Direction of CO_2 Capture R&D at EPRI

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Palo Alto, CA

NETL CO_2 Capture Technology Meeting

Pittsburgh, PA

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EPRI Overview

Mission

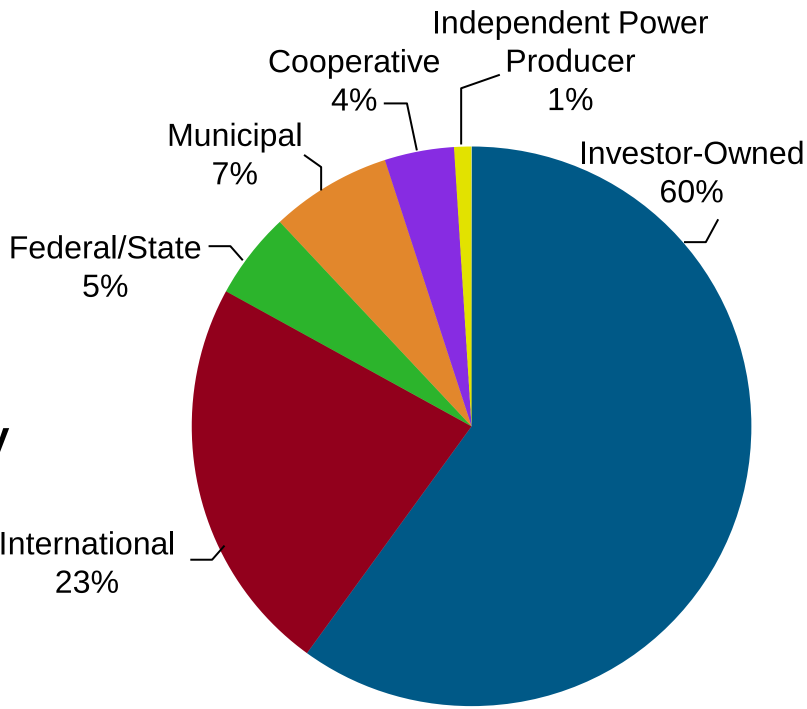
To conduct research, development, and demonstration on key issues facing the electricity sector on behalf of our members, energy stakeholders, and society

Members

450+ participants in more than 30 countries

EPRI members generate approximately 90% of the electricity in the United States

Total revenue ~$390 M/year



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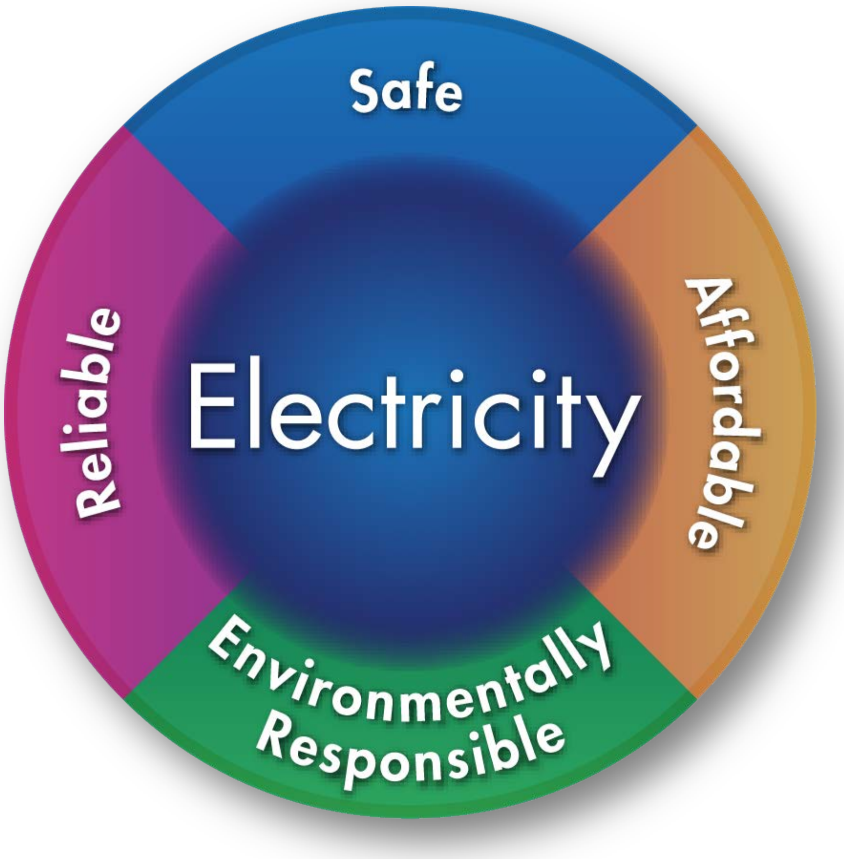
Three Key Aspects of EPRI

