Reducing the Cost of CCS through "Learning By Doing"

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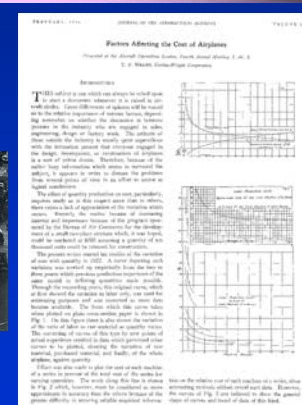
Outline of Talk

- A brief overview of learning curves
- Application to power plants
- Application to emission control technologies
- Implications for future CCS costs

Overview of learning curves

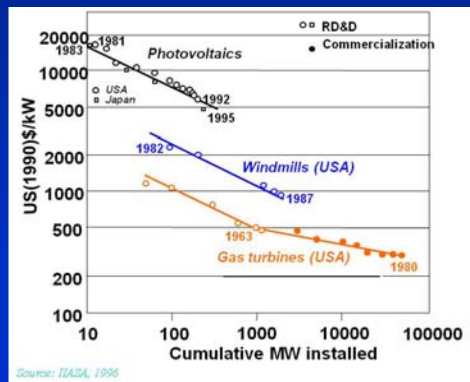
T.P.Wright (1936) found that the cost of making airplanes declined with increasing experience



"Learning by doing" reduced manufacturing costs exponentially

Learning Curve Concept Later Extended to Technology "Experience Curves"

Examples of Technology Cost Trends Used to Derive Experience (Learning) Curves



The Common (One-Factor) Learning Curve Model

General equation:

$$C_i = a\,P_i^{\,-b}$$

where,

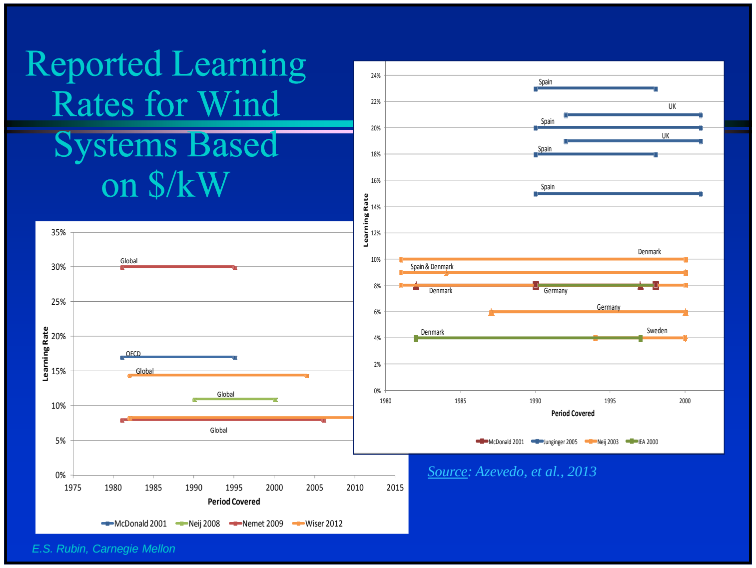
C_i = cost to produce the i^{th} unit
P_i = cumulative production or capacity thru period <u>*i*</u>
b = learning rate exponent
a = coefficient (constant)

Fractional cost reduction for a doubling of cumulative capacity (or production) is defined as the <u>learning rate</u>:
$LR = 1 - 2^b$

Application to power plants

Literature Review of Learning Rates for Power Generation Technologies

- PC plants
- PC with CCS
- IGCC plants
- IGCC with CCS
- NGCC plants
- NGCC with CCS
- NG turbines
- Biomass plants
- Nuclear
- Hydroelectric
- Geothermal
- On-shore wind
- Off-shore wind
- Solar PV
- Conc. solar thermal


