Calcium Looping for Post-Combustion CO_2 Capture:

System performance and cost analysis

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Outline of Talk

- Background
- Calcium looping process
- Performance model
- Cost model
- Case study
- Conclusions

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Background

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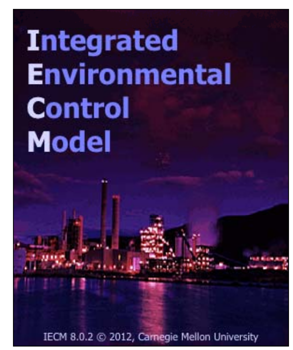
IECM: A Tool for Analyzing Power Plant Design Options

- A desktop/laptop computer simulation model developed for DOE/NETL
- Provides systematic estimates of performance, emissions, costs and uncertainties for preliminary design of:
  - PC, IGCC and NGCC plants
  - All flue/fuel gas treatment systems
  - CO_2 capture and storage options (pre- and post-combustion, oxy-combustion; transport, storage)
- Free and publicly available at: www.iecm-online.com



Current IECM Technologies for CCS (Version 8.0.2)

- CO_2 Capture Options
  - Pre-Combustion (IGCC):
    - Water gas shift + Selexol
    - Chemical looping
  - Oxy-Combustion (PC)
  - Post-Combustion (PC, NGCC):
    - Amine systems (MEA, FG+)
    - Chilled ammonia
    - Membrane systems
    - Auxiliary NG boiler or power plant (optional)
- CO_2 Transport Options
  - Pipelines (six U.S. regions)
- CO_2 Storage Options
  - Deep Saline or Other Formations
  - Enhanced Oil Recovery (EOR)

Advanced Capture Technology Models Under Development (Version 9.0)

Post-Combustion Capture
- Advanced membranes
- **Calcium looping**
- Solid sorbents
  - Amine-based
  - Activated carbon-based
  - Metal organic frameworks
- Ionic liquids

Oxy-Combustion Capture
- Low-sulfur coals
- High-sulfur coals

Pre-Combustion Capture
- Ionic liquids
- Chemical looping
- Sorbent-enhanced WGS

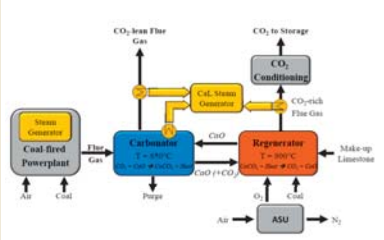
Calcium Looping Process

CaL concept and continuous operation tested successfully at lab and small pilot scales

- 75 kW_{th} CANMET [Lu et al, 2008]
  - Moving or BFB carbonator, O_2-fired CFB calciner
- 10 kW_{th} at IFK (U of Stuttgart) [Charitos et al, 2010]
  - BFB and CFB, alternating as carbonator or calciner
  - Electrically heated or natural gas fired
- 30 kW_{th} at INCAR-CSIC Spain [Rodriguez et al, 2011]
  - Interconnected CFB reactors, air-fired calciner
- 200 kW_{th} at IFK, U of Stuttgart [Dieter et al, 2013]
  - Turbulent FB carbonator, Oxy-fired (wood) CFB calciner
- 1.7 MW_{th} at INCAR, Spain [Arias et al, 2013]
  - CFB carbonator and calciner, Air-fired or oxy-fired (coal)

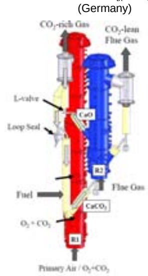
Proposed Designs for Post-Combustion CO_2 Capture Using Calcium Looping

Integrated Process Schematic

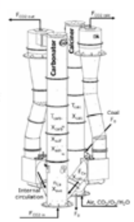


Source: Dieter, 2013; Energy Procedia; 37;148-56

IFK 200 kW_{th} setup (Germany)



"La Pareda" 1.7 MW_{th} setup (Spain)



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Techno-economic model

- Performance model
  - Calculates capture system mass and energy flows for specified operating conditions and a specified CO_2 removal efficiency
  - Calculates the overall performance, emissions and resource requirements of the entire power plant
- Cost model
  - Calculates capital and O&M costs of the capture unit
  - Calculates capital cost, O&M costs and levelized cost of electricity (LCOE) for the entire power plant

