Methods and Measures for CCS Costs

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

Presentation to the
CCS Cost Workshop
Paris, France
March 22, 2011

Outline of Talk

- What measures of CCS cost are most useful?
- What methods are used to quantify these costs (and their uncertainties)?
- How consistent are the costing methods and assumptions used by different organizations?
- How can the CCS community improve the quantification and reporting of CCS costs?

Déjà vu

From GHGT-6, October 2002:

Many Factors Affect CCS Costs

- Choice of Power Plant and 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 fuel cycle
- Time Frame of Interest
  - First-of-a-kind plant vs. n^{th} plant
  - Current technology vs. future systems
  - Consideration of technological "learning"

Measures of CCS cost

Recent CCS Cost Estimates

- 2005: IPCC Special Report on CCS
- 2007: Rubin, et al., *Energy Policy*
- 2007: EPRI Report No. 1014223
- 2007: DOE/NETL Report 2007/1281
- 2007: MIT *Future of Coal* Report
- 2008: EPRI Report No. 1018329
- 2009: Chen & Rubin, *Energy Policy*
- 2009: ENCAP Report D.1.2.6
- 2009: IEAGHG Report 2009/TR-3
- 2009: EPRI Report No. 1017495
- 2010: Carnegie Mellon IECM v. 6.4
- 2010: UK DECC, Mott MacDonald Report
- 2010: Kheshgi, et al., SPE 139716-PP
- 2010: DOE/NETL Report 2010/1397
- 2010: DOE EIA Cost Update Report
- 2011: OECD/IEA Working Paper
- 2011: Global CCS Institute Update

Measures of CCS Cost

- Cost of CO_2 avoided
- Cost of CO_2 captured
- Added cost of electricity
- Capital cost
- Dispatch (variable) cost

Dollars per Ton

- This is the metric most commonly used in technical and policy forums to quantify the cost of CCS (as well as other methods of reducing carbon emissions)
- Also the measure most easily misunderstood, misleading and most often misapplied

Similar Units, 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 ($/t CO_2)

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

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

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

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Cost of CO_2 Avoided

- Cost of CO_2 Avoided ($/t CO_2)

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

- This is the measure most frequently used to quantify the cost of CCS
- It should (but often does not) include the full cost of CCS, i.e., capture, transport and storage (because emissions are not avoided unless/until the CO_2 is sequestered)
- It is a relative cost measure that is very sensitive to the choice of reference plant without CCS

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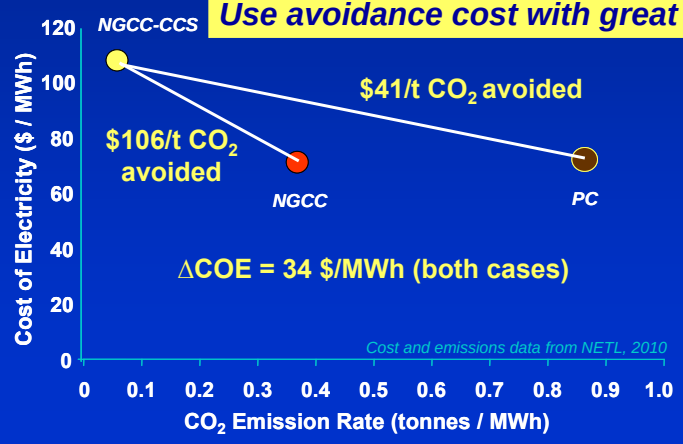
Cost of CO_2 avoided is sensitive to assumed reference plant w/o CCS

- *Q: What is the cost of CCS for an NGCC plant?*

Use avoidance cost with great care!



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Cost of Electricity (COE)

$$\text{COE (\$/MWh)} = \frac{(TCC)(FCF) + FOM}{(CF)(8760)(MW)} + VOM + (HR)(FC)$$

TCC = Total capital cost ($)
FCF = Fixed charge factor (fraction)
FOM = Fixed operating & maintenance costs ($/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)

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COE Comes in Different Flavors

- Year-by-year COE
  - Uses a discounted cash flow analysis with parameter values specified for each year of plant construction and operation
- First year COE
  - Uses parameter values for first year of operation
- Levelized COE
  - Uniform annual value giving the same net present value as the year-by-year case

Levelized COE

- This is the most common method of reporting COE. Also used to calculate the cost of CO_2 avoided.
- LCOE implies that parameters in the COE equation (such as FCF and CF) reflect their levelized values over the life of the plant.
- Annual O&M costs in the COE equation are multiplied by a "levelization factor" (LF) that is calculated from specified rates of inflation and real cost escalations over the life of the plant.
- Until recently most studies assumed LF = 1.0.