Reported Learning Rates for Wind Systems Based on $/kW
Learning Rate
Period Covered
Global
OECD
Spain
UK
Spain & Denmark
Denmark
Germany
Sweden
McDonald 2001
Neij 2008
Nemet 2009
Wiser 2012
Junginger 2005
Neij 2003
IEA 2000
Source: Azevedo, et al., 2013
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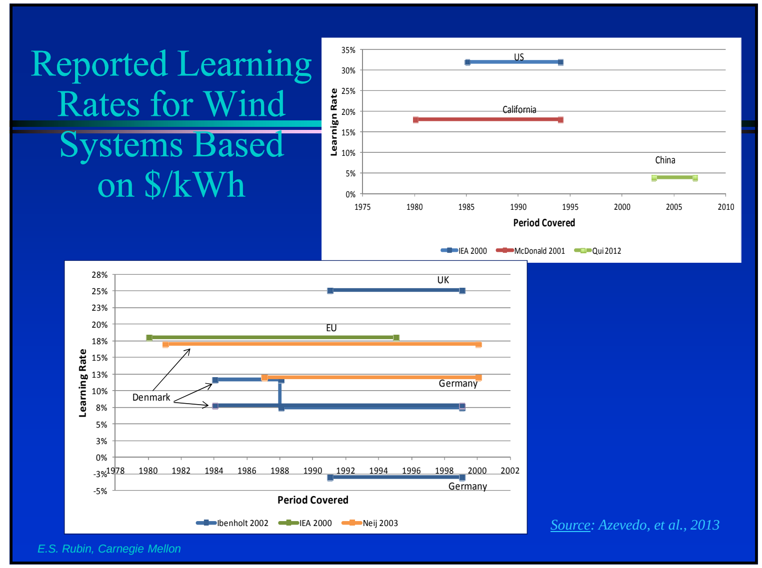
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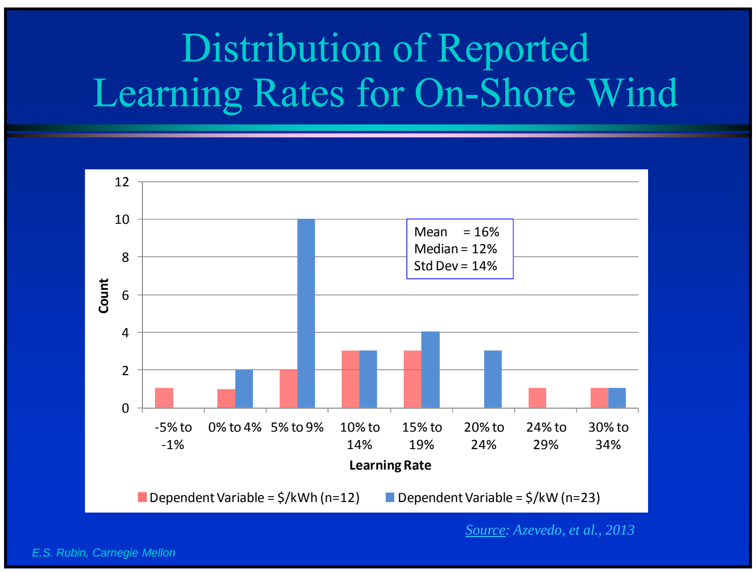
Distribution of Reported Learning Rates for On-Shore Wind
Count
Mean = 16%
Median = 12%
Std Dev = 14%
-5% to -1%
0% to 4%
5% to 9%
10% to 14%
15% to 19%
20% to 24%
24% to 29%
30% to 34%
Learning Rate
Dependent Variable = $/kWh (n=12)
Dependent Variable = $/kW (n=23)
Source: Azevedo, et al., 2013
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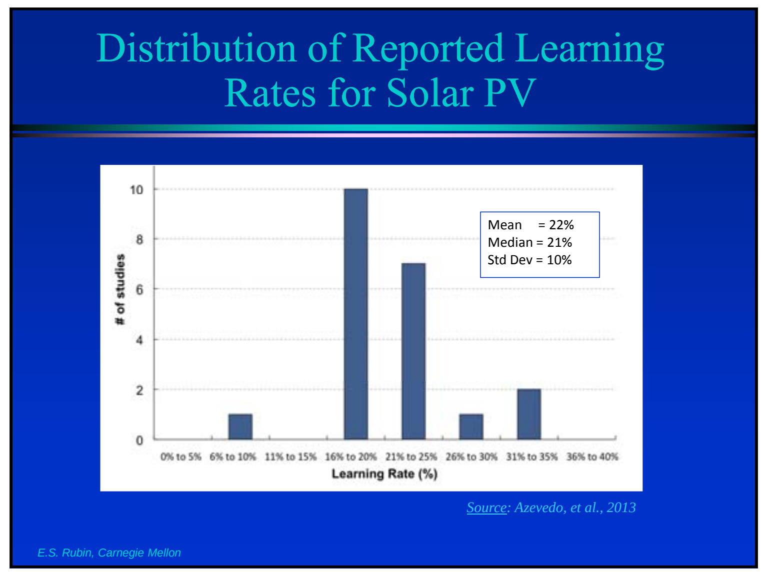
Distribution of Reported Learning Rates for Solar PV
# of studies
Mean = 22%
Median = 21%
Std Dev = 10%
0% to 5%
6% to 10%
11% to 15%
16% to 20%
21% to 25%
26% to 30%
31% to 35%
36% to 40%
Learning Rate (%)
Source: Azevedo, et al., 2013
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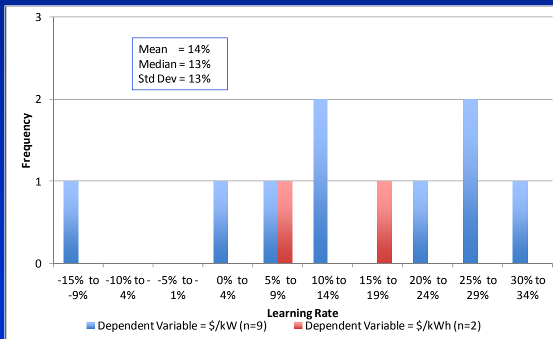
Distribution of Reported Learning Rates for Gas-Fired Power Plants



