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UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN

CO_2 Capture and Utilization for Driving Regional Economic Growth in Illinois

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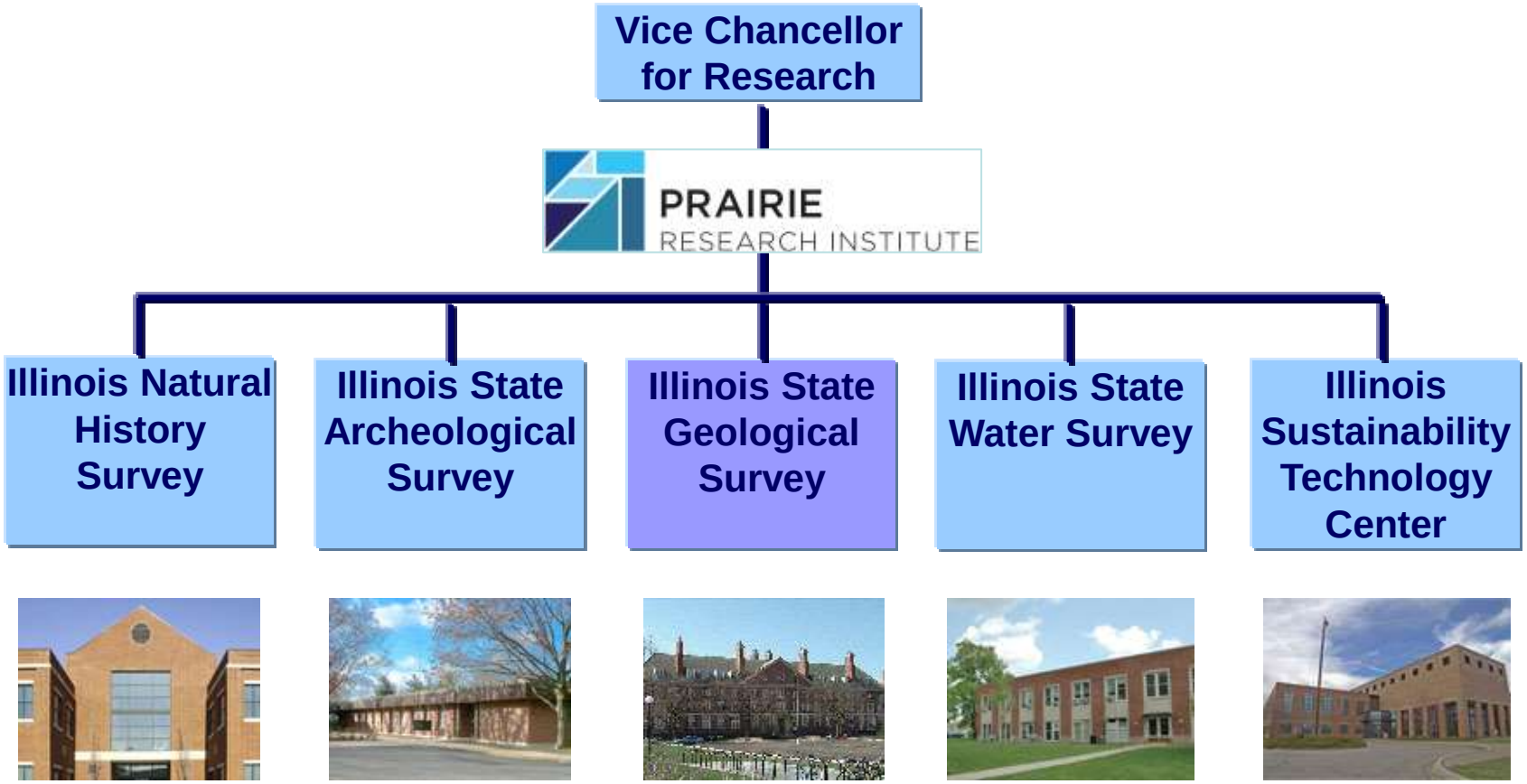
Prairie Research Institute (PRI) at UIUC

- ~1,000 scientists and technical support staff; annual budget of $84 million; basic & applied research and service in resource science & technology and related subjects