Independent
Objective, scientifically based results address reliability, efficiency, affordability, health, safety and the environment

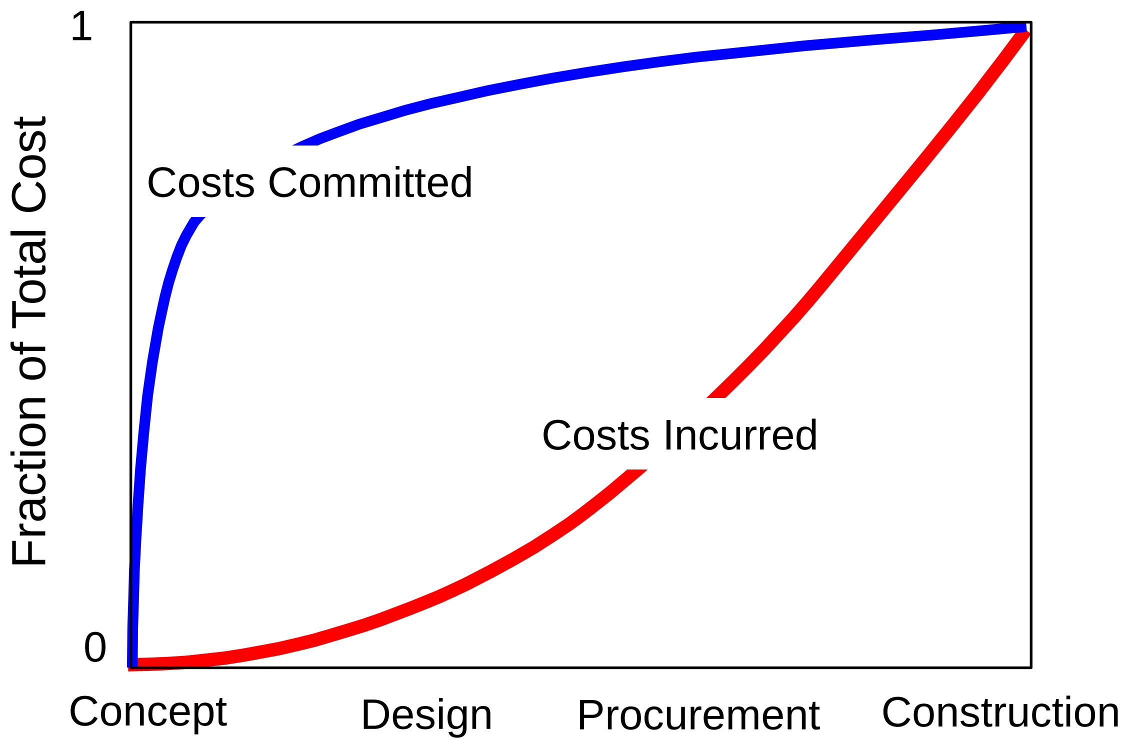
Nonprofit
Chartered to serve the public

Collaborative
Bring together scientists, engineers, academic researchers, industry experts



