EPRI | ELECTRIC POWER RESEARCH INSTITUTE

CO_2 Capture and Storage for Coal-Based Power Generation

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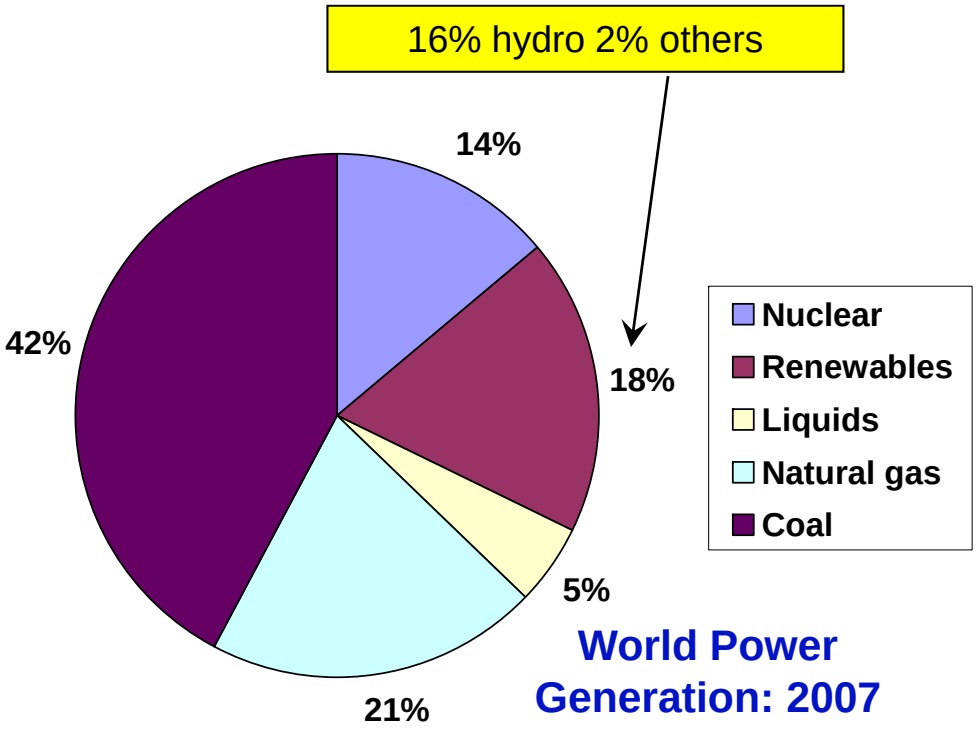
Electric Power Research Institute (EPRI)

- EPRI is an independent, non-profit organization that conducts research and development into the generation, delivery, and use of electricity.
- Member organizations generate and deliver over 90% of the electricity in the USA: international participation extends to over 40 countries.
- Broad array of collaborative research programs to help resolve the many issues facing the power industry in providing reliable, affordable, and environmentally responsible electricity. Topics covered include:
  - Environmental controls, air and water quality, climate change
  - Generation technologies, operations & maintenance, reliability
  - Transmission and distribution, end use efficiency
  - CO_2 capture and storage (CCS).
- EPRI also provides technology, policy and economic analyses to guide long-range research and development planning.

www.epri.com

Society Demands a Plentiful Supply of Low-Cost, Environmentally Responsible Electricity

- Multiple societal benefits offered by electricity
  - Lighting, heating and cooling, refrigeration, medical technology, motor drives, computers, internet, telecommunications, television, radio etc.
  - Life without electricity is inconceivable.



World Power Generation: 2007
18.8 x 10^9 MWh

- Without fossil fuels nuclear is the only mass generator.
- Unlikely renewables can supply all power required at acceptable cost.
- Diversity of supply essential to cost control.
- Everyone recognizes need to protect environment.
- The challenge is how to strike a balance between requirements.

Source: DOE-EIA International Energy Outlook 2010

Fossil Energy Usage Worldwide, and CO_2 Emitted: 2007

60% of world's CO_2 emissions do NOT come from coal.

	Energy used, Quads/yr			
	Liquids	Coal	Gas	Total
Residential/commercial	14.0	4.6	28.1	46.7
Industrial	57.6	43.1	43.2	143.9
Transportation	93.4	0.1	3.5	97.0
Power	10.2	84.5	37.3	132.0
TOTAL	175.2	132.3	112.1	419.6
CO_2 B-tonnes/yr	11.3	12.5	5.9	29.7
M-tonnes CO_2/quad	64.5	94.5	52.6	

Quad = 10^{15} Btu = 1.055×10^{15} kJ

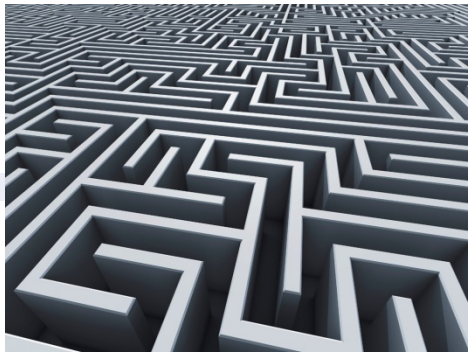
Although each fuel type and economic sector may include unique solutions, all benefit from increased efficiency.

