How to Improve Cost Estimates for Fossil Fuel Power Plants with CO_2 Capture and Storage

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A Pop Quiz

Which of these power plants with CCS has the lowest cost?

500 MW coal plant, 90% CO_2 capture,
Levelized cost of electricity (COE) =

Plant A?	Plant B?	Plant C?
115 $/MWh	99 $/MWh	135 $/MWh

***Answer**: All three plants are the same. But studies employed different costing methods and (a few) different assumptions*

My Premise

- Despite many recent studies on the cost of CO_2 capture and storage (CCS) at power plants, there remain significant differences in the costing methods (as well as key assumptions) employed by different organizations that are not readily apparent.
- Such differences contribute to confusion, misunderstanding and (in some cases) the mis-representation of CO_2 abatement costs, especially among audiences unfamiliar with details of CCS costing.

Who Cares About CCS Cost?

Audiences for CCS Cost Estimates

Government

- Policymakers
- Analysts
- Regulators
- R&D agencies

Industry

- Vendors
- A&E firms
- Plant operators
- Venture capital
- Tech developers
- R&D organizations

NGOs

- Environmental
- Media
- Academia
- Foundations

Some of these groups are also sources of cost estimates

Source: Based on Herzog, 2011

Uses of CCS Cost Estimates

Cost Estimates for CCS
(and other technologies)

Technology Assessments

- R&D priorities
- Capital investments
- Marketing

Policy Assessments

- Legislation
- Regulation
- Advocacy

Source: Based on Herzog, 2011

Where Do Costs Come From?

A Hierarchy of Cost Estimation Methods

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

Recent CCS Cost Studies

- 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

Common Measures of CCS Cost

- Increased cost of electricity ($/MWh)
- Cost of CO_2 avoided ($/ton CO_2)
- Increased capital cost ($/kW)
- Cost of CO_2 captured ($/ton CO_2)

All measures are relative to a reference plant without CCS, whose performance and cost also must be specified