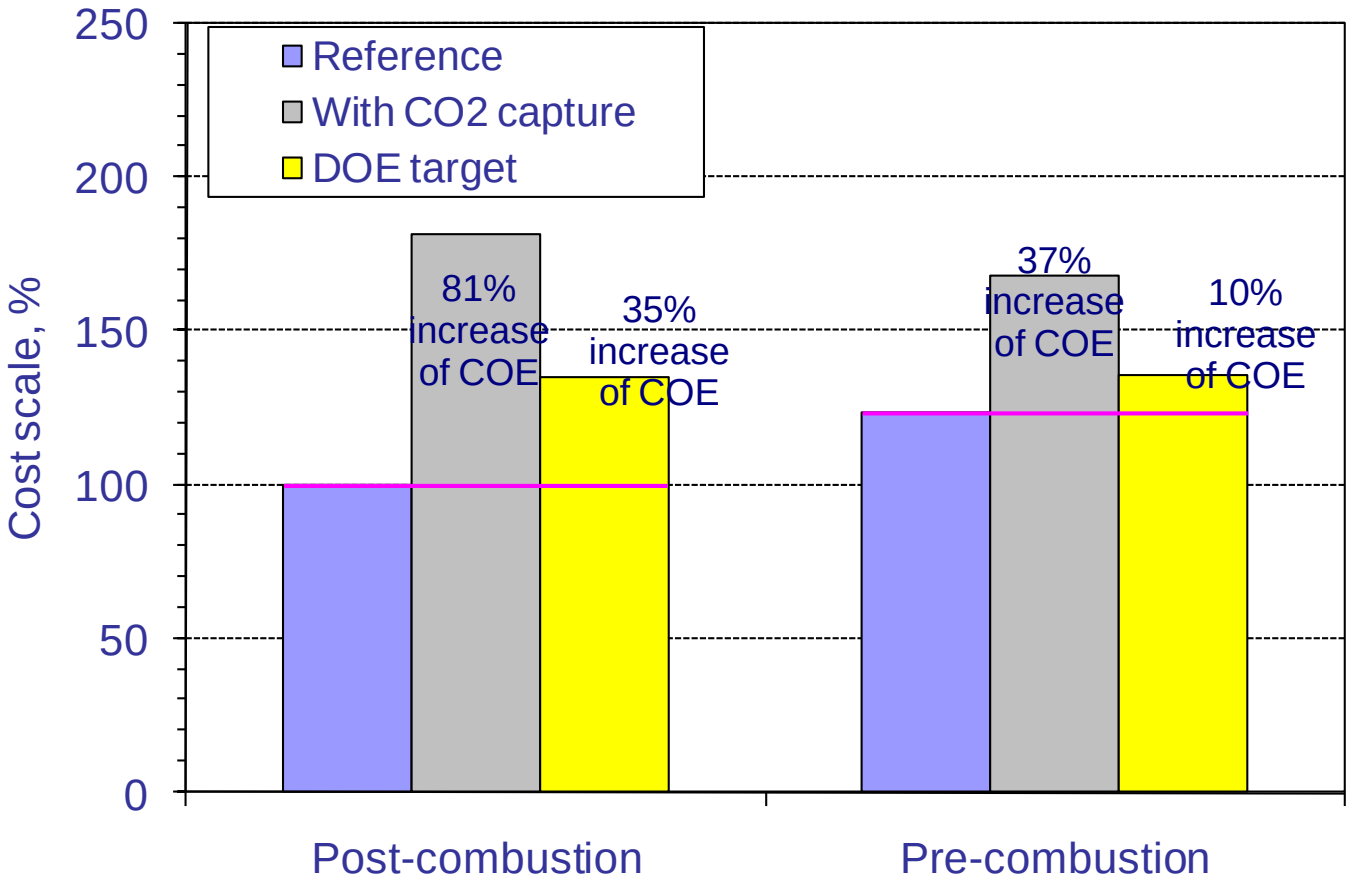


Presentation Outline

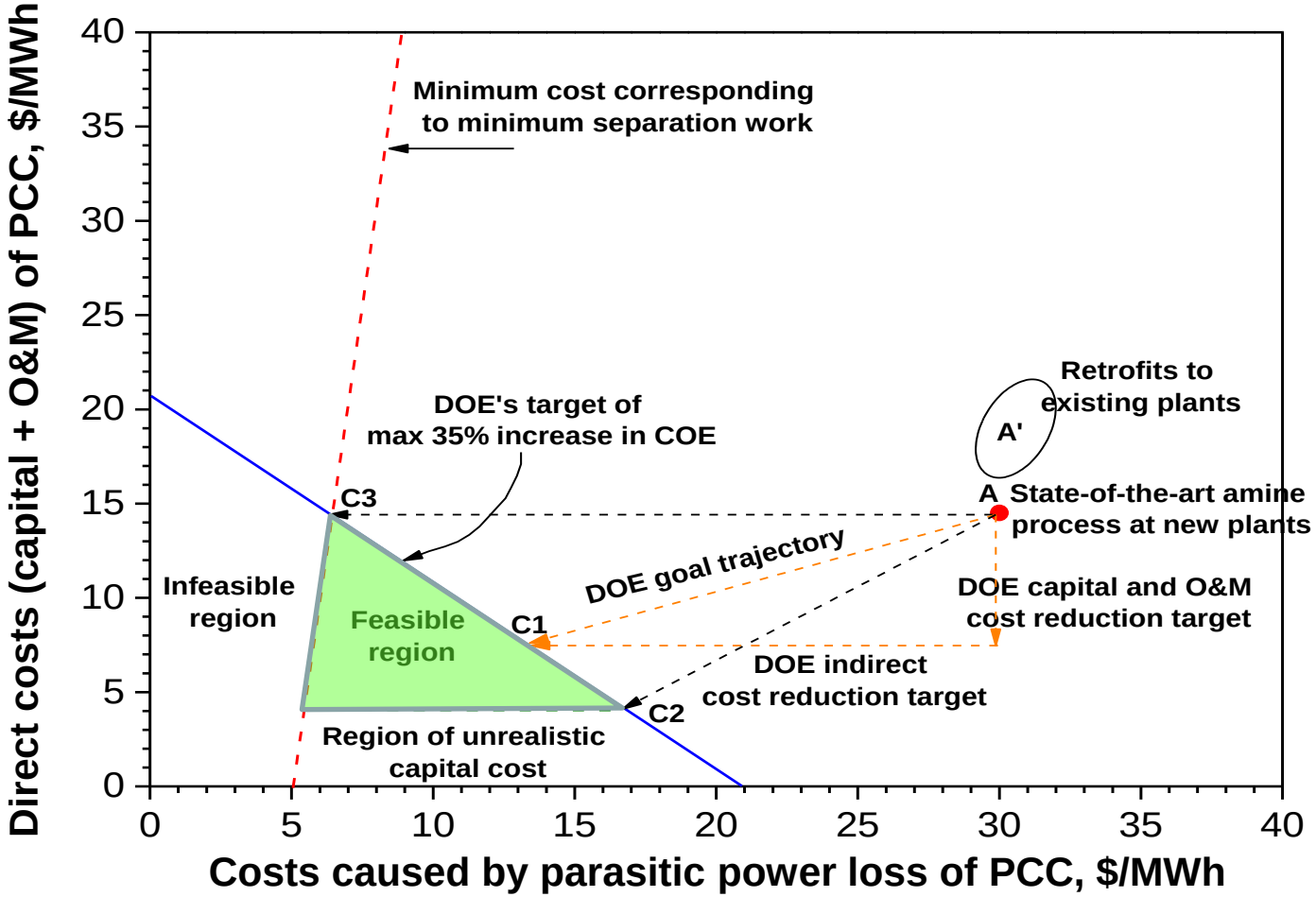
- Lab/Bench-Scale Research on Innovative CO_2 Capture Technologies
- Large Pilot CO_2 Capture at University Power Plant
- Potential CO_2 Utilization in Illinois

US DOE's Cost Target for CO_2 Capture

- 90% capture efficiency
- 35% increase in COE for post-combustion
- 10% increase in COE for pre-combustion



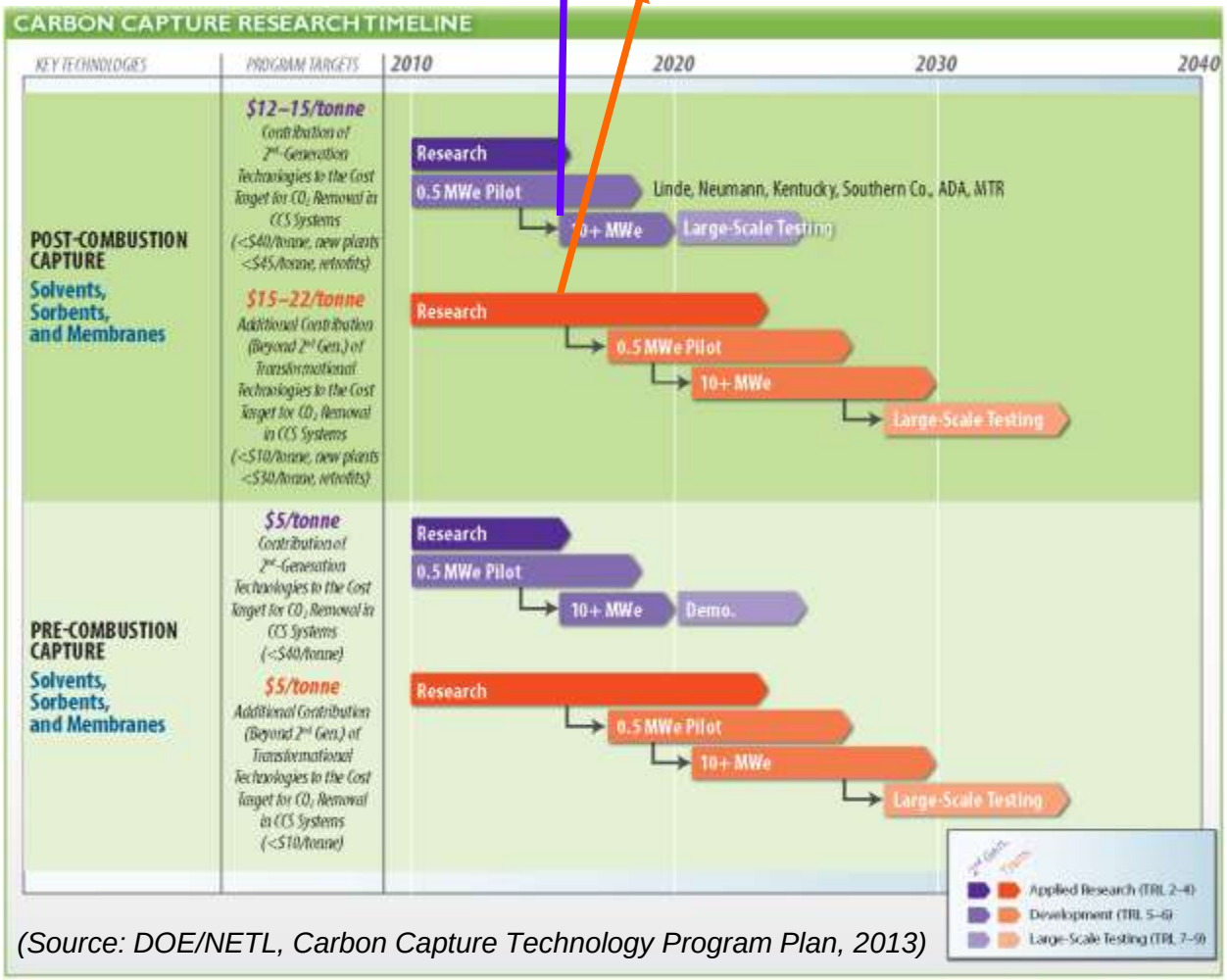
Trajectories for Meeting USDOE Cost Goals



- Reducing parasitic power loss has a significant effect on total cost
- Reducing direct cost (especially capital) also required to fulfill cost goals

USDOE Carbon Capture Program RD&D Roadmap

- DOE needs *large pilot-scale testing (10-25 MWe) of 2nd Generation Technologies* thru 2020
- DOE needs R&D efforts of *Transformational Technologies* thru 2030

