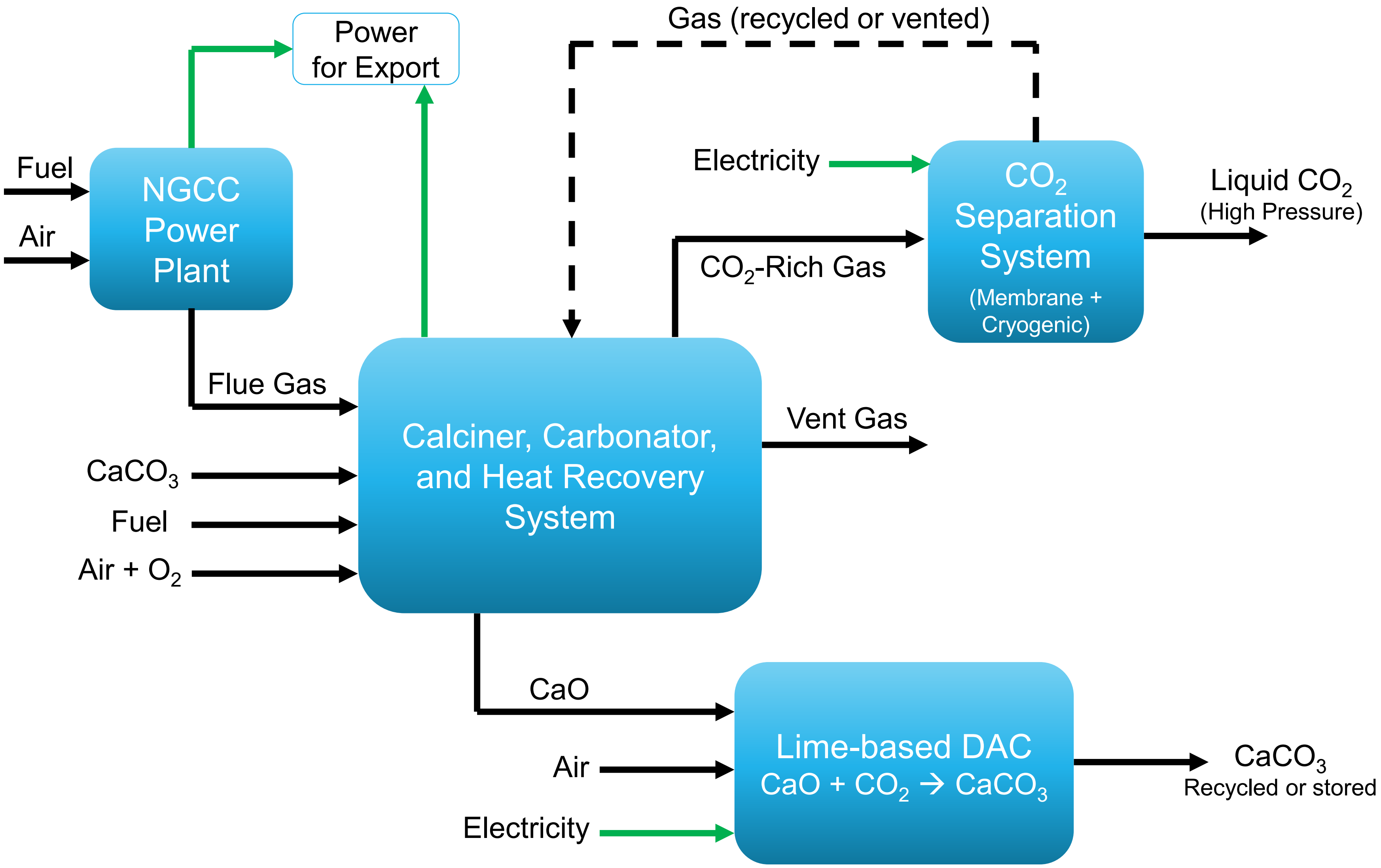
Power Plant CO_2 capture integrated with lime-based direct air capture

Howard J Herzog, Massachusetts Institute of Technology

Team Members: Dharik Mallapragada, Emre Gencer, Edward Graham, Moataz Sheha, Phillip Cross, Adam Goff, James Custer, Ian Cormier

Investigating the cost-effective design and operation of a negative emission power plant concept that combines flue gas CO_2 capture with a lime-based direct air capture (DAC) process in a way that enables power plant flexibility.