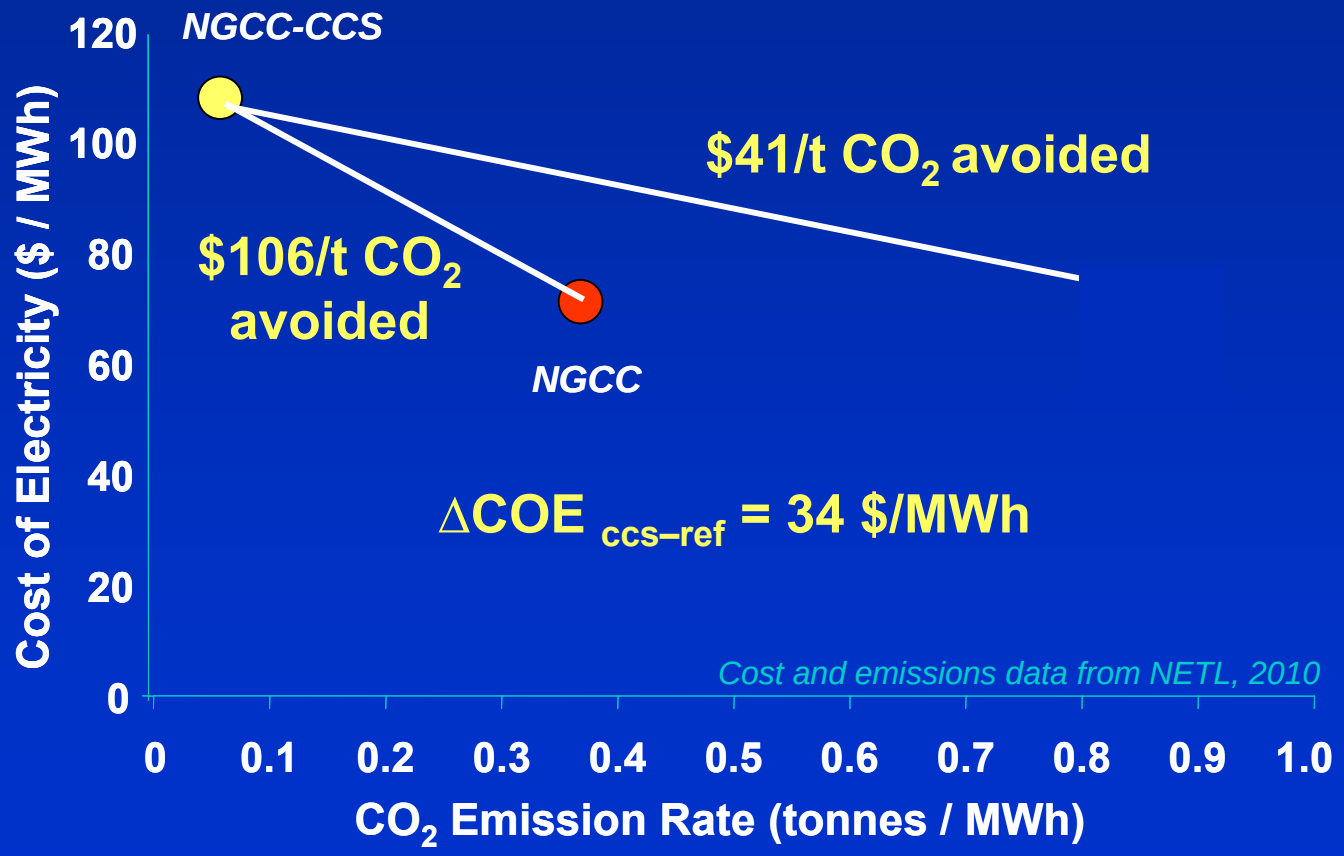
Cost of CO_2 Avoided

- 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 most commonly reported measure of CCS cost
- 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 measure that is sensitive to the choice of reference plant without CCS

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



How consistent are underlying costing methods ?

Capital Cost Elements (Recent Studies)

EPRI (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)		

O&M Cost Elements in Recent Studies

Category	USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI (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

No consistent set of cost categories or nomenclature across studies

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

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

USDOE/NETL (2007)	USDOE/NETL (2010)	EPRI (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

How consistent are key assumptions ?

Many Factors Affect CCS Cost

- Choice of power plant and CCS technology
- Process design and operating variables
- Economic and financial parameters
- Choice of system boundaries
- Time frame of interest

The choice of key assumptions can have a significant influence on study results. For example . . .

Ten Ways to Reduce CCS Costs

(Inspired by D. Letterman)

10. Assume high power plant efficiency
9. Assume high-quality fuel properties
8. Assume low fuel cost
7. Assume high credits for CO_2–EOR
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 haven't yet considered the CCS technology!

Key Cost Assumptions Vary Across 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

Transparency of assumptions is critical for understanding

What about uncertainty, variability and bias ?

Uncertainty, Variability & Bias

- Variability and uncertainty can (in principle) be accounted for in costing methods, e.g., via parametric (sensitivity) analysis, choice of parameter values, and/or probabilistic analysis

- Bias can arise in project design specifications and choice of parameters and values for cost estimates
  - Can be difficult to detect or prove
  - Independent (3rd party) evaluations can be helpful

Especially important for evaluating new or emerging technologies, but often ignored or not treated rigorously

Further Details Available in a Recent Publication

- CCS costing methods and assumptions for several organizations are discussed and compared in a recent paper published in the International Journal of Greenhouse Gas Control *(IJGGC, 2012)*

International Journal of Greenhouse Gas Control 10 (2012) 181–190

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International Journal of Greenhouse Gas Control

Journal homepage: www.elsevier.com/locate/ijggc

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Understanding the pitfalls of CCS cost estimates