Source: DOE-EIA International Energy Outlook 2010

The Challenge for Coal-Based Generation

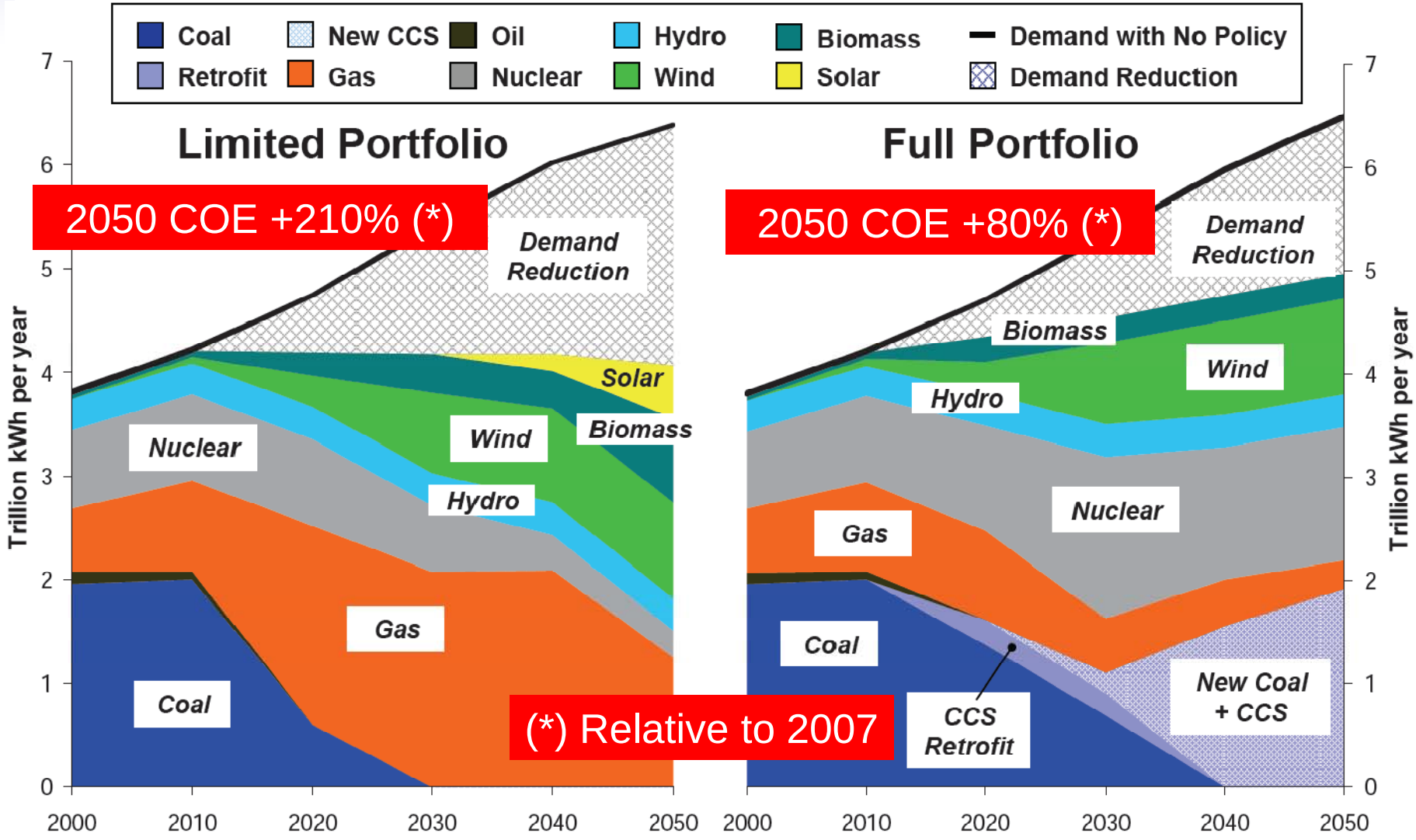
- Coal-based power has met many previous challenges and environmental controls can reduce SO_X, NO_X, mercury and particulate matter down to very low levels at acceptable cost
  - These technologies evolved over more than 40 years.
- Reducing CO_2 poses an extreme challenge: CO_2 released from internationally traded bituminous coal is ~120 times more than SO_2
  - Development has to take place in no more than 10 to 15 years.
- The EPRI-MERGE analysis identifies the economically optimum technology portfolio in response to a given CO_2 emissions constraint
  - Full Portfolio approach projected to reduce emission to ~1965 levels by 2030 and ~1905 levels by 2050: matches proposed US legislation.
- Eventually gas-fired units will also require CCS
  - Capture is more expensive than for coal and will greatly reduce the perceived cost advantage of gas over coal.

