# Methods and Measures for CCS Costs


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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*

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*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"

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## *Measures of CCS cost*

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# 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

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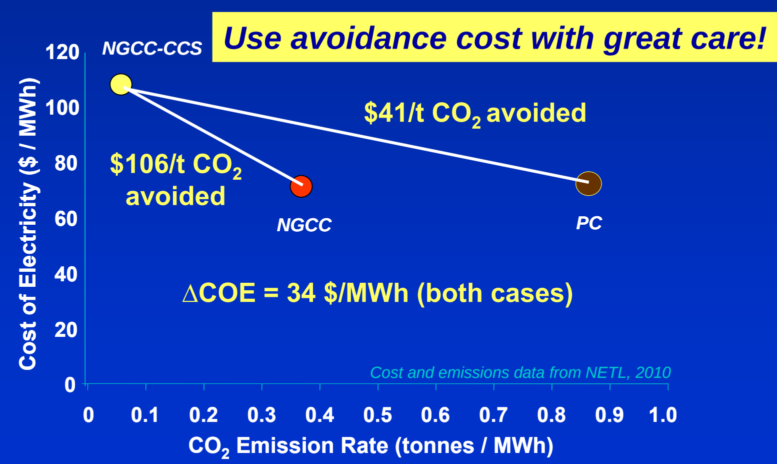
# Cost of $CO_2$ avoided is sensitive to assumed reference plant w/o CCS

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






# Cost of Electricity (COE)

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

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

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## 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 !***

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## 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

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# 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<br><br>(Similar to Amer. Assoc. of Cost Engineers (AACE) Class 5/4) | Simplified | 30–50 | General site conditions, geographic location and plant layout<br>Process flow/operation diagram<br>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<br><br>(Similar to Amer. Assoc. of Cost Engineers Class 3) | Preliminary | 15–30 | As for Type Class I plus engineering specifics, e.g.:<br>Major equipment specifications<br>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<br><br>(Similar to Amer. Assoc. of Cost Engineers Class 3/2) | Detailed | 10–20 | A complete process design<br>Engineering design usually 20–40% complete<br>Project construction schedule<br>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<br><br>(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.

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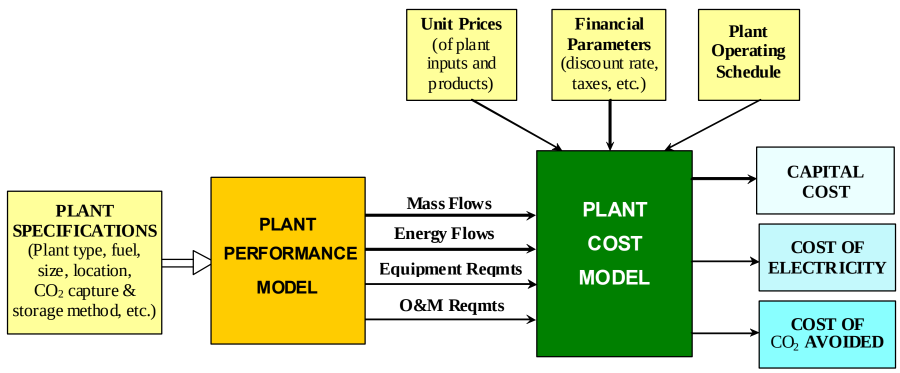
# Framework for Cost Estimation

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# 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

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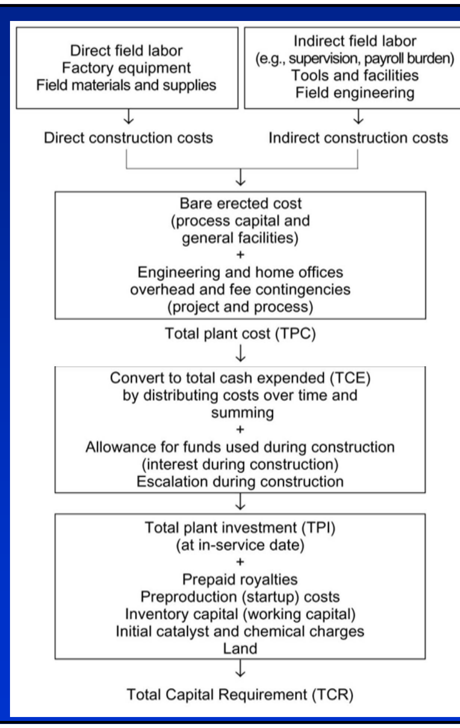
# EPRI Capital Cost Elements