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ABSTRACT

This paper reviews and compares the prevailing methods, metrics and assumptions underlying cost estimates for CO_2 capture and storage (CCS) technologies applied to fossil fuel power plants. This assessment reveals a number of significant differences and inconsistencies across different studies, not only in key technical, economic and financial assumptions related to the cost of a CCS project (such as differences in plant size, fuel type, capacity factor, and cost of capital) but also in the underlying methods and cost elements that are included (or excluded) in a particular study (such as the omission of certain "owner's" costs or the cost of transport and storage). Such differences often are not apparent in the cost results that are reported publicly or in the technical literature. In other cases, measures that have very different meanings (such as the costs of CO_2 avoided, CO_2 captured and CO_2 abated) are all reported in similar units of "dollars per ton CO_2". As a consequence, there is likely to be some degree confusion, misunderstanding and possible mis-representation of CCS costs. Given the widespread interest in the cost of CCS and the potential for lower-cost CO_2 capture technology, methods to improve the consistency and transparency of CCS cost estimates are needed.

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1. Introduction and objectives

Carbon dioxide capture and storage (CCS) is a potentially critical technology for mitigating global climate change, but its current cost is a major barrier to applications at power plants and other large industrial sources of CO_2 (NRC, 2010; IEA, 2011; GCCSI, 2011). Efforts are thus underway worldwide to develop new lower-cost technologies, especially for CO_2 capture—the costliest component of a CCS system (IPCC, 2005; Figueroa et al., 2008; Rubin et al., 2012). Given its potential importance in reducing greenhouse gas emissions, information on CCS costs is sought by a broad range of actors in government, industry and other organizations for purposes of policy analysis, investment decisions, technology assessments, R&D activities, and energy-environmental policy-making, including development of legislation and regulations involving CCS.

Yet, as this paper will show, there are significant differences and inconsistencies in the way CCS costs are currently calculated and reported by various authors and organizations. The major objective of this paper, therefore, is to highlight key methodological issues related to CCS cost estimates, including the specification of project scope, terminology, calculation procedures, and the items included (or excluded) in reported CCS costs. The paper also discusses the various measures of CCS cost that are commonly sought and reported, and identifies some of the critical (and sometimes controversial) assumptions underlying such estimates. Also discussed are how or whether CCS costing methods treat such issues as the level of technological maturity, technological change over time, and the vintage of facility analyzed (e.g., new vs. retrofitted plants). Issues related to uncertainty, variability and bias in assumptions and data also are discussed.

2. Cost measures and metrics

A variety of measures are used in the literature to report the cost of CO_2 capture and storage systems, as well as other CO_2 reduction measures. The most common metrics include the cost of CO_2 avoided; cost of CO_2 captured; cost of CO_2 abated (or reduced); and the increased cost of electricity (for studies related to power plants) (IPCC, 2005). As discussed below, the first three of these measures have very different meanings, but because all three are reported in similar units of "dollars (or other currency) per ton CO_2," there is significant potential for misunderstanding. Similarly, the metric of increased cost of electricity also is used in different contexts. Users of these CCS cost measures must therefore be careful to clearly understanding their meaning.

2.1. Cost of CO_2 avoided

The cost of CO_2 avoided is one of the most commonly reported measures of CCS cost (e.g., IPCC, 2005; EPRI, 2009; NETL, 2010; Finkenrath, 2011; GCCSI, 2011). It compares a plant with CCS to a "reference plant" without CCS, and quantifies the average cost of

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The Need

- Need to improve the consistency, reporting, and transparency of costing methods and assumptions to enhance the understanding and rigor of CCS cost estimates

A Path Forward

Toward a Common Method

- Need for improved costing methods was affirmed at a 2011 international workshop on CCS costs*
- An *ad hoc* Task Force was formed in fall 2011 to work on ways to:
  - Harmonize methods of estimating and reporting CCS costs
  - Improve methods of characterizing the variability and uncertainty in CCS costs (especially for new and emerging technologies)
  - Improve methods for comparing costs of CCS to other GHG mitigation options

* <https://kminside.globalccsinstitute.com/community/extranet/ccs_costs_network>

CCS Costing Methods Task Force

- George Booras (EPRI)
- John Davison (IEAGHG)
- Clas Ekström (Vattenfall /ZEP)
- Mike Matuszewski (USDOE)
- Sean McCoy (IEA)
- Ed Rubin (CMU) *(Chair)*
- Chris Short (GCCSI)

