Advanced Research Projects Agency—Energy (ARPA-E)

Carbon Capture and Conversion

Workshop Summary

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Pittsburgh Airport Marriott

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Why we're here, and what we hope to accomplish

Technical Objectives

1. Identify promising technical directions with the potential to radically decrease the energy/cost penalties associated with CO_2 capture
2. Identify potential carbon conversion applications that satisfy ARPA-E mission areas, and methods to reduce the energy needed to convert CO_2

Workshop Context

Provide input as to how ARPA-E might structure an upcoming FOA so that an impactful 2-3 year program is created that complements existing DOE/NETL research programs and accelerates promising ideas up the development ladder

Format

Focused breakout sessions with reports to the group

- Carbon capture
- Carbon conversion

10 minute "report out" by chair of each session

Workshop Agenda

8:30 AM - 9:00 AM Registration & Continental Breakfast

9:00 AM - 9:15 AM Welcome and Opening Remarks — Mark Hartney

- Welcome, introduction to the mission areas of ARPA-E, what this workshop is and IS NOT trying to accomplish. Introduce format of workshop.

9:15 AM - 9:35 AM NETL Capture Research & Workshop Summary — Jared Ciferno and Geo Richards

- Overview of DOE/NETL funding of carbon capture, and the relevant technologies. What are current metrics, and current barriers to achieving them? Highlights from October 5-6 workshop in College Park, including big-picture conclusions about BES and FE research directions.

9:35 AM – 9:55 AM Carbon Capture Technology Strategies — Howard Herzog

- Overview of capture technologies and portfolio approach of basic research to implementation.

9:55 AM – 10:05 AM Introduction to Capture Breakout Sessions

10:05 AM – 10:20 AM Coffee Break and Report to Breakout Sessions

10:20 AM - 11:40 AM Capture Breakout Sessions

Catalysis & Electrochemical Techniques	John Kitchin – leader
Dilute Source Capture Technologies	Roger Aines – leader
Membrane Capture	Jared Ciferno – leader
Solvent and Sorbent Based Capture	Gary Rochelle – chair

11:40 AM – 12:00 PM Preparation for Working Lunch

12:00 PM – 1:00 PM Working Lunch: Report of First Breakout Session

- One speaker from each team summarizes key points of discussion for ten minutes with time for Q&A after each and at conclusion

1:00 PM – 1:20 PM Overview of Carbon Conversion — Berend Smit

- Report from recent workshop on carbon conversion options

1:20 PM – 1:30 PM Introduction to Conversion Breakout

1:30 PM – 1:45 PM Coffee Break and Report to Breakout Session

1:45 PM – 3:05 PM Conversion/Use Breakout Sessions

Accelerated Weathering	Kurt House – leader
Coal Bed Gasification	Julio Friedmann – leader
CO_2 to Fuels	Karl Littau – leader
Other Conversion/Use Approaches	Berend Smit – leader

3:05 PM – 4:00 PM Report of Second Breakout Session

- One speaker from each team summarizes key points of discussion for ten minutes with time for Q&A after each and at conclusion

4:00 PM – 4:15 PM Workshop Summary

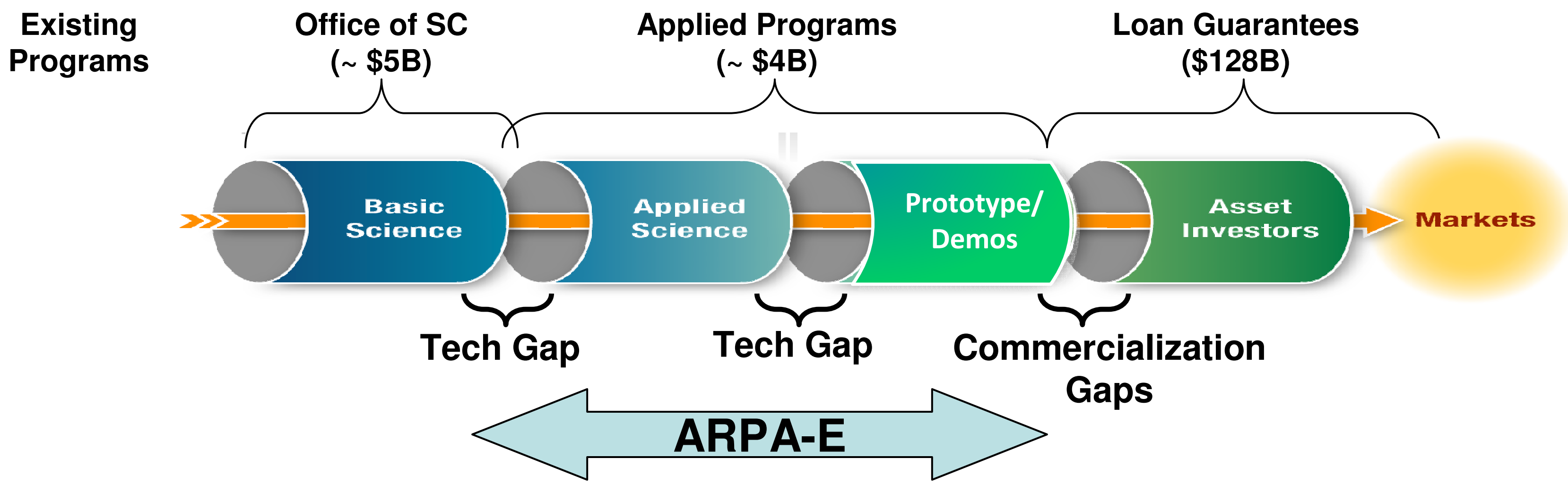
- Wrap-up of the workshop. Notify attendees what to expect going forward in terms of future ARPA-E opportunities.