The Concept



- At low electricity prices, power plant off and DAC process runs at full capacity
- At high electricity prices, power plant runs at full capacity and the DAC process runs at reduced capacity

arpa·e
CHANGING WHAT'S POSSIBLE

The Team

MIT team: Leading process modeling and design optimization efforts.

Howard J Herzog
Senior Research Engineer
(Project PI)

Dharik Mallapragada
Research Scientist

Emre Gencer
Research Scientist

Edward Graham
Postdoctoral Associate

Moataz Sheha
Postdoctoral Associate

8 Rivers team: Leading capital cost and DAC system design.

Phillip Cross
Principal Engineer

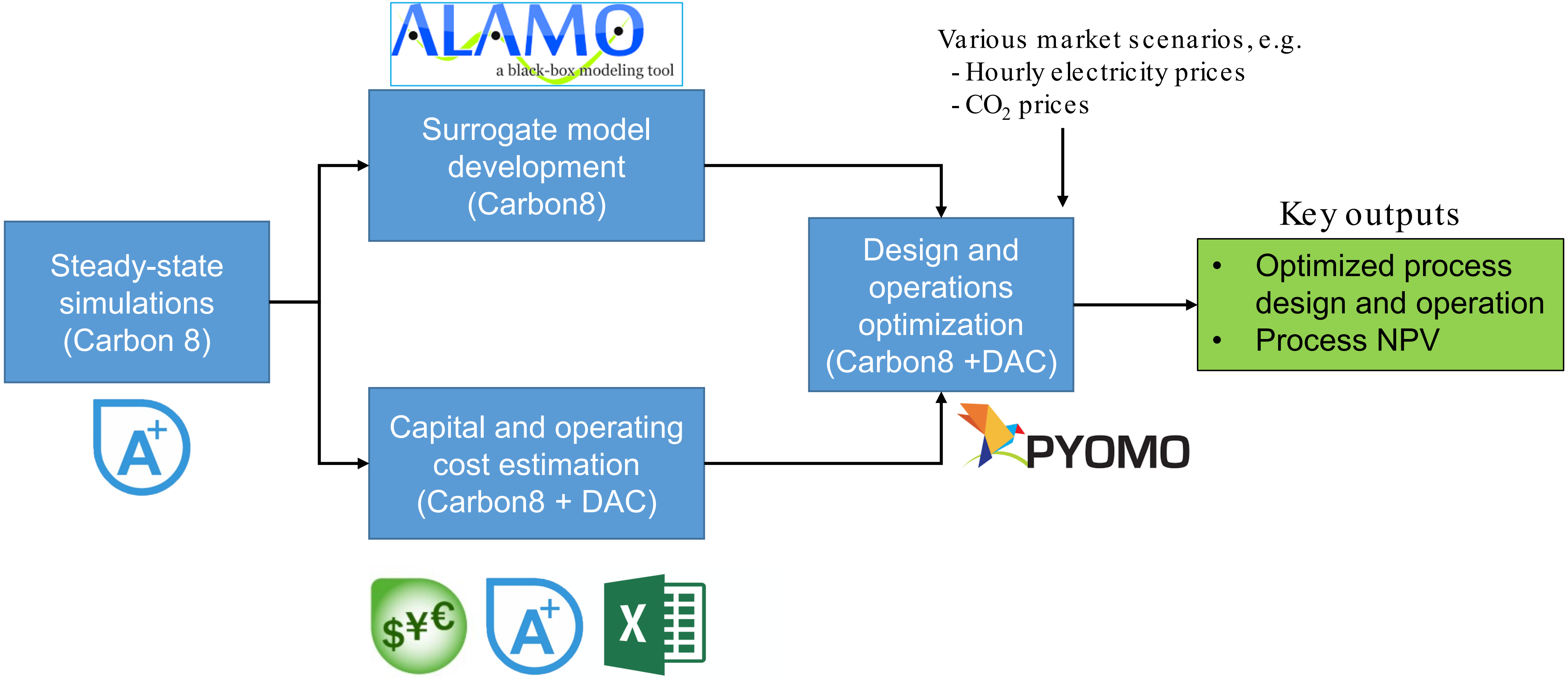
Adam Goff
Commercial Lead

James Custer
Chief of Staff