We examined in detail the power plant and CCS costing methods developed or used by four leading organizations

A draft White Paper was vetted at a 2012 CCS Cost Workshop

~45 international participants from industry, government, NGOs, and academia

Proceedings available at GCCSI website

White Paper now Published:

addresses six major topics relevant to CCS costs

- Project Scope and Design
- Nomenclature and Cost Categories for CCS Cost Estimates
- Quantifying Elements of CCS Cost
- Defining Financial Structure and Economic Assumptions
- Calculating the Costs of Electricity and CO_2 Avoided
- Guidelines for CCS Cost Reporting

I will briefly discuss the two highlighted topics

Recommended Costing Method

- With just a few changes to each of the costing methods studied, a common language and costing methodology can indeed be achieved.
- Here is what it would look like for capital costs …

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)

Task Force Recommendation (con't.)

- … and here's what it would look like for plant operating and maintenance (O&M) cost items

Representatives of leading organizations have agreed to move toward this common nomenclature

Operating & Maintenance Cost Item to be Quantified	Sum of All Preceding Items is Called:
Operating labor	
Maintenance labor	
Administrative & support labor	
Maintenance materials	
Property taxes	
Insurance	
	Fixed O&M Costs
Fuel	
Other consumables, e.g.: - chemicals - auxiliary fuels - water	
Waste disposal (excl. CO_2)	
CO_2 transport	
CO_2 storage	
Byproduct sales (credit)	
Emissions tax (or credit)	
	Variable O&M Costs

While this is a major step forward, the Devil is still in the details

- Even with a common nomenclature and common set of cost elements, different assumptions and methods of quantifying each cost item will still result in different costs.

- Some cost items are amenable to guidelines (e.g., process contingency cost adders); others are far more difficult to harmonize (e.g., cost items "specified by the contractor").

The White Paper emphasizes the importance of <u>full reporting</u> to reveal sources of cost differences

Reporting Guidelines

- The Task Force developed a series of "checklists" of essential data that should be reported in:
  - Technical reports
  - Journal/conf. papers
  - Presentations

(in light of typical length constraints for each medium)

Table 8. Guidelines for reporting CCS cost assumptions in presentations

Information Needed	Presentations
Power plants without CO_2 capture (reference/baseline plants)	
Fuel type (class of hard coal, lignite, gas)	X
Power plant type (e.g. PF, BFB, CFB or NGCC)	X
Plant capacity (MW electric)	
– Gross (to define boiler or gas turbine size class)	X
– Net	X
Environmental control requirements (for major pollutants)	X
Net electric efficiency and/or heat rate (state if based on LHV or HHV)	X
CO_2 emissions (per MWh net electricity or per MWh fuel; state if LHV or HHV)	X
In addition to the above for power plants with CCS	
Type of power plant CO_2 capture; e.g. post-combustion, oxy-combustion, IGCC with pre-combustion	X
Capture technology (e.g. MEA, advanced amine, chilled ammonia, Selexol, solid absorption/desorption process, etc.	X
Captured CO_2 per MWh net electricity or per MWh fuel (state if LHV or HHV) or "CCS capture rate" (% of produced CO_2)	X
Capital costs	
Type of plant, e.g. first-of-a-kind, N*-of-a-kind	X
Year and currency of cost estimate	X
Contingencies (sum of process and project contingencies)	X
Resulting "Total Overnight Cost"	X
– Construction cost escalation rate (if applied)	X
O&M costs (excluding CO_2 transport & storage)	
Total fixed and variable costs (in appropriate units)	X
CO_2 emissions cost (or tax) per tonne (if included)	X
CO_2 transport & storage costs	
Overall net cost per tonne of CO_2 stored, with breakdown into transport and storage (if available).	X
Cost of electricity (COE)	
State whether levelized or first-year (or other)	X
Method/approach used; also state if calculation uses real (constant money values) or nominal (current money values)	X
Interest rate/discount rate/WACC; also state if real or nominal	X
Inflation and other price escalation rates (if applied)	X
Economic lifetime	X
Load factor/equivalent full load operation hours	X
– Fuel prices per GJ or MWh fuel (state HHV or LHV)	X
CO_2 avoidance cost	
State and define reference plant case	X