ARPA-E Orientation

Funding Program Schedule

Meeting Goals

Filling the Gaps in Research Funding



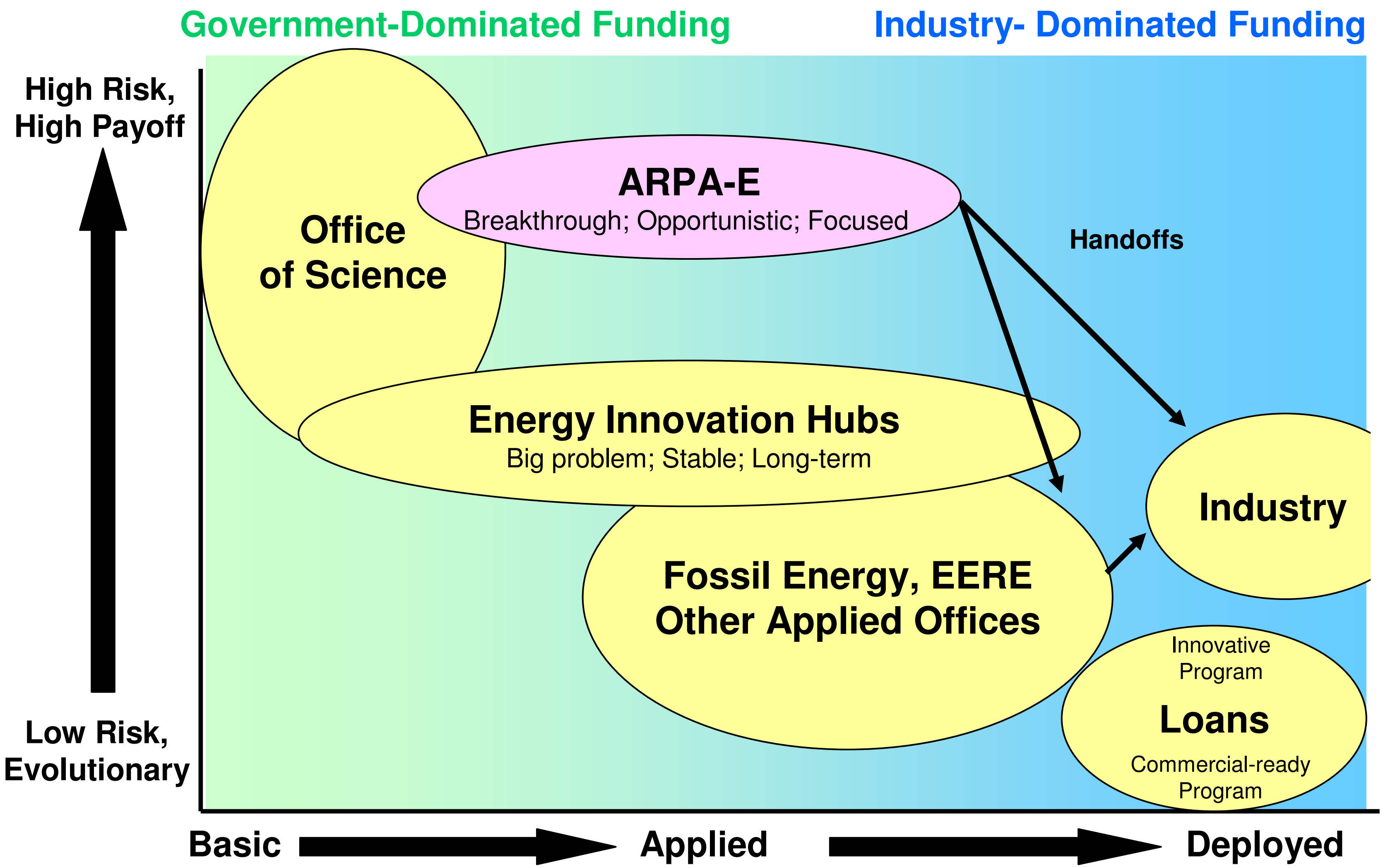
What ARPA-E WILL do

- Disruptive transformational projects
- High risk, high potential programs
- Projects in need of rapid and flexible experimentation/engineering
- Marry technical opportunities with mission gaps
- Breakthrough science that can transform a field
- Outcome focused: to meet climate & energy security objectives; not on a particular scientific problem
- Technology development

What ARPA-E will NOT do

- Basic Research
- Lowest Technology Readiness Levels project
- Projects longer than 5 years
- Evolutionary improvements
- Large scale commercial viability demos
- Projects other DOE program offices are already focused on