Ian Cormier
Principal Engineer

CHANGING WHAT'S POSSIBLE

Design, analysis and optimization methodology



Steady-state simulations (Carbon 8)

ALAMO a black-box modeling tool

Surrogate model development (Carbon8)

Capital and operating cost estimation (Carbon8 + DAC)

Various market scenarios, e.g.
- Hourly electricity prices
- CO_2 prices

Design and operations optimization (Carbon8 +DAC)

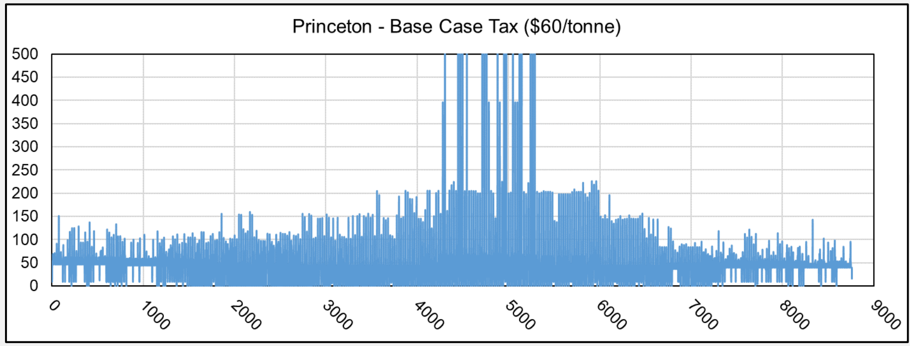
PYOMO

Key outputs
- Optimized process design and operation
- Process NPV

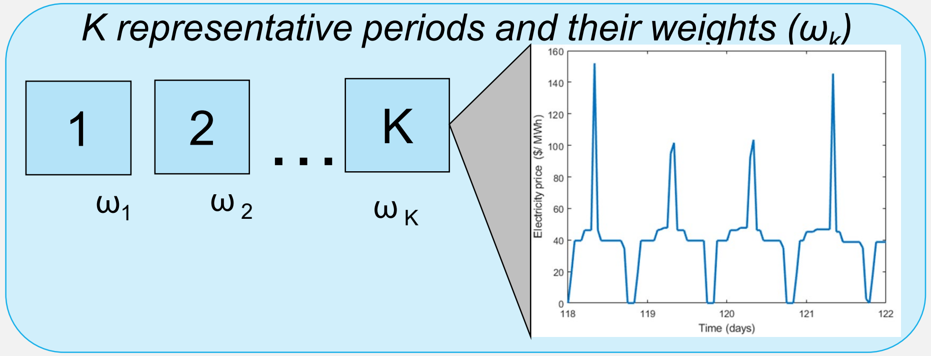
ALAMO reference: https://www.minlp.com/alamo

Design optimization approach accounts for temporal variability in grid electricity prices and its impact on plant operations