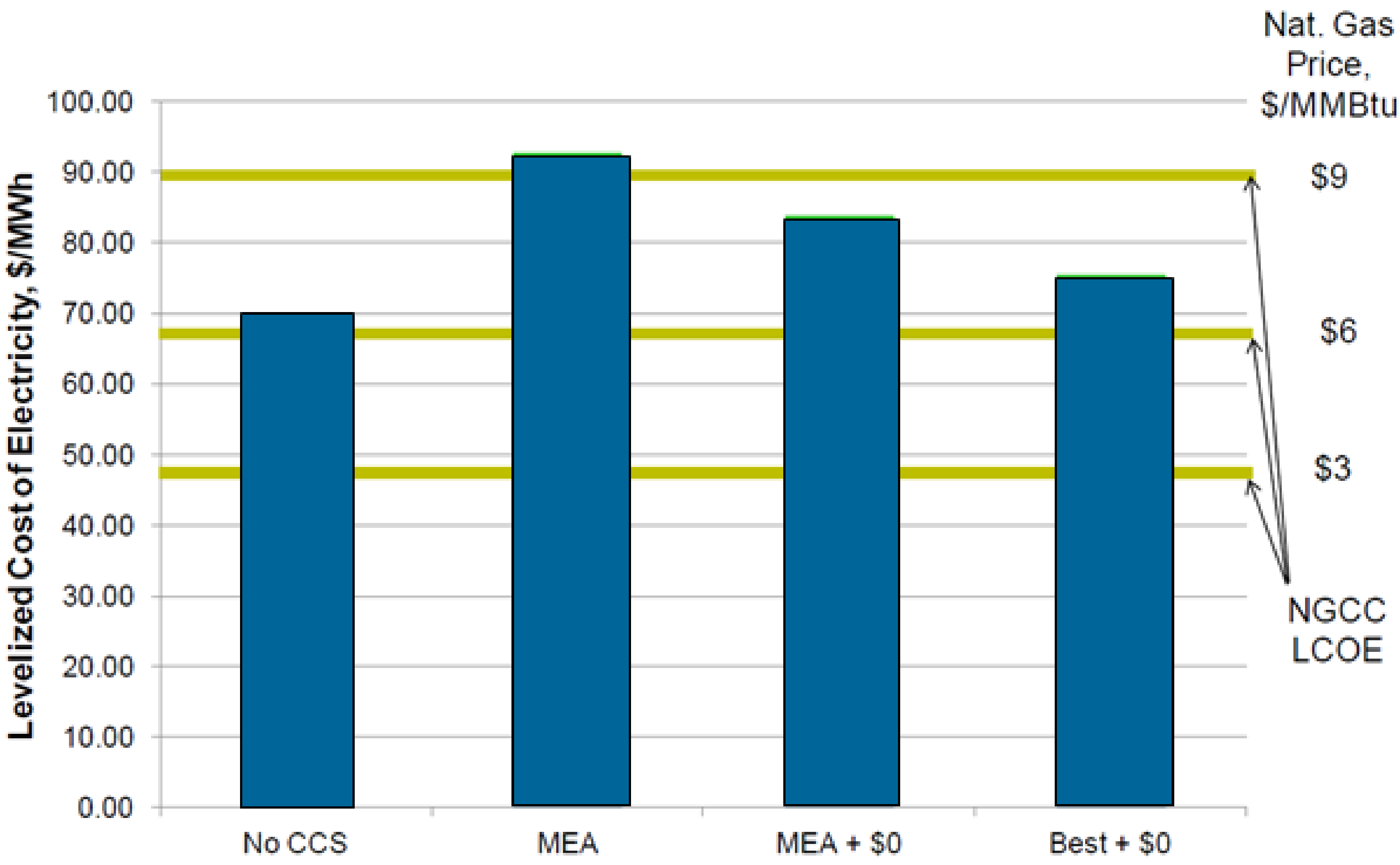
Estimated Cost of CCS

- 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

Impact of CO_2 Emission Standards for New US USC Coal Power Plant



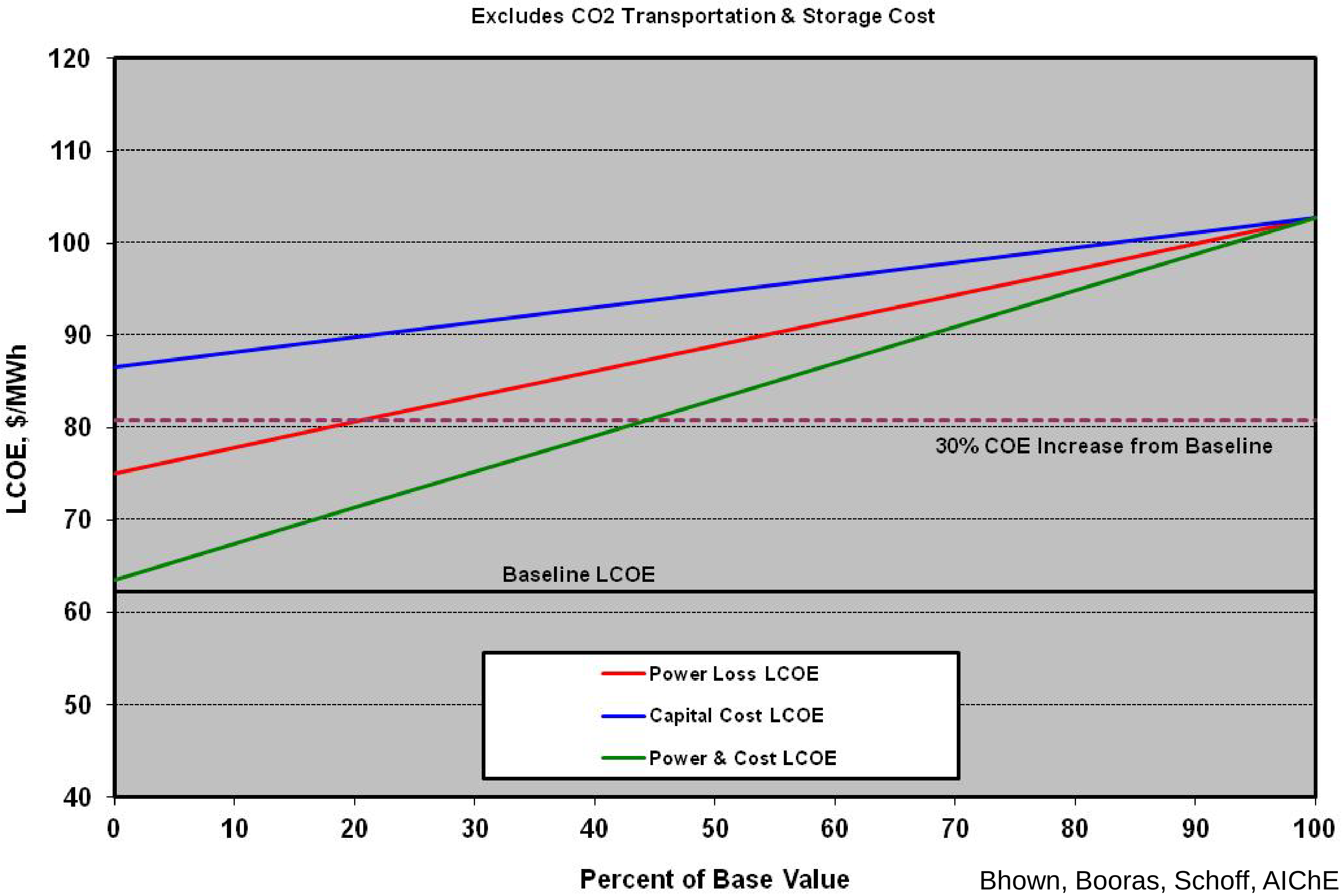
CO_2 Capture Cost vs Current Markets

Application or Market	$/tonne
Capture Technologies*	
Generic amine retrofit to existing coal plants	60-90
Chilled Ammonia on new coal plant	58-68
Advanced amine on new coal plant	68
Advanced amine on NGCC	81-95
CO_2 Markets	
Regional Greenhouse Gas Initiative	4-5
European Trading Scheme	7-7.5