Reporting Guidelines

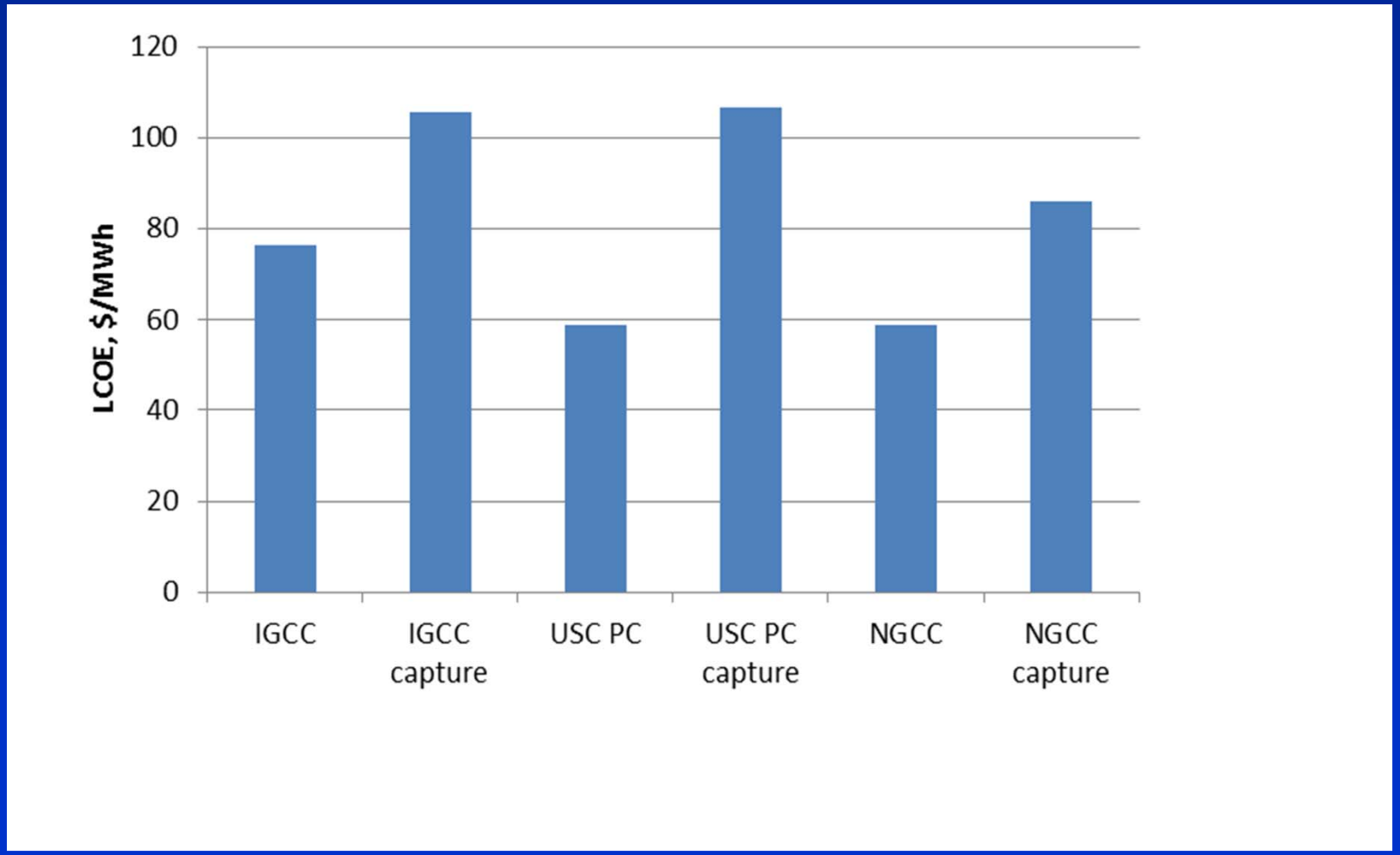
- The complete set of checklists appear in the White Paper (Table D1)