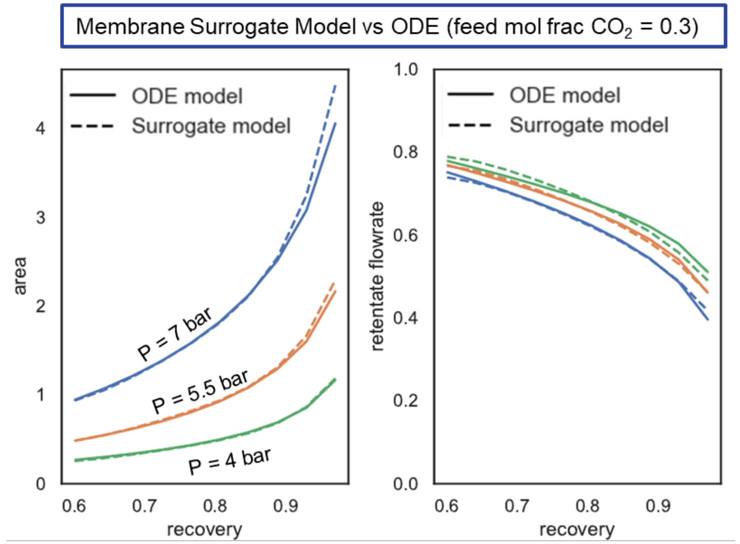
Representation of grid dynamics in design optimization model



Time-domain reduction via clustering[1]



Surrogate model development (Membrane example)



Integrated Design and Operations Optimization

$$Maximize\ NPV = \sum_{t=1}^{K} \omega_t GridPower_t ElecPrice_t$$

$$- \sum_{g \in Units} CRF_g CapCost_g CapSize_g - \sum_{g \in Units} \sum_{t=1}^{K} \omega_t OPEX_{g,t}$$

Constraints

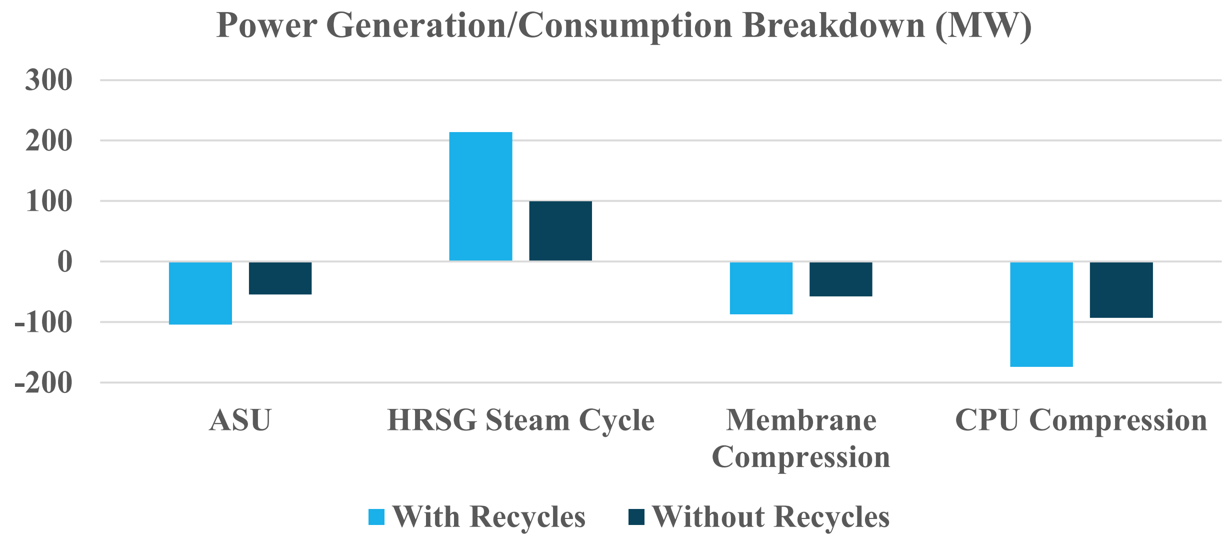
- Mass, energy balances and process connectivity (including surrogate models)
- Intertemporal operational constraints
- CO$_2$ accounting at hourly and annual time-scales

---

1. Mallapragada, D.S., Sepulveda, N.A. and Jenkins, J.D., 2020. Long-run system value of battery energy storage in future grids with increasing wind and solar generation. Applied Energy, 275, p.115390.