California Carbon Allowance	11-12
Enhanced Oil Recovery	25-35

* Costs based on recent EPRI studies, excludes cost of storage & transport

CO_2 Capture Costs Currently 2x to 20x > What Markets Are Paying

Late-Stage Technologies: Power Loss Dominates CCS Cost



Bhown, Booras, Schoff, AIChE (2012)

Energy for CO_2 Capture and Compression

Assumed 25.2 t CO_2/day/MWe

~13% CO_2 flue gas at 40^{o}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

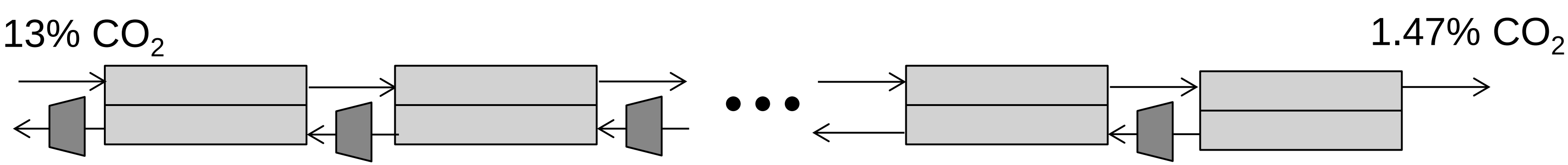
How can Thermodynamic Minimum Work be Actually Achieved?

