Seven Simple Steps to Improve Cost Estimates for Advanced Carbon Capture Technologies

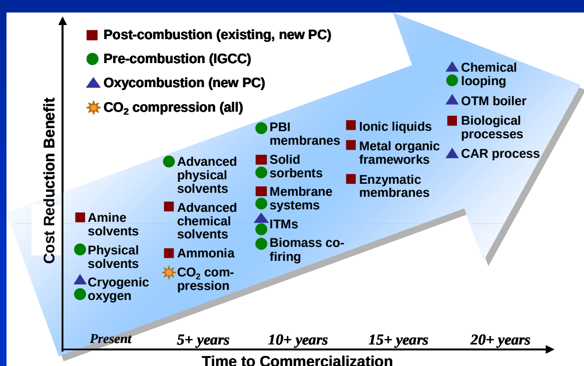
Edward S. Rubin
Department of Engineering and Public Policy
Department of Mechanical Engineering
Carnegie Mellon University
Pittsburgh, Pennsylvania

Presentation to the
DOE Transformational Carbon Capture Technology Workshop
Arlington, Virginia
September 23, 2014

Here, "Advanced Carbon Capture Technology" Means …

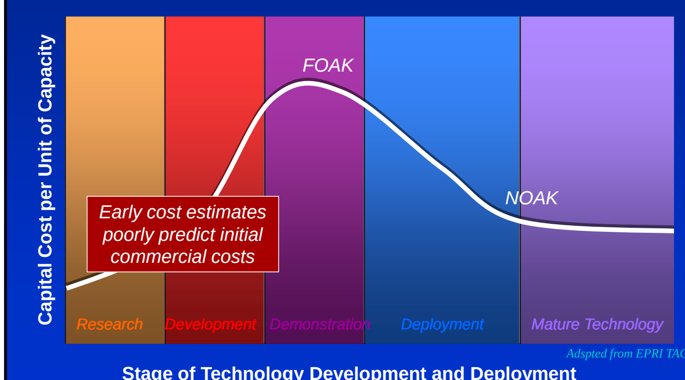
- Any technology that is not yet deployed or available for purchase at a commercial scale
  - Current stage of development may range from concept to large pilot or demonstration project
- Process design details still preliminary or incomplete
- Process performance not yet validated at scale, or under a broad range of conditions
- May require new components and/or materials that are not yet manufactured or used at a commercial scale

Examples of Advanced Technologies: Everything beyond *Present*



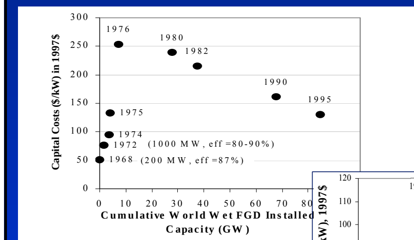
Source: USDOE, 2010

Typical Cost Trend of a New Technology



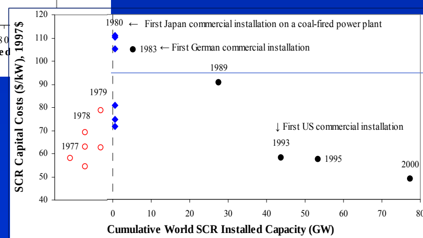
Adspted from EPRI TAG

Historical cost of SO_2 and NO_x controls follow trend shown in previous slide



Capital Cost of Power Plant Flue Gas Desulfurization (FGD) and Selective Catalytic Reduction (SCR) Technologies

Source: Rubin et al. 2007



All costs based on a standardized 500 MW coal-fired power plant (except where noted)

E.S. Rubin, Carnegie Mellon

How can we do a better job of costing advanced technologies ?

E.S. Rubin, Carnegie Mellon

Step 1

E.S. Rubin, Carnegie Mellon

Avoid Cost Estimates at the Earliest Stages of Development

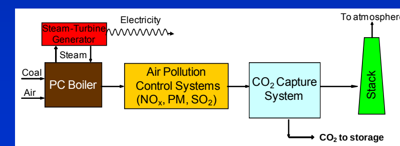
- Don't ask about cost for new capture technologies or process concepts. Instead ….
- Use performance metrics and other non-economic criteria to evaluate and screen novel materials, components and early-stage concepts (low TRLs), e.g.