Extent of recycling of low-CO_2 streams from membrane + distillation process is a key design variable, involving OPEX-CAPEX and negative emissions trade-offs

Parameter	Full Loading Case with 100% Recycle[1]	Full Loading Case without Recycle[1]
Net Power (MW)	544	663
Net CO_2 Emissions (tonne/hr)	-473	-141
Relative CAPEX	1.4	1.0
Fresh $CaCO_3$ (tonne/hr)	1242	664
Calciner Solids Feed (tonne/hr)	2299	1227
Emissions Intensity (tCO_2/MWh)	-0.869	-0.229
CO_2 Recovery	98%	84%

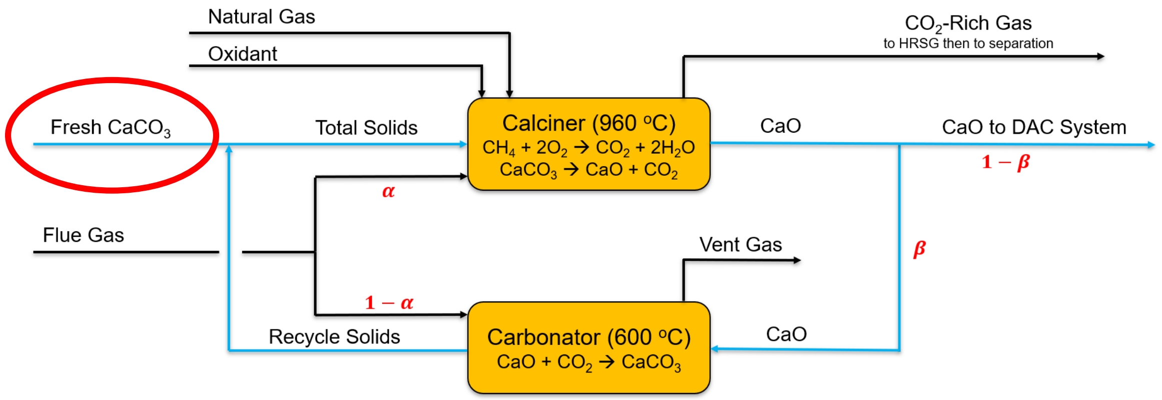


All results in this slide are preliminary and subject to change

---

[1] The results are based on 20/80 split fraction for the flue gas (i.e., 20% of the flue goes to the calciner) and 50/50 split fraction for the solids (i.e. 50% of the solids goes to the carbonator).

CO_2 capture system operates at part loading of power plant due to availability of non-power carbon source ($CaCO_3$)



Natural Gas

Oxidant

CO_2-Rich Gas
to HRSG then to separation

Fresh $CaCO_3$

Total Solids

Calciner (960 °C)
$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
$CaCO_3 \rightarrow CaO + CO_2$