ARPA-E Role in the Innovation Pipeline

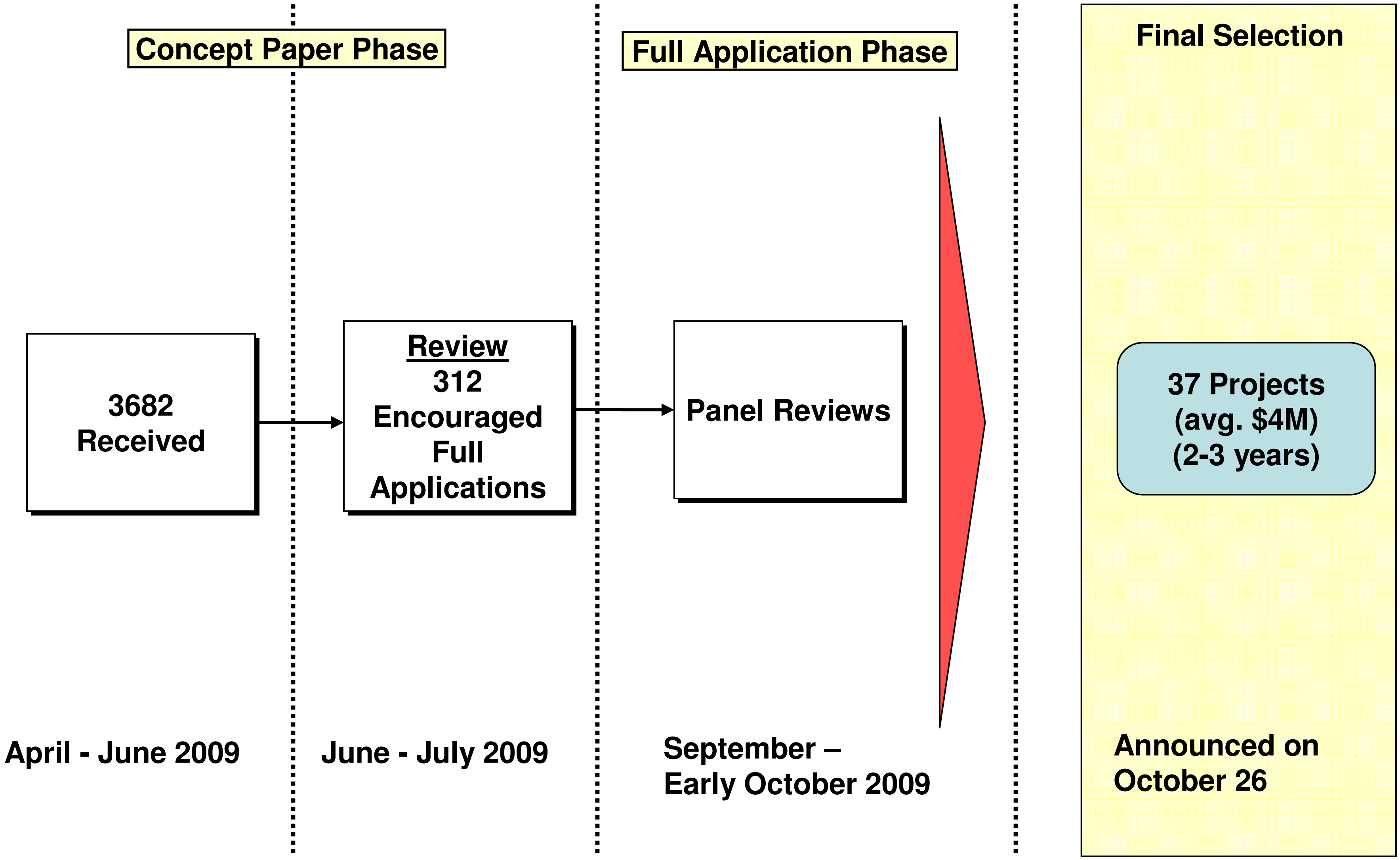


ARPA-E Orientation

Funding Program Schedule

Meeting Focus

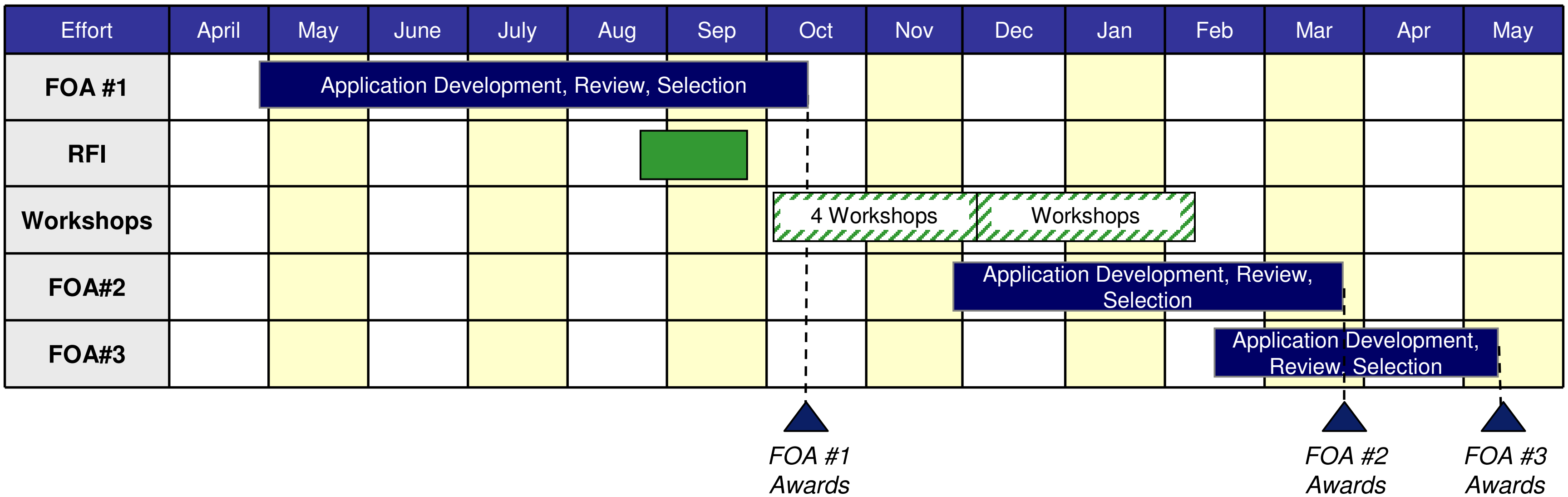
ARPA-E's first solicitation spanned the entire realm of novel energy topics ($150M, open to all energy technology areas)



5 CCS projects were funded as part of the first FOA

P.I.	Institution	Title
Bakajin, Olgica	Porifera, Inc.	Carbon nanotube membranes for energy-efficient carbon sequestration
Carlson, Wayne	Nalco Co.	Energy Efficient Capture of CO_2 from Coal Flue Gas
Cordatos, Harry	United Technologies Research Center	CO_2 Capture with Enzyme Synthetic Analogue
Fan, Liang-Shih	Ohio State University	Pilot Scale Testing of Carbon Negative, Product Flexible Syngas Chemical Looping
Moore, David	Lehigh University	Electric field swing adsorption for carbon capture applications

ARPA-E is operating under an aggressive schedule to build programs with potential for transformational impact



Late October 2009 Selection

FOA #1: *Concepts*

- Open to all ideas, best well formulated high impact projects across all energy technologies
- Utilize concept papers as first phase before selecting best for full proposals

March 2010 Selection

FOA #2: *Areas*

- Solicit proposals on topics with clear needs and some emergent opportunities
- Goal is to build portfolios around specific technology challenges

May 2010 Selection

FOA #3: *Programs*

- Program focused approach
- Specific challenges with cost and / or performance metrics
- Topics that need more development and input to formulate

ARPA-E Orientation

Funding Program Schedule

Meeting Focus

This workshop concerns ***capture*** of CO_2 from point sources or the air, and ***conversion*** to useful products

- CCS is increasingly viewed as a necessity to obtain balance between the Nation's and world's energy requirements and mitigation of the rising CO_2 concentration in the atmosphere
- If today's technology was applied to existing coal plants, the levelized cost of electricity (COE) would increase 75-85%

↓

- DOE/NETL has created a sustained effort to develop and demonstrate promising solutions to carbon capture, transportation, storage, and monitoring
- DOE targets: 90% CO_2 capture with 35% increase in COE
- ARPA-E seeks to create a 2-3 year high risk/high return program that will focus on one or more aspects of CCS
- Program success would mean that the concept is accelerated on the path towards DOE demonstration and widespread commercialization

