The Outlook for CO_2 Capture Costs

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Outline of Talk

- A brief review of cost metrics
- Capture cost trends over the past decade
- The potential for future cost reductions
- What it takes to achieve cost reductions

Pop Quiz

(for conference presentation only)

A brief review of CCS cost metrics

Common Measures of CCS Cost

- Capital cost
- Increased cost of electricity
- Cost of CO_2 avoided
- Cost of CO_2 captured

Elements of Capital Cost

Capital Cost Element to be Quantified	Sum of All Preceding Items is Called:
Process equipment	
Supporting facilities	
Labor (direct & indirect)	
	Bare Erected Cost (BEC)
Engineering services	
	Engineering, Procurement & Construction (EPC) Cost
Contingencies: - process	
- project	
	Total Plant Cost (TPC)
Owner's costs:	
- Feasibility studies	
- Surveys	
- Land	
- Permitting	
- Finance transaction costs	
- Pre-paid royalties	
- Initial catalyst & chemicals	
- Inventory capital	
- Pre-production (startup)	
- Other site-specific items unique to the project (such as unusual site improvements, transmission interconnects beyond busbar, economic development incentives, etc.)	
	Total Overnight Cost (TOC)
Interest during construction	
Cost escalations during construction	
	Total Capital Requirement (TCR)

Note:

- Nomenclature and cost items may vary across studies and organizations …
- … as do methods for quantifying each item

Cost of Electricity (COE)

$$\text{COE (\$/MWh)} = \frac{\text{(TCR)(FCF)} + \text{FOM}}{\text{(CF)(8766)(MW)}} + \text{VOM} + \text{(HR)(FC)}$$

TCR = Total capital requirement ($)
FCF = Fixed charge factor (fraction)
FOM = Fixed operating & maintenance costs ($/yr)
VOM = Variable O& M costs, excluding fuel cost ($/MWh)
HR = Power plant heat rate (MJ/MWh)
FC = Unit fuel cost ($/MJ)
CF = Annual average capacity factor (fraction)
MW = Net power plant capacity (MW)

Most studies report the "levelized" COE over life of the plant

Cost of CO_2 Avoided

$$= \frac{(\$/\text{MWh})_{ccs} - (\$/\text{MWh})_{ref}}{(\text{t CO}_2/\text{MWh})_{ref} - (\text{t CO}_2/\text{MWh})_{ccs}} \quad (\$/\text{t CO}_2)$$

- Cost of avoiding a ton of CO_2 emissions while still delivering a unit of electricity (e.g., one MWh)
- It should (but often does not) include the full chain of CCS processes, i.e., capture, transport and storage (emissions are not avoided until sequestered)
- It is a relative cost measure that is very sensitive to the choice of reference plant without CCS

Other cost measures have same units ($/ton), but different meanings

- Cost of CO_2 Avoided ($/t CO_2)

$$= \frac{(\$/MWh)_{ccs} - (\$/MWh)_{reference}}{(t\ CO_2/MWh)_{ref} - (t\ CO_2/MWh)_{ccs}}$$

- Cost of CO_2 Captured ($/…

$$= \frac{\ldots}{\ldots - (t\ CO_2/MWh)_{ccs}}$$

Use with caution!

- Cost of CO_2 Abated (Reduced) ($/t CO_2)

$$= \frac{(\$\ NPV)_{ccs} - (\$\ NPV)_{reference}}{(t\ CO_2)_{ref} - (t\ CO_2)_{ccs}}$$

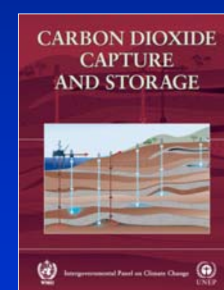
For More Information See …

http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002000176

How have CCS cost estimates changed over the past decade?

