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CCS cost trends and outlook

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CCS Cost Trends and Outlook

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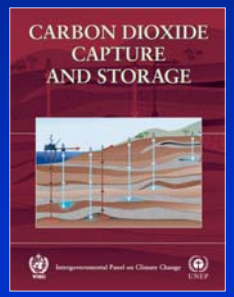
Outline of Talk

- Changes in CCS costs over past ten years
- The outlook for future costs
- What it takes to achieve cost reductions

Motivation: 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



Special Issue of *IJGGC*: 10 Years After the SRCCS

SRCCS Costs for CO_2 Capture

(excludes transport and storage costs; 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**

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Source: IPCC, 2005

SRCCS Costs for New Power Plants Using Current Technology

Includes capture, pipeline transport and storage costs

Power Plant System	Natural Gas Combined Cycle Plant	Supercritical Pulverized Coal Plant	Integrated Gasification Combined Cycle Plant
Levelized Cost of Electricity (constant 2002 US$/kWh)			
Reference Plant Cost (without capture)	*0.03–0.05*	*0.04–0.05*	*0.04–0.06*
Added cost of CCS with geological storage	**0.01–0.03**	**0.02–0.05**	**0.01–0.03**
Added cost of CCS with EOR storage	**0.01–0.02**	**0.01–0.03**	**0.00–0.01**
Cost of CO_2 Avoided (constant 2002 US$/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

(Rubin, Davison and Herzog, *IJGGC*)

- 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 recent cost estimates to SRCCS values

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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

16 studies, each with multiple cases

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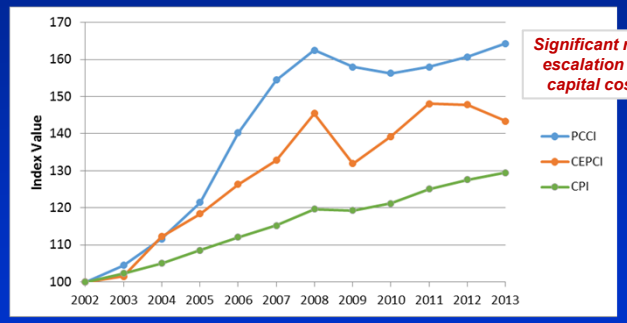
Differences in Key Assumptions

- Basic power plant design parameters such as net plant efficiency, CO_2 emission rates, and CO_2 capture rates have not changed appreciably since the SRCCS
- Some assumptions affecting CCS costs have changed:
  - 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)
  - Parameter values often differ for plants with and w/o CCS
  - Increased focus on potential for utilization via CO_2–EOR

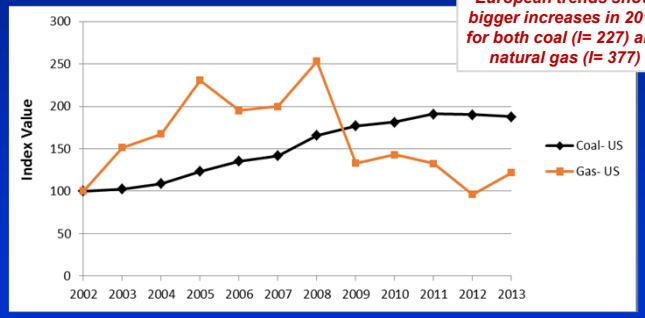
Capital Cost Trends



Significant real escalation in capital cost

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)

Fuel Cost Trends for U.S. Power Plants



European trends show bigger increases in 2013 for both coal (I= 227) and natural gas (I= 377)

(Data Source: EIA, 2014)

Capture System Costs Then and Now:
New SCPC Plants w/ Post-Combustion Capture

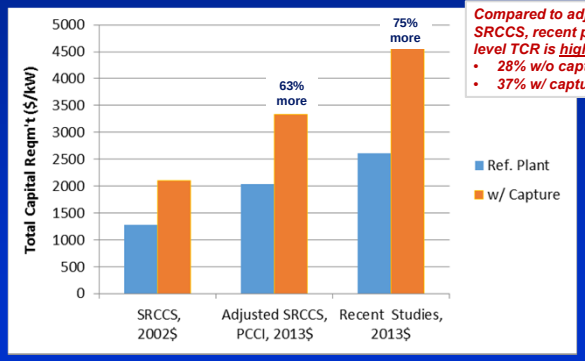
Bituminous coals; 90% capture; all costs in constant 2013 US dollars)

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: Rubin, Davison, Herzog, 2015)

Total Capital Cost of SCPC Plants

(representative values of cost ranges across studies)



Compared to adjusted SRCCS, recent plant-level TCR is higher by:
- *28% w/o capture*
- *37% w/ capture*