E.S. Rubin, Carnegie Mellon

Step 2

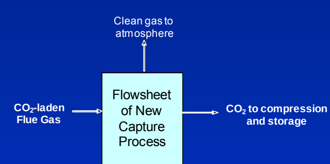
When a cost estimate is needed, define the full system involved

- The cost of power plant carbon capture is correctly calculated as the difference in cost between similar plants with and without the capture technology
- Care must be taken to include all relevant plant components within the system boundary (battery limits) analyzed

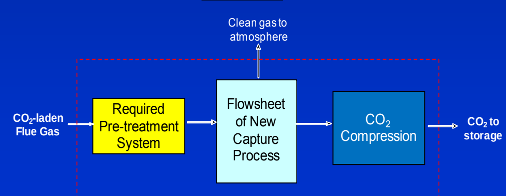


Capture system boundaries should include all components needed

For example, some studies report cost for only the "bare" capture process



… ignoring other components that are also needed



Step 3

Use Proper Costing Method

Different organizations have used different costing methods, but …

A standardized costing method is now available

Items to be Included in a Power Plant or Capture Technology Cost Estimate

Recommended nomenclature for power plant capital cost estimates.

Capital cost element to be quantified	Sum of all preceding items is called:
Process equipment	
Supporting facilities	
Labor (direct and 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	
Insurance	
Permitting	
Finance transaction costs	
Pre-paid royalties	
Initial catalyst and 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 (IDC)	
Cost escalations during construction	
	Total Capital Requirement (TCR)

Recommended nomenclature for power plant O&M costs.

Operating and maintenance cost item to be quantified	Sum of preceding items
Operating labor	
Maintenance labor	
Administrative and support labor	
Maintenance materials	
Property taxes	
Insurance	
	Fixed O&M Costs
Fuel	
Other consumables, e.g.:	
Catalysts	
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

Source: Rubin et al., IJGGC, 2013

Step 4

Use Appropriate Values of Cost Elements to Estimate Full-Scale Cost

- The value of many cost elements in the preceding lists depends upon the technical maturity of the process; thus, use of an appropriate value is especially important for processes at early stages of development
- This is particularly true for Process and Project Contingency Costs, which constitute a significant fraction of the total capital requirement of a project
- Currently, most cost estimates for advanced carbon capture processes ignore established guidelines for process and project contingency costs

EPRI/DOE/AACE Guidelines for Process Contingency Cost

- "Factor applied to new technology … to quantify the uncertainty in the technical performance and cost of the commercial-scale equipment" based on the current state of technology. *- EPRI TAG*

Current Technology Status	Process Contingency Cost (% 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

Source: EPRI, 1993; AACE, 2011; NETL, 2011

Most advanced capture system cost estimates assume ***much smaller*** process contingencies than guidelines require (e.g., zero to <20%)

E.S. Rubin, Carnegie Mellon

EPRI/DOE/AACE Guidelines for Project Contingency Cost

- "Factor covering the cost of additional equipment or other costs that would result from a more detailed design of a definitive project at an actual site." *- EPRI TAG*

EPRI Cost Classification	Design Effort	Project Contingency (% of total process capital, eng'g. &home office fees, and process contingency)
Class I (~AACE/DOE Class 5/4)	Simplified	30–50
Class II (~AACE/DOE Class 3)	Preliminary	15–30
Class III (~ AACE/DOE Class 3/2)	Detailed	10–20
Class IV (~AACE/DOE Class 1)	Finalized	5–10

Source: EPRI, 1993

Many Class I-III studies assume ≤10%

E.S. Rubin, Carnegie Mellon

Contingency Costs Assumptions for Advanced Capture Technology

Parameter	Typical Assumption	Guideline Value*	Capital Cost Increase
Process Contingency (%TPC)	10%	~40%	***30%***
Project Contingency (%TPC)	10%	~30%	***20%***
TOTAL Contingency (%TPC)	**20%**	**~70%**	***50%***

*Based on proposed designs for membrane, solid sorbents, and other post-combustion processes with limited data.

The total contingency cost for advanced capture processes is significantly under-estimated in most cost studies, leading to systematically low capital cost estimates relative to guidelines

E.S. Rubin, Carnegie Mellon

Step 5

E.S. Rubin, Carnegie Mellon

Use Learning Curves to get NOAK Costs
(Supplemented by Conventional Bottom-Up Analysis)

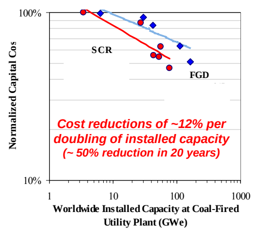
- Cost studies of advanced technologies often assume cost parameters for a mature (N^{th}-of-a-kind) plant in a bottom-up analysis to show potential benefits of a new technology
- But research on technology innovation shows that "learning by doing" is needed to achieving cost reductions
- So to realize N^{th}-of-a-kind costs you have to build N plants
- Historical learning (experience) curves can provide an empirical estimate of expected cost reductions relative to FOAK costs as a function of technology deployment
- They can be used together with bottom-up analyses to estimate the deployment needed to achieve N^{th}-plant costs

