ELECTRIC POWER RESEARCH INSTITUTE

Capture Technology

Abhoyjit S. Bhown

Palo Alto, CA

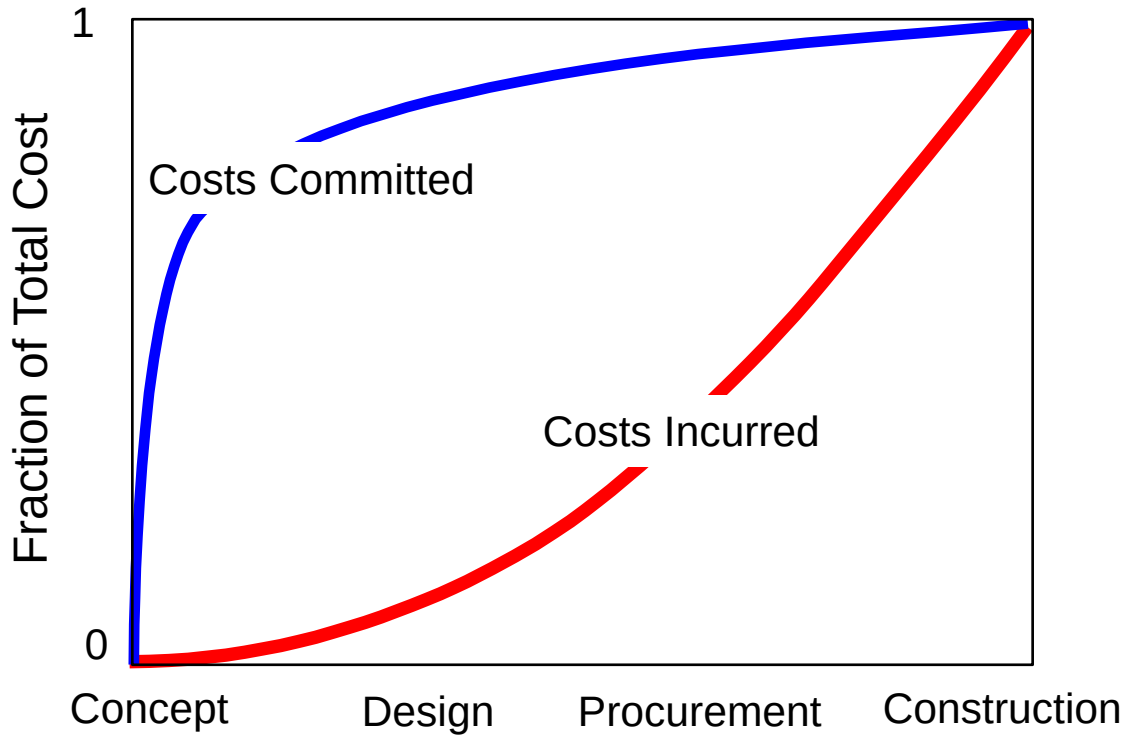
DOE Transformational Capture Technology Workshop

Arlington, VA

September 23 – 24, 2014

Estimated Cost of CCS

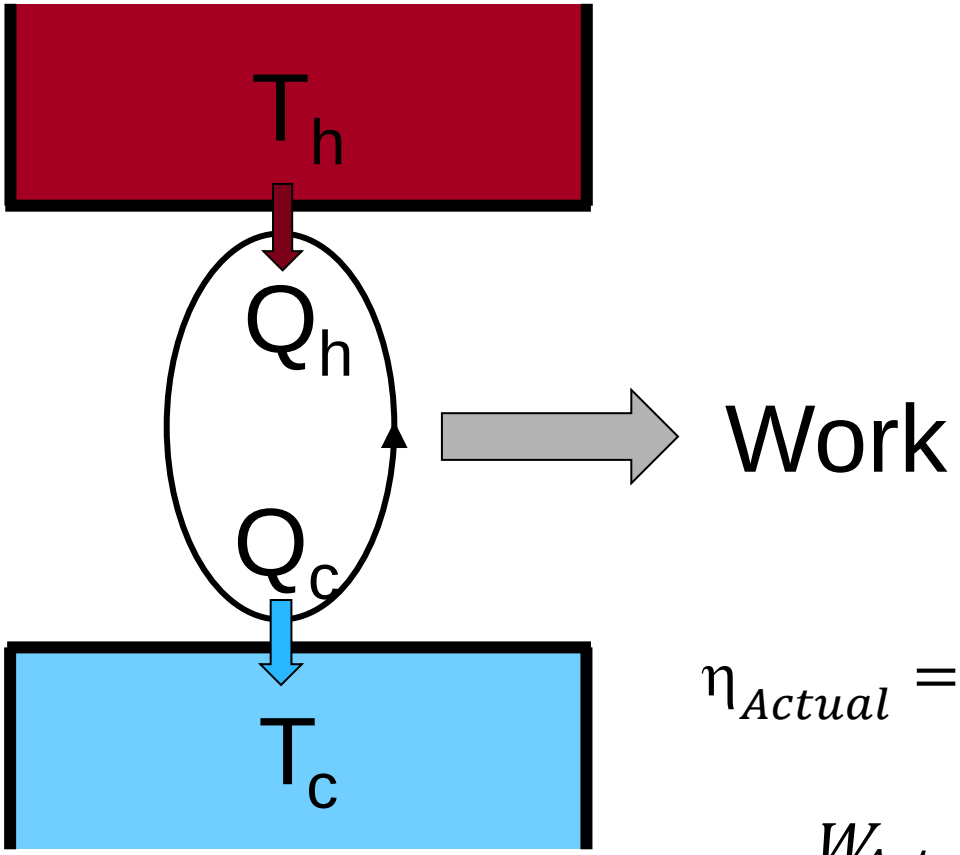
- International Energy Agency, 2013 CCS Roadmap:
  - Total investment through 2050: $3.6 Trillion for 2°C
  - Reduce emissions without CCS: $1.4 trillion more (+40%)



	$ Trillion in 2012-13
US Federal Budget	$2.8
US Deficit	$0.68
US Debt	$17.1
US GDP	$15.7
World GDP (Nominal)	$71.8
World GWP (PPP)	$85.0