CO_2 Emissions Control is Complex



- Economic impact, political fall out
  - Jobs may be lost and trade affected
  - Less wealthy may be more affected as energy charges represent higher proportion of their income.
- Sometimes the debate is not as well informed as it should be
  - "We are going to reduce our dependency on fossil fuels by switching to natural gas", influential US law maker.
- Objections are raised for all types of new generation, not just coal:
  - "I fully support wind turbines, just not here", Nantucket
  - "The solar panel project will destroy the Mojave ecosystem", California.
- Global political decisions still to be made on climate change abatement
  - How do we as technology researchers and developers prepare for that time when it is agreed to implement CCS?

EPRI's MERGE Analysis for USA: 2009
Why Coal with CCS is Essential



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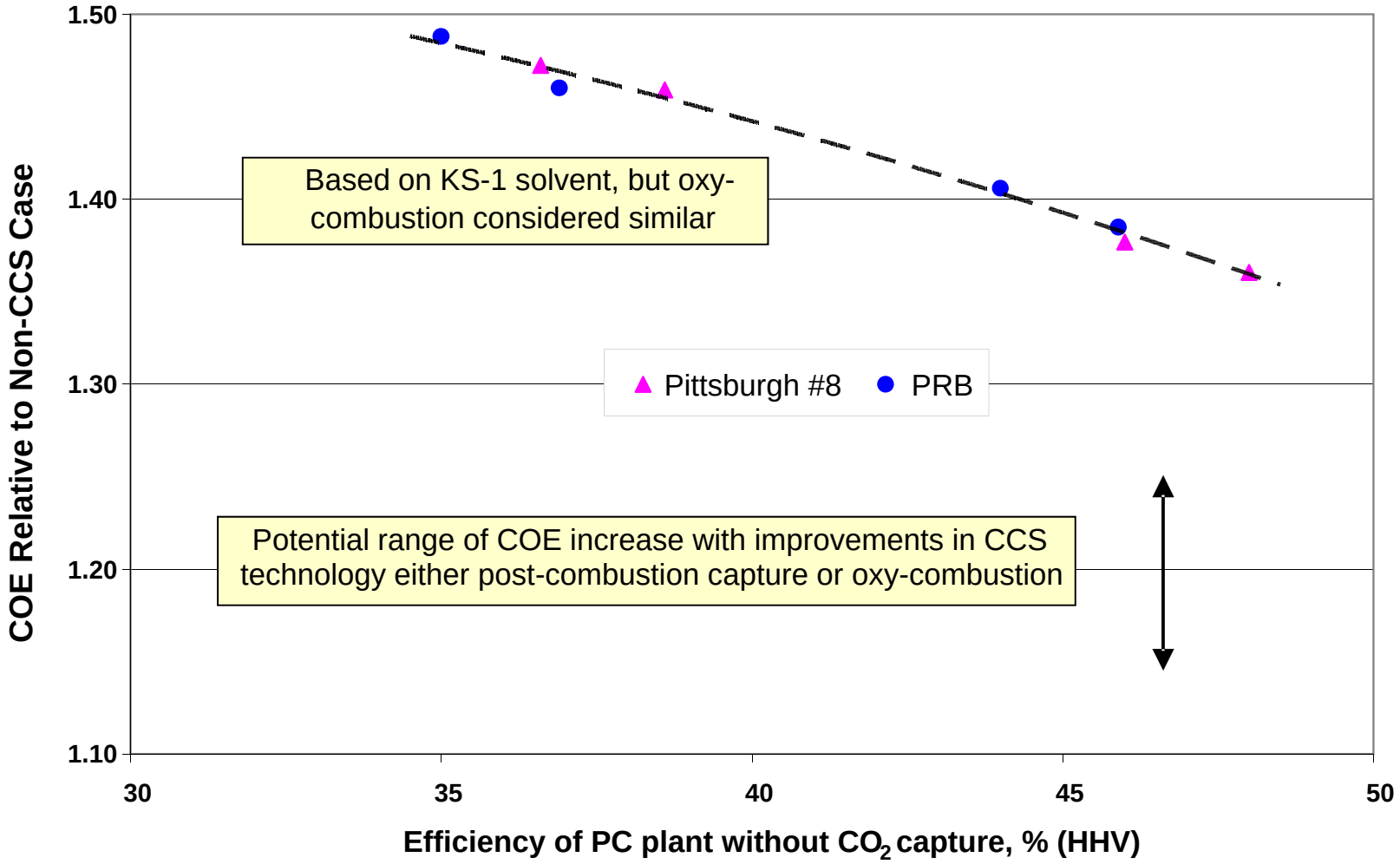
Three Means of Capturing CO_2 from Coal-Based Power Plants

- For combustion processes, new or retrofit
  - Post-combustion capture (PCC)
  - Oxy-combustion.
- For gasification processes
  - Pre-combustion.
- In the time available the presentation concentrates on post-combustion but the points raised are applicable in the main to the other two technologies.
- All three technologies benefit from raising generating efficiency to lower CO_2/MWh and so the cost to capture, transport, and store CO_2.
- For a pulverized coal (PC) plant fired with sub-bituminous coal the effect of main steam temperature upon generating efficiency is as follows:

Main steam, °F (°C)	1005 (540)	1080 (580)	1120 (600)	1290 (700)	1400 (760)
Efficiency, % (HHV)	36.2	38.5	39.2	43.7	45.7

To achieve these benefits improved boiler materials needed.