- Thermodynamic minimum work is achieved when process is reversible
- In separations, this means apply an infinitesimally small driving force

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

- J_i: Total Flux, mol/s
- k_i: Transport Coefficient, m/s
- A: Area for Mass Transfer, m^2
- c_i: Concentration, mol/m^3
- c_i^*: Concentration at Equilibrium, mol/m^3

- For J_i>0 and finite k_i, need infinite stages and infinite area



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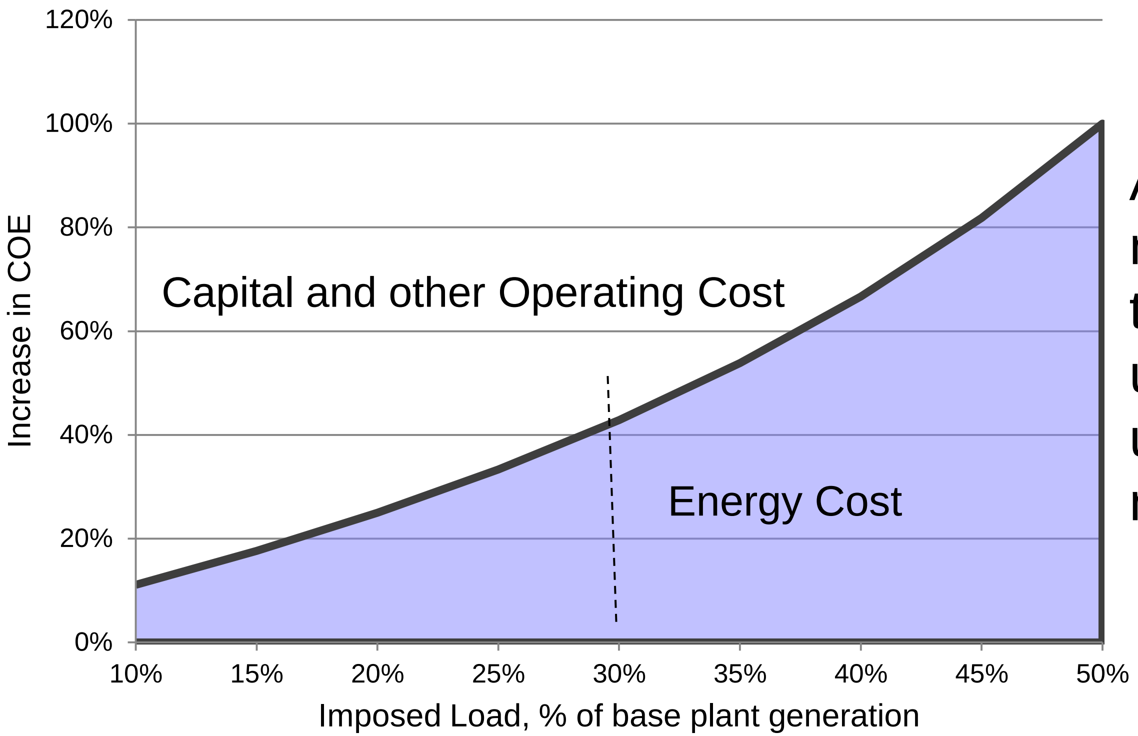
Trade off Capital vs. Operating Cost

- There is no inherent energy advantage of one separation technology over another: each one can achieve thermodynamic minimum energy using infinite hardware
- Must balance benefit of smaller hardware (capital) vs. cost of wasted energy (operating), leading to technology selection based on optimal economics
- 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 other separations applications.

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!