Re-emphasis on the workshop objectives

What we are NOT trying to accomplish

- Duplicate existing DOE/NETL research programs, including the recently-released FOA for bench-scale and slipstream development for existing coal-fired power plants
- Fund basic (discovery) research
- Engage in policy debate

What we ARE trying to accomplish

- Identify high risk concepts that, if successful, would drastically reduce the COE/power output penalty associated with CO_2 capture (quantitative goals are ideal)
- Explore alternatives to CO_2 geologic sequestration, where the strategy is consistent with ARPA-E's mission areas – e.g. reduction in oil imports
- Identify potential cross-cutting thrusts where researchers benefit from synergistic collaboration with new participants

ARPA-E Orientation

Funding Program Schedule

Meeting Goals

Breakout Session #1: Carbon Capture

Breakout Session #2: Carbon Conversion

Breakout Session #1: Carbon Capture

Catalysis and Electrochemical Techniques — John Kitchin (Leader)

- Is there potential for electrochemical capture to have a lower energy/cost penalty than current capture methods?
- Could electrochemical techniques be deployed on a widespread scale in real industrial conditions? If not, what is holding them back?
- There is a constant call for improved catalysts, such as from the DOE BES workshops on energy research needs. What capture technologies would benefit the most from improved catalysts and how similar are their requirements?

Dilute Source Capture — Roger Aines (Leader)

- Does it make sense to develop air capture solutions in parallel with point sources? What are the factors that influence this decision?
- Are there technologies that can't work in a coal flue gas environment but would be appropriate for natural gas or air capture?
- What are the key technical barriers that keep the cost too high for widespread use?
- What are promising approaches to address those barriers?

Breakout Session #1: Carbon Capture

Membranes — Jared Ciferno (Leader)

- If optimal membrane properties were available, could membranes be scaled up for widespread deployment at point sources?
- What are the most critical factors limiting membrane adoption: cost, selectivity, flux, low driving force
- What material properties are currently lacking that, if available, would accelerate membrane adoption?

Solvents/Sorbents — Gary Rochelle (Leader)

- Can current technologies be advanced to meet the 35% COE goal and scaled up for widespread deployment?
- If not, what are the key technical barriers that keep the energy/cost penalty too high?
- What are promising approaches to address those barriers?
  - What are promising alternative means (other than temperature and pressure) of modulating capture and release of CO2

Breakout Session #1: Carbon Capture

Catalysis and Electrochemical Techniques:

- Is there potential for electrochemical capture to have a lower energy/cost penalty than current capture methods? What are technical barriers?

- Group consensus: in principle, electrochemical techniques with high Faradaic efficiency could be less energy intensive than thermal swing processes; however, non-equilibrium operation results in energy dissipation that must be understood and minimized
- Differences between use of thermal and electrical energy inputs must clearly be defined.
- For MEA system, thermal penalty is 1200 BTUt/lb of CO_2, or 600 BTUe/lb including pressurization. Electrochemical methods can theoretically be as low as 175 BTUe/lb CO_2; another metric proposed was work: 0.2 MWhr per metric ton captured was described by Rochelle for MEA
- What are the barriers?
  - Membranes - catalyst incorporation in membranes - active surface area
  - Stability of catalysts - lifetime, corrosion, etc.
  - Robustness - effect of impurities in gas stream
  - Integration into existing plants
  - Need the ability to screen materials for catalysts, modeling

Breakout Session #1: Carbon Capture

Catalysis and Electrochemical Techniques:

- Novel approaches
  - Electrocatalytic membrane separation:
  - Electrodialysis/electrodionization: essentially change the pH for CO_2 capture
  - Electrochemical O_2 production (noted that there is commercial work on this)
  - Direct electrolysis to produce O_2 and H_2
  - Redox cycles - reduced carriers are reactive to O_2
  - Direct carbon fuel cells (oriented towards power production at present)
  - Role of novel catalysts (e.g., metalorganic frameworks) that reduce energy of binding, etc.
  - Use of electric fields to change material phase or properties (ex: ionic liquids)
  - Advanced catalysts may enable systems (ex: solvents) with superior thermodynamics, but very slow kinetics
  - Integrated systems (ex: CO_2 capture plus water purification)
  - Use of non-aqueous media

Breakout Session #1: Carbon Capture

Catalysis and Electrochemical Techniques:

- Issues
  - Effect of gaseous impurities on performance - especially SOx, NOx, and O_2
  - Energy harvesting methods that could potentially power electrochemical processes
    - Solar thermal to supply energy to separation processes
    - Geothermal energy sources
    - Thermoelectric
  - A clear method must be establish to benchmark novel approaches against conventional methods
  - Advanced process modeling and scale-up
  - Catalyst lifetime/turnover number must be enhanced

Breakout Session #1: Carbon Capture

Dilute Source Capture:

- Does it make sense to develop air capture solutions in parallel with point sources? What are the factors that influence this decision?

- Consider low-concentration, large-scale sources
  - Industrial sources: Aluminum smelters; refineries heaters; natural gas processing; blast furnaces; cement kilns
  - "De-centralized" capture
  - Diffuse sources: residential heating
- Consider technologies that may not work in [coal or gas] power plant environments but might work in other environments?
- Need to concentrate CO_2?
- Isolation/storage/use other than sequestration?
- Any way to take CO_2 out of atmosphere is worth pursuing
- Prioritize opportunities by reduction potential
- Diffuse and dilute sources

Breakout Session #1: Carbon Capture

Dilute Source Capture:

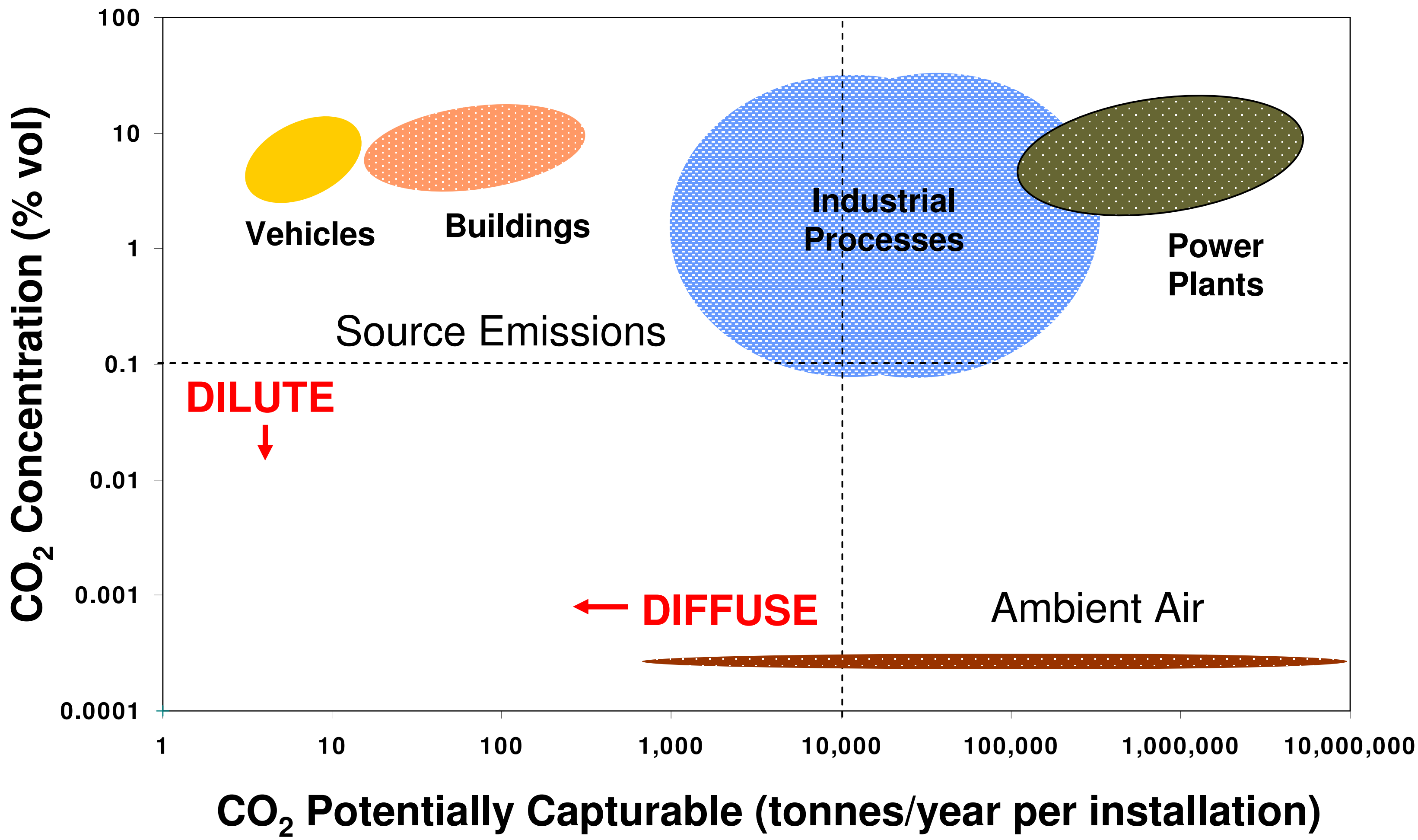
- Define dilute and diffuse

- Identifiable sources
- Not just a capital cost challenge – institutional and infrastructure costs
  - Levelized cost of carbon (cost per tonne)
  - Scale of opportunity (tonnes avoided)
- Technology / application specific call vs. air-capture call [FOA]
- Align capture and sequestration / utilization
- Adaptation of existing technologies and infrastructure
  - Infrastructure to dispose of CO_2
  - Value of re-use (eg, EOR)
  - Synergies – energy/water use? (de-salinized water as co-product)
  - Low energy use

Breakout Session #1: Carbon Capture

Dilute Source Capture:

- Sources of dilute and diffuse CO_2



Source: E.S. Rubin, CMU

Breakout Session #1: Carbon Capture

Dilute Source Capture:

- Are there technologies that can't work in a coal flue gas environment but would be appropriate for natural gas or air capture?

- Technical limitations:
  - Ratio of reactant to CO_2
  - Kinetics at low partial pressures
  - Long-term stability of sorbents under operating environments – steam stripping
  - Accurate testing protocols for diffuse sources (lack of comparable data)
  - Performance metrics? (sorbent or solvent in context of process)
  - Purity of CO_2
- Characteristics / Criteria
  - Capacity per capital cost
  - Exergy rather than energy performance
  - Diffuse source process kinetics

- Need for de-capture?
  - Carbon conversion

Breakout Session #1: Carbon Capture

Dilute Source Capture:

- What are the key technical barriers that keep the cost too high for widespread use?
- What are promising approaches to address those barriers?

- Capital costs

- Passive systems
  - Best schemes are entirely passive
  - Must be low cost
  - Environmentally benign
  - Secondary effects
  - Uncertainty barriers
  - Baseline comparison with firing / co-firing biomass

Breakout Session #1: Carbon Capture

Membranes:

- What are the most critical factors limiting membrane adoption: cost, selectivity, flux, low driving force, etc.?

- High selectivity polymers for CO_2/N_2 separation available 20-30
- Compression more than ratio of 5/1 is not economical
- Permeance critical: greater than 1000 gpu necessary. (4000 gpu potentially practical).
- Permeance is the important property, not permeability. When permeability is reported, achievable permeance should be discussed.
- Development of new module types is as important as developing new materials. Manage not only gas flow, but also contaminants, particulate effects, etc. Large increases in membrane module size would be a major breakthrough.
- Process integration is another important piece of membrane adoption. End of stack use of membranes not necessarily the most desirable case. To encourage new process integrations schemes: industrial partners in materials development projects? SBIR type solicitations seeking innovative process design
- Lack of practical experience with membranes in the power industry. Piping schemes, membrane disposal, failure concerns, etc.
- Scale up of chemical production to produce the polymers for the membranes must occur but is not a critical issue to consider at this point. Lifecycle analysis is more important on the disposal side.

Breakout Session #1: Carbon Capture

Membranes:

- In addition to selectivity and permeability, are there other technical barriers to membrane scale-up? What are potential solutions?