When CO_2 Capture Included, Higher PC Efficiency Lowers Levelized Cost-of-Electricity



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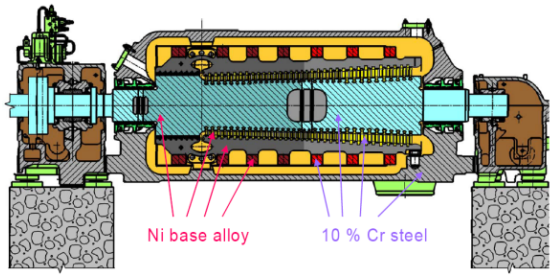
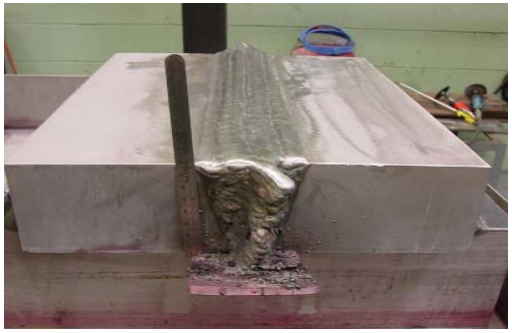
Accomplishments of US-DOE's Advanced Materials Program

HP Turbine Concept



Corrosion and Coatings Investigation



Welding Technology Developments

Fabrication Processes

Material properties determined (corrosion resistance, creep strength, etc.) and fabrication procedures established. Need to move to component testing phase for 1400°F (760°C) exposure in commercially representative conditions prior to power plant demonstration.

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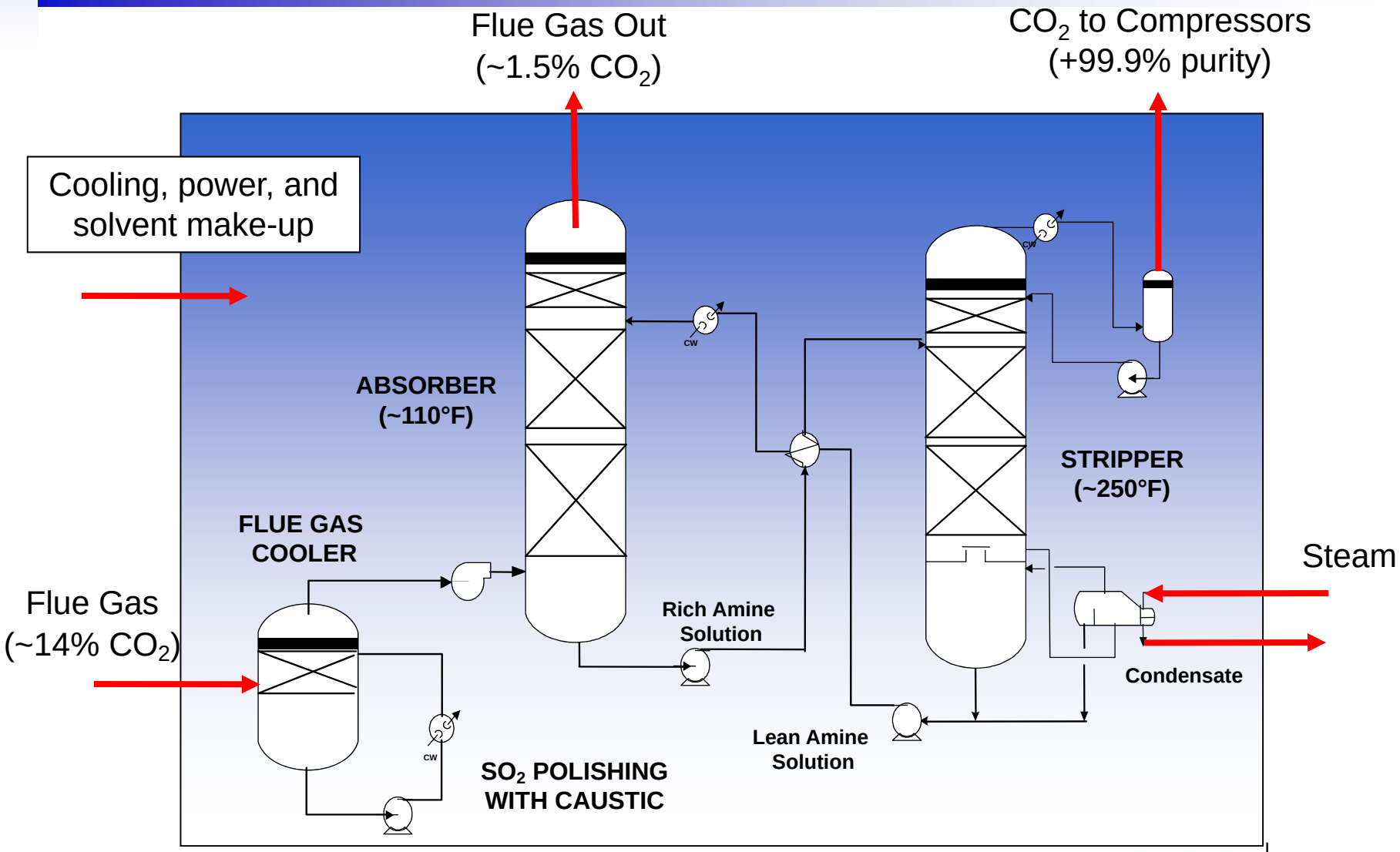
Longer Range Option: Innovative Power Cycle