Source: Azevedo, et al., 2013

Range of Reported Learning Rates

Technology	Number of studies reviewed	Number of studies with one factor	Number of studies with two factors	Range of learning rates for "learning by doing" (LBD)	Range of rates for "learning by researching" (LBR)	Years covered across all studies
Coal*						
PC	2	2	0	5.6% to 12%		1902-2006
IGCC	1	1	0	2.5% to 7.6%		Projections
Natural Gas*	8	6	2	-11% to 34%	2.38% to 17.7%	1980-1998
Nuclear	4	4	0	<0 to 6%		1975-1993
Wind (on-shore)	35	29	6	-3% to 32%	10% to 26.8%	1980-2010
Solar PV	24	22	2	10% to 53%	10% to 18%	1959-2001
BioPower						
Biomass production	4	4	0	12% to 45%		1971-2006
*Power generation***	7	7	0	0% to 24%		1976-2005
Geothermal power	3	0	0			1980-2005
Hydropower	3	0	2	0.48% to 11.4%	2.63% to 20.6%	1980-2001

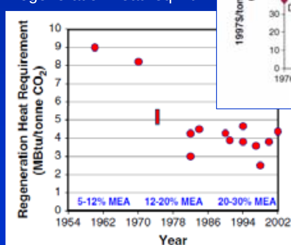
*Does not include plants with CCS. **Includes combined heat and power (CHP) and biodigesters.

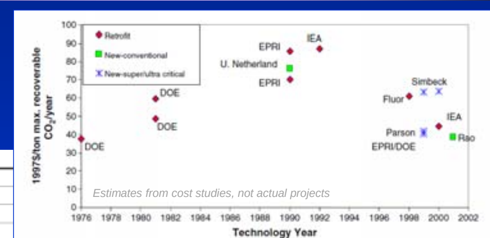
Source: Azevedo, et al., 2013

Application to emission control technologies

Early Trends in Amine System Performance and Cost Measures

Decreasing trend of MEA regeneration heat reqm't.





Capital cost estimates for an amine system at a 500 MW coal-fired plant (on a gross power basis)

Source: Yeh & Rubin, 2012

What can be learned from the history of other pollution control systems?

U.S. Government Actions Affecting SO_2 and NO_x Control Technology

- Legislation / Regulation
  - Clean Air Act Amendments of 1970, 1977, 1990
  - New Source Performance Standards of 1971, 1979, 1992
- R&D Funding / Financial Incentives
  - EPA multi-million $ research budget in 1970s
  - DOE Clean Coal Technology Program (since 1985)
- Facilitating Technology Transfer
  - SO_2 Control Symposium (starting 1969)
  - Symposia and workshops on multiple pollutants (starting in 1970s)