    - Development of innovative membrane module types. Funding for this type of development.
    - Permeance more important than permeability.
    - Effect changes membrane separations have on contaminant levels at all stages of the power process.
    - Facilitated transport membranes are interesting as an advanced technique, but it must be shown why a given facilitated transport scheme is superior to other methods.
    - Membrane contactors are also interesting, but it is necessary to show why they are superior to other types of gas liquid contactors.
    - Hybrid techniques which use multiple separation types along with membranes.
    - Hybrid mechanisms/combination processes that have attributes of sorption type processes and membranes
    - Membranes have a major advantage in terms of water use over MEA

Breakout Session #1: Carbon Capture

Membranes:

- What material properties are currently lacking that, if available, would accelerate membrane adoption?

  - Robust, high temperature O_2 separation membranes could facilitate both oxy-fuel combustion and gasification-based separation.
  - Minimum flue gas energy for separation is 3.5% (no compression). 10% is a more realistic minimum achievable energy. MTR estimates ~20% of plant energy for a membrane technique.
  - Revolutionary decreases in effective membrane layer thickness and an understanding of gas interactions with ultra-thin membrane layers could be transformative.

Breakout Session #1: Carbon Capture

Solvents/Sorbents:

- Can current technologies (amine scrubbing) be advanced to meet the 35% COE goal and scaled up for widespread deployment?

- No one knows
- Most of us say that amine scrubbing will not achieve 35%.
- Some of us say that no technology can achieve this goal.
- Energy intensity and capital cost would be more useful metrics.

Breakout Session #1: Carbon Capture

Solvents/Sorbents:

- If not, what are the key technical barriers that keep the energy/cost penalty too high?

- Material heat and cooling results in irreversibilities.
- Mechanical compression results in irreversibilities
- Good energy needs careful analysis of irreversibilities
- Unit ops that take out contaminants

Breakout Session #1: Carbon Capture

Solvents/Sorbents:

- What are promising approaches to address those barriers?
  - What are promising alternative means (other than temperature and pressure) of modulating capture and release of CO_2

- Switching technologies, but with good understanding of reversibility
- High temperature absorption/desorption may offer exergy benefits if T>400C. Many reluctant to endorse.
- Generic work on effects of impurities
- Temperature and pressure swing should be included because it can be improved.
- Processes that are more reversible in the use of waste heat & material
- All proposals should include an analysis of lost work?
- Eliminate process steps

ARPA-E Orientation

Funding Program Schedule

Meeting Goals

Breakout Session #1: Carbon Capture

Breakout Session #2: Carbon Conversion

Breakout Session #2: Carbon Conversion

Accelerated Weathering — Kurt House (Leader)

- Can accelerated weathering make a substantial impact on atmospheric concentrations or annual emissions?
- Besides CO_2 what inputs are needed and what outputs result from accelerated weathering and how can they be managed at scales appropriate for CCS?

Coal Bed Gasification — Julio Friedmann (Leader)

- What are unique options for carbon sequestration when utilizing UCG?
- What monitoring techniques are needed for underground coal gasification, and would they also be applicable to monitoring sequestration sites?

Breakout Session #2: Carbon Conversion

CO_2 to Fuels — Karl Littau (Leader)

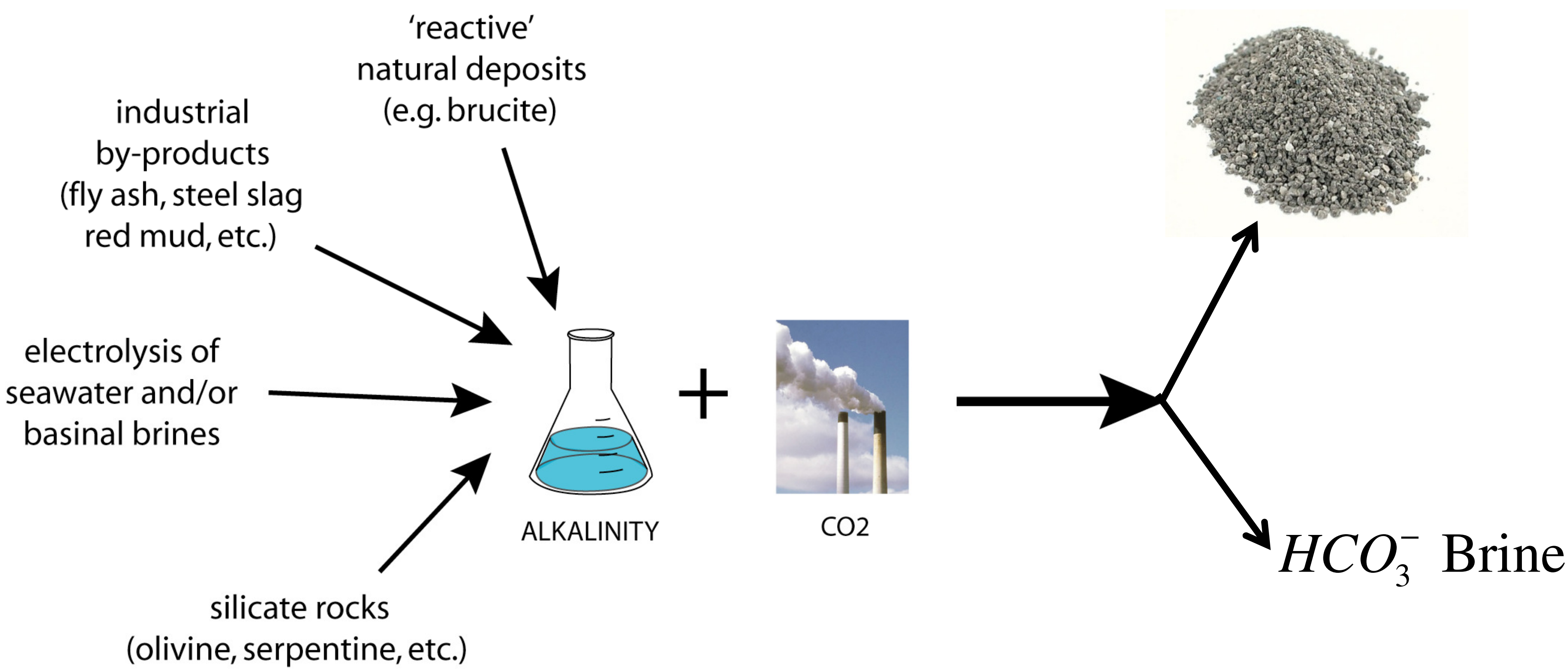
- Conversion to fuels is one of the few products that scale to quantities comparable to CO_2 emissions: what are the most appropriate fuels – eg. methane for electricity or liquid fuels for transportation?
- What opportunities are there to improve the energy costs of conversion?