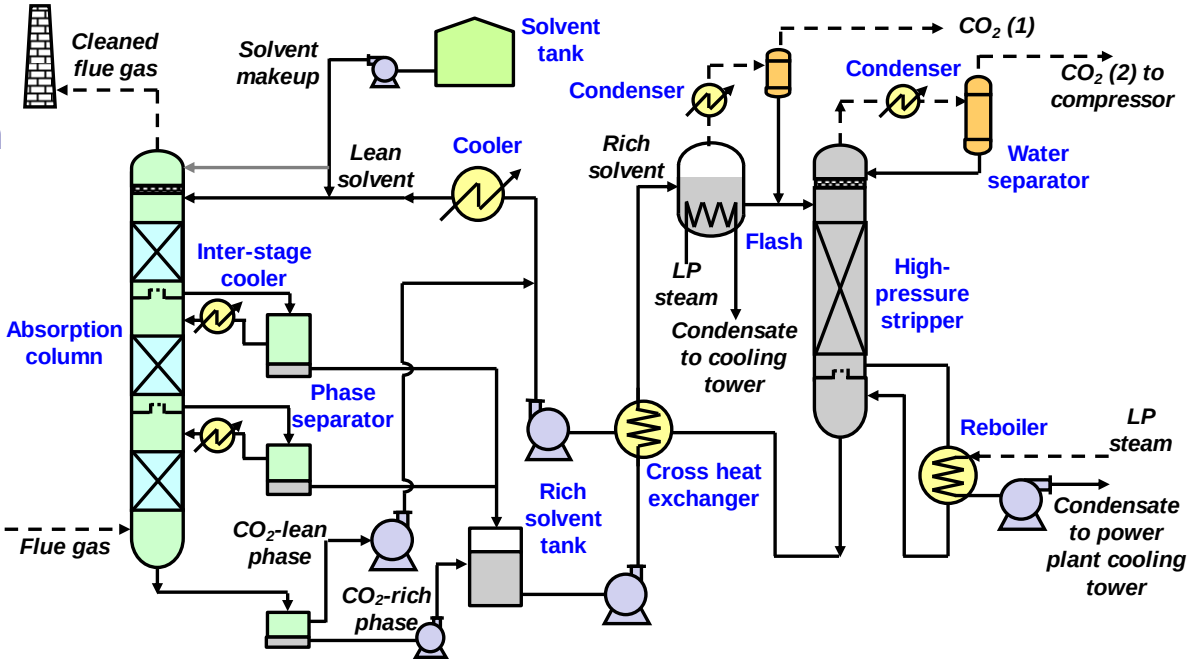


(Source: DOE/NETL, Carbon Capture Technology Program Plan, 2013)

Post-Combustion CO_2 Capture

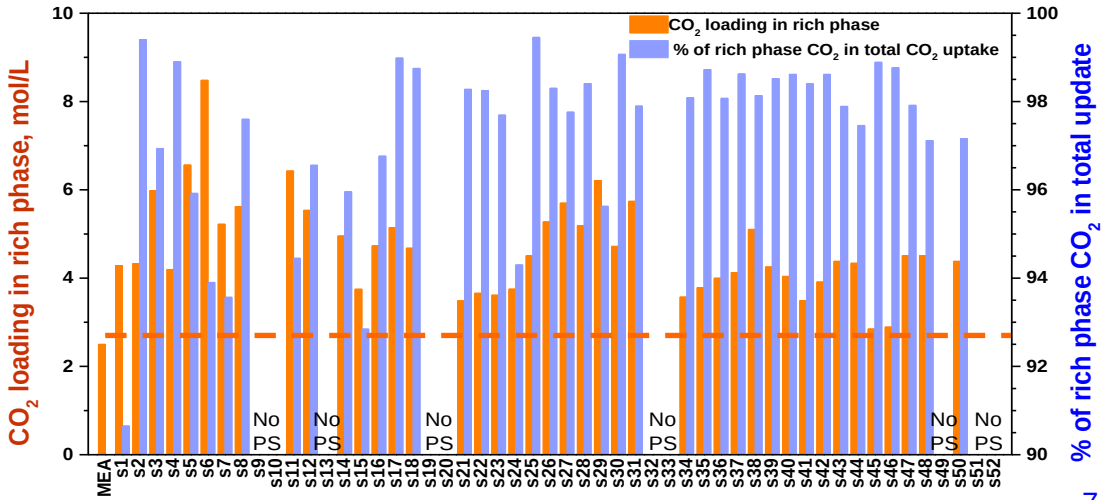
Biphasic CO_2 Absorption Process with Multiple Stages of Liquid–Liquid Phase Separation

- Biphasic solvents development
- Bench testing to demo phase separation-coupled CO_2 absorption
- Ongoing project funded by USDOE



Technology merits

- New solvents allow for tunable phase transition behavior (e.g., CO_2 distribution & rich phase vol%)
- Reduced viscosity with separation of rich, viscous phase during absorption improves mass transfer rate and kinetics
- Reduced mass and elevated P for CO_2 stripping



(1) Ye et al. IJGGC 2015, 39: 205-214); (2) Ye et al IJGGC 2017, 57:278-288.

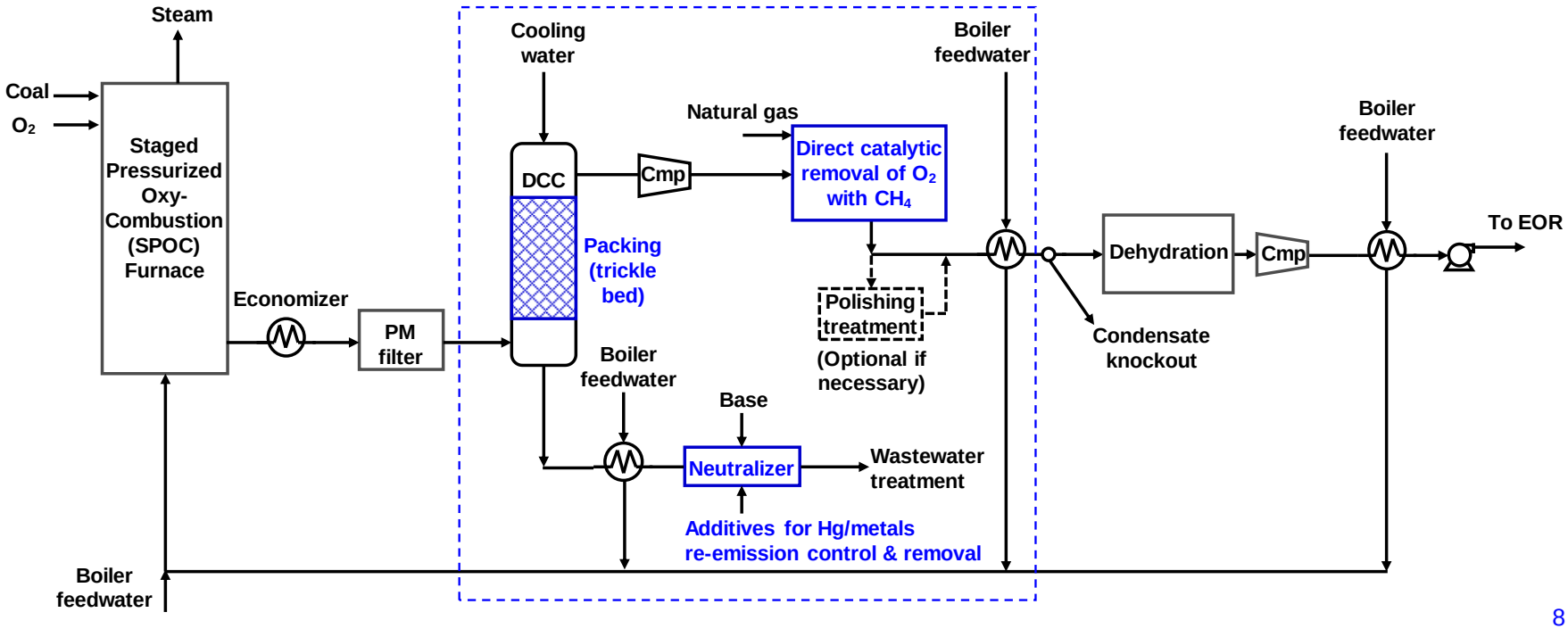
Oxy-combustion CO_2 Capture and Purification

Catalytic Removal of Oxygen and Pollutants in Exhaust Gases from Pressurized Oxy-Combustors (POC)

- Purified CO_2 meeting EOR specs
- Catalysts development & evaluation
- Slipstream testing at a POC facility
- Ongoing project funded by USDOE

Technology merits

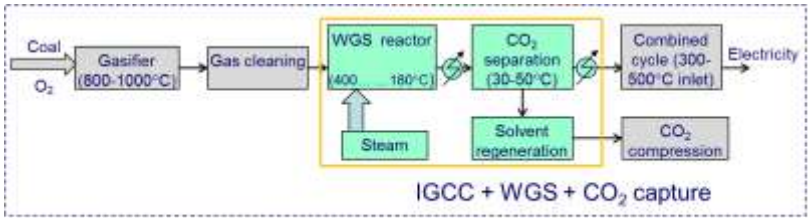
- Catalytic direct O_2 reduction by a reductant (e.g. CH_4) in a single reactor to avoid multiple steps and reduce costs
- Catalytic direct contact cooler (DCC) for simultaneous NOx/SO_2/Hg removal in a single device using inexpensive carbon-based catalysts to replace 2 DCCs + 1 Hg adsorption bed