Many different parameters influence the cost of CCS !

Ten Ways to Reduce CCS Costs

(First presented at GHGT-6, Oct. 2002; Inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
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!

Methods for CCS cost estimates

A Hierarchy of Methods

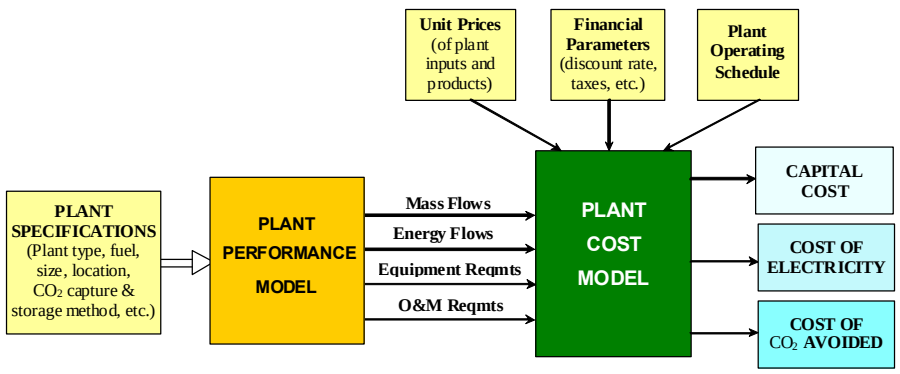
- Ask an expert
- Use published values
- Modify published values
- Derive new results from a model
- Commission a detailed engineering study

EPRI/AACE Categories of Cost Estimates (and their attributes)

Item	Design-Estimate Effort	Project Contingency Range[a] (%)	Design Information Required	Cost Estimate Basis		
				Major Equipment	Other Materials	Labor
Class I (Similar to Amer. Assoc. of Cost Engineers (AACE) Class 5/4)	Simplified	30–50	General site conditions, geographic location and plant layout Process flow/operation diagram Product output capacities	By overall project or section-by-section based on capacity/cost graphs, ratio methods, and comparison with similar work completed by the contractor, with material adjusted to current cost indices and labor adjusted to site conditions.		
Class II (Similar to Amer. Assoc. of Cost Engineers Class 3)	Preliminary	15–30	As for Type Class I plus engineering specifics, e.g.: Major equipment specifications Preliminary P&I[b] flow diagrams	Recent purchase costs (including freight) adjusted to current cost index	By ratio to major equipment costs on plant parameters	Labor/material ratios for similar work, adjusted for site conditions and using expected average labor rates
Class III (Similar to Amer. Assoc. of Cost Engineers Class 3/2)	Detailed	10–20	A complete process design Engineering design usually 20–40% complete Project construction schedule Contractual conditions and local labor conditions	Firm quotations adjusted for possible price escalation with some critical items committed	Firm unit cost quotes (or current billing costs) based on detailed quantity take-off	Estimated man-hour units (including assessment) using expected labor rate for each job classification
				Pertinent taxes and freight included		
Class IV (Similar to Amer. Assoc. of Cost Engineers Class 1)	Finalized	5–10	As for Class III, with engineering essentially complete	As for Class III, with most items committed	As for Class III, with material on approximately 100% firm basis	As for Class III, some actual field labor productivity may be available

[a] Expressed as a percentage of the total of process capital, engineering and home office fees, and process contingency.

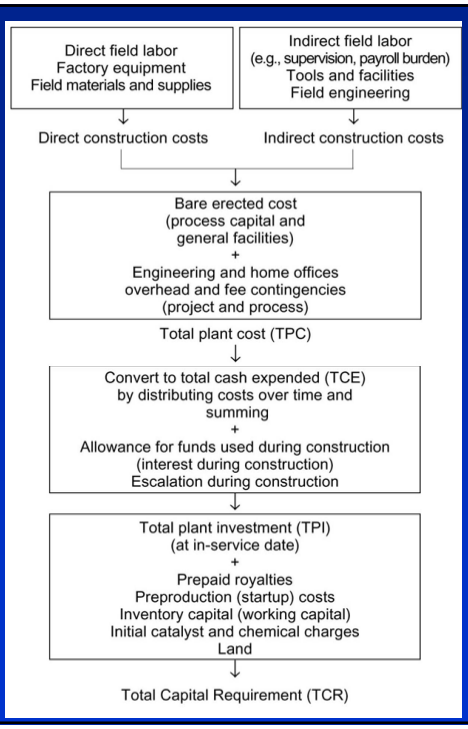
Framework for Cost Estimation



Current Status

- Individual organizations have developed detailed procedures and guidelines for calculating power plant costs (capital, O&M, COE) in a consistent fashion
- However, there are significant differences in the costing methods used by different organizations concerned with CO_2 capture and storage