- Major corporation investigating replacing steam with supercritical CO_2 as working fluid
  - A bottoming steam cycle is included.
- Supercritical CO_2 pressure at turbine inlet ~ 3000 psia expanded to ~ 1150 psia (205 to 80 bar) (temperatures up to 1400°F (760°C) possible)
  - Compact turbine with high output; reduced capital cost
  - No condenser for CO_2, lower boiler feed pump head, potential for reduced water consumption.
- Using CO_2 cycle for 1290°F (700°C) PC design could raise efficiency from 43.7 to 46.7 percent.

Are there other novel power cycle concepts to be developed?

CO_2 Post-Combustion Capture Plant



Greenfield Ultra-Supercritical PC Plant with Post-Combustion Capture

- 750-MW 1100°F (590°C) subbit-fired USC PC retrofitted with advanced amine PCC technology to capture 90% of CO_2 in flue gas.
- Design incorporates projections of future PCC improvements to identify full potential of technology.

	Base plant	With PCC
Net power, MW	750	601
Efficiency, % (HHV)	38.4	30.7
Cost of electricity, $/MWh	64	105
Avoided cost of CO_2, $/ton ($/tonne)		40 (44)

- Proposed US legislation valued CO_2 at ~$25/ton: no incentive to proceed with CCS
  - Is this the maximum politically acceptable number?

Great incentive to develop more cost-effective technologies.

Breakdown of Energy Loss from PCC Study

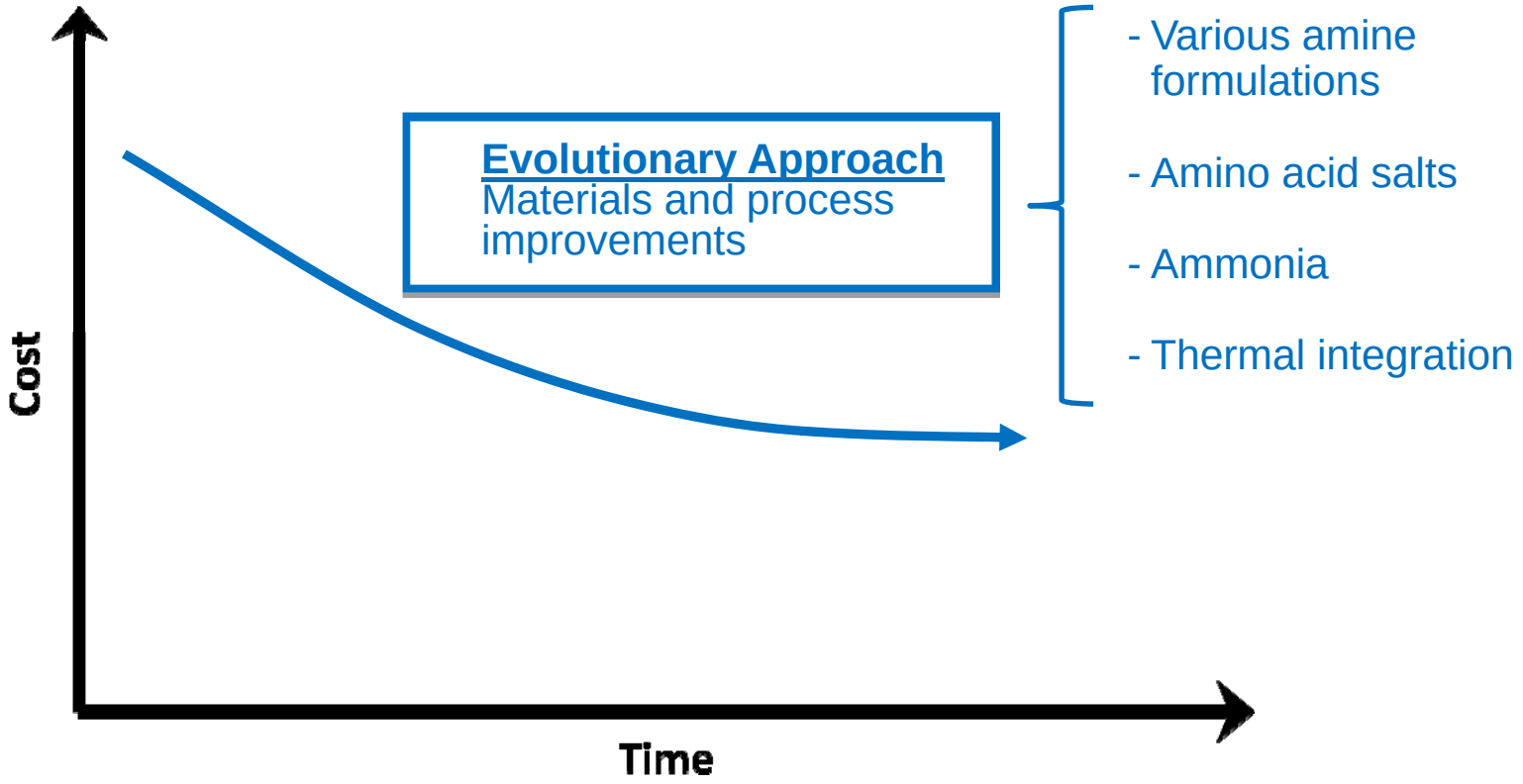
	MW
CO_2 compression	72
Turbine output reduction	50
PCC aux power (1)	19
Absorber cooling	8
TOTAL	149