Regulatory requirements established markets for environmental technologies

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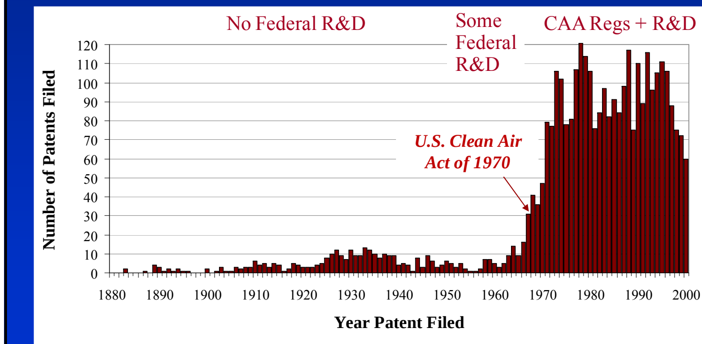
U.S. Patenting Activity in SO_2 Control Technology (1880–2000)



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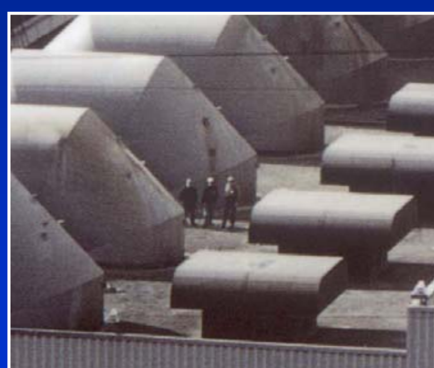
Atop an Early SO_2 Absorber

Many of the early flue gas desulfurization (FGD) system designs were complex and costly



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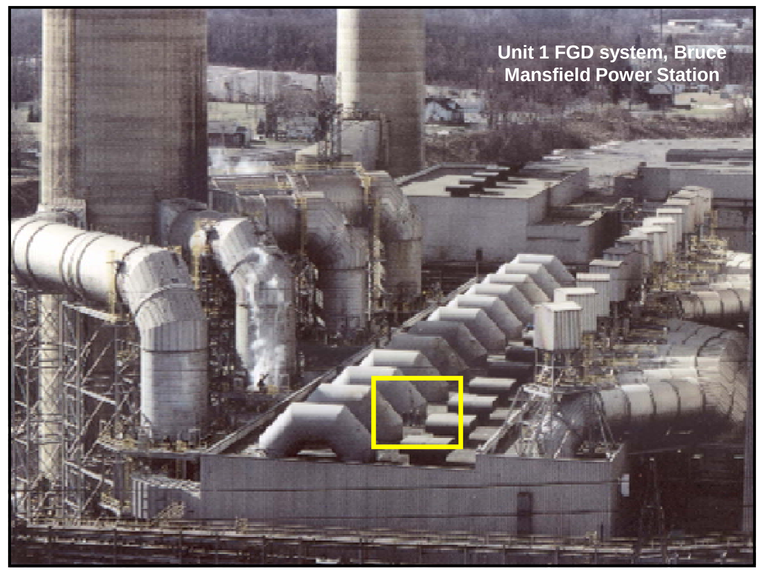
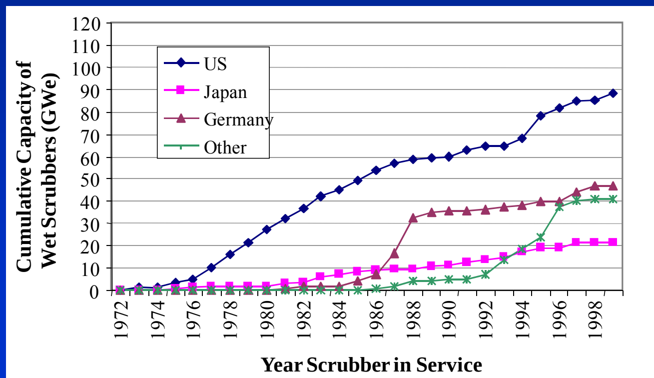


Adoption of FGD Technology
(Coal-Fired Power Plants)



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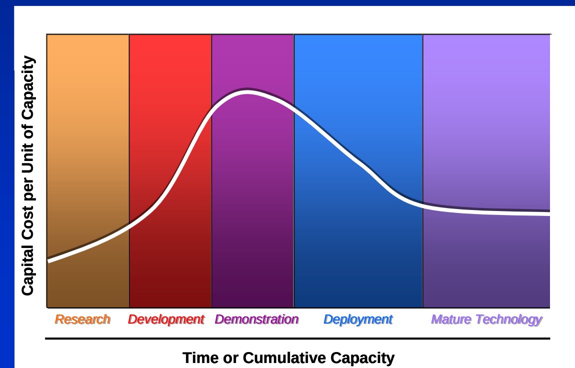
Typical Cost Trend for a New Technology