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Basics – Heat and Work



$$W = Q_h - Q_c$$

$$\eta = \frac{W}{Q_h} = 1 - \frac{Q_c}{Q_h}$$

$$\eta_{Carnot} = 1 - \frac{T_c}{T_h}$$

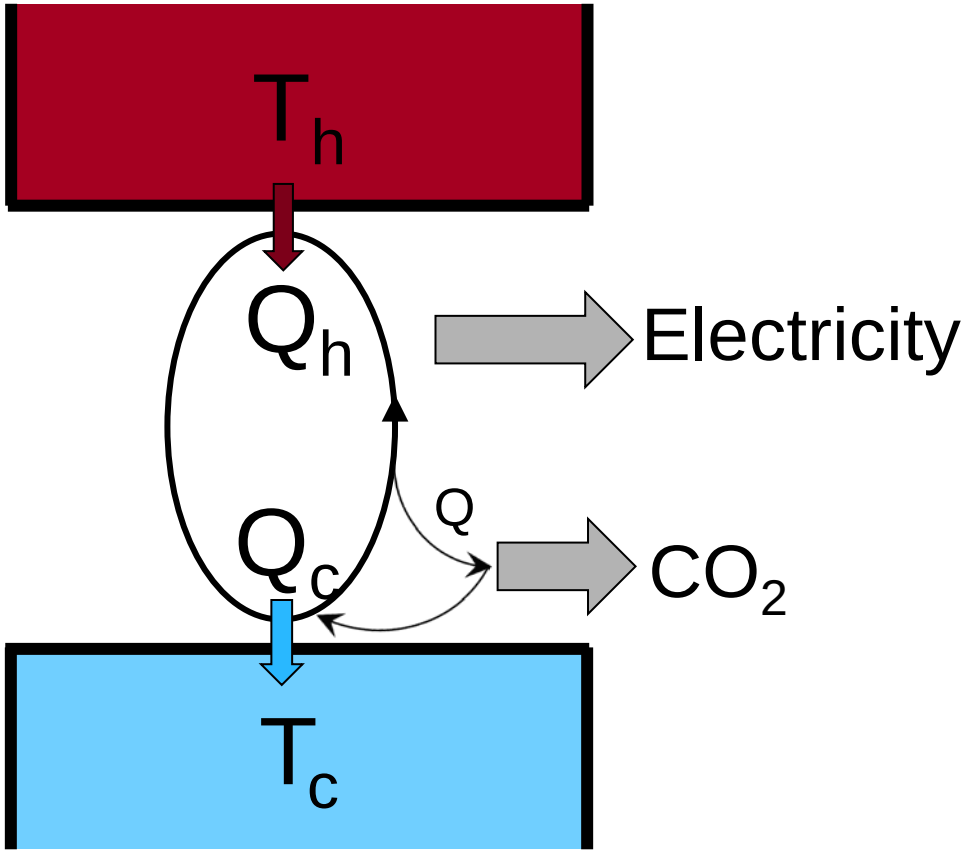
$$\eta_{Actual} = \mathrm{f}(\mathrm{T_h}, \mathrm{T_c}, \mathrm{losses}) < \eta_{Carnot}$$

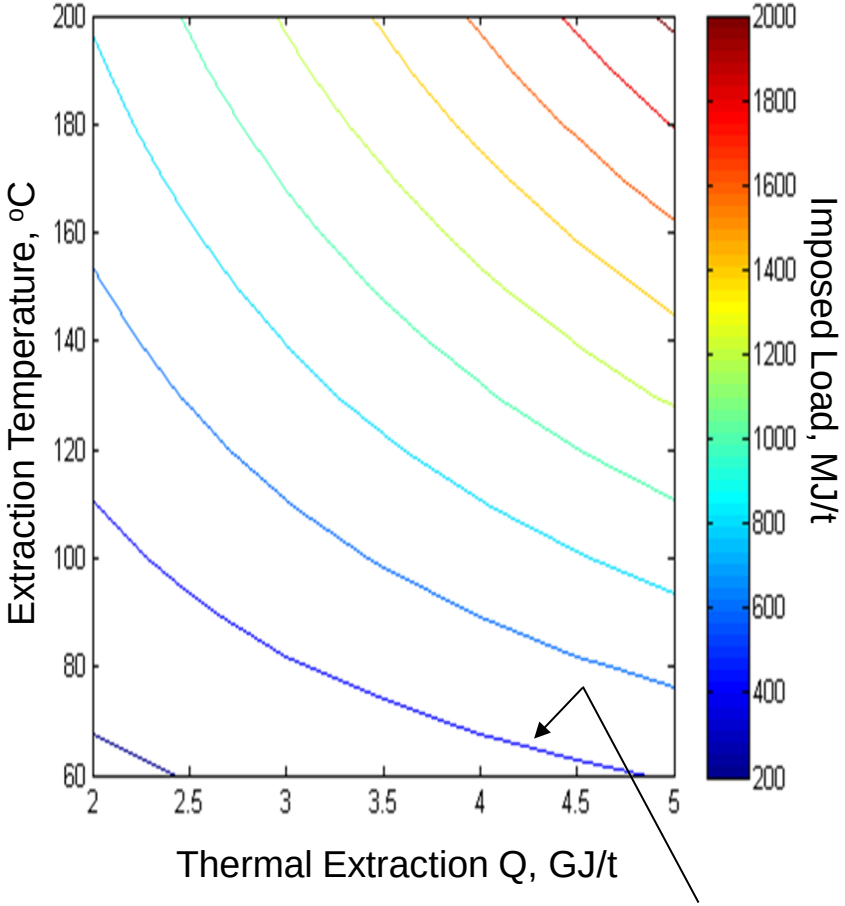
$$W_{Actual} = \mathrm{f}(\mathrm{T_h}, \mathrm{T_c}, \mathrm{losses}) Q_h$$

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Generate Electricity and Separate CO_2
Both are work derived from same cycle