Other Approaches — Berend Smit (Leader)

- What is a feasible fraction of CO_2 emissions that could be converted to useful products?
- What are energetically favorable conversion strategies that make economic sense, or what would be needed to make them economic?

Breakout Session #2: Carbon Conversion

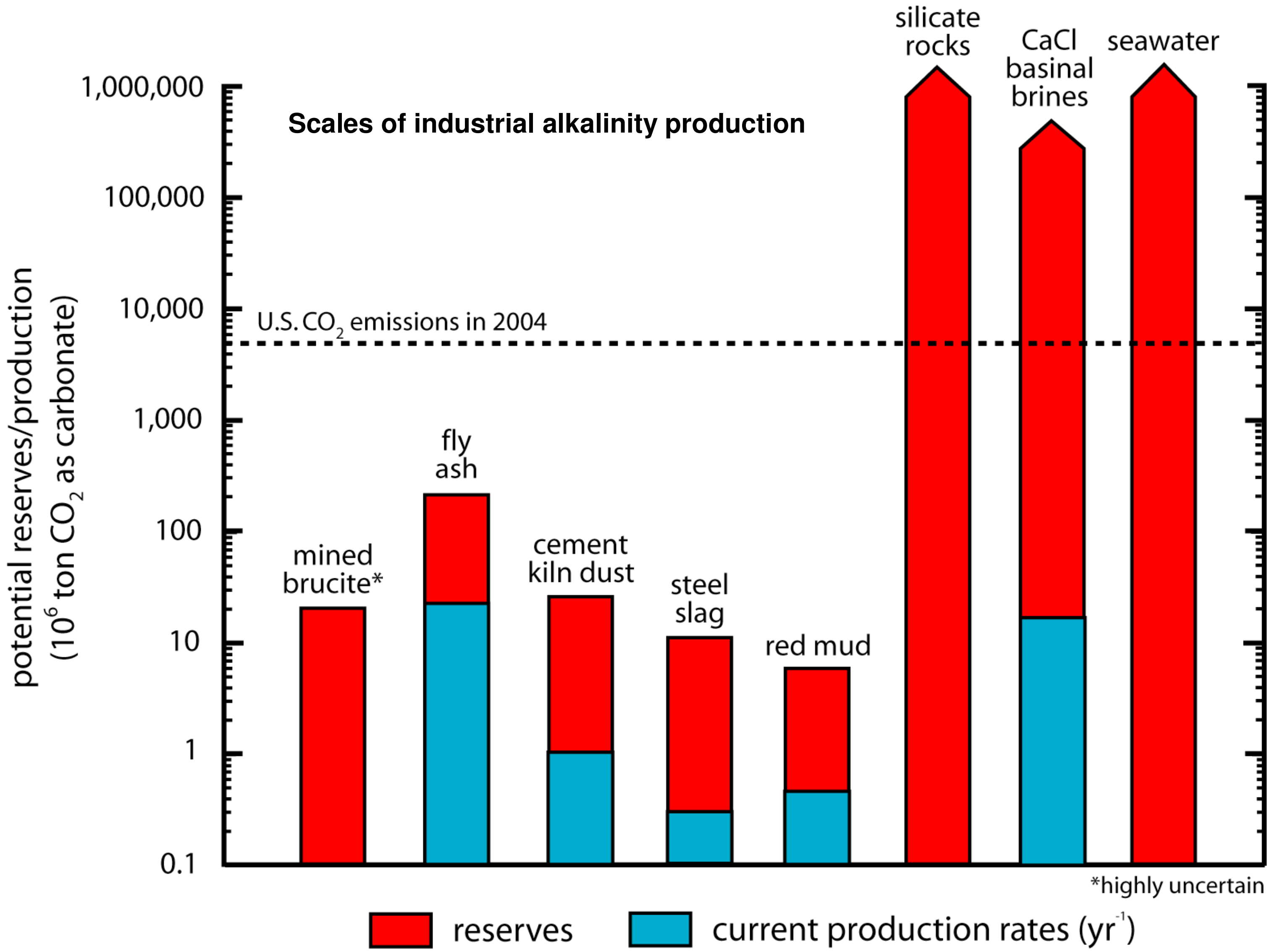
Accelerated Weathering



Accelerated Weathering is About Large-Scale, Low-Cost Production of Alkalinity

Breakout Session #2: Carbon Conversion

Accelerated Weathering:



Breakout Session #2: Carbon Conversion

Accelerated Weathering:

- Conclusions:
- Benefits
  - 1) Thermodynamically stable
  - 2) Multi-pollutant control
  - 3) Might be the only solution in regions without good geologic reservoirs
- Challenges
  - 1) Current energetic estimates for accelerated silicate weathering are ~50% parasitic load (better for carbonate and waste streams of alkalinity)
  - 2) Environmental – water use, hazard chemical leaching, etc.
- Three potential programs of study:
  - 1) Chemical engineering of contacting and CO2 absorption from waste Alkalinity steams
  - 2) Use of Chemical/biological promoters to accelerate Carbonic Acid dissolution of silicate minerals by 10^3 – 10^5
  - 3) Storage as bicarbonate from either carbonate or silicate weathering

- GROUP CONSENSUS: VERY CHALLENGING HURDLES…MAY BE INTERESTING IN CERTAIN REGIONS…UNLIKELY TO EVER BE MORE THAN 10% SOLUTION

Breakout Session #2: Carbon Conversion

Accelerated Weathering:

- Can accelerated weathering make a substantial impact on atmospheric concentrations or annual emissions?
- Hard to say…but total global weathering would have to be accelerated 10x to capture 10% of anthropogenic emissions

Breakout Session #2: Carbon Conversion

Accelerated Weathering:

We have 2 options to sequester carbon with alkalinity:

1) Mix with excess CO_2 then dilute/store.

PROS: 1 mol of alkalinity added =~ 1 mol of C sequestered though this will not be true on timescales > 100 yrs.