CaO

CaO to DAC System

$1-\beta$

α

Flue Gas

Vent Gas

β

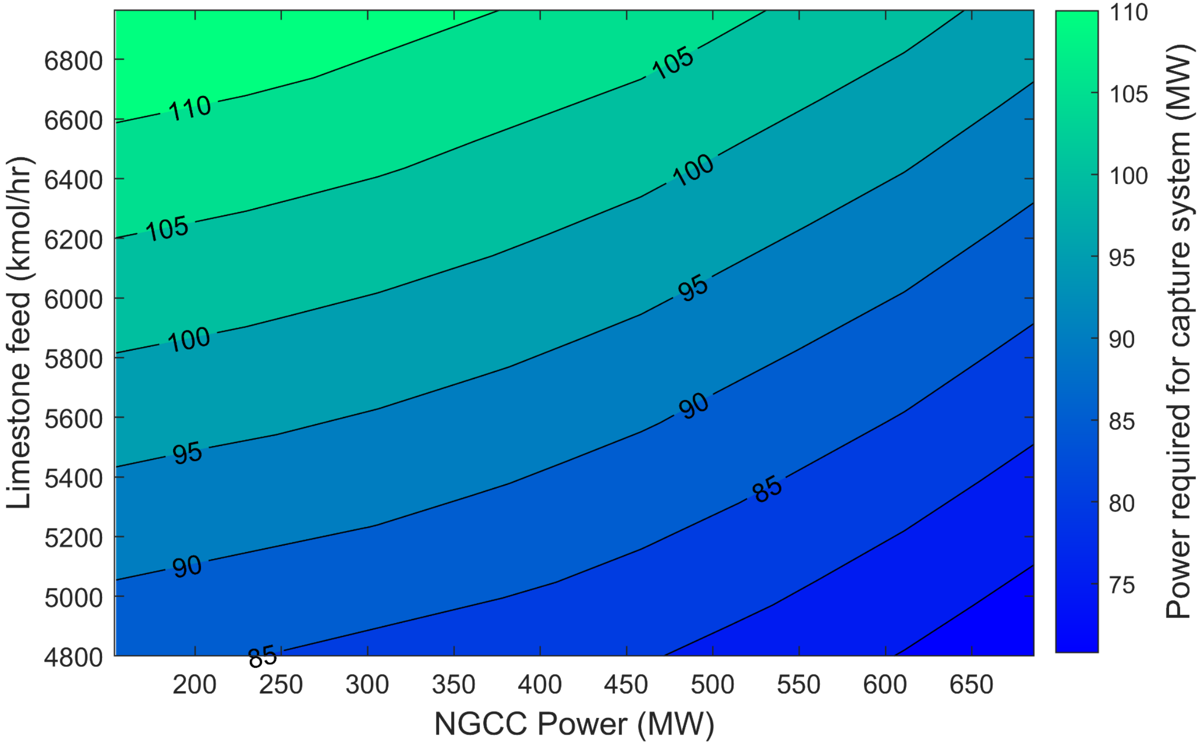
$1-\alpha$

Recycle Solids

Carbonator (600 °C)
$CaO + CO_2 \rightarrow CaCO_3$

CaO

Effect of Power Plant Loading and Limestone Feed on Capture System Power Requirements[1]



Key variables to be optimized for part load operations

- Limestone fresh feed
- Flue gas split fraction (α)
- Solids recycle fraction (β)

---

[1] The results are based on the case without any recycles, with 20/80 split fraction for the flue gas (i.e., 20% of the flue goes to the calciner) and 50/50 split fraction for the solids (i.e. 50% of the solids goes to the carbonator).

All results in this slide are preliminary and subject to change

CHANGING WHAT'S POSSIBLE

Project Status

- We have developed the three key modeling components
  - Steady state simulation model
  - Costing module
  - Preliminary design optimization model (using surrogate models)