The IPCC Special Report on CCS

- Commissioned by IPCC in 2003; completed in December 2005
- First comprehensive look at CCS as a climate change mitigation option (9 chapters; ~100 authors)
- Included a detailed review of cost estimates for CO_2 capture, transport and storage options



SRCCS Costs for CO_2 Capture

(all costs in constant 2002 USD)

Performance and Cost Measures	New NGCC Plant		New SCPC Plant		New IGCC Plant	
	Range	*Rep. Value*	Range	*Rep. Value*	Range	*Rep. Value*
Emission rate w/o capture (kg CO_2/MWh)	344 - 379	367	736 - 811	762	682 - 846	773
Emission rate with capture (kg CO_2/MWh)	40 - 66	52	92 - 145	112	65 - 152	108
Percent CO_2 reduction per kWh (%)	83 - 88	86	81 - 88	85	81 - 91	86
Plant efficiency w/ capture, LHV basis (%)	47 - 50	48	30 - 35	33	31 - 40	35
Capture energy reqm't. (% more input/MWh)	11 - 22	16	24 - 40	31	14 - 25	19
Total capital reqm't. w/o capture (US$/kW)	515 - 724	**568**	1161 - 1486	**1286**	1169 - 1565	**1326**
Total capital reqm't. w/ capture (US$/kW)	909 - 1261	**998**	1894 - 2578	**2096**	1414 - 2270	**1825**
Percent increase in capital cost w/ capture	64 - 100	76	44 - 74	63	19 - 66	37
COE w/o capture (US$/MWh)	31 - 50	**37**	43 - 52	**46**	41 - 61	**47**
COE w/ capture only (US$/MWh)	43 - 72	**54**	62 - 86	**73**	54 - 79	**62**
Increase in COE w/ capture (US$/MWh)	12 - 24	17	18 - 34	27	9 - 22	16
Percent increase in COE w/ capture (%)	37 - 69	**46**	42 - 66	**57**	20 - 55	**33**
Cost of CO_2 captured (US$/t CO_2)	33 - 57	44	23 - 35	29	11 - 32	20
Cost of CO_2 avoided (US$/t CO_2)	37 - 74	**53**	29 - 51	**41**	13 - 37	**23**

Source: IPCC, 2005

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SRCCS Costs for New Power Plants Using Current Technology

Power Plant System	Natural Gas Combined Cycle Plant	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
Levelized Cost of Electricity (constant 2002 US$/kWh)			
Reference Plant Cost (without capture) ($/kWh)	*0.03–0.05*	*0.04–0.05*	*0.04–0.06*
Added cost of CCS with geological storage	**0.01–0.03**	**0.02–0.05**	**0.01–0.03**
Added cost of CCS with EOR storage	**0.01–0.02**	**0.01–0.03**	**0.00–0.01**
Cost of CO_2 Avoided (constant 2002 US$/tonne)			
Same plant with CCS (geological storage)	40–90	30–70	15–55
Same plant with CCS (EOR storage)	20–70	10–45	(-5)–30

Source: IPCC, 2005

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2015 Cost Update

(J. Davison, H. Herzog, E. Rubin)

- Compiled data from recent CCS cost studies in the U.S. and Europe for new power plants with:
  - Post-combustion CO_2 capture (SCPC and NGCC)
  - Pre-combustion CO_2 capture (IGCC)
  - Oxy-combustion CO_2 capture (SCPC)
- Adjusted all costs to constant 2013 US dollars
- Adjusted SRCCS costs from 2002 to 2013 USD using:
  - Capital /O&M cost escalation factors +
  - Fuel cost escalation factors (for COE)
- Compared current cost estimates to SRCCS values