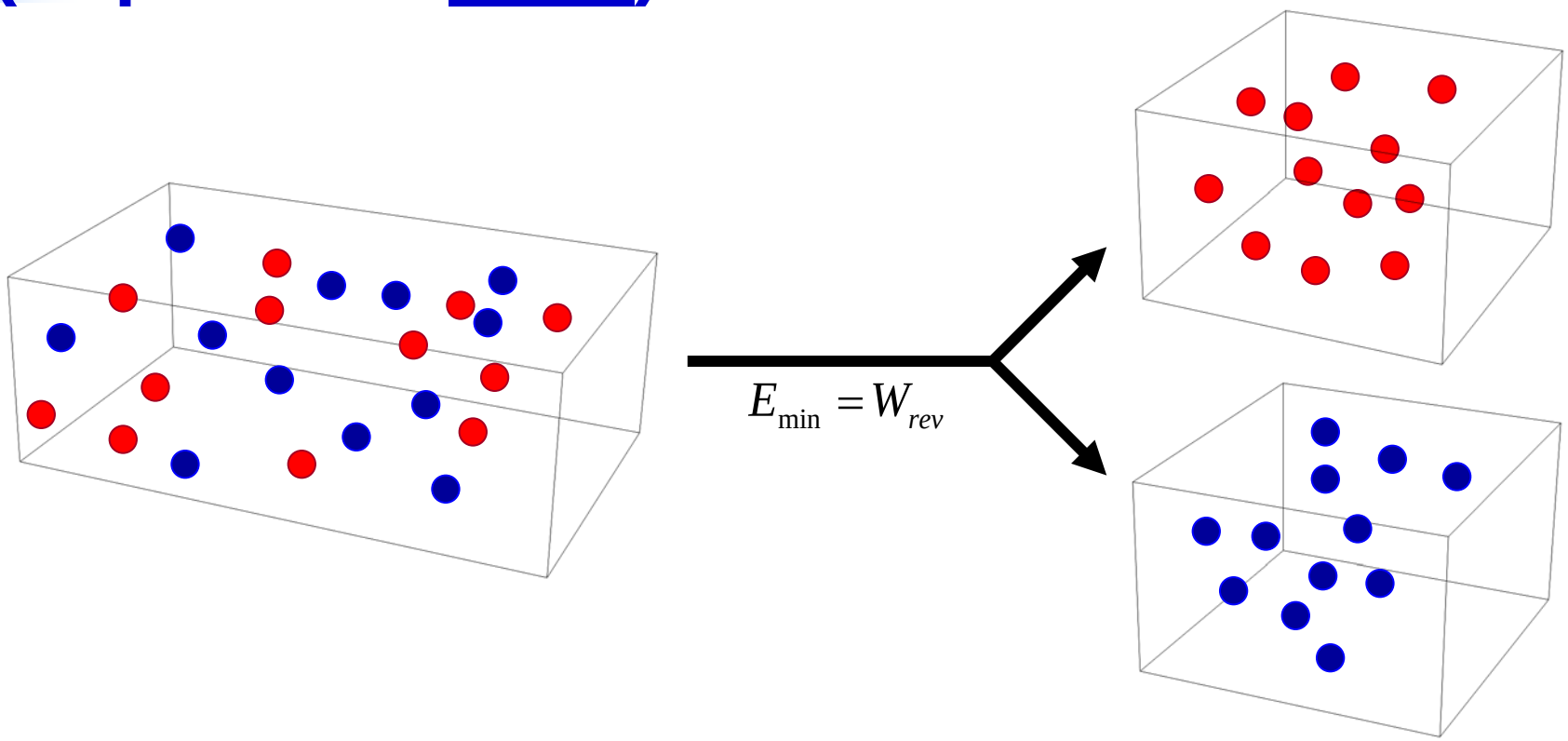


Q = 2 GJ/t @ 110°C imposes the same load as Q = 5 GJ/ton @ 60°C

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Thermodynamic Minimum Work (Separation work)



$$E_{\min} = \Delta G_{mix} = -T\Delta S_{mix} = -RT\sum_i x_i \ln x_i = -RT\left[x_{CO2}\ln x_{CO2} + \left(1 - x_{CO2}\right)\ln\left(1 - x_{CO2}\right)\right]$$

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Work for CO_2 Capture and Compression

2009 US Coal Fleet Average 25.2 t CO_2/day/MWe

Assumed 13% CO_2 flue gas at 40°C

	Capture 90%	Compression 140 bar	Total
Minimum Energy	0.161 GJ/t	0.245 GJ/t	0.406GJ/t
Minimum Load	~4.2%	~7.1%	~11.3%
Readily Achievable	17%-22%	9%-10%	25%-30%
Current Multiple	5x-6x	1.4x-1.5x	2.2x-2.8x

© 2014 Electric Power Research Institute, Inc. All rights reserved.

How can Thermodynamic Minimum Work be Actually Achieved?

- Thermodynamic minimum work is achieved when process is reversible
- In <u>any</u> separation, this means apply an infinitesimally small driving force