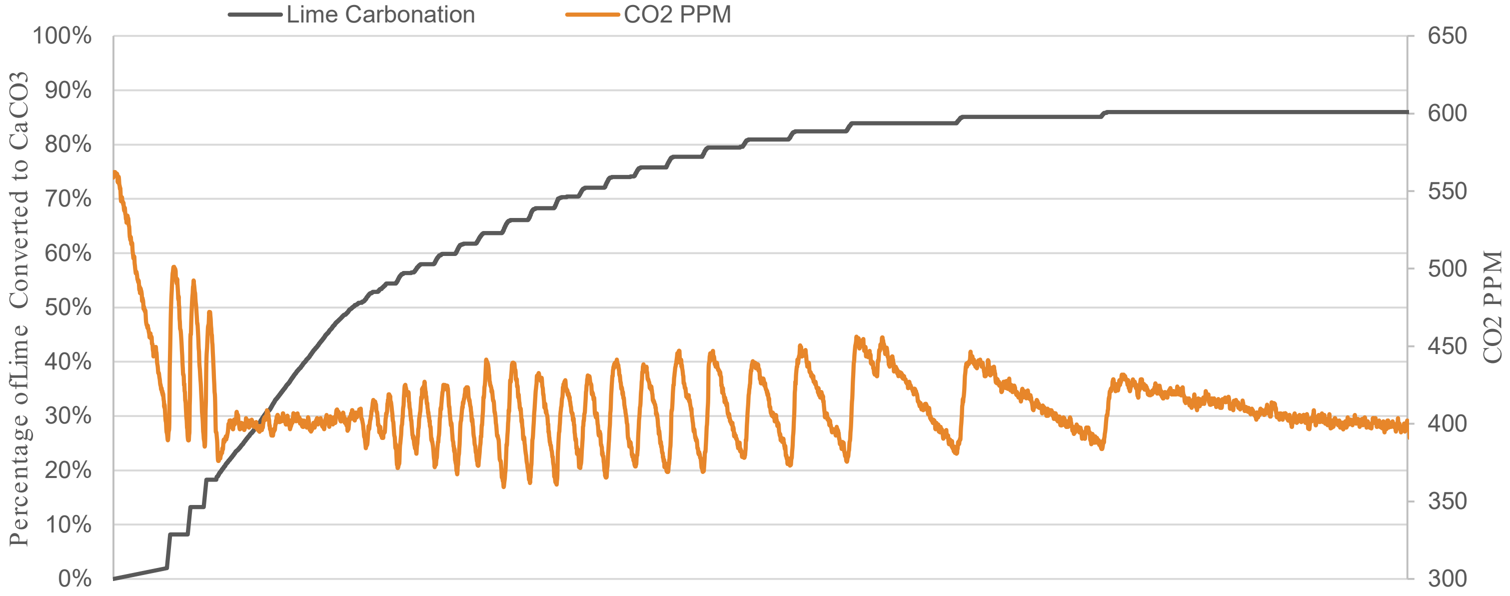
- Next step: evaluate optimization model for CO_2, electricity price scenarios
  - Determine the design and dispatch of the system
  - Explore NPV outcomes

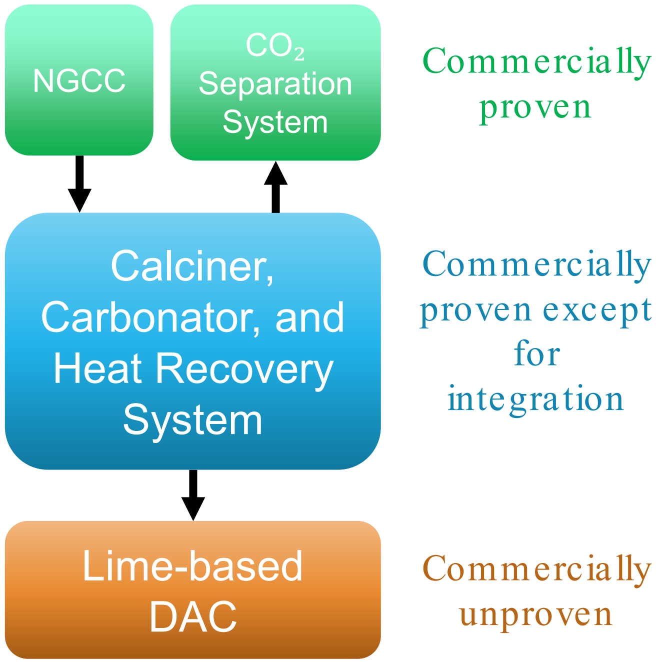
- Preliminary results indicate that positive NPV designs are achievable, with higher profitability in higher carbon price scenarios