(1) Fans, pumps, SO_2 polishing

Great need for reduction by improved compressor technology or alternatives to underground storage of CO_2.

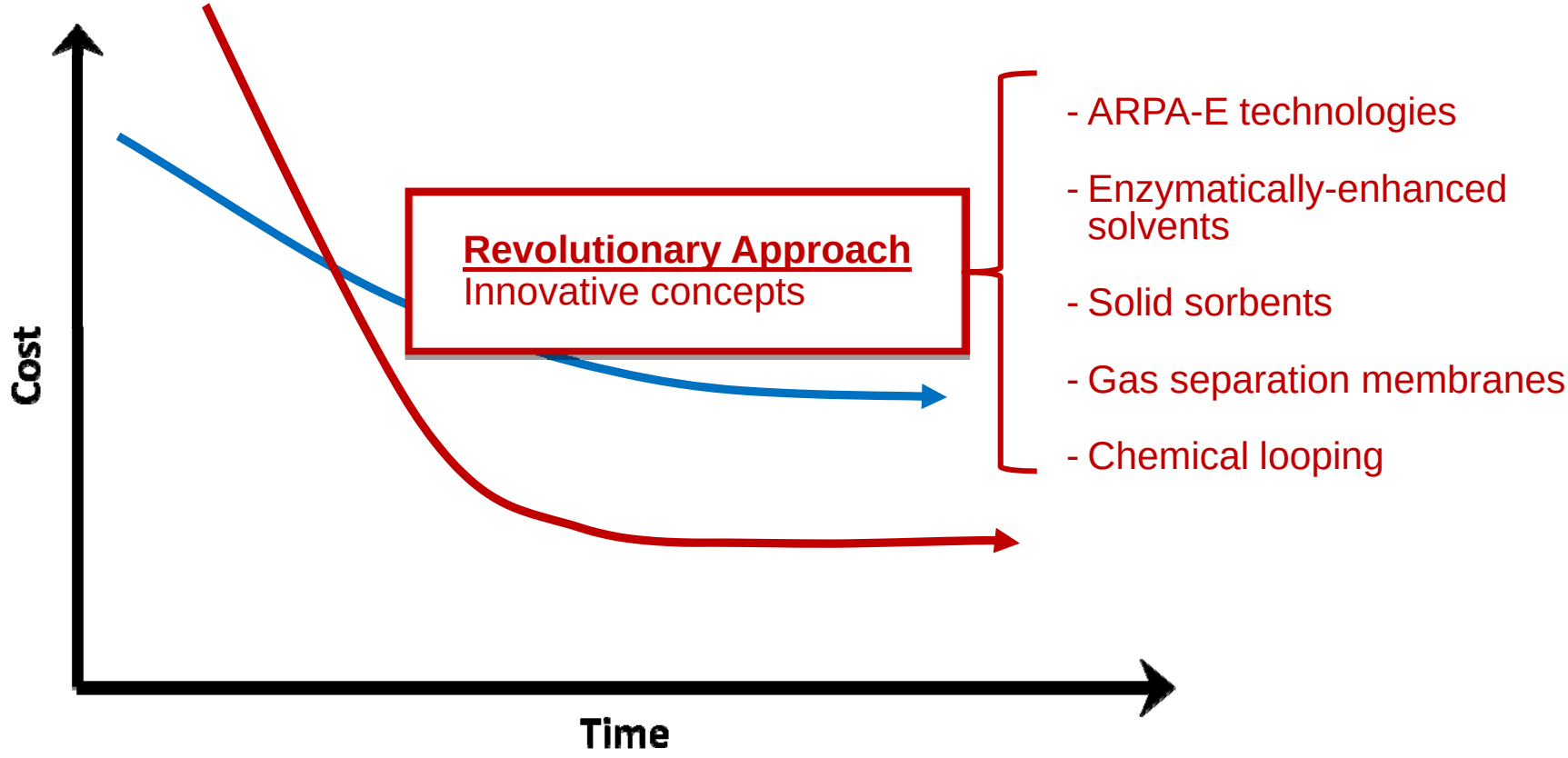
- Compression to 2200 psia (150 bar) consumes most energy but most effort concentrates on lowering heat of regeneration to lower steam extraction and increase power generation.
- Most solvents can regenerate at pressure and help lower compressor duty, but higher CO_2 partial press. requires higher regeneration temperature
  - Increased steam extraction offsets reduction in compressor duty: higher temperature degrades amine solvents.