$$J_i = k_i A \overbrace{(c_i - c_i^*)}^{\text{driving force}}$$

Total Flux, mol/s

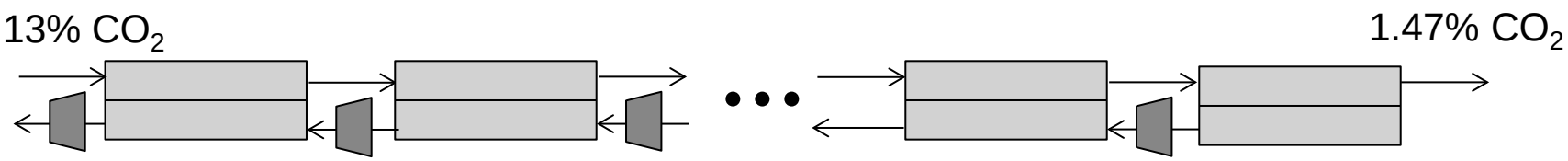
Transport Coefficient, m/s

Area for Mass Transfer, m^2

Concentration, mol/m^3

Concentration at Equilibrium, mol/m^3

- For flux>0, need infinite stages, infinite area… infinite capital



© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

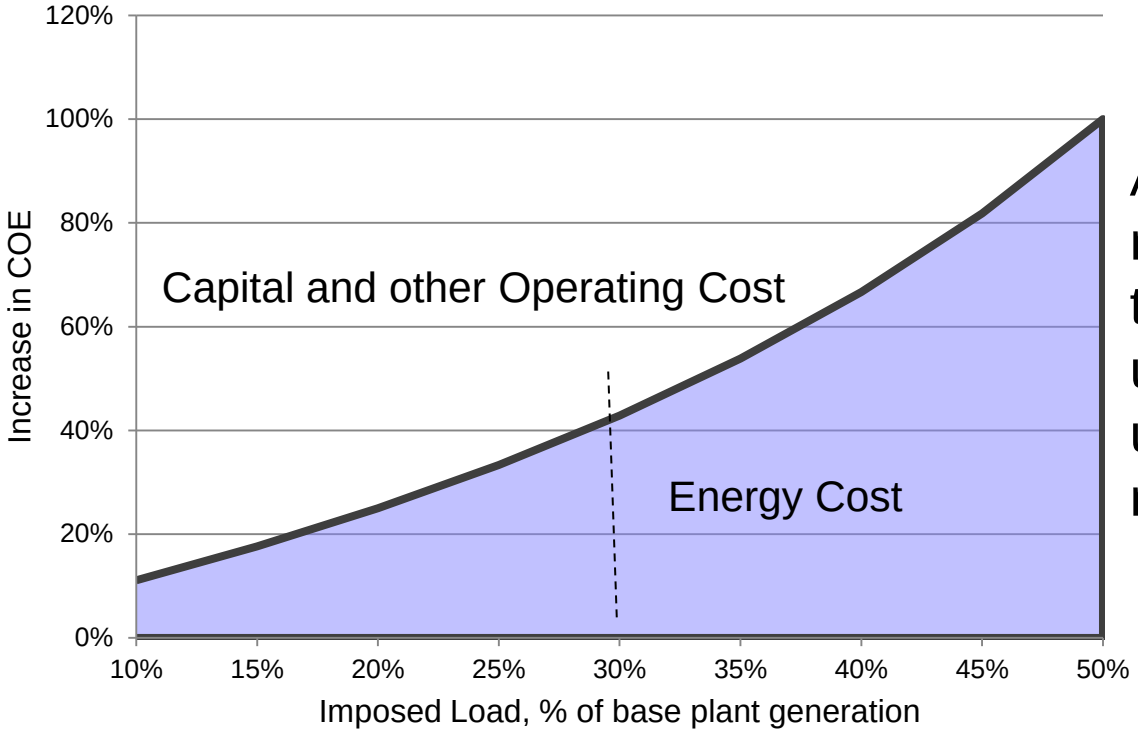
Trade off Operating and Capital Cost

- There is no inherent energy advantage of one separation technology over another: each one can achieve thermodynamic minimum using infinite hardware
- Trade off between energy cost (operating) and hardware cost (capital) – an economic decision
- For power plants, Cost of Electricity of late-stage carbon capture technologies, such as aqueous amines, is dominated by energy consumption
- Hence, for carbon capture, the initial focus is on reducing energy consumption. This is not true for separations in other applications.

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Why Focus on Energy Consumption?

Imposing a load that reduces a base plant's generation by a 30% automatically increases the cost of electricity by 43%, worse if the load has a capital and operating cost on top!



A new process that uses more energy than near-term technologies is unlikely to be competitive, unless its capital cost is much lower.

© 2014 Electric Power Research Institute, Inc. All rights reserved.

ELECTRIC POWER RESEARCH INSTITUTE

Energy Consumption is Easier to Calculate (Fortunately)

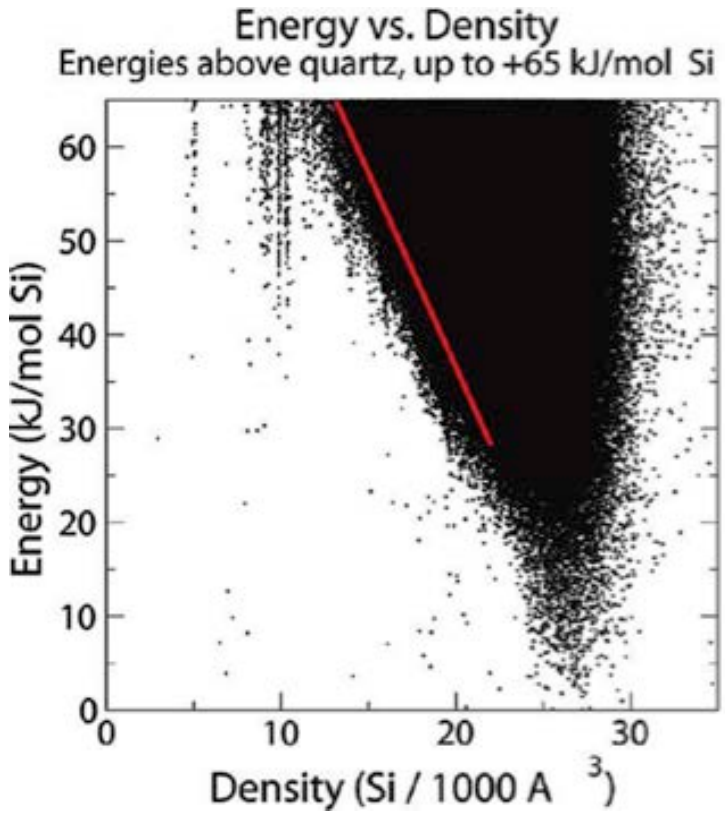
- Energy Consumption
  - For equilibrium-based separations, primarily dependent on thermodynamics
  - For rate-based separations, primarily dependent on transport properties and hardware efficiency
  - Straight forward to calculate lower bound
- Capital Cost
  - Primarily dependent on hardware size and its cost
  - More difficult to calculate since it depends on rates, e.g., chemical kinetics, transport coefficients, etc.
- Cost of Electricity
  - Even more difficult to calculate since it depends on economic assumptions in addition to technical assumptions

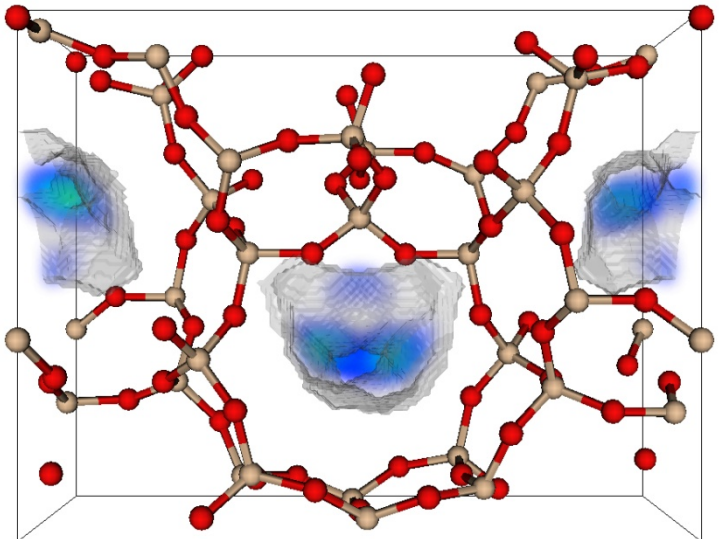
© 2014 Electric Power Research Institute, Inc. All rights reserved.