Source: Based on EPRI, 2008

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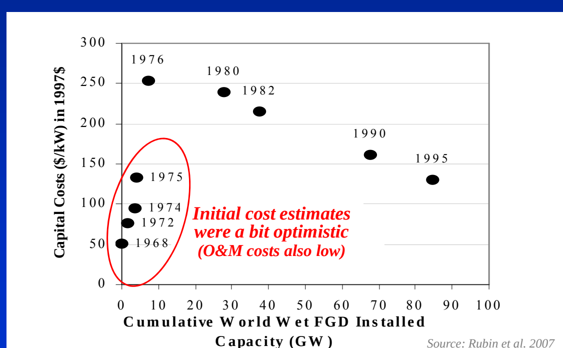
Trend of FGD Capital Cost



(Post-1976 data based on 90% SO_2 removal, 500 MW plant, 3.5%S coal)

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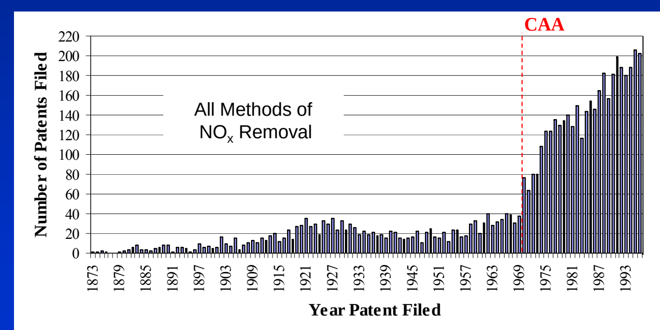
Patenting Activity in NO_x Controls
(U.S. Patents, Class-based dataset)



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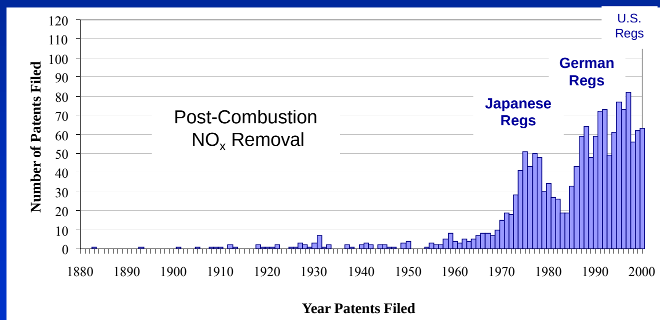
Patenting Activity in Post-Combustion NO_x Controls



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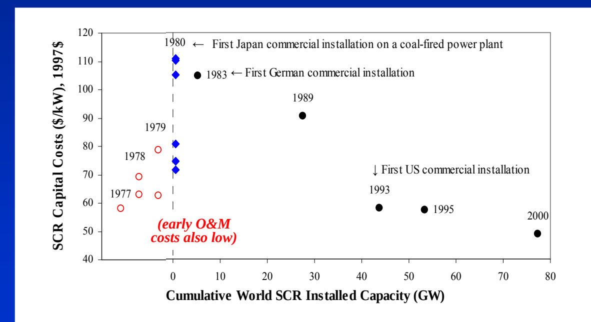
Trend of SCR Cost Estimates



Source: Rubin et al. 2007

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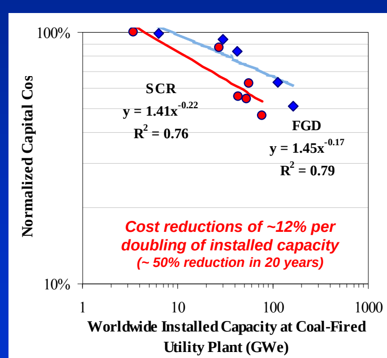
Historical Learning Curves for FGD and SCR Systems

Standard log-linear models fit to data for declining FGD and SCR capital costs

These values reflect the real change in cost of doing the same job at different points in time for the same power plant and fuel specifications



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Implications for future cost of carbon capture and storage (CCS)

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Cost of CCS for New Coal-Based Plants Using Current Technology

Increase in levelized cost for 90% capture

Incremental Cost of CCS ***relative to same plant type*** without CCS (based on bituminous coals)	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
% Increases in capital cost ($/kW) and generation cost ($/kWh)	**~ 60–80%**	**~ 30–50%**