Dual Technical Approach for Cost Reduction: Evolution



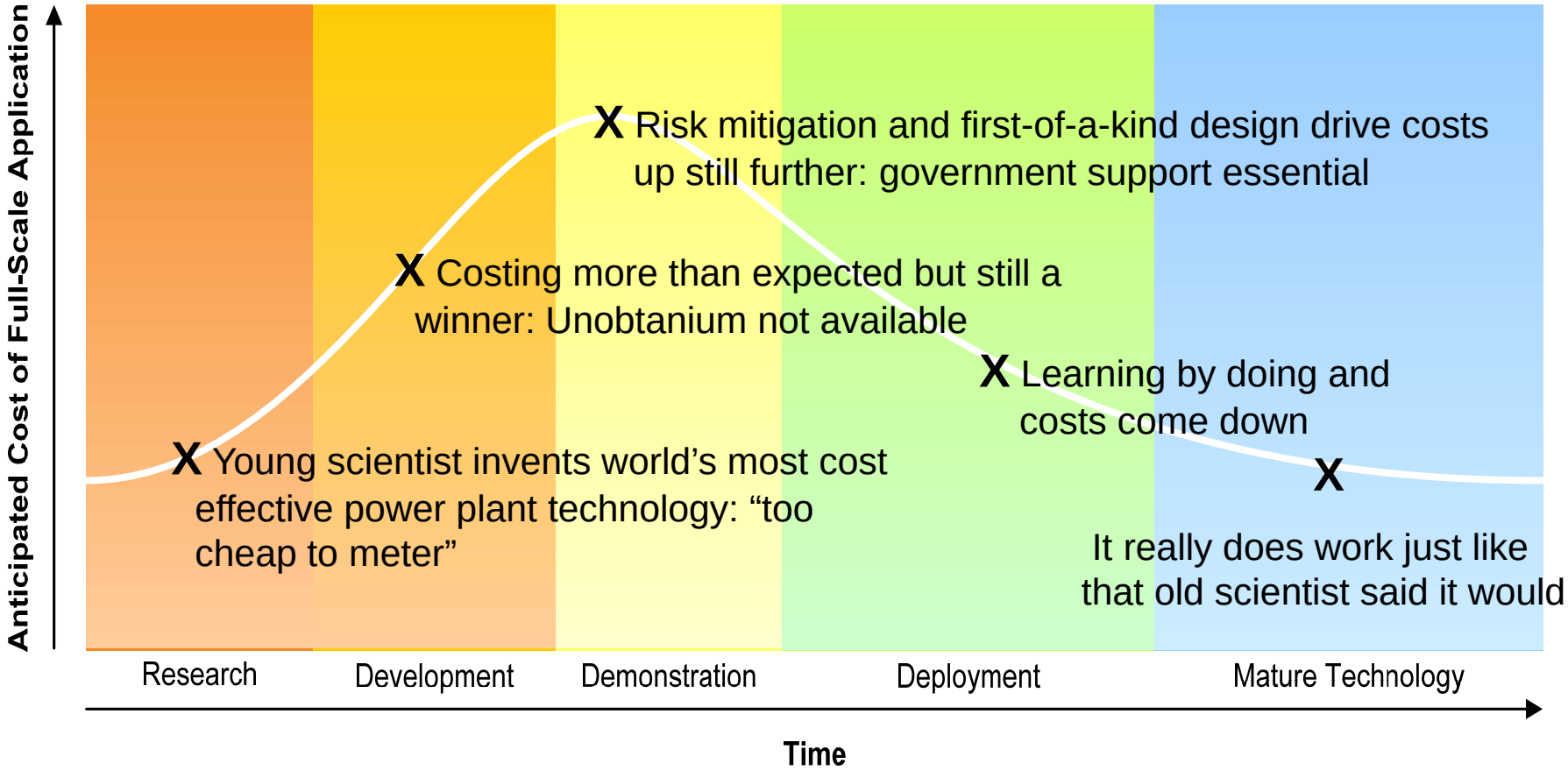
Refinement and improvement of existing technologies.

Dual Technical Approach for Cost Reduction: Revolution



Novel approaches with potential for significant improvement over existing technologies.

Technology Deployment Curve



Many ideas initiated but few reach fruition. Still fewer reach fruition quickly.