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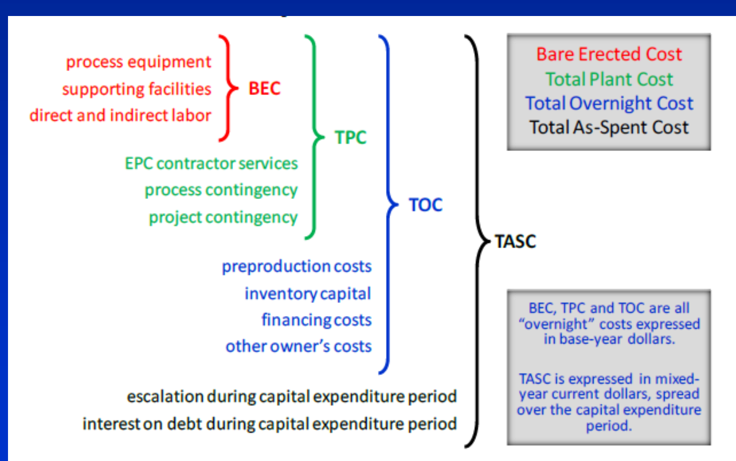
# DOE/NETL Capital Cost Elements

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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)** | |

*No consistent set of cost categories or nomenclature across studies*

| 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)** | | |

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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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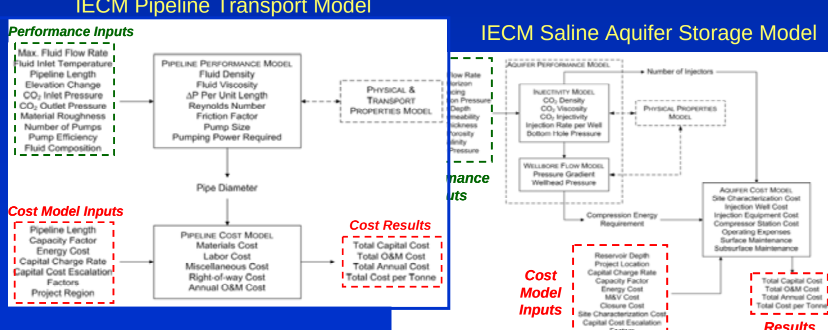
# Transport and Storage Cost Models Also Differ in Scope and Complexity

- 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)<br>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)<br>1.1618 (other) | 1.2676 | 1.00 | 1.00 | N/A |
| - w/ CCS | 1.2022 (coal)<br>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*

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## 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

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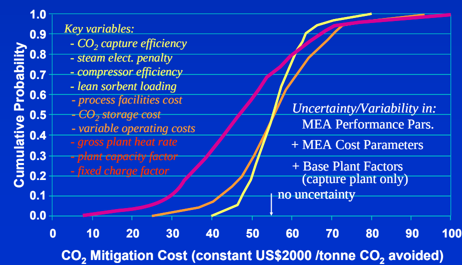
# Variability

- 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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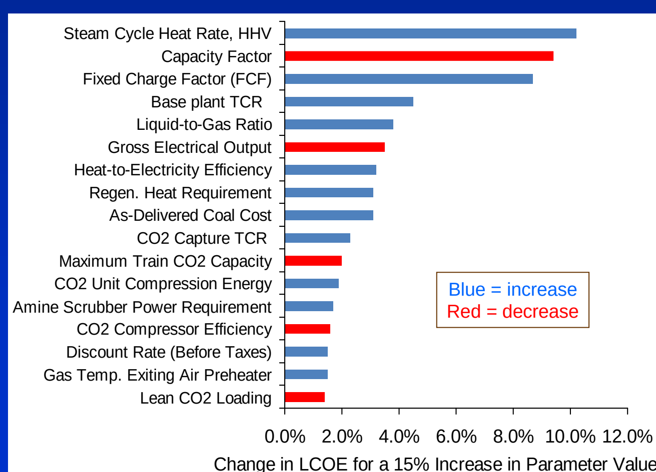
# Important to Identify Key Parameters that Affect Results of Interest

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

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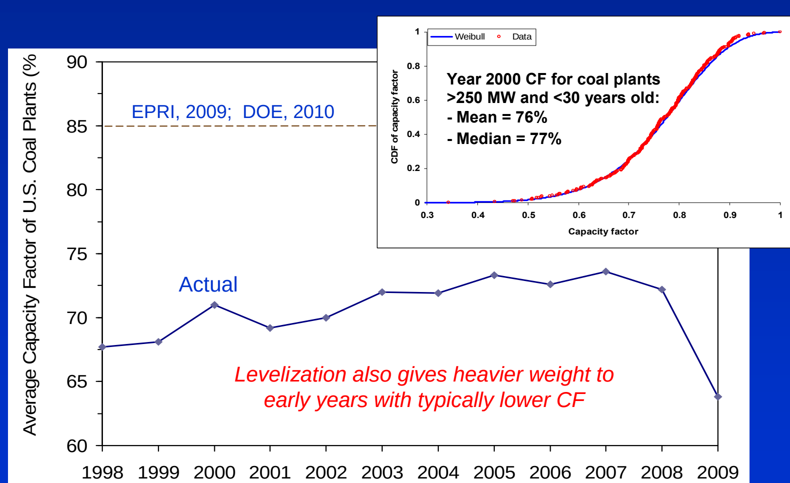
# Actual vs. Assumed Capacity Factors for U.S. Coal Plants

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# 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*

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