CONS: environmental regulations for ocean disposal; no co-product production; Pumping requirements for subsurface storage

2) Mix with CO_2 and precipitate carbonate minerals.

PROS: C locked up in a solid (1 ton $MgCO_3$ = 0.52 ton CO_2) ?useful co-product?

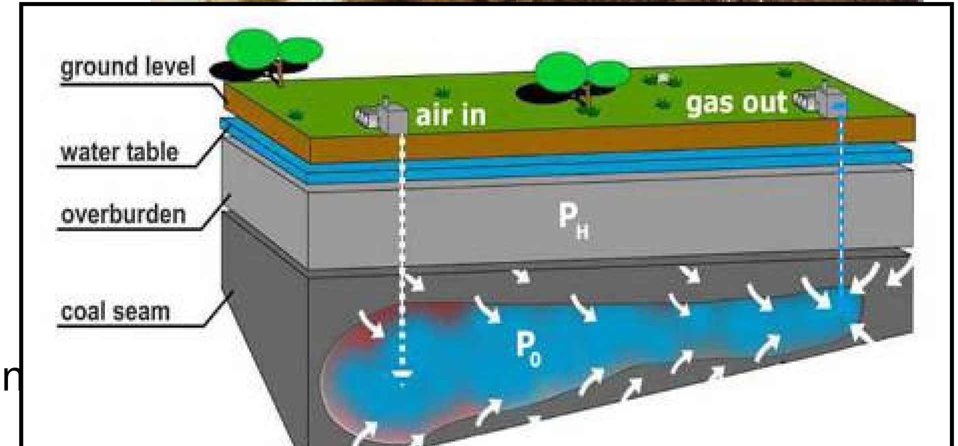
CONS: 1 mol alkalinity = 0.5 mol C sequestered.

$$2HCO_3^- + Ca^{2+} \longrightarrow CaCO_3 + CO_2 + H_2O$$

Underground coal gasification (UCG) could change the game for energy and environmental security – Julio Friedmann, LLNL

Coal Bed Gasification:

- Secure domestic supply
  - 3–4 times increase in coal reserves
  - Low-cost synthetic natural gas
- Economics and energy supply
  - Appears substantially cheaper ($1.5/MBTU for raw syngas)
  - Lower CAPEX and OPEX
- Greenhouse gas emission reduction
  - 30–50% reduction in carbon capture and sequestration (CCS) deployment costs
  - Cheap hydrogen production; more H_2/ton that surface equiv. pre-shift
- Environmental quality gains
  - No mining required (acid drainage, mountain top removal)
  - Criteria pollutant emission management (SO_x, NO_x, Hg, ash)
  - Much less water consumption



Courtesy ErgoExergy

Breakout Session #2: Carbon Conversion

Coal Bed Gasification:

- What are unique options for carbon sequestration when utilizing UCG?

- Not immediate direct carbon capture and separation benefit, but potential large benefit as “alternative gasifier”
  - Gasfiier with low cost and low environmental impact
  - Gasifier with small degree of process control
- Possibility for sub-surface actions for process step (e.g., H_2O-gas shift)
  - Can it be done? (e.g., gas recirculation)
  - Is this necessarily something that could be done only at depth?
- Possibility for CO_2 co-storage in spent reactors

- Challenges remain with scalability, both physically (e.g., hydrology) and human capital
- Possible role for ARPA-E in a short-lived, targeted in-situ process science program
- Looking at the “ladder” of innovation, where are there gaps that can be readily addressed

Breakout Session #2: Carbon Conversion

Coal Bed Gasification:

- What monitoring techniques are needed for underground coal gasification, and would they also be applicable to monitoring sequestration sites?

- Improving the subsurface diagnostics and monitoring would be important for acceptance, operation, and reliability
- Possibility to couple UCG monitoring with CCS monitoring is largely unexplored

- Questions regarding what science is needed to understand this as an option for the country

Breakout Session #2: Carbon Conversion

CO2 to Fuels:

Energy:

1. Source. Carbon "free" energy which is otherwise not suitable for grid desirable.
   1. Stranded resources.
   2. Consider implications of Domestic v. Foreign sources.
   3. Depends strongly on value of CO_2.

Barriers:

1. What barriers can ARPA-E help address?
   1. Thermo, photo, and electrochemical pathways
   2. Thermal research and development
      1. High specificity to hydrocarbons (v. H_2)
      2. Mulitfunctional catalysts and processes
         1. Fewer process steps
         2. Direct CO_2 to higher order hydrocarbons
      3. Catalysts cost and stability
      4. Most thermal processes utilize hydrogen and would benefit greatly by improvements in H_2 electrolyzer cost and efficiency.

Breakout Session #2: Carbon Conversion

CO2 to Fuels:

3. Photochemical
    1. Very low reaction rates
    2. Not stable in solar environments
    3. Complex system requirements significantly reduced if photocatalysts which operate at > 1 sun would be an enabler
    4. Team notes this is an area becoming well addressed by BES and otthers.
4. Electrochemical
    1. Increase Faradaic Efficiency
    2. Low temperature electrolytic catalysts have very low selectivity
    3. High temperature electrolytic materials (cost, stability, ionic conductivity, etc)
5. New, Breakthrough Processes
    1. Alternatives to traditional approaches such as new chemistries for thermal conversion. Are there novel cycles?

Breakout Session #2: Carbon Conversion

Other Approaches:

- What is a feasible fraction of CO_2 emissions that could be converted to useful products?
- What are energetically favorable conversion strategies that make economic sense, or what would be needed to make them economic?

- Keep carbon in the ground
- There is a need to develop alternative to large-scale geological storage, e.g., cost-competitive solid mineralization (even if its not useful), other examples, ….
- Need to implement life cycle analysis (LCA) tools across technology platforms on a common basis
- Expect many applications on smaller scale that may re-emit CO_2, but need to be thorough in LCA. Not everyone can do this yet, hence support would be welcome
- Carbon conversion could make sense in integrated solutions if LCA makes sense. May especially be true for hybrids.

Breakout Session #2: Carbon Conversion

Other Approaches:

- Cross-cutting

- Centralized facility for testing of materials (consortium); Means of connecting with other scientists working in space
- Conversion processes that don't require CO2 separation a priori, i.e., use CO_2 in flue gas directly
- Provide opportunities material scientists/chemists and process developers to work together
- Keep carbon in the ground