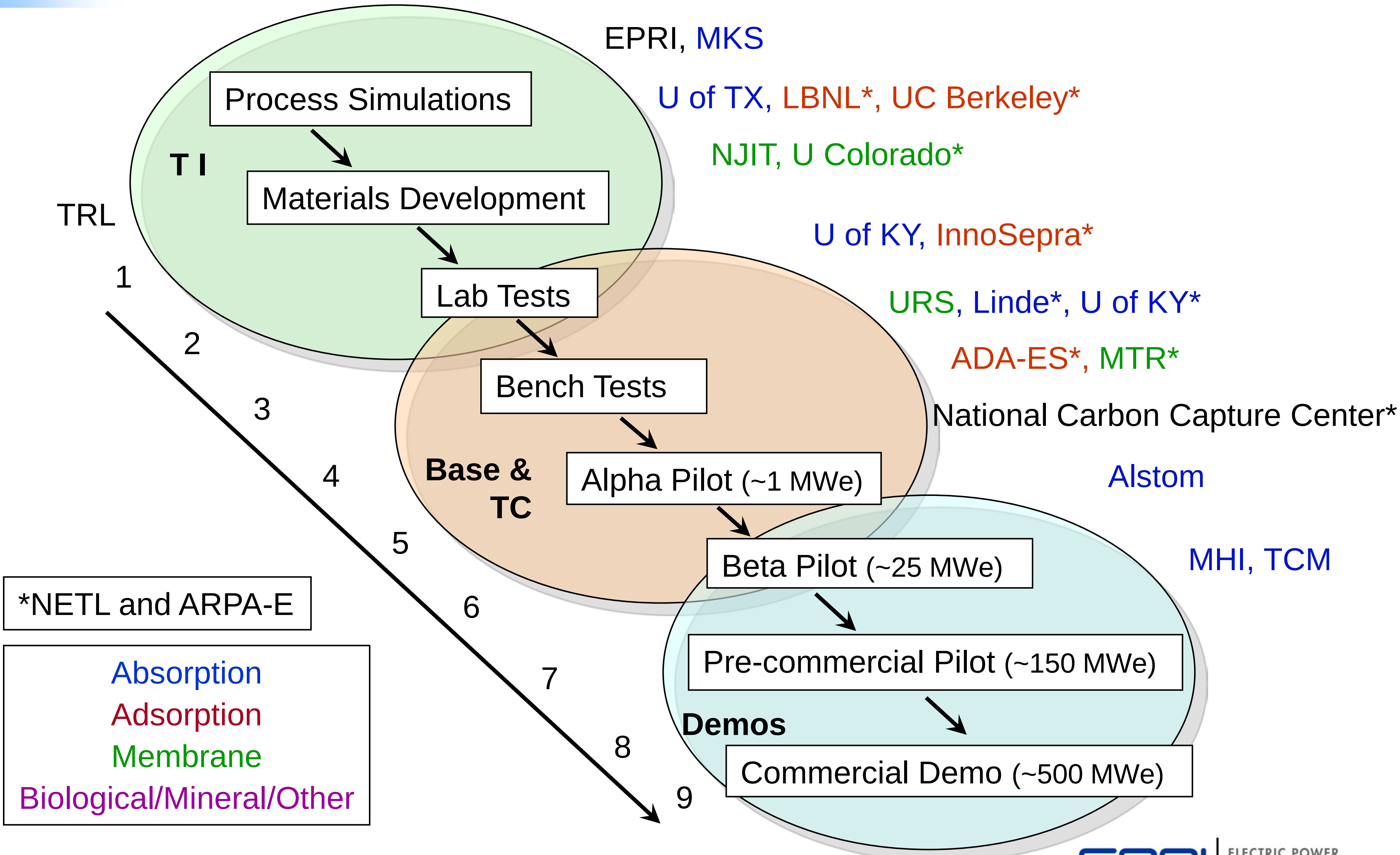


A new process that uses more energy than near-term technologies is unlikely to be competitive, unless its capital cost is much lower.