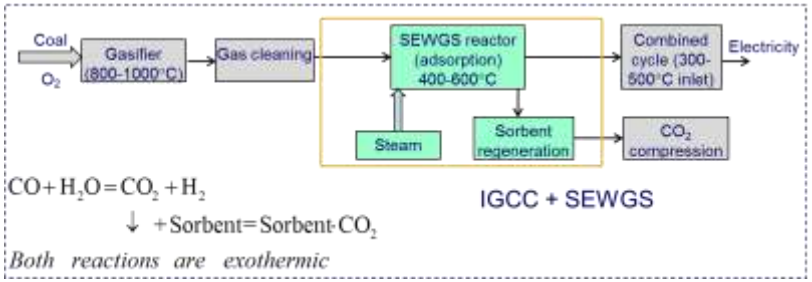


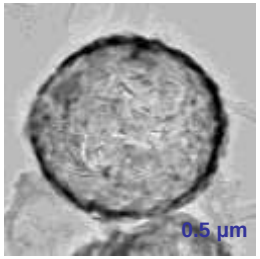
Pre-Combustion CO_2 Capture

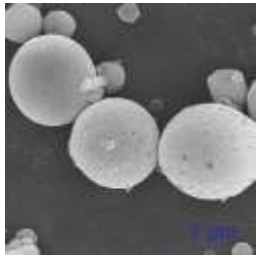
Dry sorbent technology for sorption enhanced WGS (SEWGS)

- Materials development & preliminary engineering analysis
- Lab-scale project funded by USDOE
- Bench-scale testing next stage

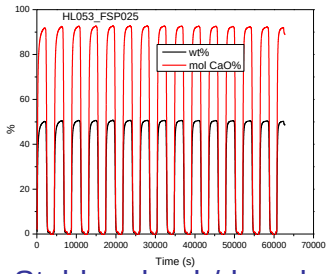








Novel hollow sorbents with high BET surface



Stable adsorb/desorb performance over multi-cycles

Technology merits

- Simultaneous WGS + CO_2 Capture with complete conversion of CO to CO_2 at >400 ^oC
- No gas cooling/reheating requirement downstream
- No separate CO_2 capture unit required
- High CO conv. with reduced steam use

Major activities

- Seven desired sorbents via thermodynamic modeling
- Molecular Dynamics simulations to guide sorbent morphology and dopants selection
- Synthesis of composite sorbents by:
  - ✓ Ultrasonic spray pyrolysis
  - ✓ Flame spray pyrolysis
  - ✓ Mechanical alloying
- Sorbent evaluation testing in simulated syngases
- Preliminary engineering feasibility study (reactor design, sizing, and cost analysis)

(1) Sayyah et al. ChemSusChem. 2013, 6: 193-198;
(2) Lu et al. Int. J. Hydrogen Energy 2013, 38(16): 6663-6672)

Pilot Testing at University of Illinois' Abbott Power Plant

University of Illinois' Abbott Power Plant:

- Cogeneration of electrical power and heat
- Total electric capacity: 84 MW; Steam capacity: 460 tonne/hr
  - 3 coal-fired boilers (~35 MW)
  - 2 natural gas-fired boilers
  - 2 gas turbines
  - 2 heat recovery steam generators
- ESPs and a wet FGD scrubber in place for coal boilers

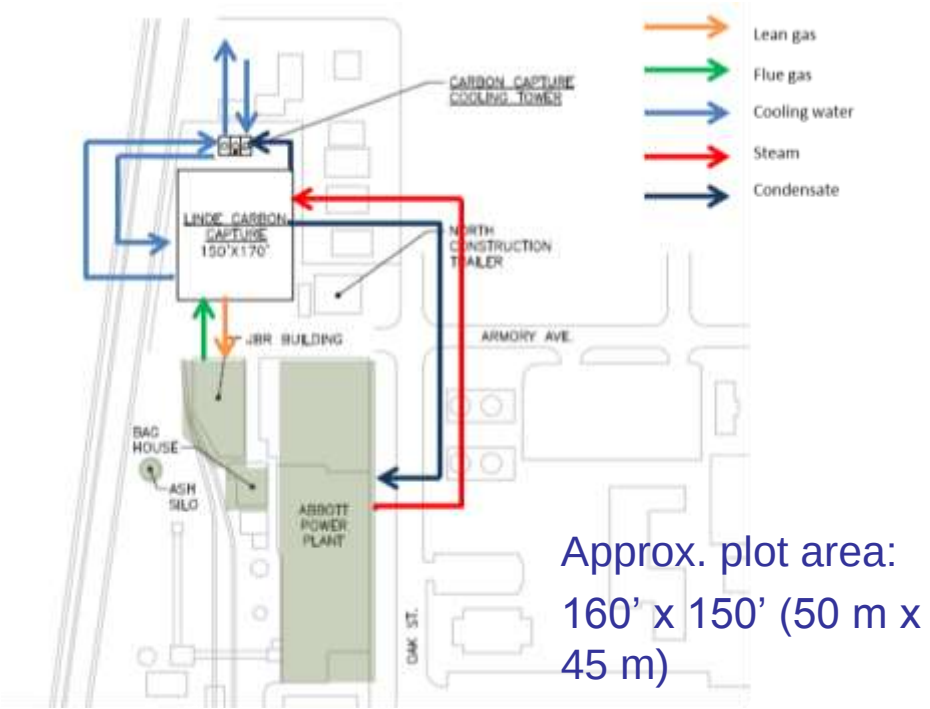
- ***Ideal site for pilot testing of coal and natural gas***
- ***Tradition of evaluating new emission technologies***
- ***Tradition of showcasing technologies to other power plants and education groups***

Large Pilot Capture Testing (15 MWe) for Abbott Plant Coal Boilers

- Illinois team led by University: University of Illinois, Linde/BASF, Affiliated Engineers Inc., ACS, and Washing University in St. Louis

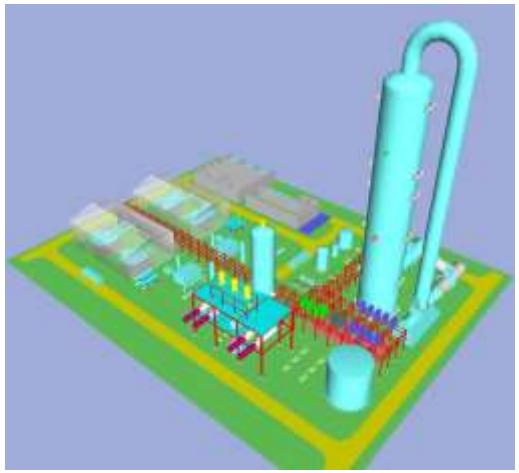
- Phase I (Pre-FEED study) awarded to University by USDOE: 10/1/2015- date

- Phase II (build & test): $75 million project with $60 million from DOE and $15 million cost share: proposal pending at USDOE