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Performance Model

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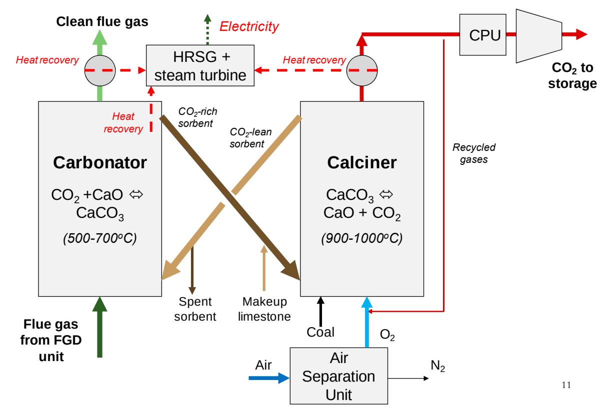
CaL process model for CO_2 capture



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Solids mass balance

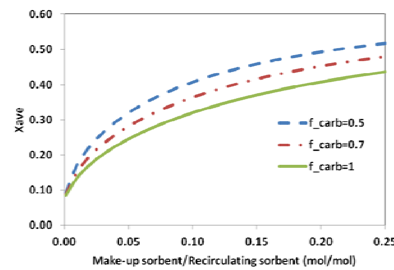
- Calciner reactions
  - $C + O_2 \rightarrow CO_2$; $2H + ½O_2 \rightarrow H_2O$; $S + O_2 \rightarrow SO_2$ (coal combustion)
  - $CaCO_3 \Leftrightarrow CaO + CO_2$
  - $CaO + SO_2 + ½O_2 \rightarrow CaSO_4$
- Carbonator reactions
  - $CaO + CO_2 \Leftrightarrow CaCO_3$
  - $CaO + SO_2 + 1/2\ O_2 \Leftrightarrow CaSO_4$
- Solids streams consist of CaO, $CaCO_3$, $CaSO_4$ and ash
  - $CaSO_4$ and ash rates depend on calciner coal combusted
- Overall mass balance in carbonator:
  - $M_{CaCO3\ formed,carbonator} = \eta_{CO2} M_{CO2,fluegas}$
    $= X_{carb} F_{CaO,avail} = X_{carb}(M_{CaO,inlet,carb} - M_{SO2,fluegas})$

Sorbent conversion depends on number of cycles, and amounts of recycled and fresh sorbent

Maximum conversion of CaO to $CaCO_3$ (X_{ave}):

$$X_{ave} = f_{calc}\left(\frac{f_m + 1}{f_m + f_{calc}}\right)\left[\frac{0.100813 f_m}{f_m + 0.0178 f_{carb} f_{calc}} + \frac{0.48654 f_m}{f_m + 0.2095 f_{carb} f_{calc}} + 0.07709\right]$$

f_{carb} = degree of carbonation; f_{calc} = degree of calcination;
f_m = make-up $CaCO_3$ / recirculating sorbent (mol/mol)



Actual conversion in carbonator (rich-loading):

$$X_{carb} = \frac{f_{carb}}{1 - (1 - f_{carb})(1 - f_{calc})} X_{ave}$$

Actual conversion in calciner (lean-loading):

$$X_{calc} = (1 - f_{calc}) X_{carb}$$

Adapted from: Rodriguez et al,. Chem Eng J 2010; 156:388-394

Energy balance

- Calciner heat requirement is sum of:
  - Calcination reaction energy, plus
  - Sensible heat to heat solids from carbonator, make-up limestone ,and recycled gas stream

$$H_{calc} = F_{CaCO3,calcined}\Delta H_{carb} + (F_{CaO,2}C_{p,CaO} + F_{CaCO3,2}C_{p,CaCO3} + F_{CaSO4,2}C_{p,CaSO4})\Delta T_{calc} + F_{CaCO3,m}C_{p,CaCO3}\Delta T_{makeup} + \sum F_{i,r}C_{p,i}\Delta T_r$$

- Coal flow to calciner then calculated:
  - $m_{coal} = (H_{calc}/HHV_{coal})/\ \eta_{comb}$
- Additional power is generated from heat recovery in carbonator, and gases exiting carbonator and calciner