- ***Capture accounts for most (~80%) of the total cost***
- *Retrofit of existing plants typically has a higher cost*
- *Added cost to consumers will be much smaller*
(reflecting the CCS capacity in the generation mix at any given time)

CCS Cost for New NGCC Plants (Current Technology)

Increase in levelized cost for 90% capture

Cost Measure	New NGCC Cost Increase with CCS
% Increase in generation cost ($/kWh) (relative to NGCC w/o CCS)	**~ 30–45%**
Cost of CO_2 Avoided:	
Relative to NGCC:	**~$100 /t$CO_2$**
Relative to SCPC:	**~$40 /t$CO_2$**

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Ten Ways to Reduce CCS Cost

(inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel price
7. Assume EOR credits for CO_2 storage
6. Omit certain capital costs
5. Report $/ton CO_2 based on short tons
4. Assume long plant lifetime
3. Assume low interest rate (discount rate)
2. Assume high plant utilization (capacity factor)
1. Assume **all of the above !**

. . . and we have not yet considered the CCS technology!

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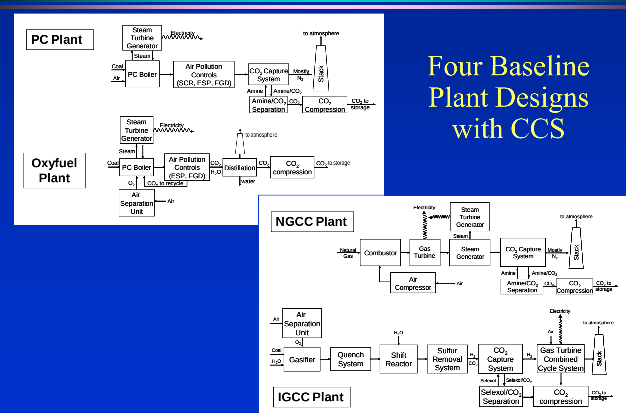
Application of Learning Curves to Power Plants with CCS



Four Baseline Plant Designs with CCS

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Seven Steps to Project Future Costs

- Disaggregate plant into major components
- Estimate current plant cost and component contributions
- Select learning rate for each plant component
- Estimate current installed capacity of each component
- Set capacity additions for start and end of learning
- Aggregate component results back to plant level
- Conduct sensitivity analysis on key uncertain variables, e.g.,
  - Starting point for learning curve
  - End point for learning curve
  - Choice of and basis for current capacity data
  - Basis for multi-year cost adjustments
  - Plant cost parameters

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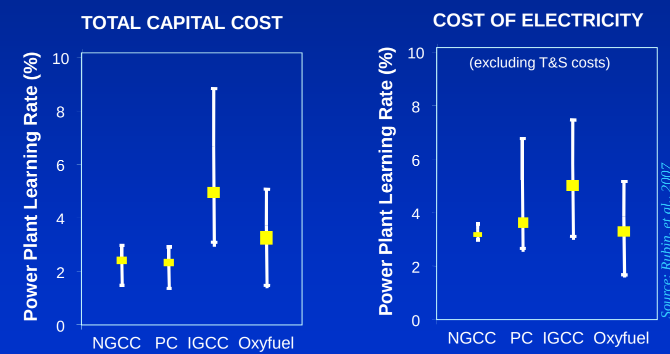
Learning Rates for Plants w/ CO_2 Capture

(based on improvements in major plant components)



Learning rates for a given plant type vary by about a factor of 3

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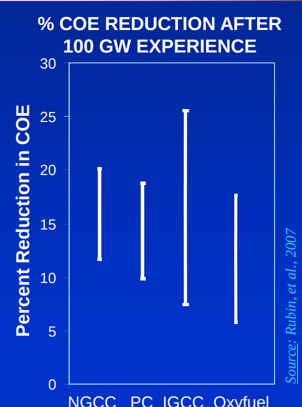
Projected Reductions in COE after 100 GW of Experience

- *Projected reduction in cost of electricity generation (COE) for each plant type varies by factors of ~2 to 4*
- *Projected reductions in CO_2 mitigation cost are larger than for the overall plant*



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Projected Cost Reductions in 2050 for Global Energy Scenarios

Cost reductions, 2001–2050, based on energy-economic modeling with endogenous learning curves for power plants with CCS*

Power Plant System	Reduction in Cost of Electricity ($/MWh)	Reduction in Mitigation Cost ($/t$CO_2$ avoided)
NGCC–CCS	12% – 40%	13% – 60%
IGCC–CCS	22% – 52%	19% – 58%
PC–CCS	14% – 44%	19% – 62%

* Range based on low and high global carbon price scenarios.