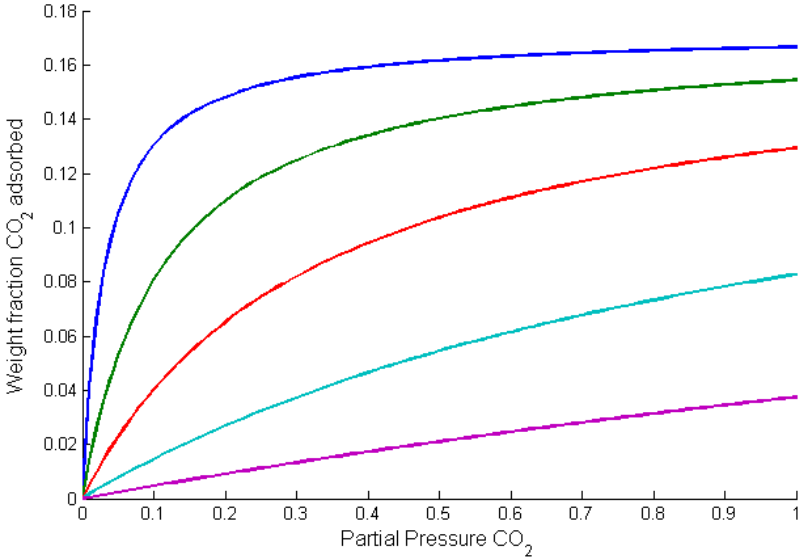
Screening of Zeolites as Adsorbents

Hypothetical zeolites

~4 million unique structures were enumerated



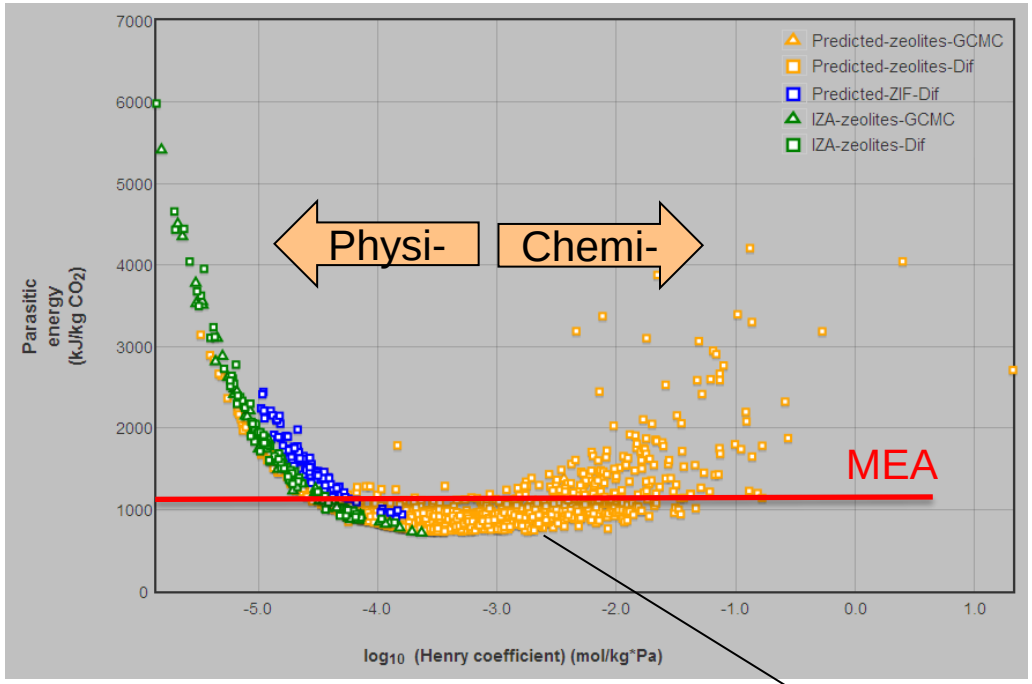




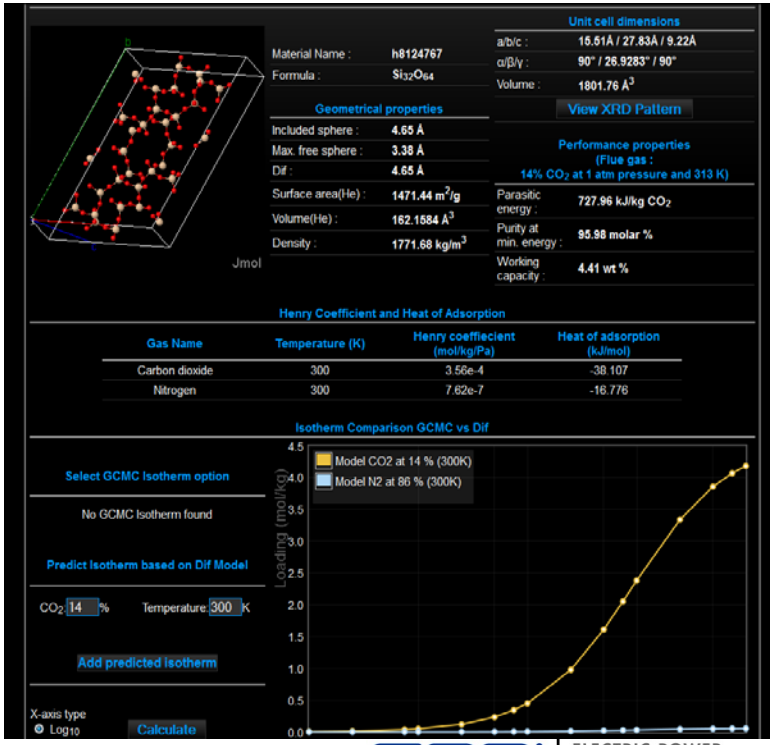
Deem et al. *J. Phys. Chem. C.* 2009, *113*, 21353.