Energy Consumption is Easier to Calculate

- 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

Post-Combustion CO_2 Capture R&D at EPRI

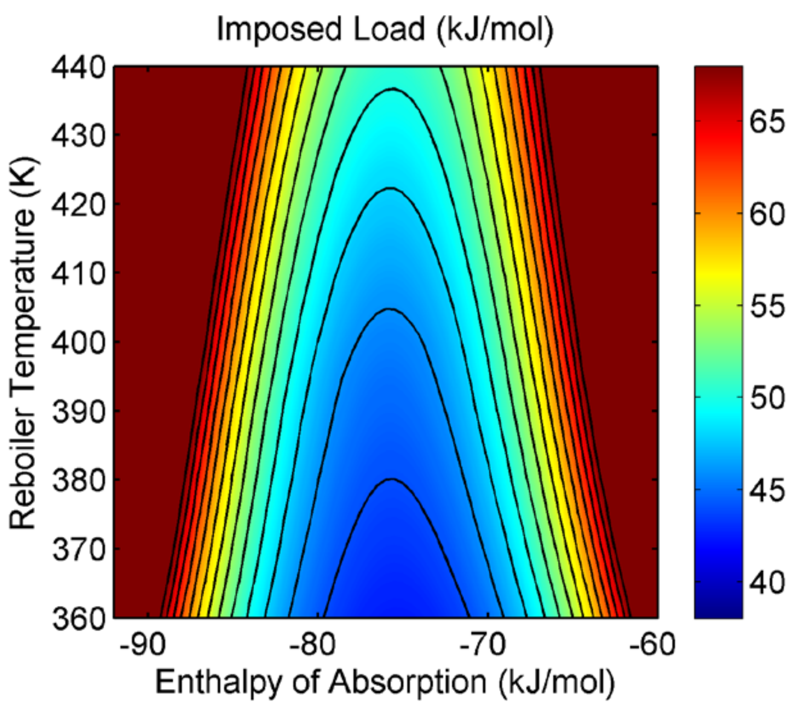


Process Simulations at EPRI
Focus on Minimizing Energy Consumption

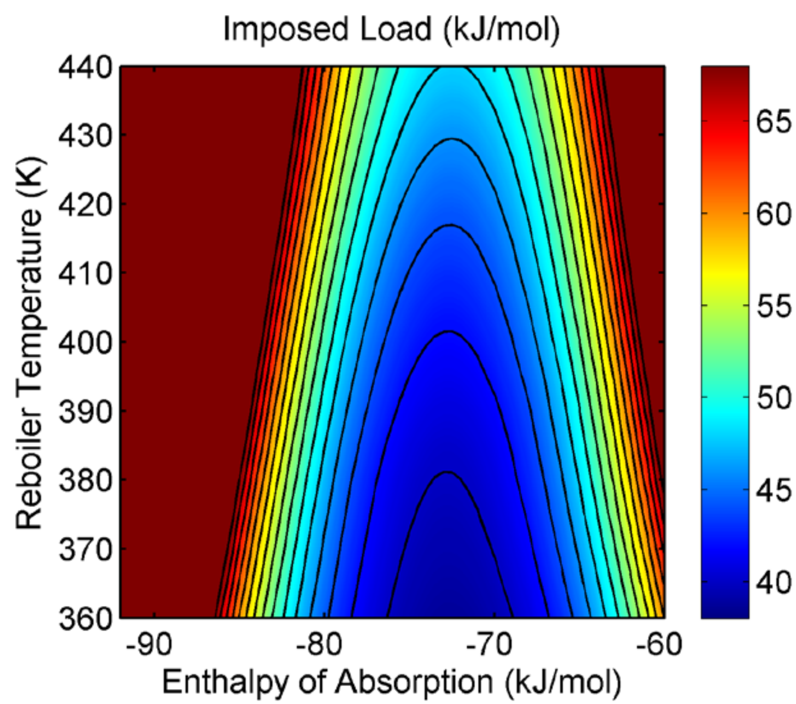
- Complete
  - Solvents, Membranes, Adsorbents, Cryogenic
  - Coal and Gas Plants
  - Include various transport models, various isotherm models, various reaction chemistries, etc.
  - Useful for guiding materials development
- On-going
  - Integration of capture systems with power plants
  - Study of hybrid systems
  - Adding transport and thermodynamic models especially for novel materials
  - Cost (large error bars for early-stage capture)
- Developing simplified correlations, heuristics, guidelines for complex behavior

Effect of Absorber Height

Finite height (P^*_{CO2} = 0.5 to 5 kPa)



Infinite height (P^*_{CO2} = 1.74 to 13.5 kPa, equilibrium for 90% capture)



- As absorber height increases:
  - Imposed load decreases some, but by at most 9% compared to the case shown on the left
  - Optimum enthalpy of desorption decreases (preferred solvent changes when system changes)