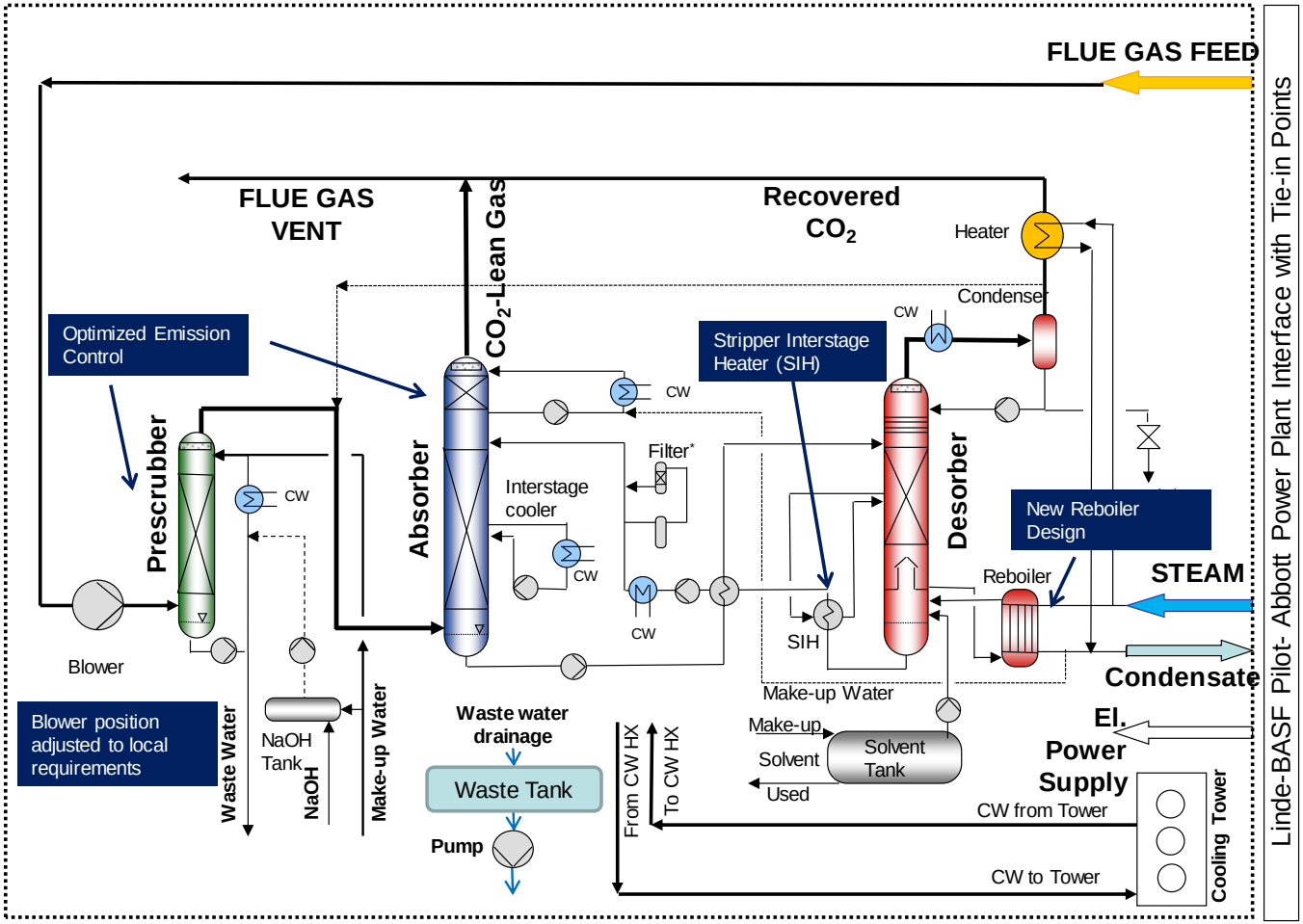


Approx. plot area:

160’ x 150’ (50 m x 45 m)



Overview of Linde/ BASF Capture System



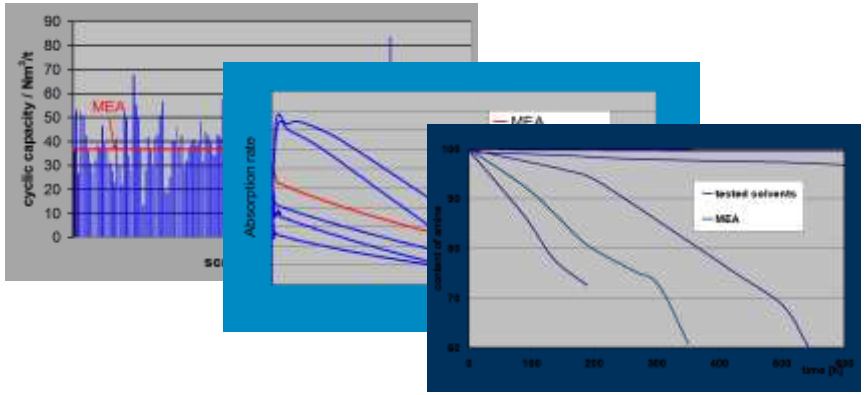
- Innovative water wash section at column top to reduce amine losses;
- High-capacity structured packing;
- Innovative plate & frame design of the reboiler;
- Stripper Interstage Heater (SIH) used to enhance energy efficient CO_2 stripping;
- Variations of the stripper-reboiler flashing configuration

Linde/ BASF OASE® Blue Technology Development

Equilibria

Kinetics

Stability



Mini plant

—2001, Ludwigshafen
—Solvent performance verification

Pilot: 0.5MWe

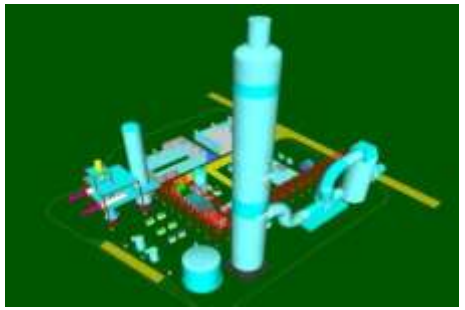
—2009, Niederaussem
—Process optimization, materials testing

Pilot: 1.5 MWe

—2014, Wilsonville, AL
—Design improvements,

Large Pilot: 15 MWe

—2016/20, proposed
—PCC plant cost reduction



Process Performance and Cost Summary 550 MW

Parameter	NETL Case 11	NETL Case 12	Linde Case LB1	Linde Case SIH
Scenario	No capture	CO_2 Capture with MEA	CO_2 Capture with OASE® blue	CO_2 Capture with OASE® blue and SIH
Net power output (MWe)	550	550	550	550
Gross power output (MWe)	580.3	662.8	638.9	637.6
Coal flow rate (tonne/hr)	186	257	236	232
Net HHV plant efficiency (%)	39.3%	28.4%	30.9%	31.4%
Total overnight cost ($2011)	1,348	2,415	1,994	1,959
Cost of captured CO_2 with TS&M($/MT)	N/A	67	52	50
Cost of captured CO_2 without TS&M ($/MT)	N/A	57	42	40
COE (mills/kWh)	81.0	147.3	128.5	126.5

LB1: Linde-BASF PCC plant incorporating BASF's OASE® blue aqueous amine-based solvent;
SIH: LB1 + an advanced stripper inter-stage heater design

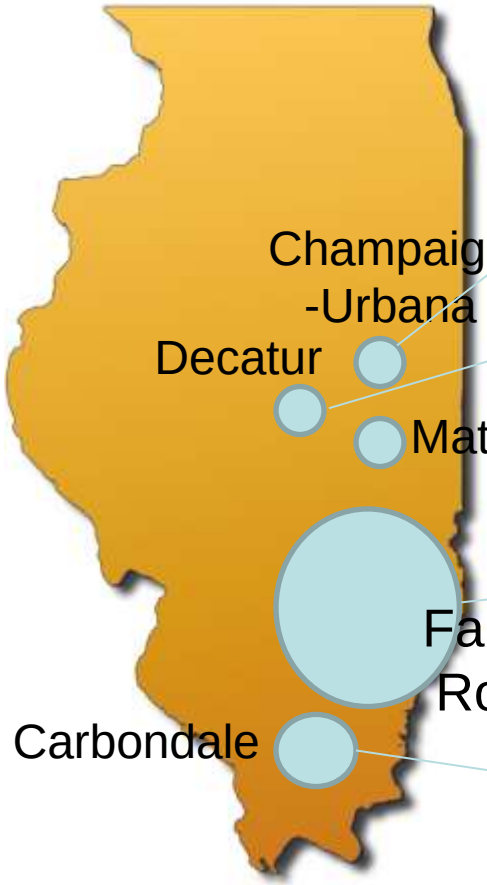
Regional & Global Test Bed for CCUS

Concentration of natural resources and intellectual capital

- Capture of CO_2 : Abbott Power Plant, UIUC

ADM MGSC Richland COMMUNITY COLLEGE

- Storage of CO_2: ADM Project



MATTOON
MATTOON, ILLINOIS: Working Together to Build the Future

- Utilization of CO_2: Enhanced Oil Recovery (EOR)