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Adsorbents (BES/EFRC, ARPA-E, EPRI) UC Berkeley, LBNL, Rice U, EPRI



- Rapidly calculate properties and least imposed load for each material
- Predicted ~30% lower imposed load than MEA possible



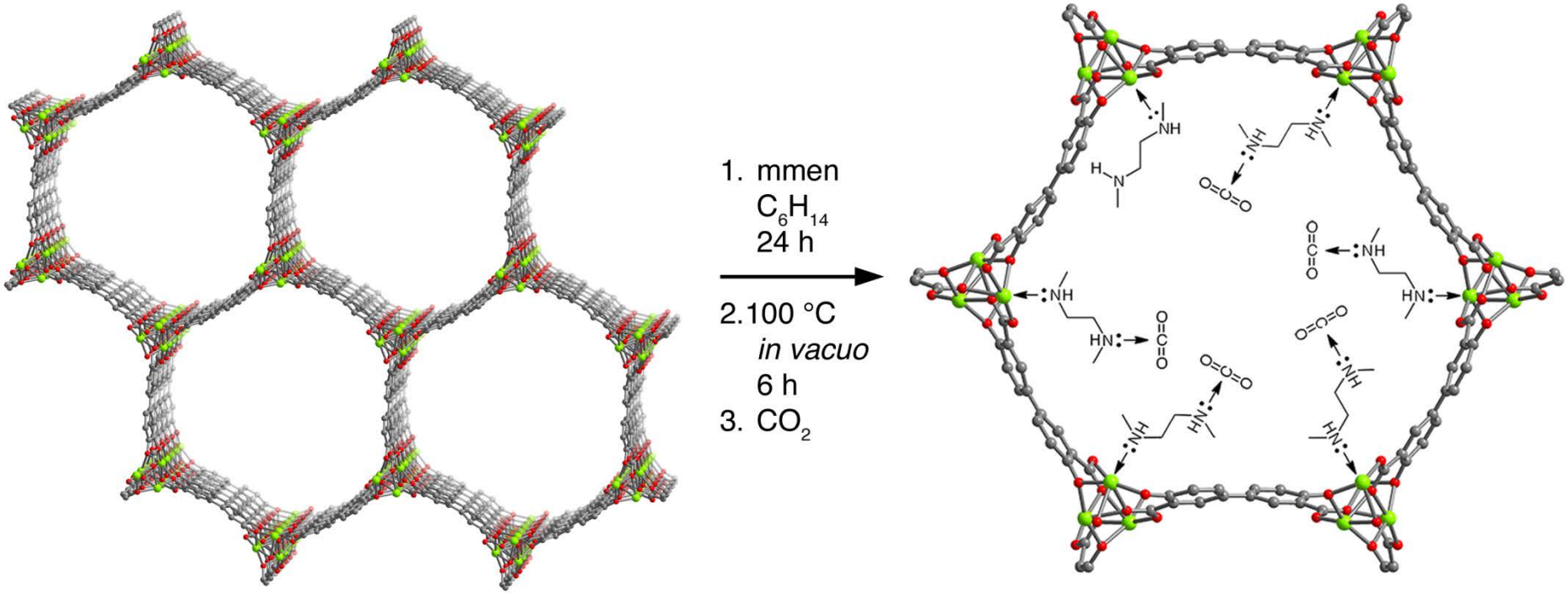
- Very broad minimum; thousands of promising new compounds identified
- $2x10^{-4}$ < Henry's Coefficient < $2x10^{-3}$
- No single defining characteristic
- www.carboncapturematerials.org

Lin et al., Nature Materials, 11, 633 (2012)

© 2014 Electric Power Research Institute, Inc. All rights reserved.

EPRI ELECTRIC POWER RESEARCH INSTITUTE

Amine-appended Metal Organic Frameworks UC Berkeley, ADA-ES, EPRI (ARPA-E)



Mg_2(dobpdc)