Table D1. Recommended data to be presented in reports, papers, and presentations

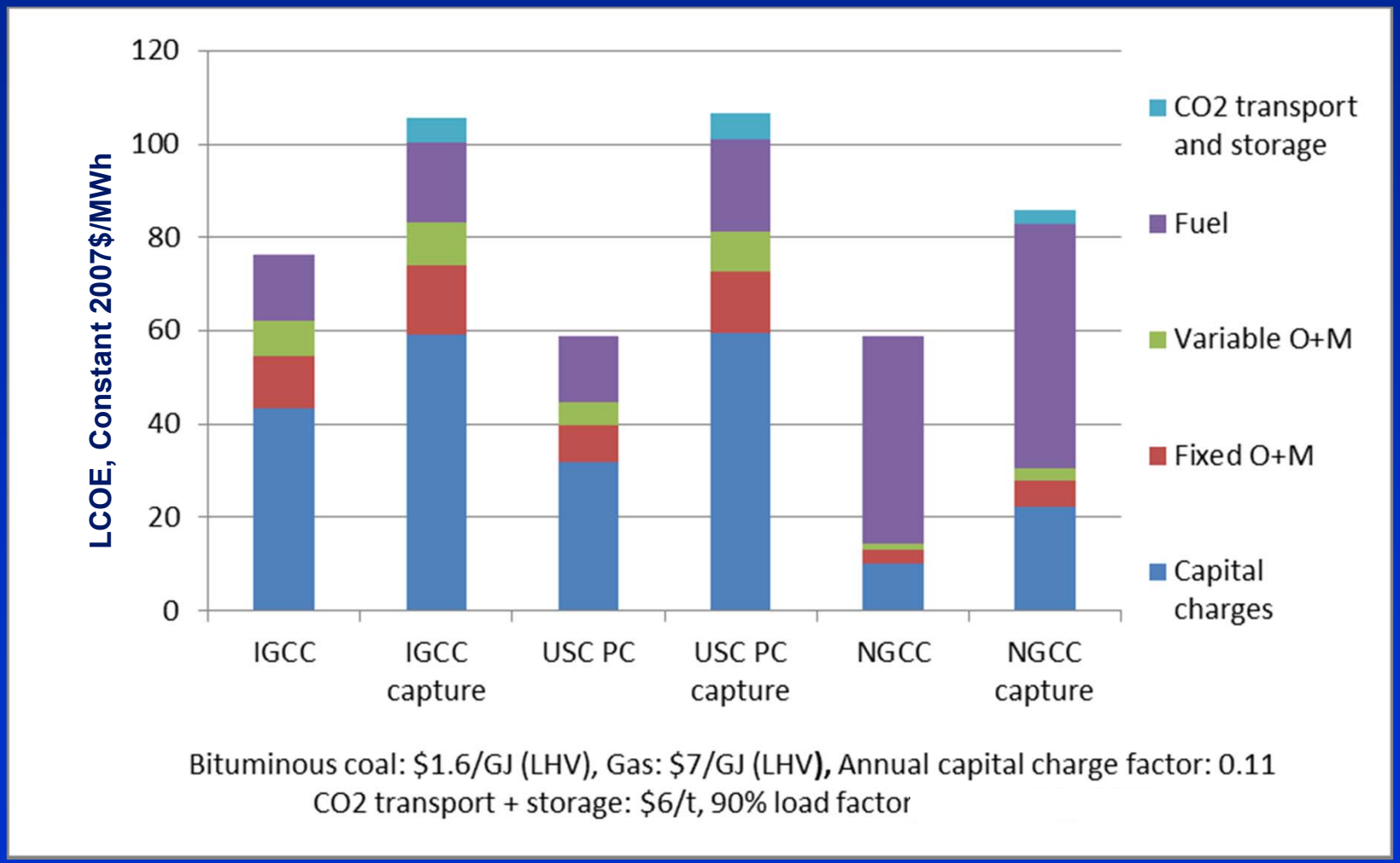
Information Needed	Reports	Papers	Presentations
Power plants without CO_2 capture (reference/base line plants)			
Battery limits	X		
Fuel type (class of hard coal, lignite, gas)	X	X	X
– Moisture and ash contents	X	X	
– LHV and HHV. (state "as received", dry matter, dry and ash free).	X	X	
– Definition of LHV	X		
Power plant type (e.g. PF, BFB, CFB or NGCC)	X	X	X
– Steam parameters (pressures/temperatures)	X	X	
– GT-class (e.g. F-class, H-class)	X	X	
– Gasifier type (for IGCC)	X	X	
Plant location type (immediate to port, inland)	X	X	
– Ambient conditions (ISO, other conditions)	X	X	
Cooling water (cooling tower or once through sea/lake/river water)	X	X	
Plant capacity (MW electric)			
– Gross (to define boiler/GT size class)	X	X	X
– Net	X	X	X
Net electric efficiency and/or heat rate (state if based on LHV or HHV)	X	X	X
CO_2 emissions (per MWh net electricity or per MWh fuel; state if LHV or HHV)	X	X	X
Environmental control requirements (for major pollutants)	X	X	X
In addition to the above, for power plants with CO_2 capture			
Plant capacity (Is the boiler/GT capacity or the gross or net output the same as the reference plant)	X	X	
Type of concept for power plant with CO_2 capture; e.g. post-combustion, oxy-fuel, IGCC with pre-combustion	X	X	X
Capture technology (e.g. MEA, advanced amine, chilled ammonia, Selexol etc or solid absorption/ desorption process	X	X	X
Delivered captured CO_2:			
– Pressure, temperature	X	X	
– Purity requirements anticipated (at least state if sufficient for transport in carbon steel pipelines or ships)	X		
Captured CO_2 per MWh net electricity or per MWh fuel (state if LHV or HHV), or "capture rate" (% of produced CO_2)	X	X	X
Capital costs			
Type of plant, e.g. first-of-a-kind, Nth-of-a-kind	X	X	X