Illinois Eastern Community Colleges

- Operator Training

Southern Illinois University Carbondale

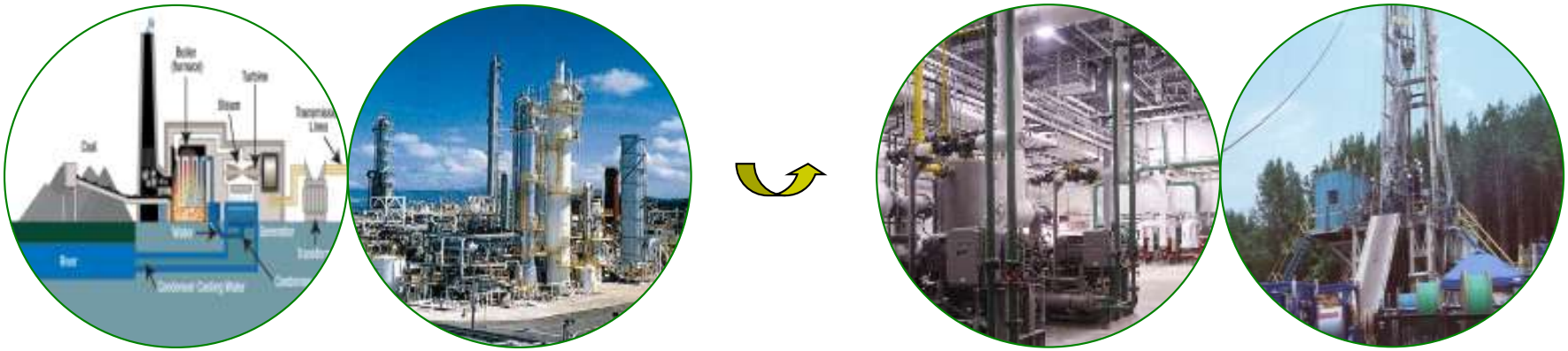
- Coal combustion

Utilization and Sequestration of Captured CO_2

CO_2 Source

Capture/ Compression

Utilization or Sequestration



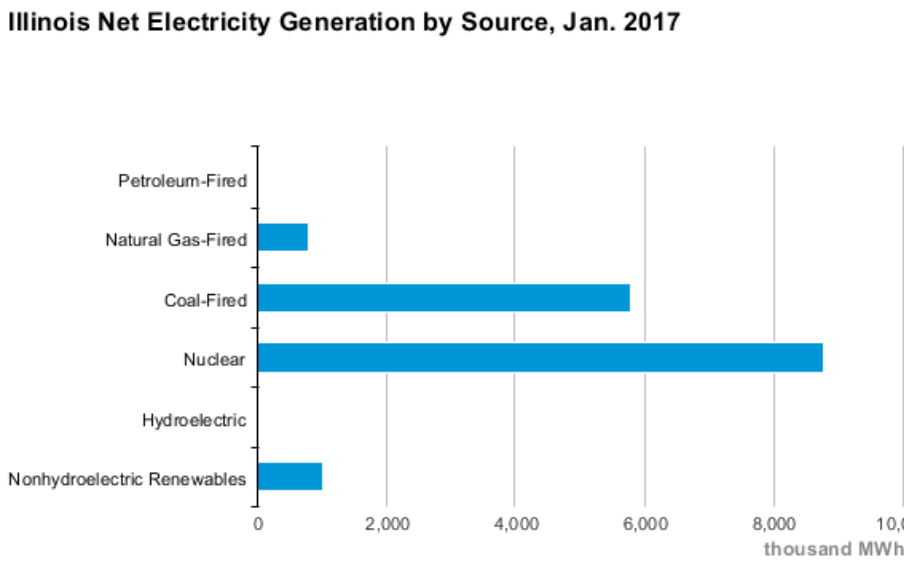
Utilization of captured CO_2 could creates a new market for Illinois:

- CO_2 for enhanced oil recovery and coalbed methane recovery
- CO_2 to enhance growth of crops
- CO2 for fuels/chemicals
- CO_2 for food & beverage manufacturing applications
- CO_2 for industrial & manufacturing applications (e.g., metal manufacture)
- CO_2 for large volume water treatment
- CO_2 for potential treatment of wastes

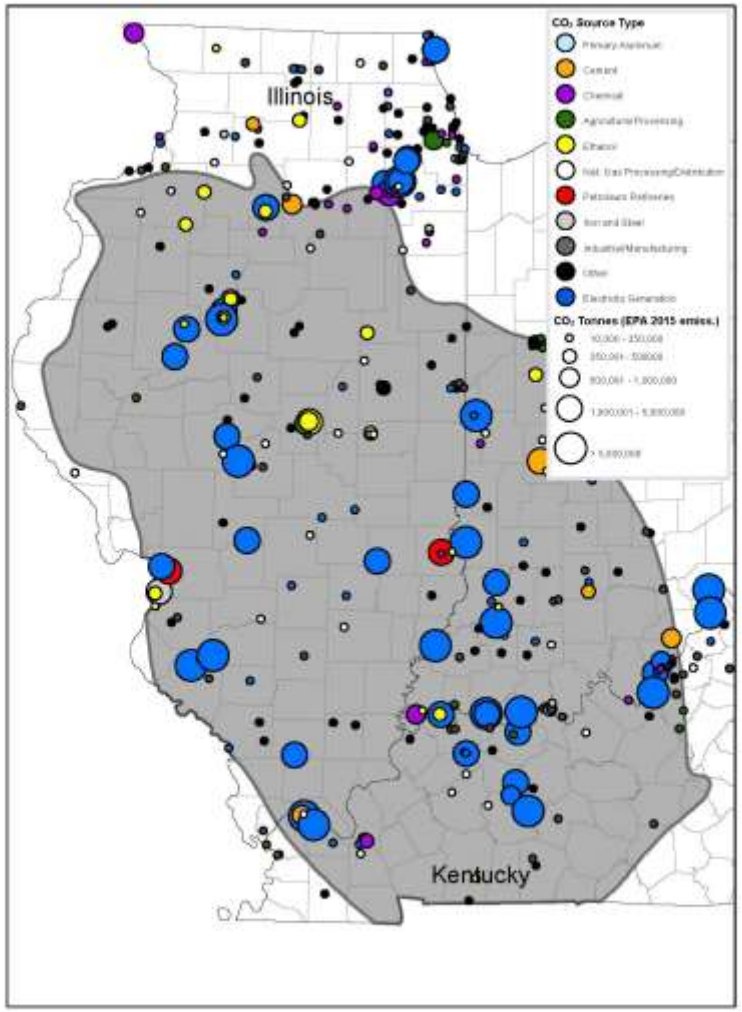
Illinois CO_2 Emission Sources

Stationary emissions

- Power plants: 101 MT (272 MT in Illinois Basin)
- Industries: 24 MT (32 MT in Illinois Basin)



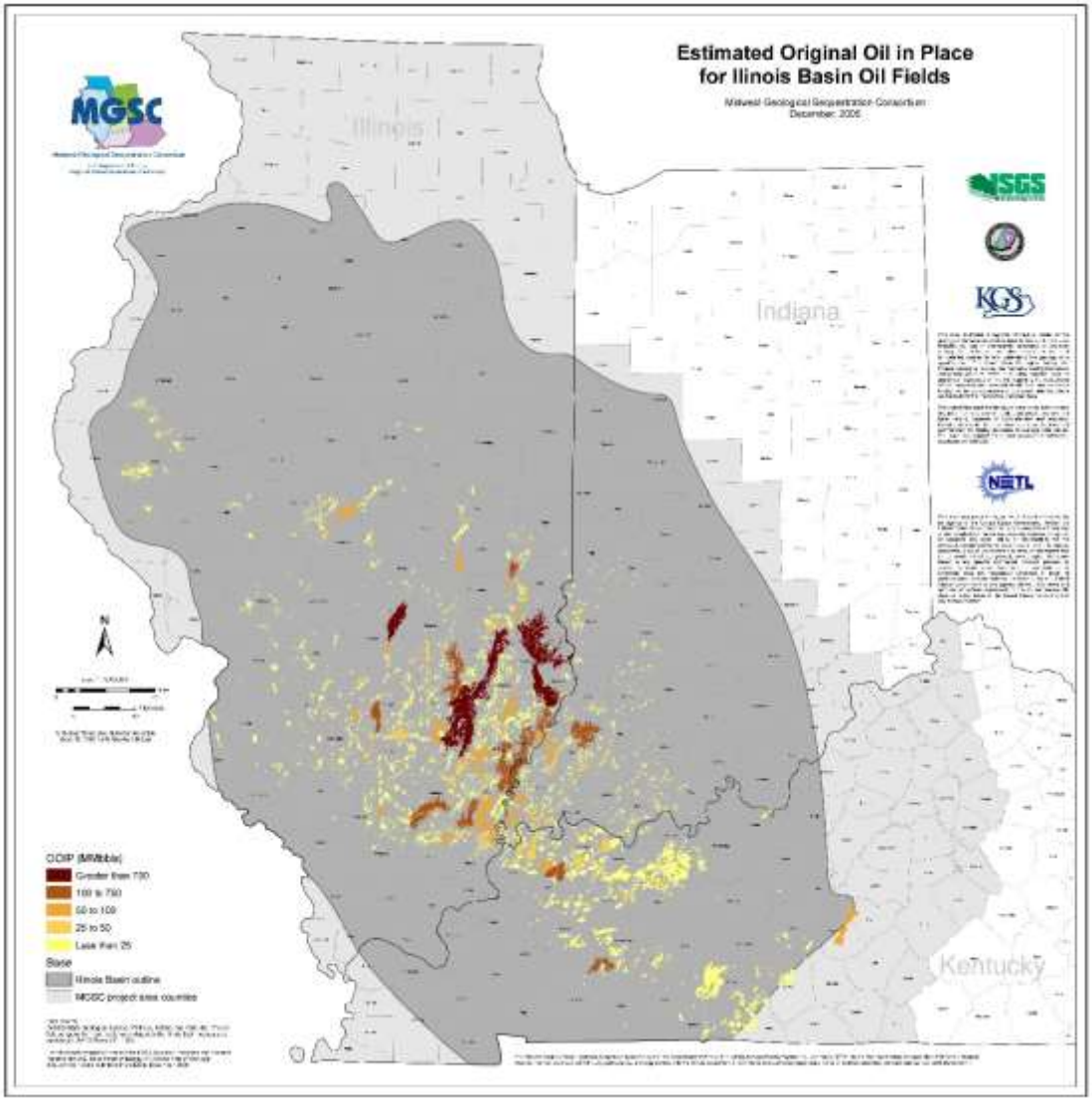
eia Source: Energy Information Administration, Electric Power Monthly