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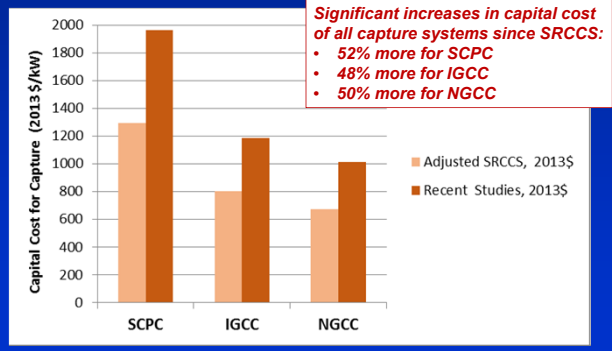
Added Capital Cost for CO_2 Capture

(over and above the reference plant cost without capture)



Significant increases in capital cost of all capture systems since SRCCS:
- *52% more for SCPC*
- *48% more for IGCC*
- *50% more for NGCC*

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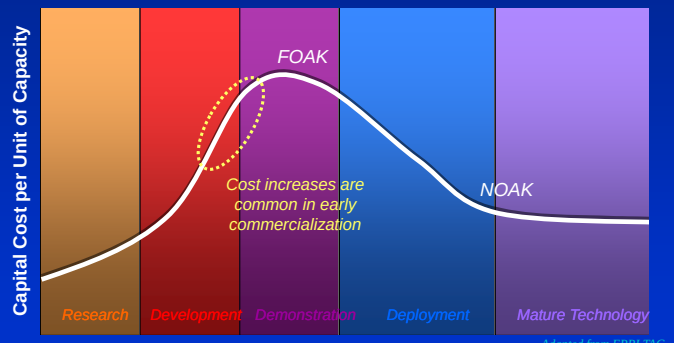
Typical Cost Trend of a New Technology



Stage of Technology Development and Deployment

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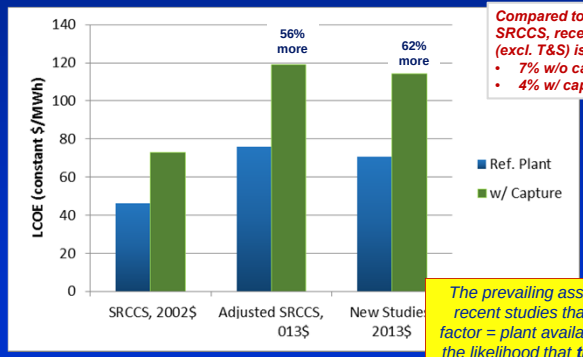
LCOE for SCPC Plants

(representative values, excluding transport & storage costs)



Compared to adjusted SRCCS, recent LCOE (excl. T&S) is lower by:
- *7% w/o capture*
- *4% w/ capture*

*The prevailing assumption in recent studies that capacity factor = plant availability masks the likelihood that **true LCOEs are higher than those reported***

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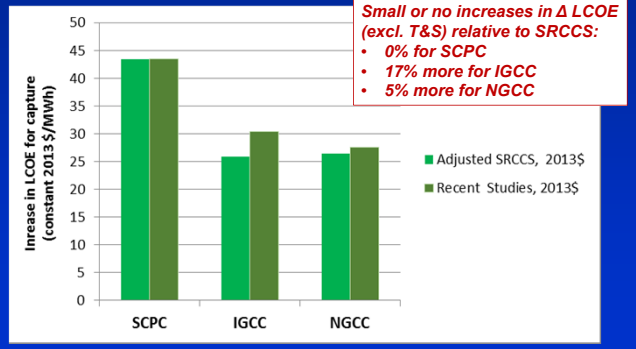
Added COE for Capture

(excluding transport & storage costs)



Small or no increases in Δ LCOE (excl. T&S) relative to SRCCS:

- ***0% for SCPC***
- ***17% more for IGCC***
- ***5% more for NGCC***

Transport and Storage Costs

(relative to adjusted SRCCS)

Onshore pipelines (250 km):

- Recent U.S. costs are similar to SRCCS; European costs are significantly higher (esp. for 3 $MtCO_2$/yr)

Geological storage (onshore):

- Low end of cost range is substantially higher; high end of cost range is slightly higher
- EOR credits are substantially higher (~$15–40/$tCO_2$)

Total Plant LCOE (2013 $/MWh)

for CO_2 capture, transport and geological storage

Case	NGCC with post-combustion capture	SCPC with post-combustion capture	IGCC with pre-combustion capture
Without EOR			
SRCCS (adjusted)	56 – 110	94 - 163	92 – 150
Recent Studies	**63 – 122**	**95 - 150**	**112 – 148**
With EOR credits			
SRCCS (adjusted)	48 – 100	76 – 139	77 – 128
Recent Studies	**48 – 112**	**61 – 121**	**83 – 123**

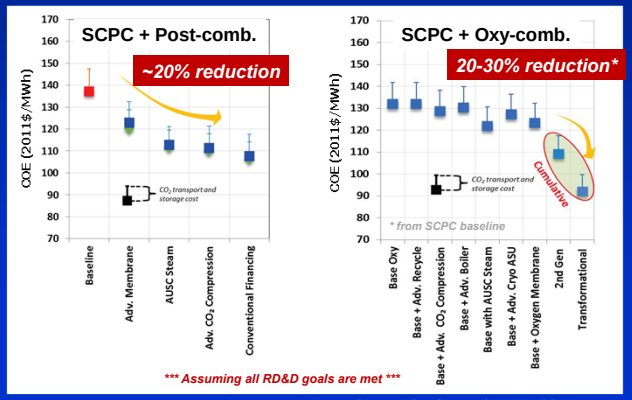
Mitigation costs ($/$tCO_2$ avoided) also are roughly similar to adjusted SRCCS costs