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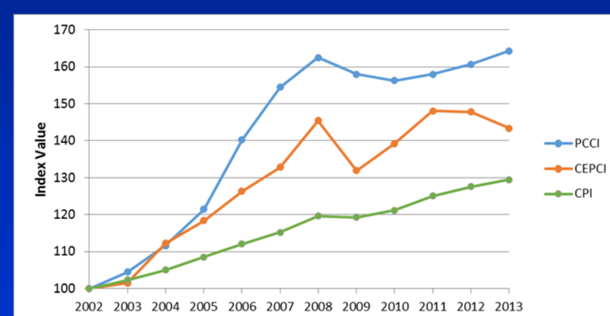
Capital Cost Trends



CPI = U.S. Consumer Price Index (BLS, 2014)
CEPCI = Chemical Engineering Plant Cost Index (CE, 2014)
PCCI = Power Capital Costs Index (excluding nuclear) (IHS-CERA, 2014)

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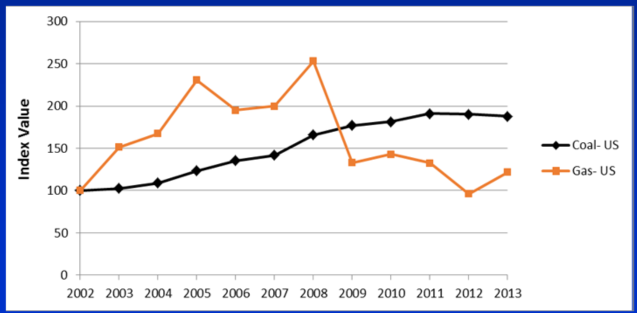
Fuel Cost Trends for U.S. Power Plants



(Data Source: EIA, 2014)

Recent Cost Studies Reviewed

- IEAGHG, 2014
- NETL, 2014
- EPRI, 2013
- NETL, 2013a, b
- ES&T, 2012
- IEAGHG, 2012
- Léandri et al., 2011
- GCCSI, 2011
- NETL, 2011a, b, c
- ZEP, 2011a, b, c
- NETL, 2010

Recent Study Assumptions

- Basic power plant design parameters such as net plant efficiency and CO_2 emissions and capture rates have not changed appreciably since the SRCCS
- Some assumptions affecting CCS costs have changed, e.g.:
  - the average power plant sizes without CCS are about 10% to 25% larger than in SRCCS studies
  - Assumed capacity factors are higher (by 10 %-pts for PC, plants, 2 %-pts for IGCC plants, and 8 %-pts for NGCC)
  - Fixed charge factor are lower (by about 10% for NGCC, 20% for IGCC and 30% for SCPC
  - Different values often used for plants with and w/o capture
  - Increased focus on the potential for CO_2–EOR utilization

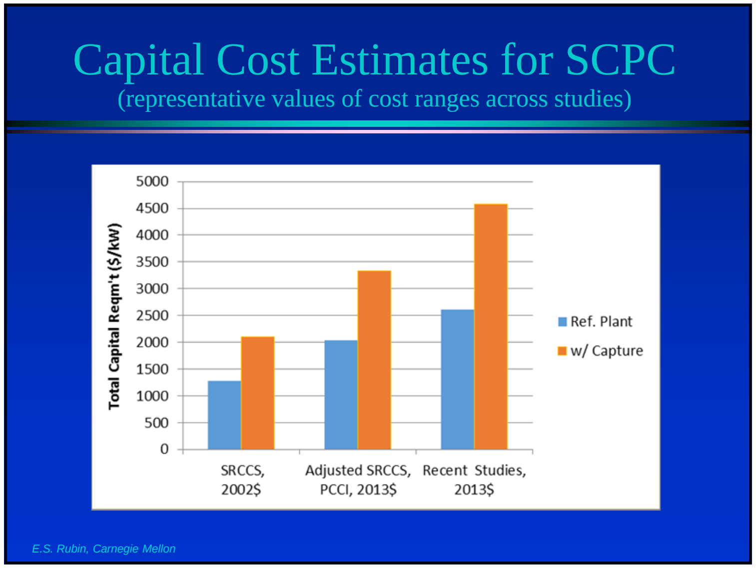
Capture System Costs Then and Now:

New SCPC Plants w/ Post-Combustion Capture

Bituminous coals; 90% capture; all costs in constant 2013 US dollars)

Performance and Cost Measures for New SCPC Plants w/ Bituminous Coal	Current Values			Adjusted SRCCS Values			Change in Rep. Value (Current –Adjusted SRCCS)	
	Range		*Rep. Value*	Range		*Rep. Value*		
	Low	High		Low	High		Δ Value	Δ%
Plant Performance Measures								
SCPC reference plant net power output (MW)	550	1030	742	462	758	587	**155**	***26***
Emission rate w/o capture (kg CO_2/MWh)	0.746	0.840	0.788	0.736	0.811	0.762	**0.03**	***3***
Emission rate with capture (kg CO_2/MWh)	0.092	0.120	0.104	0.092	0.145	0.112	**-0.01**	***-7***
Percent CO_2 reduction per MWh (%)	86	88	87	81	88	85	**2**	
Total CO_2 captured or stored (Mt/yr)	3.8	5.6	4.6	1.8	4.2	2.9	**1.7**	***57***
Plant efficiency w/o capture, HHV basis (%)	39.0	44.4	41.4	39.3	43.0	41.6	-0.2	***-1***
Plant efficiency w/ capture, HHV basis (%)	27.2	36.5	31.6	28.9	34.0	31.8	-0.2	***-1***
Capture energy reqm't. (% more input/MWh)	21	44	32	24	40	31	1.1	***3***
Plant Cost Measures								
Total capital reqm't. w/o capture (USD/kW)	2313	2990	2618	1862	2441	2040	**578**	***28***
Total capital reqm't. with capture (USD/kW)	4091	5252	4580	2788	4236	3333	**1247**	***37***
Percent increase in capital cost w/ capture (%)	58	91	75	44	73	63	**13**	
LCOE w/o capture (USD/MWh)	61	79	70	64	87	76	**-6**	***-8***
LCOE with capture only (USD/MWh)	94	130	113	93	144	119	**-6**	***-5***
Increase in LCOE, capture only (USD/MWh)	30	51	43	28	57	43	**0**	***-1***
Percent increase in LCOE w/ capture only (%)	46	69	62	42	65	56	**5**	
Cost of CO_2 captured (USD/t CO_2)	36	53	46	33	58	48	**-3**	***-6***
Cost of CO_2 avoided, excl. T&S (USD/t CO_2)	45	70	63	44	86	67	**-4**	***-6***

(Source: Davison, Herzog, Rubin, in press 2015)