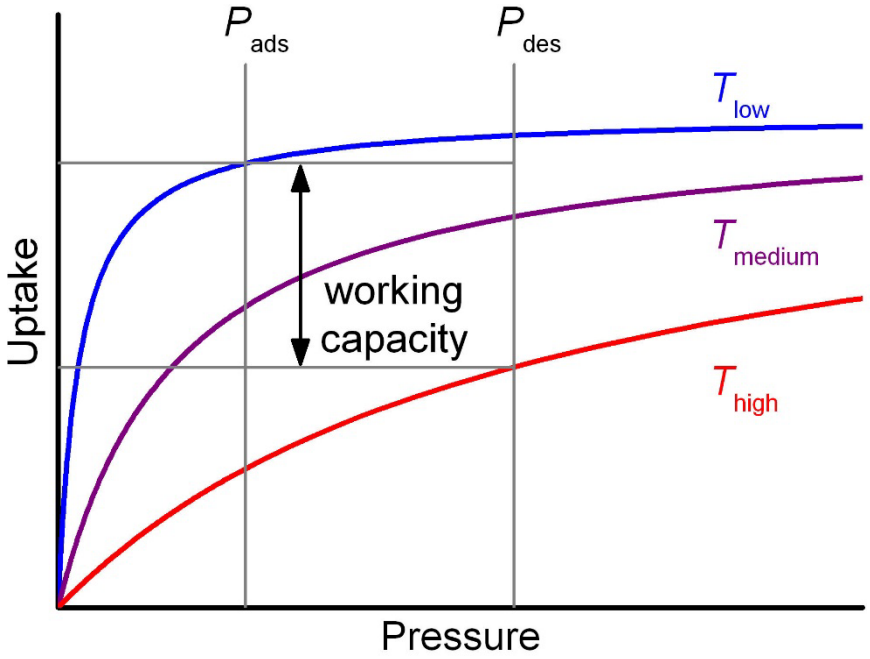
mmen-Mg_2(dobpdc) + CO_2

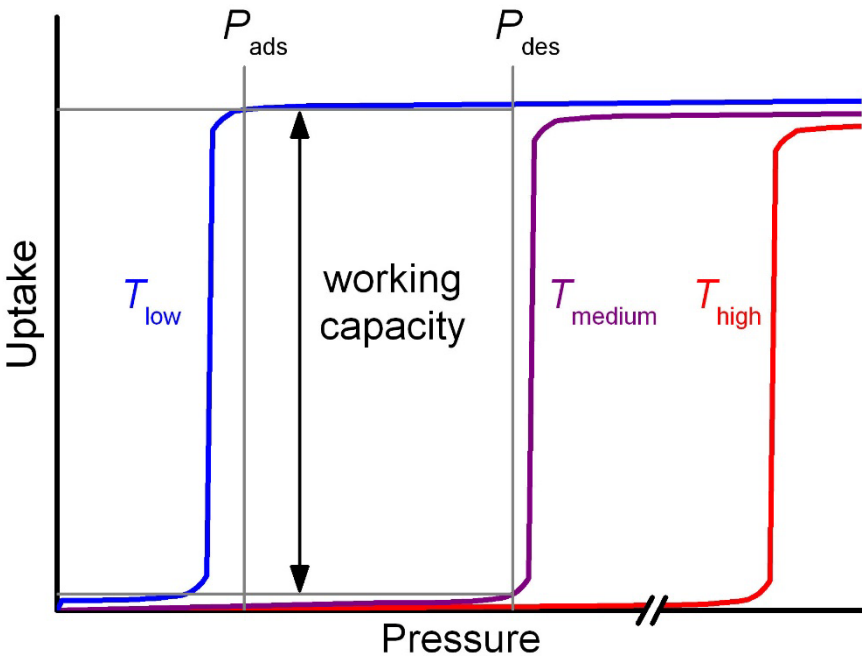
McDonald, Lee, Mason, Wiers, Hong, Long *J. Am. Chem. Soc.* **2012**, *134*, 7056

Courtesy of J. Long, UC Berkeley

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Amine-appended MOFs
Isotherms Analogous to Phase-Change

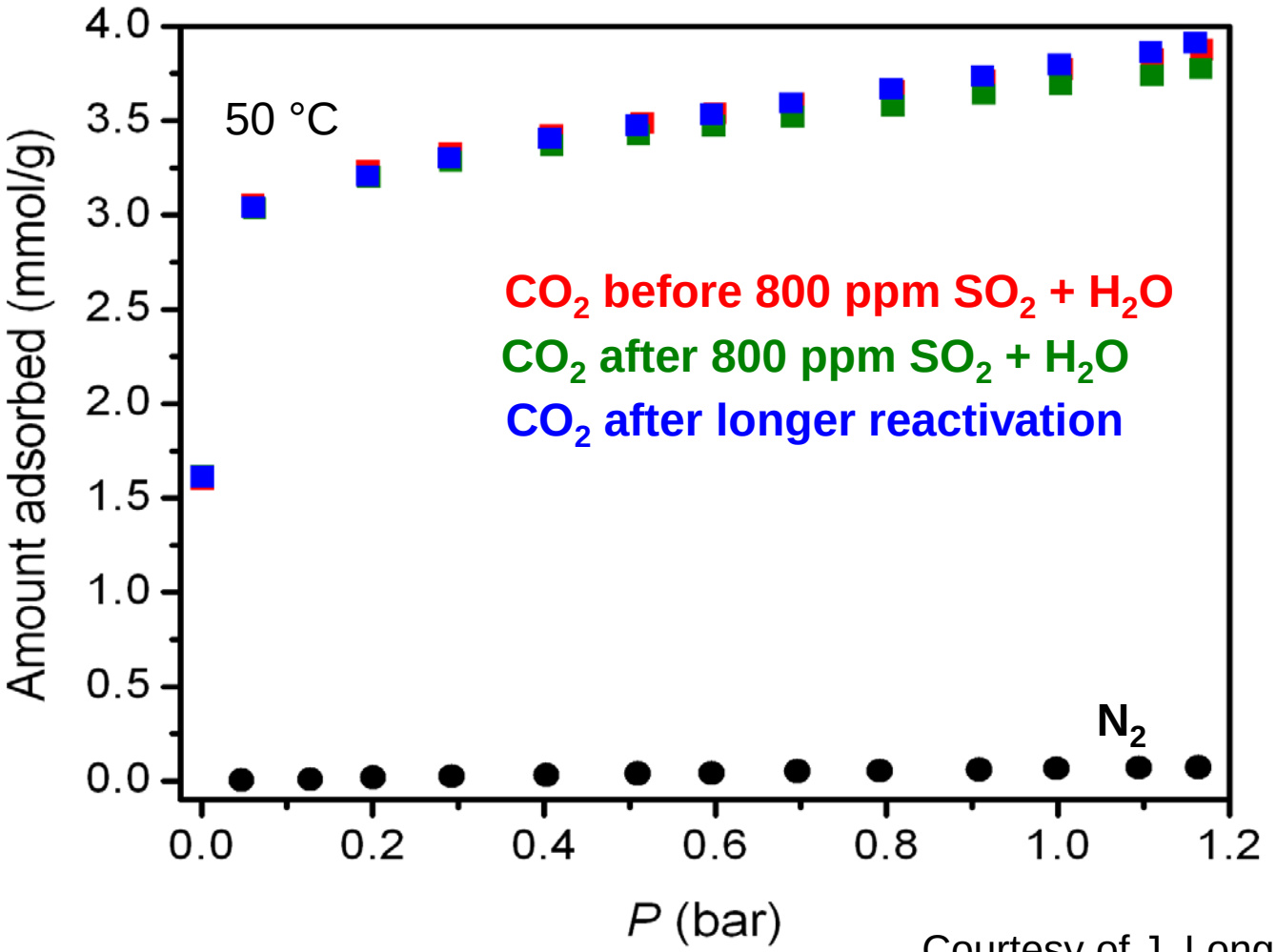




- Working capacity of ~13 wt% with temperature swings $\Delta T \leq 50\ ^{o}C$
- Current focus is to lower transition temperature and scale-up to ~kg

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Amine-appended MOFs Stable to SO_2, H_2O



