How to Improve Cost Estimates for Advanced CO_2 Capture Systems

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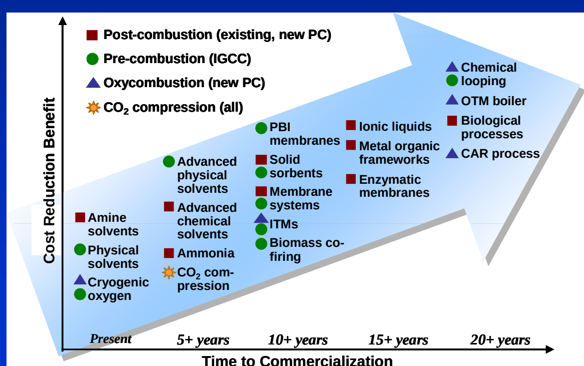
Characteristics of Advanced (Pre-Commercial) Capture Systems

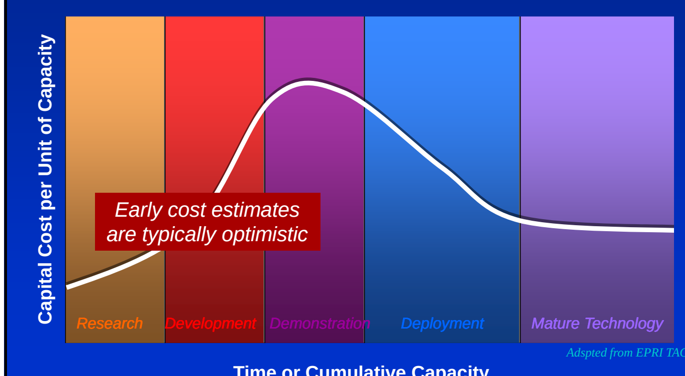
- Includes any technology not yet deployed or available for purchase at a commercial scale
  - Current stage of development may range from concept to large pilot or demonstration project
- Process design details still preliminary or incomplete
- Process performance not yet validated at scale, or under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

Examples of Pre-Commercial Systems: Everything beyond *Present*



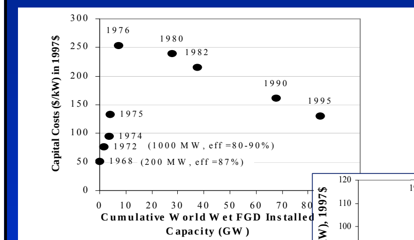
Source: USDOE, 2010

Typical Cost Trend of a New Technology

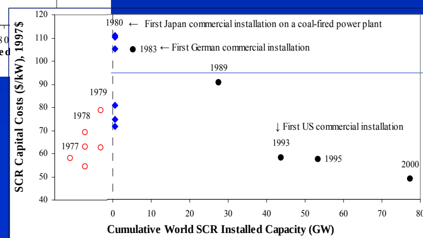


Adapted from EPRI TAG

Historical Trends of FGD and SCR (DeSOx and DeNOx) Costs . . .



Source: Rubin et al. 2007



. . . display the characteristics seen in the previous slide

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

Five Approaches to Cost Estimation for Advanced Systems

- Conventional engineering-economic estimates
- Conventional estimates with uncertainty
- Application of learning (experience) curves
- Expert judgment /elicitations
- Don't say (and don't ask)

Conventional engineering-economic costing

Most advanced capture processes use conventional costing methods …

Capital Cost Element to be Quantified	Sum of All Preceding Items is Called:	Comments
Process equipment Supporting facilities Labor (direct & indirect)		Includes all materials and sales tax (if applicable) On-site facilities needed for the project
	Bare Erected Cost (BEC)	
Engineering services		
	Engineering, Procurement & Construction (EPC) Cost	An optional intermediate cost measure of use to some organizations
Contingencies: • process • project		
	Total Plant Cost (TPC)	
Owner's costs: • Feasibility studies • Surveys • Land [illegible] • Pre-production (startup)		This group of owner costs includes items common to a plant or process installation [illegible]
• Other site-specific items unique to the project (such as unusual site improvements, transmission interconnects beyond busbar, economic development incentives, etc.)		These owner costs include items that are unique to a particular project. They may include items sometimes referred to as "outside the battery limits" (OSBL).
	Total Overnight Cost (TOC)	
Interest during construction (IDC) Cost escalations during construction		
	Total Capital Requirement (TCR)	