Capital Cost Estimates for SCPC
(representative values of cost ranges across studies)
Total Capital Reqm't ($/kW)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
SRCCS, 2002$
Adjusted SRCCS, PCCI, 2013$
Recent Studies, 2013$
Ref. Plant
w/ Capture
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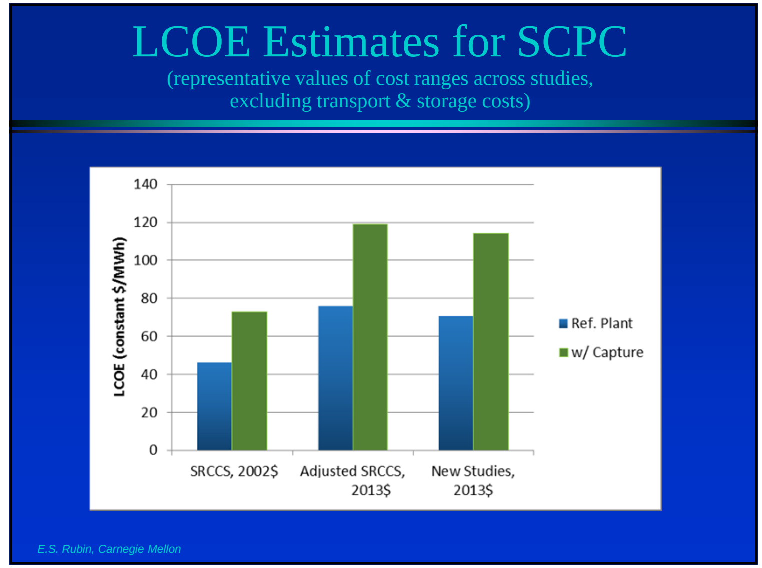
LCOE Estimates for SCPC
(representative values of cost ranges across studies, excluding transport & storage costs)
LCOE (constant $/MWh)
140
120
100
80
60
40
20
0
SRCCS, 2002$
Adjusted SRCCS, 2013$
New Studies, 2013$
Ref. Plant
w/ Capture
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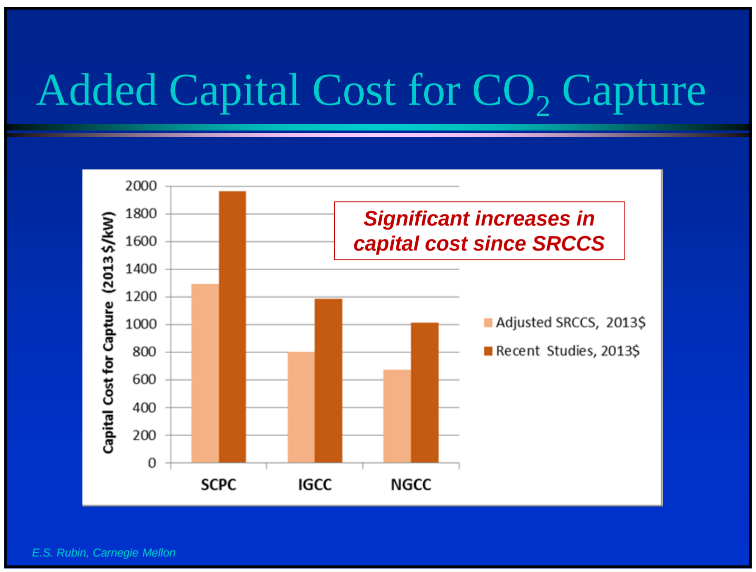
Added Capital Cost for CO_2 Capture
Capital Cost for Capture (2013 $/kW)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
SCPC
IGCC
NGCC
Significant increases in capital cost since SRCCS
Adjusted SRCCS, 2013$
Recent Studies, 2013$
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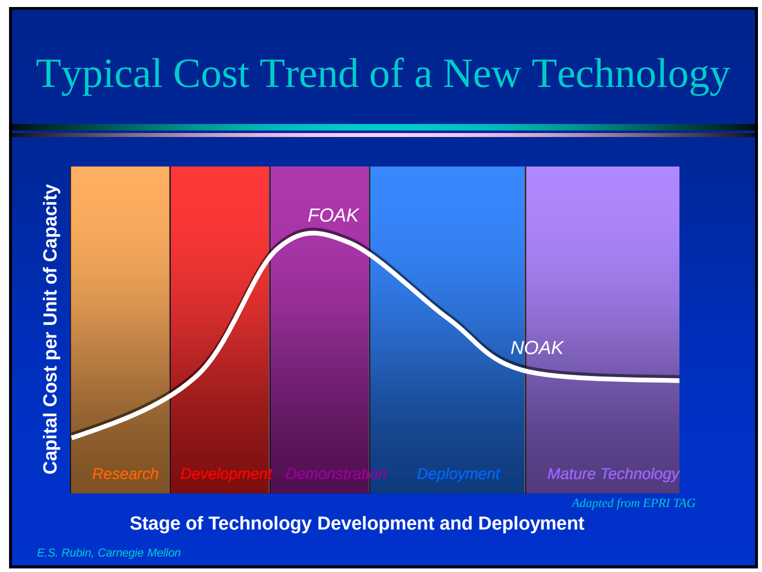
Typical Cost Trend of a New Technology
Capital Cost per Unit of Capacity
FOAK
NOAK
Research
Development
Demonstration
Deployment
Mature Technology
Adapted from EPRI TAG
Stage of Technology Development and Deployment
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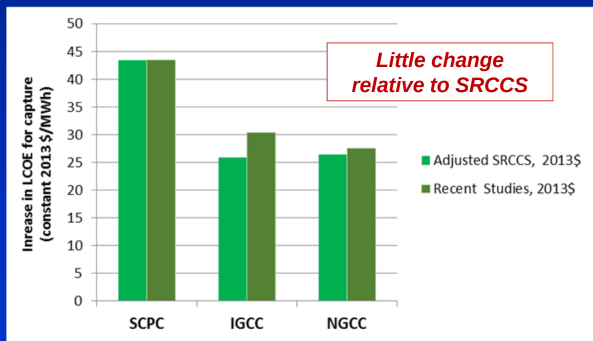
Added COE for Capture