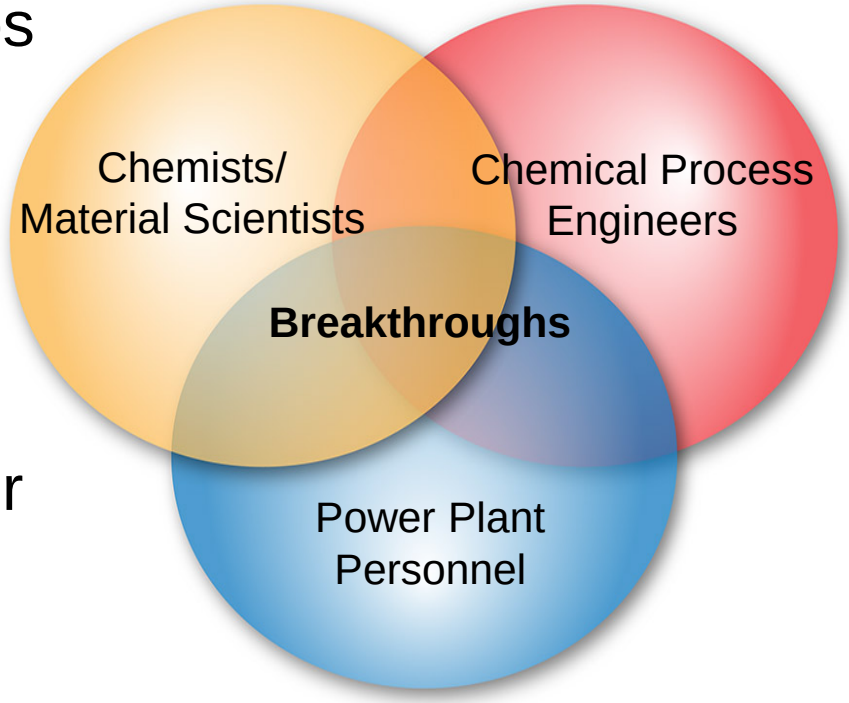
Courtesy of J. Long, UC Berkeley

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Zeolites and MOFs Thus Far…

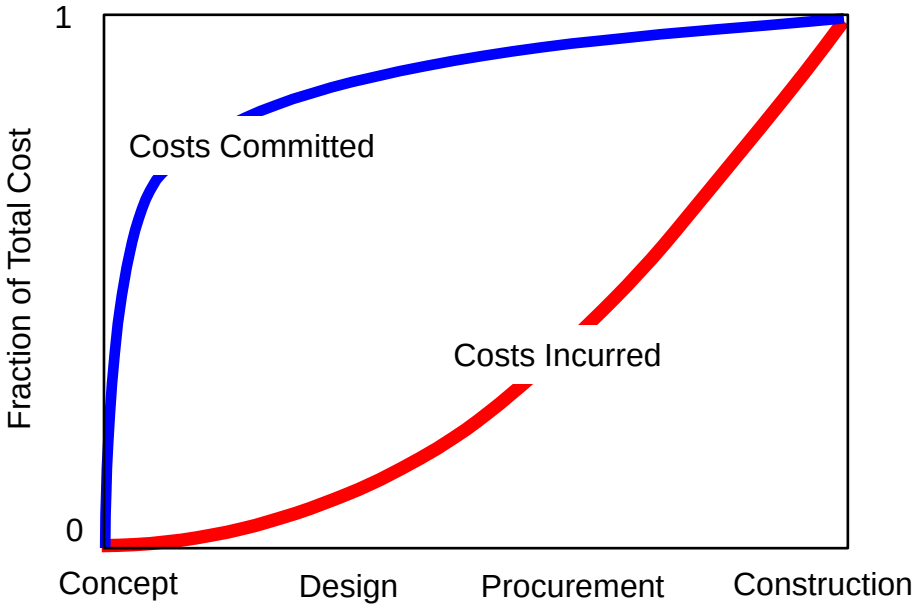
- U.C. Berkeley
- Rice University
- Lawrence Berkeley National Labs
- EPRI
- ADA-ES

- Basic Energy Sciences
- Energy Frontier Research Center
- ARPA-E
- EPRI
- Cost-share from all collaborators



© 2014 Electric Power Research Institute, Inc. All rights reserved.

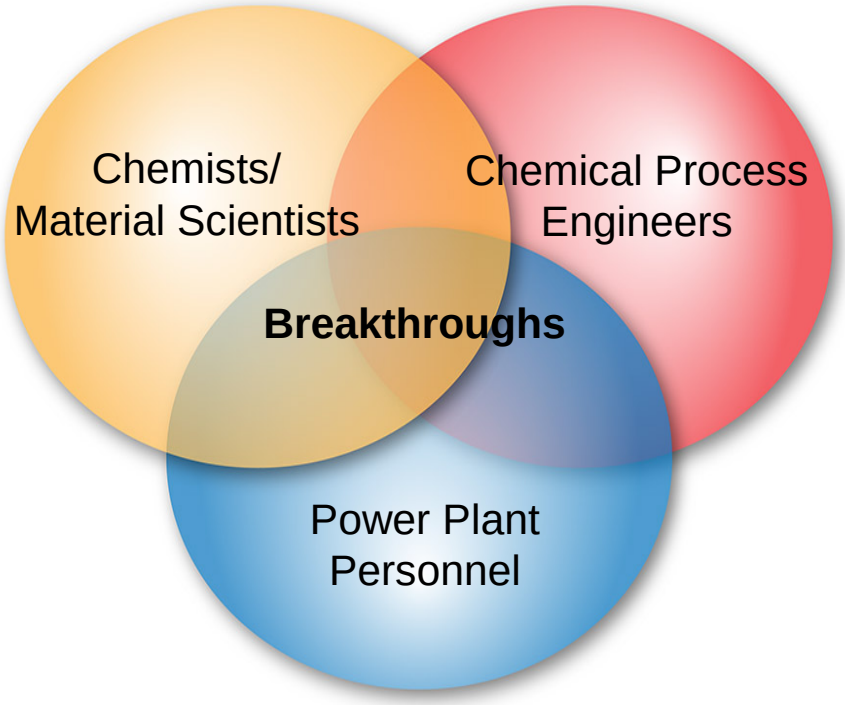
Closing Comments



- Time is running out
  - Anthropogenic emissions keep rising
- At higher TRLs, scale-up cost-effective least risky technologies now
  - Offer best chance of controlling emissions
- Keep working on more promising technologies
  - R&D inexpensive relative to large-scale deployment

© 2014 Electric Power Research Institute, Inc. All rights reserved.

Together…Shaping the Future of Electricity



© 2014 Electric Power Research Institute, Inc. All rights