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How USA is Accelerating CCS Technologies up Development Curve

- US-DOE is providing significant funds to:
  - Support research of novel technologies through programs such as the Advanced Research Program Agency for Energy (ARPA-E)
  - Fund the National Carbon Capture Center to progress most promising technologies through pilot plant stage
  - Develop predictive simulation tools to accelerate the development and deployment of industrial CCS technology
  - Demonstrate CCS technologies and advance them to commercialization.
- EPRI is supporting development activities of companies working with DOE in these programs.

www.netl.doe.gov

http://arpa-e.energy.gov/

Some Novel Approaches Under Investigation Funded by Various DOE Programs

- Ionic liquids: a solid in liquid phase with multiple possible formulae
  - Incorporated within membranes (hollow fiber thin film)
  - Amines dissolved in ionic liquid not water.
- Solvents that absorb CO_2 and form an immiscible liquid phase or a solid that is readily separated from mixture.
- Use of enzymes to accelerate kinetics for solvents with low heats of reaction but with low CO_2 reaction rates.
- Freezing CO_2 from flue gas
  - Hollow fiber membrane and cryogenic hybrid approach
  - Pass flue gas through nozzle at supersonic speeds.
- Improved adsorbents and metal oxide frameworks that can be formulated to capture either CO_2 or H_2.
- Membranes to separate CO_2 from flue gas (or H_2 from syngas) without need for regeneration energy.

Exciting area of research: more ideas welcomed.

DOE's National Carbon Capture Center

Provides first-class facilities to test developer's technologies for extended periods under commercially representative conditions with coal-derived flue gas and syngas, thereby accelerate development of cost-effective carbon capture technologies.

- All necessary infrastructure provided to support testing of developer's technology.
- Experienced operators and maintenance staff.
- Access to advanced analytical techniques at local university.
- Comprehensive data collection and analysis capability.
- Flexible facilities allow for scale-up from bench- to engineering-scale.
- Post- and pre-combustion facilities available.

www.nationalcarboncapturecenter.com

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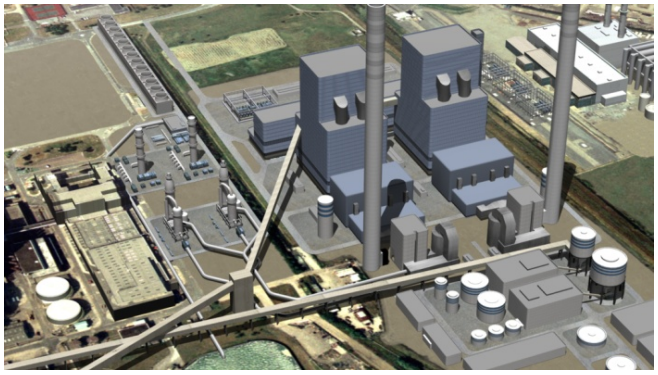
Selected North American Post-Combustion Capture Projects

Project, Utility	Net MW, Fuel	Capture	Storage, Start Up
Parish 5, NRG Energy, USA	60 MW, sub-bituminous (SS)	Fluor Econamine (amine)	EOR (0.5Mt/y) 2013 (DOE $154M)
Boundary Dam, SaskPower, Canada	100 MW, lignite (FS)	Cansolv (amine)	EOR, saline (1Mt/y) 2015 ($250 CN Govs)
Antelope Valley, Basin Electric, USA	120 MW, lignite (SS)	HTC Purenergy (amine)	EOR (0.9Mt/y) 2013 (DOE $100M)
Mountaineer, AEP, USA	235 MW, bituminous (SS)	Alstom chilled ammonia	Saline (1.5Mt/y) 2016 (DOE $334M)
Keephills 3, TransAlta, Canada	250 MW, sub-bituminous (SS)	Alstom chilled ammonia	Saline (1Mt/y) 2015 ($880 CN Govs)



SS = slip stream FS = full stream

In Europe projects with confirmed capture technology are Belchatow, Poland 250-MW Alstom/Dow amine (saline, SS), Maasvlakte, The Netherlands, 250-MW TNO amino acid (offshore depleted oil/gas field SS). Both projects received €180M from EU.

Carbon Capture Simulation Initiative

- Develop and validated predictive simulation tools to accelerate the development and deployment of industrial CCS technology.
- DOE-NETL, Berkeley Labs, Lawrence Livermore, Los Alamos, Pacific Northwest, and five universities.
- Use tools to support
  - Identifying most promising concepts and designs
  - Developing optimal process designs and integration approaches
  - Quantifying technical risk in scale up.
- Models will be updated with data and experience from demonstration projects to accelerate commercialization.

Modeling has the potential to accelerate development, but work must be based on commercially representative data and accommodate real-world plant constraints and requirements for design and operation.

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Concluding Remarks

- EPRI's MERGE analysis determines the mix of power generation technologies required for the USA to lower its CO_2 emissions to ~1905 levels by 2050.
- Coal-based generation with CCS can play a major role provided that the technology is commercially available in the next 10 to 15 years.
- The US-DOE is investing in the improvement of existing technologies and the development of novel ones, and providing support to advance them expeditiously to demonstration prior to commercial operation
  - EPRI is supporting a number of these projects and the NCCC as well as completing independent studies.
- It is a worldwide challenge that will require international cooperation
  - Pittsburgh Coal Conference attendees are part of the solution.

Together…Shaping the Future of Electricity