CO_2 Capture Demonstrations

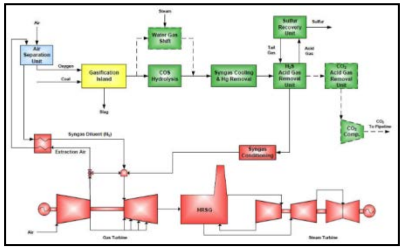
Description (Years of Operation)	Size	EPRI Role
 We Energies / Alstom at Pleasant Prairie, U.S. (2008–9) Catch-and-Release	20 tonnes-CO_2 / day (1.7 MW)	Data Collection Economics
 American Electric Power (AEP) / Alstom at Mountaineer, U.S. (2009–11) On-site Storage	100,000 tonnes-CO_2/yr (20 MW)	Data Collection Economics Monitor Storage
 EDF/ Alstom / Dow at Le Havre, France (2013–) Catch-and-Release	25 tonnes-CO_2 / day (2.2 MW)	Data Collection Economics
 Southern / Mitsubishi Heavy Industries (MHI) at Plant Barry, U.S. (2010–) Transport and Storage	500 tonnes-CO_2 / day (25 MW)	Data Collection Economics Lead Storage
 TCM DA / Aker Clean Carbon at Mongstad, Norway (2012–) Catch-and-Release, Refinery gas	500 tonnes-CO_2 / day (25 MW)	Data Collection on baseline MEA

EPRI has been involved in many of the larger-scale demos on fossil flue gas

Oxy-Combustion

- EPRI has done research on advanced cycles including both pressurized oxy and chemical looping as well as publishing several reports on oxy-combustion:
- *"Engineering and Economic Evaluation of 1300°F (700°C) Series Oxy-PC Power Plant," 1023870*
  – Presents a modeling study designed to improve heat rate and reduce costs. Using advanced ultra-supercritical steam conditions and more thermal integration between the boiler / steam cycles and the air separation and CO_2 processing units improved both the capacity and efficiency of oxy plants.
- *"Oxy-Combustion Activities Worldwide,"* 3002000763
  – Provides a review of oxy-combustion development activities and updates on oxy-combustion projects worldwide

IGCC



- Detailed engineering-economic feasibility study of IGCC power plants with partial CO_2 capture
  - To meet proposed EPA NSPS (1,100 lb CO_2/MWh gross)
- Prior series of IGCC reports were based on full capture
- Will include key gasifiers with PRB and Bituminous coals
- Includes USCPC with partial capture for comparison
  - Based on advanced amine process
- Includes updated costs for reference IGCC w/o CCS
- Detailed study report to be published December 2014

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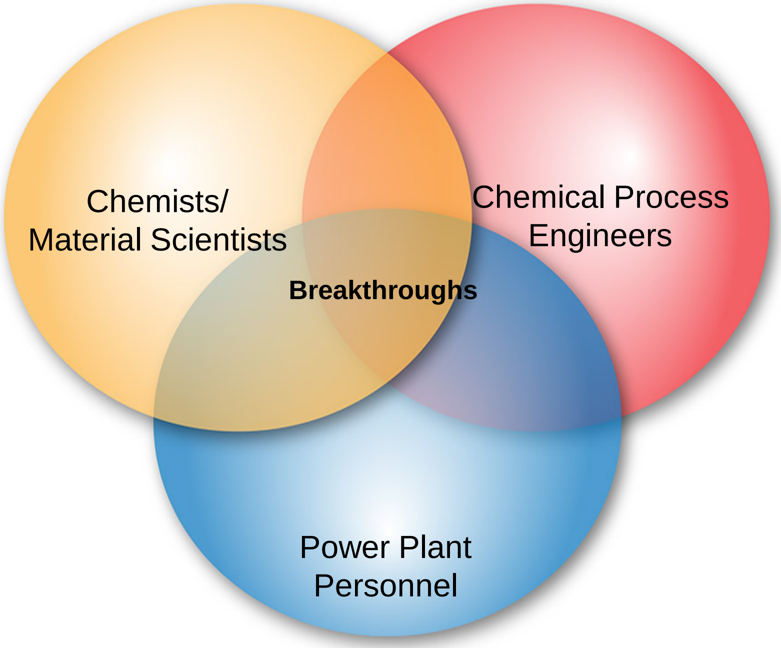
Closing Comments on EPRI's Direction



- Multi-TRL focus on CCS
- Sustained effort for early-stage technologies
- Collaborative work, not just within a discipline, but more importantly between chemists, engineers, power generators is critical to developing breakthrough technologies
- Creative and flexible approaches that are not practical today may turn out to be synergistic with one tomorrow

Together…Shaping the Future of Electricity