Nuclear and coal: two main electricity sources

Illinois Oil& Gas Metrics

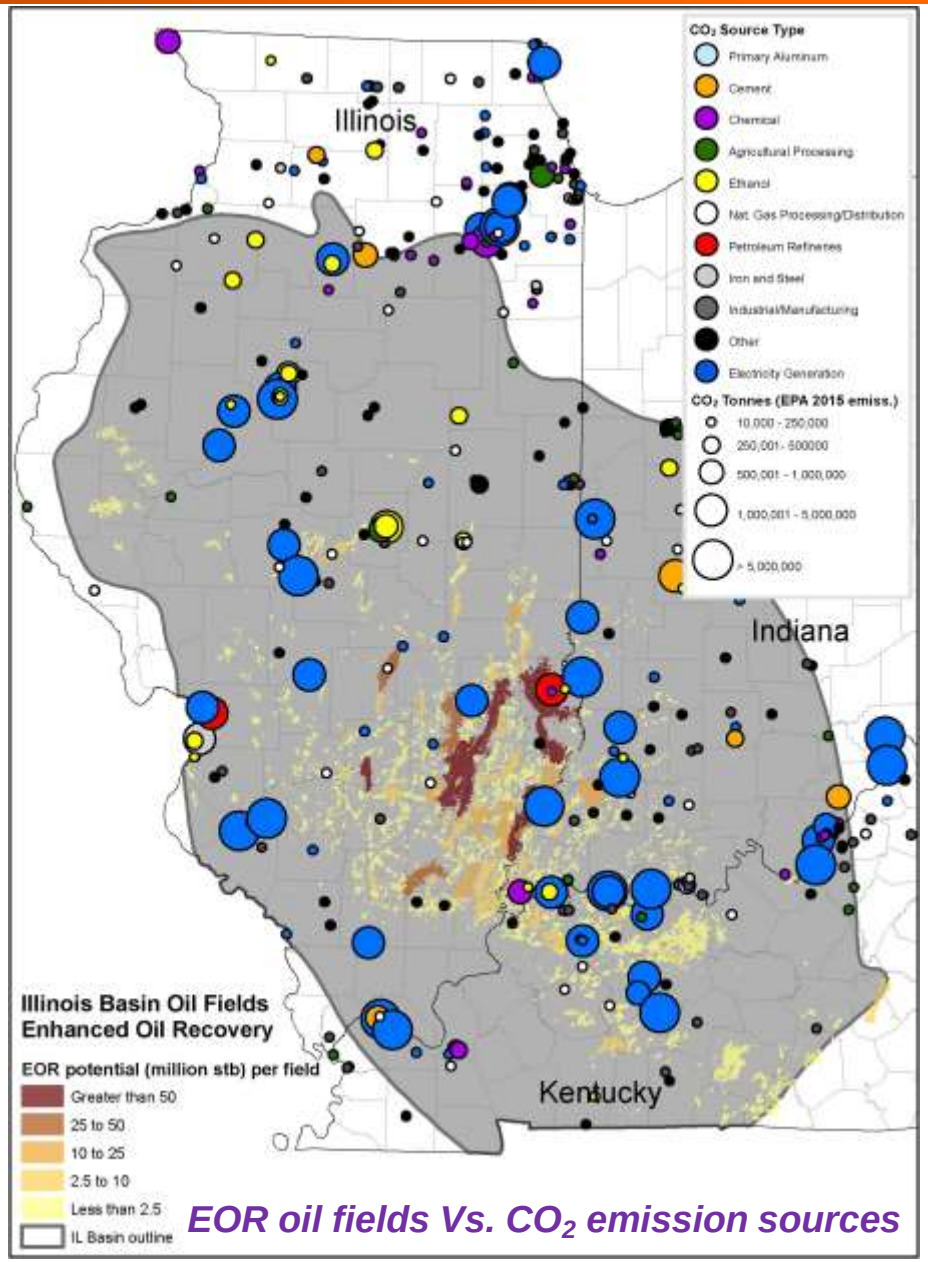
- 10 billion bbls unrecovered (4.2 produced)
- Oil & gas industry supports 263,000 jobs
- $33 billion to the state's economy (5.1% of the state GDP)
- Leads the Midwest in crude oil refining capacity (4th in the US)
- Oil production in ~40 of 102 counties (most in the south of the state)
- 532 oil fields with >16,000 active wells producing >9 million barrels /year



EOR-CO_2 Storage Potential in Illinois

State	CO_2 Storage Resource (million metric tons)	Estimated EOR* (million barrels)
Illinois	106–358	632–979
Indiana	20–47	124–162
Kentucky	14–35	104–138
Total	**140–440 million metric tons**	**860 million–1.3 billion barrels**

USDOE. Carbon Sequestration Atlas (Atlas III). Dec. 2010



EOR oil fields Vs. CO_2 emission sources

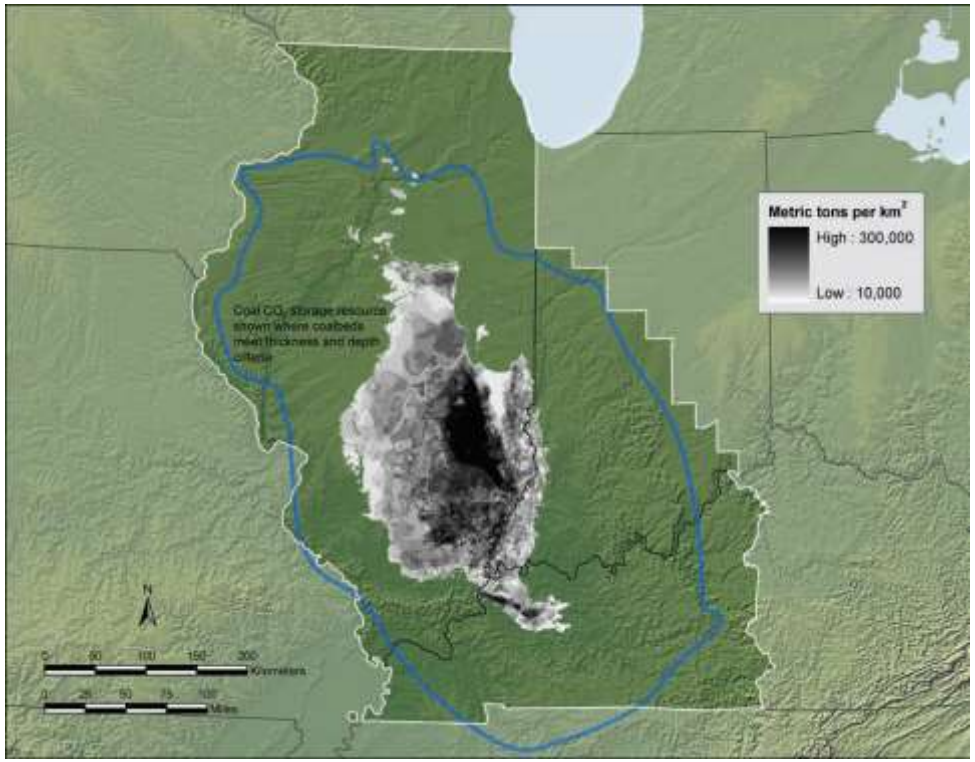
ECBM-CO_2 Storage Potential in Illinois

State	CO_2 Storage Resource* (million metric tons)	Estimated ECBM** (billion scf)
Illinois	1,470 to 2,900	2,700 to 9,800
Indiana	86 to 170	150 to 600
Kentucky	68 to 134	130 to 470
Total	1.6 to 3.2 billion metric tons	3.0 to 10.9 trillion scf

USDOE. Carbon Sequestration Atlas (Atlas III). Dec. 2010

- Unmineable coal: from 152 to 305 m in depth, seams from 0.48 to 1.1 m in thickness
- Gas contents: 3.1- 4.7 m^3/tonne; CO_2 adsorption: 14.1-21.9 m^3/tonne at 2,068 kPa