EPRI Capital Cost Elements



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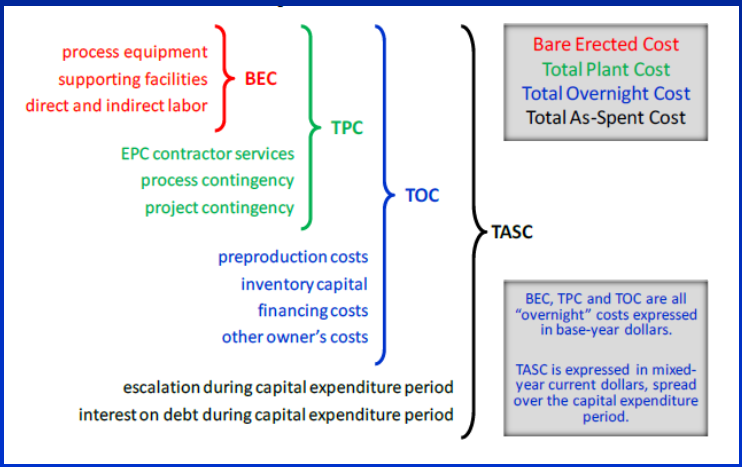
DOE/NETL Capital Cost Elements



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Capital Cost Elements in Recent Studies

EPRI TAG (2009)	USDOE/NETL (2007)	USDOE/NETL (2010)	USDOE/EIA (2010)
Process facilities capital	Bare erected cost (BEC)	Bare erected cost (BEC)	Civil Structural Material & Installation
General facilities capital	Eng. & Home Office Fees	Eng. & Home Office Fees	Mechanical Equip. Supply & Installation
Eng'g, home office, overhead & fees	Project Contingency Cost	Project Contingency Cost	Electrical/I&C Supply and Installation
Contingencies—project and process	Process Contingency Cost	Process Contingency Cost	Project Indirects
Total plant cost (TPC)	**Total plant cost (TPC)**	**Total plant cost (TPC)**	EPC Cost before Contingency and Fee
AFUDC (interest & escalation)		Pre-Production Costs	Fee and Contingency
Total plant investment (TPI)		Inventory Capital	**Total Project EPC**
Owner's costs: royalties, preproduction costs, Inventory capital, Initial catalyst and chemicals, Land		Financing costs	Owner's Costs (excl. project finance)
		Other owner's costs	**Total Project Cost (excl. finance)**
Total Capital Requirement (TCR)		**Total overnight cost (TOC)**	

IEA GHG (2009)	ENCAP (2009)	UK DECC (2010)
Direct materials	EPC costs	Pre-licencing costs, Technical and design
Labour and other site costs	Owner's costs	Regulatory + licencing + public enquiry
Engineering fees	**Total Investment**	Eng'g, procurement & construction (EPC)
Contingencies		Infrastructure / connection costs
Total plant cost (TPC)		**Total Capital Cost (excluded IDC)**
Construction interest		
Owner's costs		
Working capital		
Start-up costs		
Total Capital Requirement (TCR)		

No consistent set of cost categories or nomenclature across studies

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Elements of "Owner's Costs" in Several Recent Studies

USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI TAG (2009)	IEA GHG (2009)	UK DECC (2010)
(None)	Preproduction (Start-Up) costs	Preproduction (Start-Up) costs	Feasibility studies	(None)
	Working capital	Prepaid royalties	Obtaining permits	
	Inventory capital	Inventory capital	Arranging financing	
	Financing cost	Initial catalyst/chem.	Other misc. costs	
	Land	Land	Land purchase	
	Other			

No consistent set of cost categories or nomenclature across studies

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O&M Cost Elements in Recent Studies

Category	USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI TAG (2009)
Fixed O&M	Operating labor	Operating labor	Operating labor
	Maintenance –labor	Maintenance –labor	Maintenance costs
	Admin. & support labor	Admin. & support labor	Overhead charges (admin & support labor)
		Property taxes and insurance	
Variable O&M (excl. fuel)	Maintenance – material	Maintenance – material	Maintenance costs
	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)	Consumables (water, chemicals, etc.)
	Waste disposal	Waste disposal	Waste disposal
	Co- or by-product credit	Co- or by-product credit	Co- or by-product credit
	CO2 transport and storage	CO2 transport and storage	CO2 transport and storage