One-Factor Learning (Experience) Curves are the Most Prevalent

Model equation: $C_i = a\, x_i^{-b}$

where,
C_i = cost to produce the i^{th} unit
x_i = cumulative capacity thru period i
b = learning rate exponent
a = coefficient (constant)

Fractional cost reduction for a doubling of cumulative capacity (or production) is defined as the learning rate: $LR = 1 - 2^b$



- Most appropriate for projecting future cost of a technology that is already commercially deployed
- Application to advanced (pre-commercial) processes requires careful consideration of the "starting point" (cost and experience base) for future cost reductions

Step 6

Characterize and Quantify Uncertainty in Key Performance and Cost Metrics

A variety of methods are available for characterizing and quantifying uncertainty, including:

- Overall accuracy estimates
- Sensitivity analysis
- Probabilistic estimates (based on models, data and/or expert elicitations)

Quantification of uncertainties can improve cost estimates by identifying risks as well as opportunities

Overall Accuracy for Conventional Costing Methods

Cost Accuracy (as a %of nominal cost)

Estimate Rating[b]		Technology Development Rating[b]				
		A	B	C	D	E and F
		Mature	Commercial	Demo	Pilot	Lab and Idea
A.	Actual	0	–	–		–
B.	Detailed	-5 to +8	-10 to +15	-15 to +25	–	–
C.	Preliminary	-10 to +15	-15 to +20	-20 to +25	-25 to +40	-30 to +60
D.	Simplified	-15 to +20	-20 to +30	-25 to +40	-30 to +50	-30 to +200

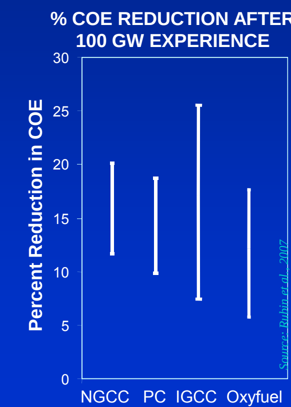
Source: AACE and EPRI

Costs for advanced processes are more likely to exceed the nominal costs

E.S. Rubin, Carnegie Mellon

Uncertainty in Learning Curve Estimates of Future Cost Reduction for Plants w/ CCS

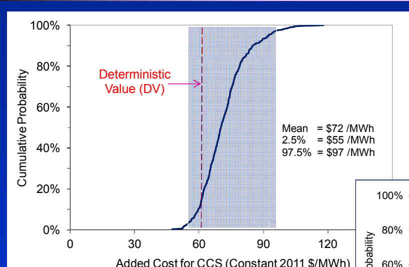
- Experience curves used to project pathway from FOAK to NOAK costs for advanced technologies
- Error bars show range of projected cost reduction based on uncertainty in key model parameters for each technology



E.S. Rubin, Carnegie Mellon

Probabilistic Case Study Results:

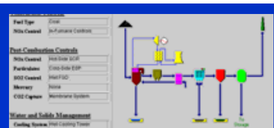
SCPC-CCS (550 MW_{net}) w/ 2-Stage Membrane Capture System

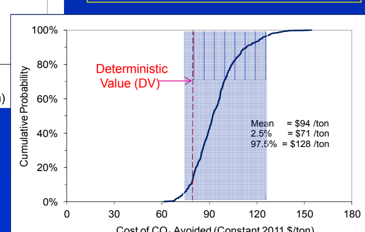


95% CONFIDENCE INTERVALS=

Added COE:
DV +31/-6 $/MWh **(+51%/ -10%)**

CO_2 Avoidance Cost:
DV +49/-8 $/ton= **(+62%/ -10%)**





E.S. Rubin, Carnegie Mellon

Step 7

E.S. Rubin, Carnegie Mellon

Report Cost Metrics that are Useful and Unambiguous

- Always report the cost year, and whether values are in constant or current dollars *(the difference can be sizeable!)*
- Useful cost metrics for CO_2 capture systems include (but are not limited to):
  - Added cost of electricity generation
  - Added capital cost
  - Cost of CO_2 avoided (for a clearly-defined ref plant)

In Summary: Seven Simple Steps to Improve Cost Estimates for CO_2 Capture

1. Use non-cost metrics for earliest-stage technologies
2. When costing a technology define the full system
3. Use proper costing methods
4. Quantify cost elements appropriately
5. Use learning curves when estimating NOAK costs
6. Characterize and quantify uncertainties
7. Report cost metrics that are useful and unambiguous

A Final Word of Wisdom

"It's tough to make predictions, especially about the future"

- Yogi Berra

Thank You

rubin@cmu.edu