Many cost elements depend on the technical maturity of the process

… but most of these estimates ignore "process contingency cost" guidelines

- Process Contingency Cost
  "factor applied to new technology … to quantify the uncertainty in the technical performance and cost of the commercial-scale equipment." *- EPRI TAG*

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 cost estimates for advanced capture systems assume much smaller contingency costs than guidelines require, e.g.:*
  - *7% (IEAGHG, 2011)*
  - *<20% (EPRI, 2011)*
  - *18% (USDOE, 2010)*
  - *10% (IECR, 2008)*

Cost studies also commonly ignore guidelines for "project contingency cost"

- 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 Class 5/4)	Simplified	30–50
Class II (~AACE Class 3)	Preliminary	15–30
Class III (~ AACE Class 3/2)	Detailed	10–20
Class IV (~AACE Class 1)	Finalized	5–10

Source: EPRI, 1993

- Many Class I-III studies assume ≤10%

Conclusion:
- ***The total contingency cost for advanced capture processes is grossly under-estimated in most cost estimates***
  (by factors of roughly ~2 to 4)

Example of Contingency Costs Impact on Capture Process Cost

Illustrative Increase in Capital Cost and COE

(based on a 2-stage membrane capture system)

Parameter	Process + Project Contingency Cost for the CO_2 capture process alone: 20%	50%	100%
Capture System Capital Cost ($/kW)	17%	**42%**	**85%**
Capture System COE ($/MWh)	8%	**20%**	**40%**

FOAK vs. NOAK

- Early commercial systems are often called First-of-a Kind (FOAK) plants, in contrast to *N*th-of-a-Kind (NOAK) plants for mature widely-deployed systems
- The major difference is usually in the system design (though some cost factors, such as financing costs, also may differ)
- Whichever case is chosen for analysis, contingency costs depend on the current state of technology

Conventional costing including uncertainty

Estimates of Overall Accuracy

Cost Accuracy (as a %of nominal cost)

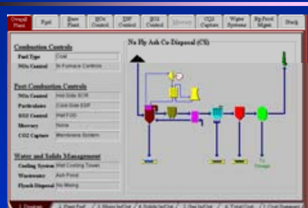
Estimate Rating[b]		Technology Development Rating[b]				
		A	B	C	D	E and F
		Mature	Commercial	Demo	Pilot	Lab and Idea
A.	Actual	0	–	–	–	–
B.	Detailed	-5 to +8	-10 to +15	-15 to +25	–	–
C.	Preliminary	-10 to +15	-15 to +20	-20 to +25	-25 to +40	-30 to +60
D.	Simplified	-15 to +20	-20 to +30	-25 to +40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

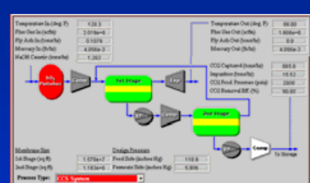
Source: AACE and EPRI

Costs for advanced processes are skewed toward higher than the nominal estimate

Probabilistic Estimates

Case Study of PC Plant with a 2-Stage Membrane Capture System





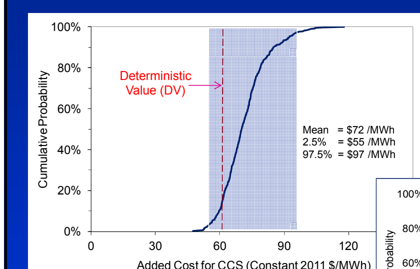
Source: IECM v.8.0.2 (2013)

Membrane System Parameter	Unit	Nominal Value	Distribution Function
Ideal CO2 Permeance (S.T.P.)	gpu	1000	triangular (500, 1000,5000)
Ideal CO2/N2 Selectivity (S.T.P.)	ratio	50	triangular (40, 50, 75)
Feed-side Compressor Efficiency	%	85	uniform (70, 85)
Vacuum Pump Efficiency	%	85	uniform (70, 85)
Expander Efficiency	%	85	uniform (70, 85)
CO2 Compressor Efficiency	%	80	uniform (70, 85)
Cost Parameters			
Membrane Module Cost	$/sq ft	4.645	triangular (2.322, 4.645,18.58)
Total Indirect Capital Cost	% PFC	37	uniform (20, 60)
CO2 T&S Costs	$/ton	5	uniform (1,10)

Probability distributions assigned to 6 performance variables and 3 cost variables

Probabilistic Case Study Results:

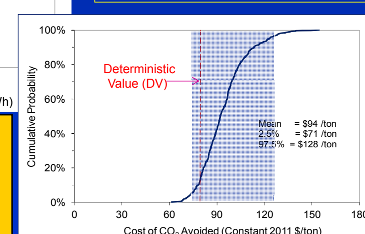
SCPC-CCS (550 MW_{net}) w/ 2-Stage Membrane Capture System



95% CONFIDENCE INTERVALS=

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

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



Conclusion:

- ***Explicit characterization of uncertainties can improve cost estimates by revealing risks as well as opportunities***

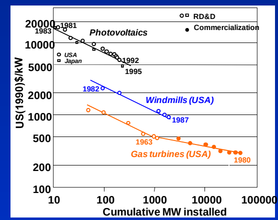
Cost estimates based on learning curves

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: $LR = 1 - 2^b$

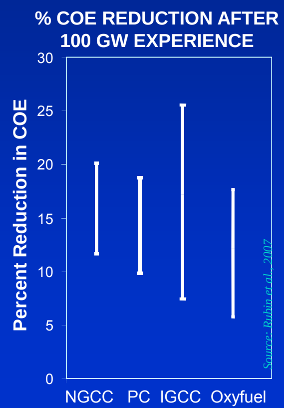


Source: IIASA, 1996

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

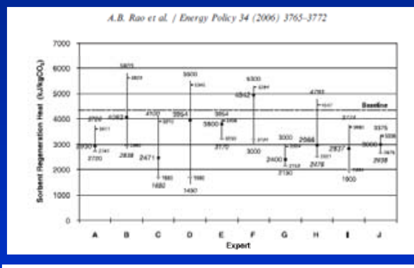
Effect of "Learning" on Future Cost of Power Plants w/ CCS

- **The judicious use of experience curves can suggest a pathway from FOAK to NOAK costs for advanced technologies**



Cost estimates based on expert elicitations

Example of Expert Elicitations to Estimate Parameter Values



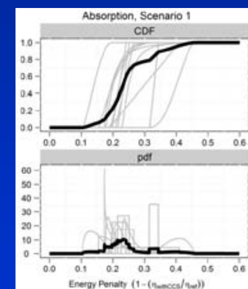
One of four amine system parameters estimated by experts and used to calculate expected cost reductions from advanced solvents (below)

Table 5
Expected reduction in cost by 2015 relative to current baseline capture systems

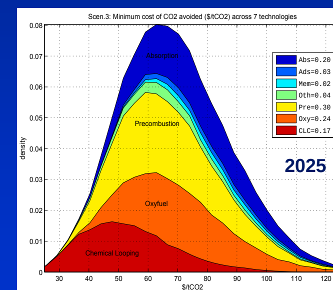
Parameter	Expected cost reduction based on	
	"Best estimate" future judgments (%)	"Most optimistic" future judgments (%)
Capital Cost ($/kW$_{gross}$)[a]	**6** [−2 to 9]	**16** [7–19]
Cost of Electricity ($/MWh)[b]	**18** [−8 to 29]	**35** [20–37]
Cost of CO_2 Avoidance ($/t$CO_2$)[c]	**18** [−8 to 30]	**36** [21–38]

Example of Expert Elicitations to Estimate Technology Costs

Elicitations by Nemet et al. of future energy penalty and avoidance cost for seven capture technologies as a function of three policy scenarios



Source: Jenni, K.E., Baker, E.D., Nemet, G.F. (2013). IJGGC, 12, 136-145.



Source: Nemet, G.F., Baker, E., Jenni, K.E. (2013). Energy, 56, 218–228.

Don't say

(and don't ask)

Avoid Cost Estimates for Processes at Early Stages of Development

- This approach uses performance metrics (such as the process energy penalty) to evaluate and screen novel components or process designs in the early stages of development
  - No guarantee, however, that improvements in these performance metrics will necessarily result in lower overall cost for an advanced technology

So where does this leave us ?

Recommendation

Use a combination of the methods above to improve cost estimates for advanced processes:

- At the earliest stages: “Don’t say”
- As data-supported process designs emerge, employ conventional methods ***appropriately***
- Characterize uncertainty using accuracy estimates or probabilistic methods to estimate FOAK plant costs
- Use expert judgments as needed for the above
- Employ learning curves (carefully) to estimate NOAK costs as a function of future deployment

A Final Word of Wisdom

“It’s tough to make predictions, especially about the future”

- Yogi Berra

Thank You

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