Category	IEA GHG (2009)	UK DECC (2010)
Fixed O&M	Operating labour	Operating labour
	Indicative cost	Planned and unplanned maintenance (additional labour, spares and consumables)
	Administrative and support labour	
	Insurance and local property taxes	Through life capital maintenance
	Maintenance cost	
Variable O&M (excl. fuel)	Consumables (water, chemicals, etc.)	Repair and maintenance costs
	By-products and wastes disposal	Residue disposal and treatment
	CO2 transport and storage	Connection & transmission charges
		Insurance
		CO2 transport and storage
		Carbon price

No consistent set of cost categories or nomenclature across studies

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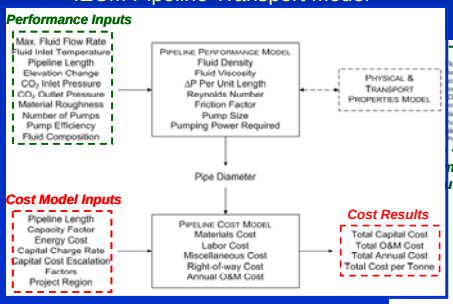
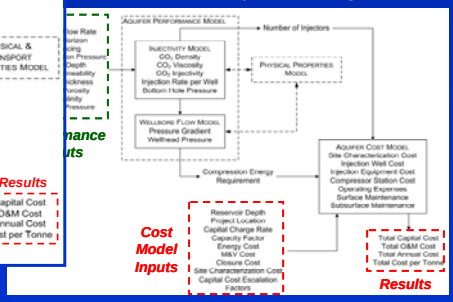
Transport and Storage Cost Models Also Differ in Scope and Complexity

- Most CCS cost estimates specify T&S costs as a lumped O&M cost.
- Some methods disaggregate T&S cost elements and/or employ more detailed performance and cost models to calculate costs.

IECM Pipeline Transport Model



IECM Saline Aquifer Storage Model



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Do We All Make the Same Assumptions?

- Different assumptions commonly reflect different circumstances or perspectives
- They can also reflect variability, uncertainty and biases (more on this later)

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Examples of Assumptions in Recent Studies

Parameter	USDOE/NETL 2007	USDOE/NETL 2010	EPRI 2009	IEA GHG 2009	UK DECC 2010
Plant Size (PC case)	550 MW (net)	550 MW (net)	750 MW (net)	800 MW (net)	1600 MW (gross)
Capacity Factor	85%	85%	85%	85% (yr 1= 60%)	varies yearly
Constant/Current $	Current	Current	Constant	Constant	Constant
Discount Rate	10%	10%	7.09%	8%	10%
Plant Book Life (yrs)	20	30	30	25	32-40 (FOAK) 35-45 (NOAK)
Capital Charge Factor					
no CCS	0.164	0.116	0.121	N/A	N/A
w/ CCS	0.175	0.124	0.121	N/A	N/A
Variable Cost Levelization Factor					
no CCS	1.2089 (coal) 1.1618 (other)	1.2676	1.00	1.00	N/A
- w/ CCS	1.2022 (coal) 1.1568 (other)	1.2676	1.00	1.00	N/A

N/A: not available

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DOE Cost Method Revisions Increased Reported CCS Costs

USDOE Baseline Bituminous Study (NETL 2007 vs. NETL rev. 2010)

Reported Cost in 2007$	SCPC (Case 11)	SCPC+CCS (Case 12)	CCS Cost (C12 - C11)
Bare Erected Cost ($/kW)	1286	2207	**921**
Bare Erected Cost, *rev* ($/kW)	1345	2239	**894**
% increase	***5%***	***1%***	***-3%***
Total Plant Cost ($/kW)	1575	2870	**1295**
Total As-Spent Capital, *rev* ($/kW)	2296	4070	**1774**
% increase	***46%***	***42%***	***37%***
LCOE ($/MWh)	63.3	114.8	**52**
LCOE, *rev* ($/MWh)	74.7	135.2	**61**
% increase	***18%***	***18%***	***17%***

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The Devil is in the Details

- Can we improve the reporting and transparency of costing methods and assumptions to improve the understanding of CCS costs?