Phase 2 Planning

- Build and operate ≈10k t CO2/y lime DAC air contactor to raise DAC to TRL 7
- Advance the integrated power concept modeling and design

Bench-Scale Lime-Based DAC Carbonation Data from Phase 1




NGCC

CO_2 Separation System

Commercially proven

Calciner, Carbonator, and Heat Recovery System

Commercially proven except for integration

Lime-based DAC

Commercially unproven

Phase 2 Planning

- Evaluating the potential of building a small kiln with CCS (50 t CaO/ day) to make the facility a commercially viable, carbon negative DAC plant.

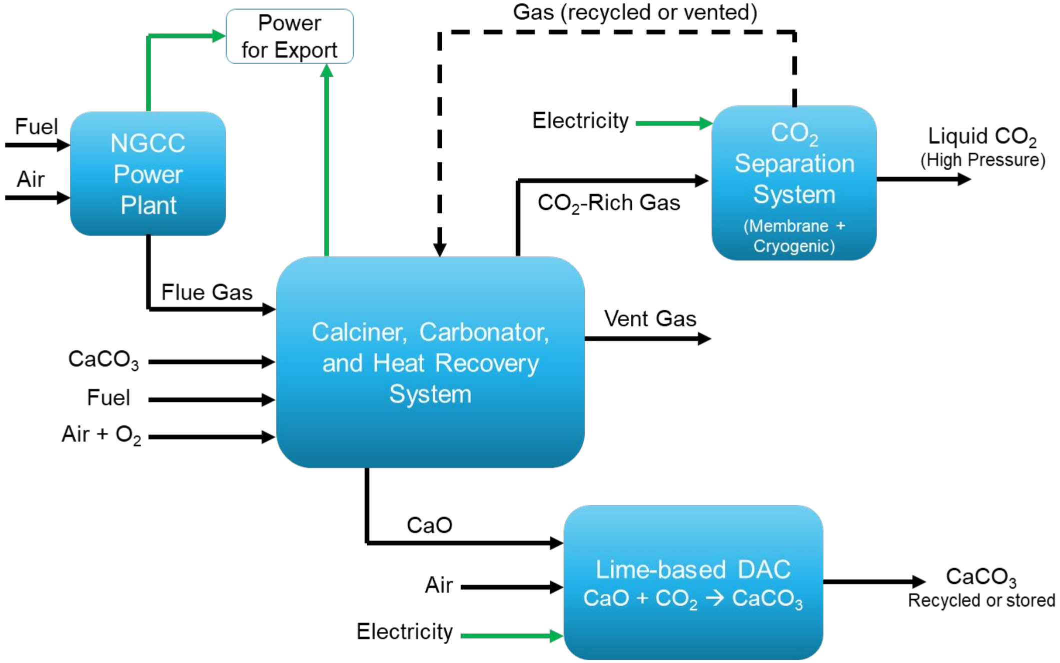
- To advance the integrated power concept in parallel, we would build on Phase I by:
  - Characterizing dynamic operation of individual unit operations
  - Incorporating insights into design optimization, improving granularity of cost modeling
  - Assessing the region specific market potential for the proposed FLECCS concept

The team will be:

- 8 Rivers (Lead)
- MIT (leading systems analysis)
- EPC (leading FEED and construction)
- Site host

EPCs and 2 sites in Southern US already under consideration

Summary



- Our process integrates a calcium looping CO_2 capture system with a lime based direct air capture system. The overall process is carbon negative and requires no power plant modification.
- The dispatchable, flexible power plant addresses two key challenges for a future power system: Load balancing and firm capacity.
- We achieve high utilization of key CCS equipment even with low utilization of the power plant. However, it requires a carbon incentive to be economical.