Year and currency of cost estimate	X	X	X
EPC, TPC or similar:	X		
– Minimum is a "lump sum" cost, plus define:	X		
○ Which major process units, buildings, construction and other major cost items are included	X		
○ Method used, e.g., "EPC" bids for major process units, step-count exponential costing method, etc.	X		
– Cost breakdowns if available	X		
Owner's costs:	X		
– Minimum is a "lump sum" cost, plus define:	X		
○ Which major cost items are included here; e.g. own engineering, planning and project management, commissioning/start-up costs, working capital	X		
○ Method used; e.g. "EPC" bids for major process units, step-count exponential costing method	X		
– Cost breakdowns if available	X		
Contingencies	X		X
– Project contingency (% of EPC, TPC w/o contingencies or similar)	X	X	
– Process contingency for novel processes (if included)	X	X	

(contined)

We also have some examples of "Bad" Practice …



… and "Good" Practice for information in graphs and tables



Next Steps

- Disseminate the White Paper broadly to the technical and policy communities
- Encourage adoption of the recommended costing methodology and reporting guidelines by all major organizations concerned with power plant and CCS costs (including journal editors and conference organizers)
- Extend Task Force activities to other issues of interest, such as costing of new/emerging capture technologies, costs for industrial processes, and comparisons with other GHG mitigation options

The White Paper is available at no cost from:

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

GCCSI:
<http://www.globalccsinstitute.com/publications/toward-common-method-cost-estimation-co2-capture-and-storage-fossil-fuel-power-plants>

Also links from DOE/NETL, IEA, and IEAGHG websites.

Thank You

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