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Uncertainty, Variability and Bias

Uncertainty

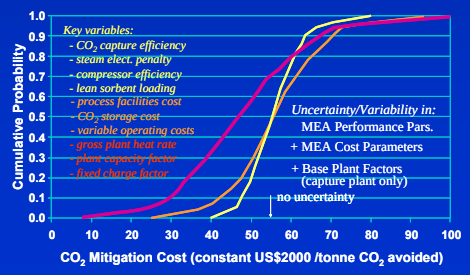
- This reflects a lack of knowledge about the precise value of parameters that affect CCS cost. Especially important for new capture processes at early stages of development.
- Cost methods may (in principle) account for uncertainties via assumptions and probability distributions for key performance, financial and cost factors (e.g., contingencies)
- Historical experience, expert elicitations and insights from relevant "learning curves" can help inform judgments

Technology Status	Process Contingency (% of Associated Process Capital)
New concept with limited data	40+
Concept with bench-scale data	30-70
Small pilot plant data	20-35
Full-sized modules have been operated	5-20
Process is used commercially	0-10

AACE Guidelines

Variability

- This refers to differences in the value of a parameter across a collection of facilities, or at a single facility
- Can be expressed as a probability distribution function or (more simply) as a range of (known) values
- Cost methods can account for variability via parametric (sensitivity) analysis or a probabilistic analysis (as below)



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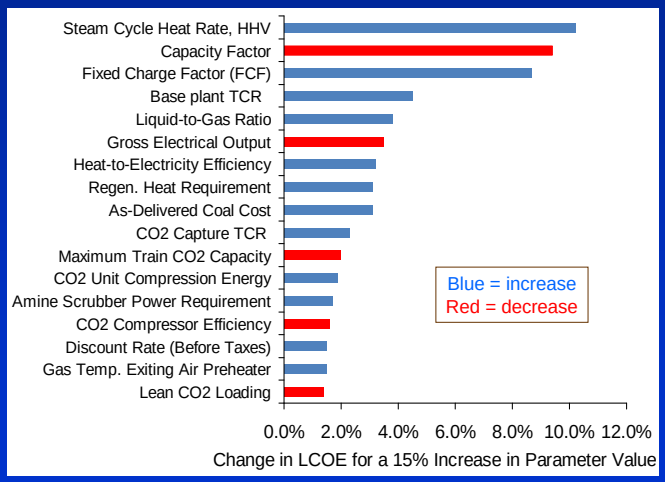
Important to Identify Key Parameters that Affect Results of Interest

Sensitivity of LCOE to a 15% increase in the nominal value of ~150 IECM parameters for a SCPC-CCS power plant.

17 parameters (shown here) changed LCOE by > 1% (other values constant)



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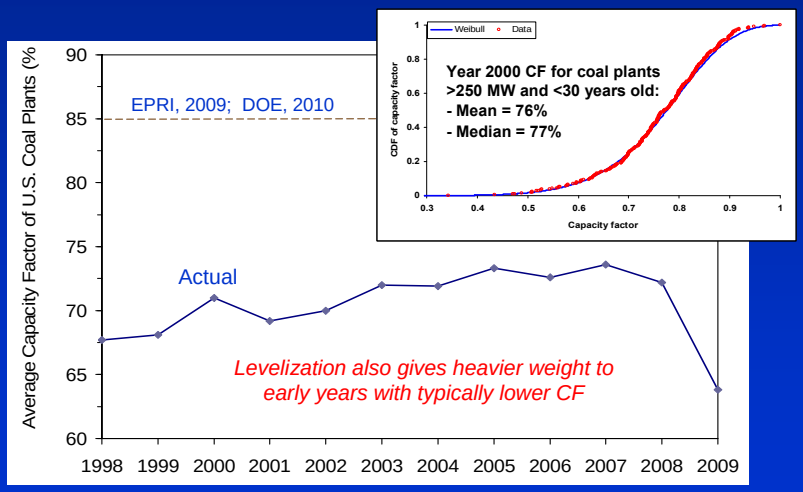
Bias

- Can be reflected in the project design specifications as well as in the choice of parameters and parameter values for cost estimates
- Can be hard to detect or "prove" since often depends on judgment. Independent (3rd party) evaluations can help identify areas and issues of concern.
- One example appears to be an optimistic assumption of levelized capacity factor in recent cost studies of U.S. coal-fired power plants

Actual vs. Assumed Capacity Factors for U.S. Coal Plants



Closing Thoughts

- *Reminder*: The *true* costs of CCS are still unknown since we have yet to build and operate full-scale power plants with CCS
- This workshop, and potential follow-on meetings, can go a long way to improve the understanding and communication of CCS costs within the technical and policy communities
- Some topics/questions for discussion:
  - Can we improve the reporting, consistency and transparency of costing methods and assumptions?
  - Can we improve our methods of characterizing and incorporating uncertainties and variability?
  - Can we improve methods to compare CCS to other options?

Thank You

rubin@cmu.edu