Other Conclusions from the Study

- For new SCPC plants oxy-combustion capture shows potential to be cost competitive with post-combustion capture
- Based on current cost estimates for the four CCS pathways analyzed, there are no obvious winners or losers

The outlook for future cost reductions

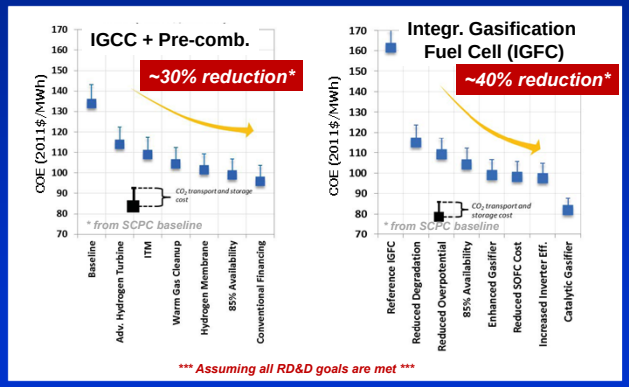
Potential Cost Reductions from "Bottom-Up" Analyses *(1)*



*** Assuming all RD&D goals are met ***

Source: Gerdes et al, NETL, 2014

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



*** Assuming all RD&D goals are met ***

Source: Gerdes et al, NETL, 2014

Projected Cost Reductions from a "Top-Down" Analysis

(Based on energy-economic modeling with technology-specific learning curves)

(Percent cost reduction, 2001–2050)*

Power Plant System	Reduction in Cost of Electricity ($/MWh)	Reduction in Mitigation Cost ($/tCO$_2$ 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 ?

- Sustained R&D
- Markets for CCS technology
  (created by policy carrots and sticks)
- Learning from experience

-- Stay tuned for updates in these areas --

Thank You

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Additional Information

Total Cost for CCS (in constant 2013 USD)

(based on recent studies of current technology for new power plants)

Cost and Performance Parameters	NGCC with post-combustion capture	SCPC with post-combustion capture	SCPC with oxy-combustion capture	IGCC with pre-combustion capture
Reference Plant without CCS: Levelized cost of electricity (USD/MWh)	42 - 83	61 – 79	56 – 68*	82 - 99
Power plants with CCS				
Increased fuel requirement per net MWh (%)	13 - 18	21 – 44	24 – 29	20 – 35
CO_2 captured (kg/MWh)	360 - 390	830 - 1080	830 – 1040	840 - 940
CO_2 avoided (kg/MWh)	310 - 330	650 - 720	760 – 830	630 - 700
% CO_2 avoided	88 - 89	86 – 88	88 – 97	82 - 88
Power plant with capture, transport and geological storage				
Levelized cost of electricity (USD/MWh)	63 – 122	95 - 150	92 – 141	112 – 148
Electricity cost increase for CCS (USD/MWh)	19 – 47	31 – 71	36 – 75	25 – 53
% increase	28 - 72	48 – 98	61 – 114	26 – 62
Power plant with capture, transport and geological storage with enhanced oil recovery credits				
Levelized cost of electricity (USD/MWh)	48 – 112	61 – 121	52 – 113	83 – 123
Electricity cost increase for CCS (USD/MWh)	3 – 37	(3) – 42	(4) – 47	(11) – 29
% increase	7 - 56	(5) – 57	(8) – 72	(11) - 33

Cost of CO_2 Avoided *(1)*

Mitigation costs in $/t$CO_2$ avoided (constant 2013 USD) for new power plants with capture and geologic storage

Capture Plant*	This Study	Adjusted SRCCS	Difference, low end	Difference, high end
NGCC	**59 - 143**	64 - 136	-5	7
SCPC	**46 - 99**	45 - 114	1	-15
IGCC	**38 - 84**	25 - 85	13	-1
IGCC w/SCPC reference plant	**53 - 137**	n/a		
OXY	**47 - 97**	n/a		

* The no-capture reference plant is assumed to be the same type plant as the capture plant, except as noted.

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Cost of CO_2 Avoided *(2)*

Mitigation costs in $/t$CO_2$ avoided (constant 2013 USD) for new power plants with capture and EOR storage

Capture Plant*	This Study	Adjusted SRCCS	Difference, low end	Difference, high end
NGCC	**10 - 112**	38 - 107	-28	5
SCPC	**(5) - 58**	17 - 77	-22	-19
IGCC	**(16) - 46**	(1) - 55	-15	-9
IGCC w/SCPC reference plant	**3 - 102**	n/a		
OXY	**(6) - 63**	n/a		

* The no-capture reference plant is assumed to be the same type plant as the capture plant, except as noted.

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