- >211 billion tons of identified resources estimated to lie beneath the state
- Demonstrated reserve base is 112 billion tons (2nd largest in US and for bituminous coal, largest)
- >$2.5 billion in annual economic activity within the State
- Employing ~5,000 miners



Coal: A Significant Resource for Illinois

SoyFACE: Evaluating Elevated CO_2 Levels on Crop Growth

FACE ring. Wind direction & speed and CO_2 concentration are measured in the center, then a computer controls which pipes release the gas and how much to release

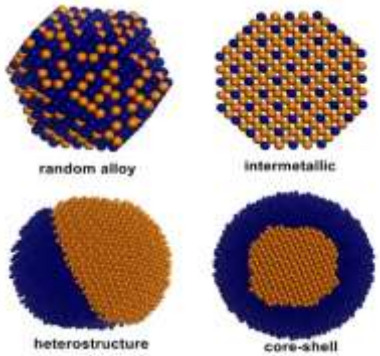
Fumigation ring is 30-m in diameter. At the center of the ring, wind speed and direction are monitored in real time

http://soyface.illinois.edu/

Free Air Concentration Enrichment (FACE) approach requires no enclosure

CO_2 to Fuels /Chemicals

- **Catalysts are key to CO_2 conversion processes**
- **Ability to dynamically tuning surface structure and composition (e.g., using a controlled chemical vapor environment to "pull" atoms to surface at proper thermal treatment conditions**

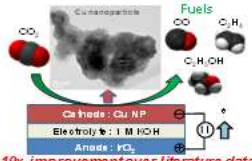


(Courtesy by Dr. Hong Yang)

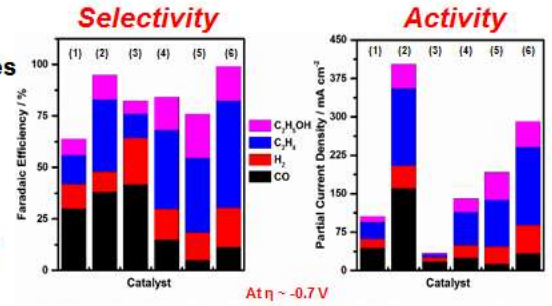
1. Commercially Available Cu Nanoparticles (NPs)

Starting point in 2013:
1 mg Cu/cm²
Total CD <125 mA/cm²

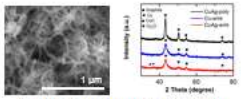
2. Active Cu Nanoparticles



10x improvement over literature data:
Partial CD C_2H_4 > 150 mA/cm²
Partial CD C_2H_5OH > 50 mA/cm²



6. Electrodeposited CuAgDAT-wire

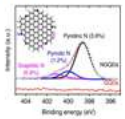


An *in situ* source for rate limiting CO (Ag) on the electrodeposited CuDAT-wire catalyst improves FE_{C2H4}

Catalyst shows world record performance:
FE_{C2H4} ~ 55% at –0.67 V *vs.* RHE
Total *FE* for C_2 product > 80%

3. N-doped Graphene Quantum Dots

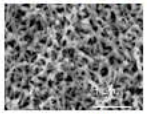
Metal free catalyst: exceptional selectivity and activity towards C_2 products



4. Cu NPs plus DAT in electrolyte

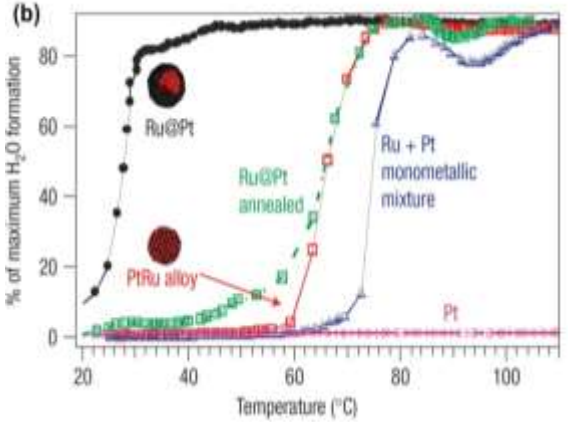
Addition of N containing ligand 3,5-diamino-1,2,4-triazole (DAT) to Cu NPs improves FE_{C2H4}

5. Electrodeposited CuDAT-wire



Wire like morphology (more steps and edges) leads to high FE_{C2H4} at low overpotentials

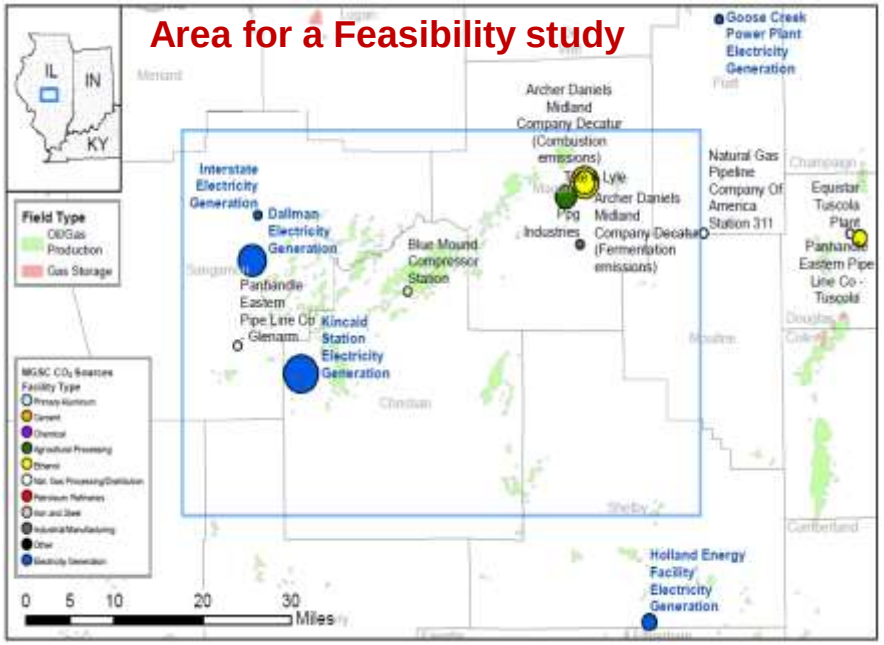
(Courtesy by Dr. Paul Kenis)

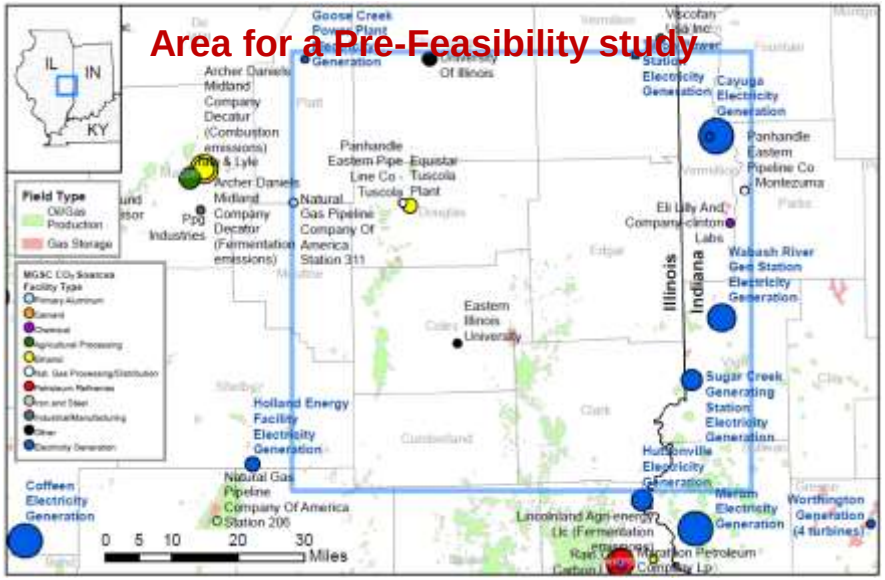


S. Alayoglu et al. *Nature Materials*, 2008, 333-338.

CarbonSAFE ILLINOIS

- $12 million funding – Commercial-scale CCS opportunities for +50 MT CO_2 CCUS in Illinois Basin
  - Geological characterization and utilization options such as EOR
    - drilling, core, modeling
  - Source suitability, options, and proximity to storage
  - Transportation needs
  - Business case scenarios
  - Pre-Feasibility and Feasibility studies





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College of Engineering / University of Illinois	Paul Kenis, Hong Yang
Linde	Krish Krishnamurthy, Makini Byron, Joseph Naumovitz, Torsten Stoffregen, Ali Jangi, Andy Poplin
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