(excluding transport & storage costs)

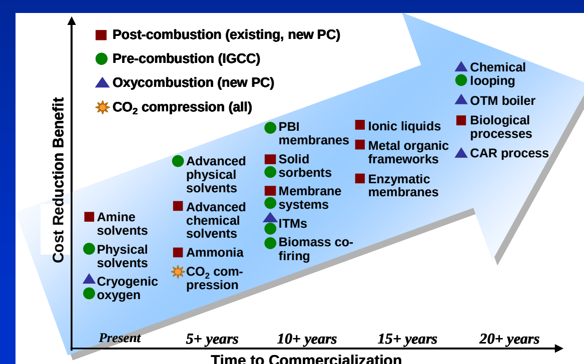


Additional Conclusions from the Study

- For new SCPC plants oxy-combustion shows potential to be competitive with post-combustion capture.
- The costs of CO_2 avoided ,including pipeline transport and geologic storage, are essentially the same as in the SRCCS, after adjusting for escalations in plant and fuel costs
- The overall cost of CCS can be reduced significantly if CO_2 can be sold for enhanced oil recovery (EOR) in conjunction with geological storage over the life of the project
- Based on current cost estimates for the four CCS pathways analyzed, there are no obvious winners or losers

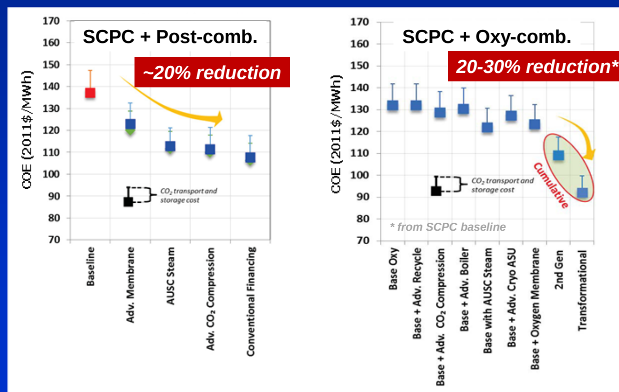
The potential for future cost reductions

Examples of Advanced Capture Technologies Under Development



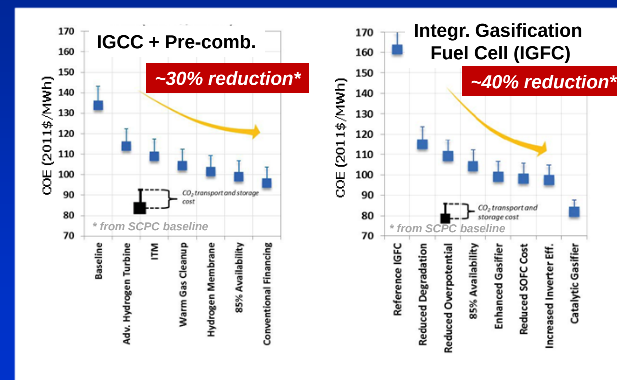
Source: USDOE, 2010

Projected Cost Reductions from "Bottom-Up" Analyses *(1)*



Source: Gerdes et al, NETL, 2014

Projected Cost Reductions from "Bottom-Up" Analyses *(2)*



Source: Gerdes et al, NETL, 2014

Projected Cost Reductions from a "Top-Down" Analysis

(Learning curves plus energy-economic modeling)

