Above + H2-GTCC = 0 GW	0.088	1,831	1,285	29.8%	0.078	62.6	45.9	26.6%
Non-CSS Exp. Multipliers = 2.0	0.062	1,831	1,432	21.8%	0.054	62.6	49.5	20.8%
Coal Price = $1.5/GJ	0.050	1,834	1,507	17.8%	0.048	68.4	56.6	17.3%
FCF = 11%, CF = 85%	0.048	1,832	1,516	17.2%	0.047	47.2	39.2	16.9%

Oxyfuel Sensitivity Case	Capital Cost ($/kW)				COE ($/MWh)			
	Learning Rate	Initial Value	Final Value	% Change	Learning Rate	Initial Value	Final Value	% Change
Nominal Base Case Assumptions	0.028	2,417	2,201	9.0%	0.030	78.8	71.2	9.6%
Learning Starts with First Plant	0.013	2,417	2,160	10.7%	0.017	78.8	68.6	12.9%
Learning up to 50 GW	0.023	2,417	2,291	5.2%	0.025	78.8	74.3	5.8%
Current Boiler Capacity = 0	0.054	2,417	2,008	16.9%	0.056	78.8	65.1	17.5%
Non-CSS Exp. Multipliers = 2.0	0.038	2,417	2,122	12.2%	0.044	78.8	68.8	12.7%
Coal Price = $1.5/GJ	0.028	2,421	2,204	9.0%	0.030	84.7	76.4	9.8%
FCF = 11%, CF = 85%	0.028	2,418	2,202	9.0%	0.031	58.8	53.0	9.9%

Summary of Learning Rate Results

(Based on 100 GW of cumulative CCS capacity)

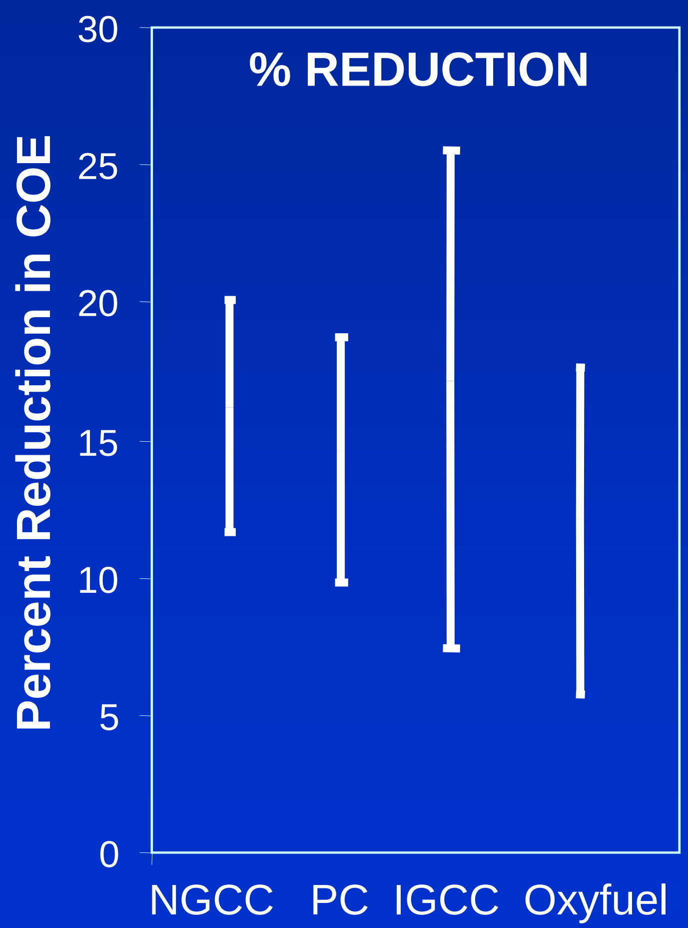


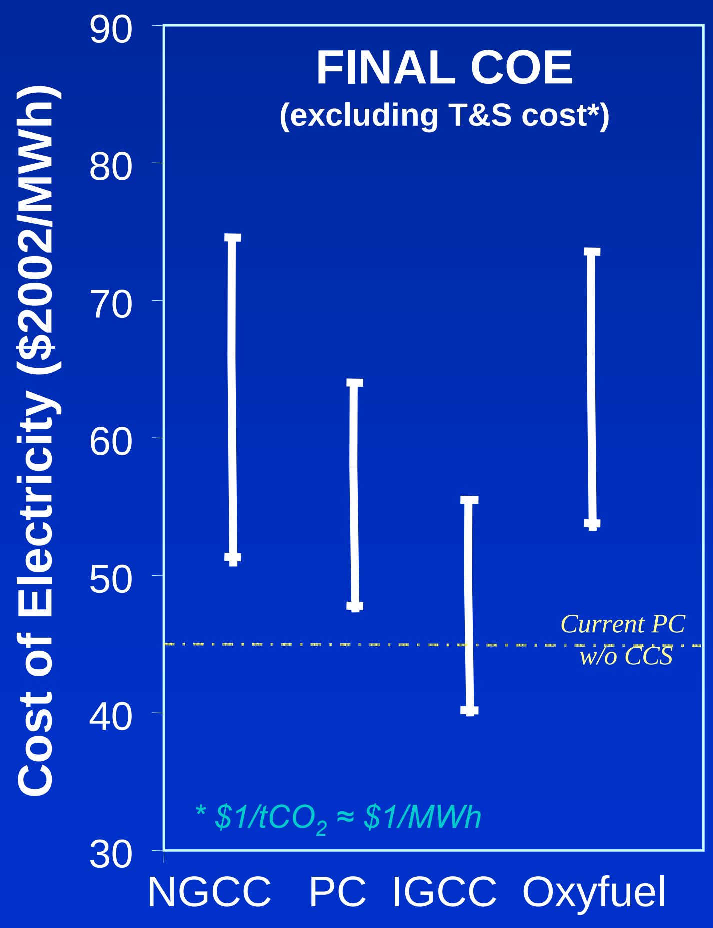


E.S. Rubin, Carnegie Mellon

Summary of COE Results

(Based on 100 GW of cumulative CCS capacity)





E.S. Rubin, Carnegie Mellon

What are the key needs to realize improved technology?

Key Needs

- Deployment, deployment, deployment !
  (to foster learning-by-doing)
- Sustained and increasing R&D support
- Resolution of current legal and institutional uncertainties surrounding geological sequestration
  - Regulatory requirements (esp.for deep injection)
  - Liabilities (near-term and long-term)
  - Financing and insurance requirements
  - Emissions allowance & trading rules for CCS projects

Concluding Comments

- Absent a climate policy with sufficiently stringent limits on CO_2 emissions, there is little or no incentive to develop and deploy CO_2 capture and storage technologies
- Market-based policies aimed broadly at reducing CO_2 emissions (e.g., cap-and-trade) are not likely to stimulate CCS until carbon price exceeds roughly \$100/tC (\$27/tCO_2)
- Policies aimed specifically at fossil fueled plants (e.g., performance and/or portfolio standards) can accelerate CCS deployment and innovation, <u>especially in conjunction with incentives for early actors</u>
- Analysis of policy options is on-going …. and the subject of another talk!

Thank You.

For more information:

rubin@cmu.edu