Source: van der Brock et al, 2010

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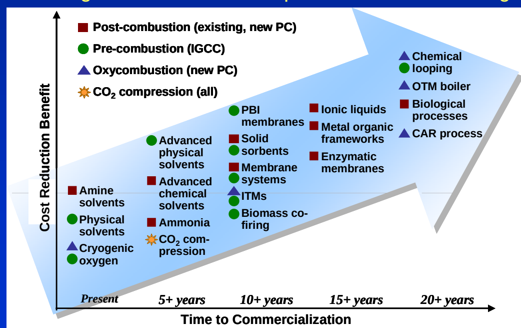
Which CO_2 capture technologies will have the lowest cost?

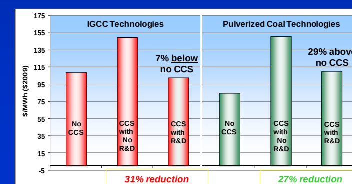
R&D Programs Seek to Develop Lower-Cost Technologies



Source: USDOE, 2010

Learning Curves Can't Pick Winners

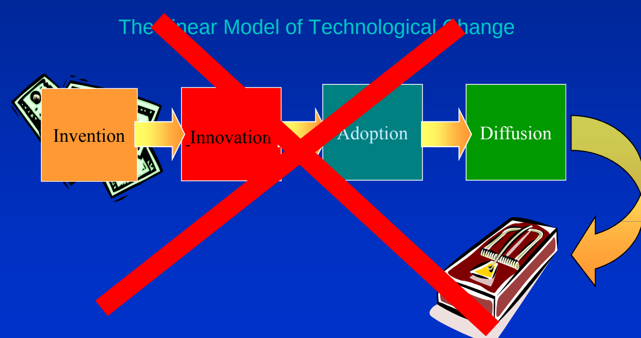
- Magnitude of future cost projected using learning curves depends strongly on assumed initial cost
- "Bottom up" engineering-economic analyses offer some insights into cost of new technology designs



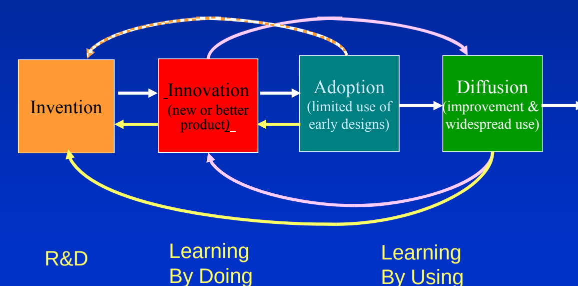
Source: DOE/ NETL, 2010

www.iecm-online.com

Can R&D Alone Achieve the Big Cost Reductions We Seek?



A More Realistic Model



Deployment of new technology is required to achieve biggest cost reductions

Government policies are needed to create market demands for CCS

Policy options that can foster innovation

"Technology Policy" Options			Regulatory Policy Options
Direct Gov't Funding of Knowledge Generation	**Direct or Indirect Support for Commercialization and Production**	**Knowledge Diffusion and Learning**	**Economy-wide, Sector-wide, or Technology- Specific Regs and Standards**
• R&D contracts with private firms (fully funded or cost-shared) • Intramural R&D in government laboratories • R&D contracts with consortia or collaborations	• R&D tax credits • Patents • Production subsidies or tax credit for firms bringing new technologies to market • Tax credits, rebates, or payments for purchasers/users of new technologies • Gov't procurement of new or advanced technologies • Demonstration projects • Loan guarantees • Monetary prizes	• Education and training • Codification and diffusion of technical knowledge (e.g., via interpretation and validation of R&D results; screening; support for databases) • Technical standards • Technology/Industry extension program • Publicity, persuasion and consumer information	• Emissions tax • Cap-and-trade program • Performance standards (for emission rates, efficiency, or other measures of performance) • Fuels tax • Portfolio standards

Source: NRC, 2010

Conclusions from Learning Curve Studies

- There is significant potential to reduce the cost of CCS …

but …

- Realization of that potential will require significant commercial deployment of CCS in addition to sustained R&D

A Final Word of Wisdom

"It's tough to make predictions, especially about the future"

- Yogi Berra

Thank You

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