(Percent cost reduction, 2001–2050)*

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

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

Source: van der Brock et al, 2010

What does it take to achieve these cost reductions ?

Ingredients of Technology Innovations that Reduce Costs

- Sustained R&D
- Markets for the technology
- Learning from experience

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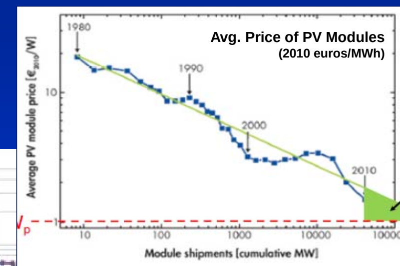
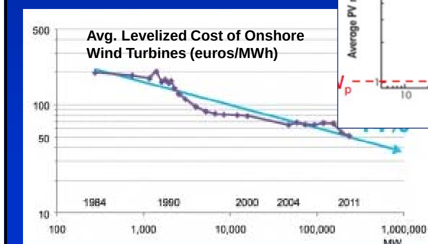
We've seen this work for other low-carbon energy technologies …

Deployment and cost reductions driven by government incentives and regulatory policies



Source: Kleiburg, ECN, 2011



Source: Bloomberg New Energy Finance

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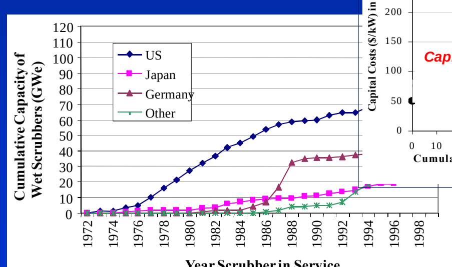
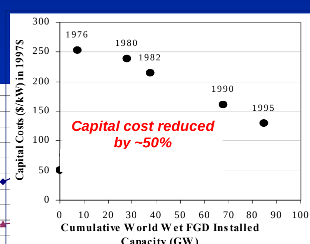
… and for post-combustion capture of other power plant air pollutants

Trends in deployment and capital cost of post-combustion flue gas desulfurization (FGD) systems at coal-fired power plants





Source: Rubin, et al. 2007

Could CCS follow a similar path?

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Key Barriers to CCS Deployment

- Policy
- Policy
- Policy

Without a policy requirement or strong incentive to reduce CO_2 emissions significantly there is no reason to deploy CCS widely

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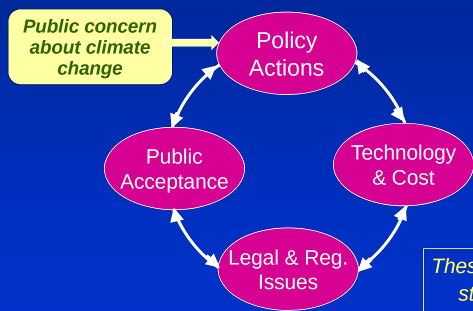
Strong Interactions Between Policy and Other Key Factors



These interactions depend strongly on local and national settings

Policy options that can foster CCS and technology 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

What is the Outlook for CO_2 Capture Costs ?

- Sustained R&D is essential to achieve lower costs; but …
- Learning from experience with full-scale projects is equally critical.
- Strong policy drivers that <u>create</u> <u>markets</u> for CCS are needed to spur innovations that significantly reduce the cost of capture
- **WATCH THIS SPACE FOR UPDATES ON PROGRESS**

Thank You

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