Mass and energy balance equations are solved simultaneously to determine mass and energy flows

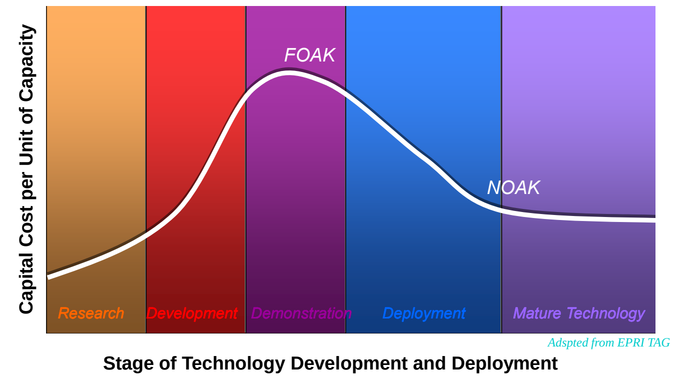
Cost model

Cost elements modeled

- Direct capital costs
  - Carbonator
  - Calciner
  - Air separation unit
  - Heat recovery system
  - Steam turbines
  - Solids handling
  - Blowers, etc.
  - CO_2 purification unit
  - CO_2 compressors
- Indirect capital costs
  - General facilities
  - Eng'g. & home office fees
  - Process contingency
  - Project contingency
  - Pre-production costs
  - Royalty fees
  - Interest during construction
- O&M costs
  - Coal
  - Fresh limestone
  - Waste disposal
  - Labor costs
  - Maintenance costs

All costs reported in constant 2012 US dollars

Typical cost trend of a new technology



E.S. Rubin, Carnegie Mellon

Case Studies

Assumptions for base plant (no CCS)

(SCPC unit; meets or exceeds current U.S. standards for new plants)

Base plant parameter	Value
Gross power output (MW)	650
Net plant power output (MW)	608
Capacity factor (levelized) (%)	75
Coal HHV (MJ/kg) (Appalachian medium sulfur)	30.5
Coal cost ($/tonne)	49.87
Flue gas CO_2 content at carbonator inlet (% vol)	11.91
Flue gas SO_2 content at carbonator inlet (% vol)	0.024

Base plant plus CaL-based CO_2 capture

(with pipeline transport and geological storage of CO_2)

CaL-based CO_2 capture process parameter	Value
CO_2 removal efficiency (%)	90
Limestone purity (%)	92.4
Carbonation conversion (f_{carb})	0.8
Calciner conversion (f_{calc})	0.95
Make-up sorbent to recirculating sorbent ratio (mol/mol)	0.025*
Sorbent cost ($/tonne)	25.8
Solid waste disposal cost ($/tonne)	14.7
CO_2 transport and storage cost ($/tonne)	3.2

* Equivalent to 1kg limestone per kg of coal feed to the calciner

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Case study performance results

Parameter	No CCS	CaL
Gross plant power output (MW)	650	1273
- Gross power from base plant (MW)	*650*	*650*
- Auxiliary power from CaL unit (MW)	-	*623*
Net plant power output (MW)	608	1056
Net plant efficiency (%HHV)	39	36
Coal flow rate for base plant (tonnes/hr)	183	183
Coal flow rate for calciner (tonnes/hr)	-	162
CO_2 captured (tonnes/hr)	-	1029

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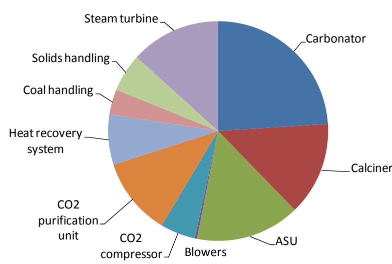
Case study cost results: CaL system direct capital costs

Component	$/kW$_{net}$
Carbonator	489
Calciner	281
ASU	313
Blowers	7
CO_2 compressors	105
CO_2 purification unit	234
Heat recovery system	151
Coal handling equipmt	76
Solids handling equipmt	114
Steam turbine	271
Process Facilities Capital (PFC)	**2,041**



All costs in constant 2012 US dollars

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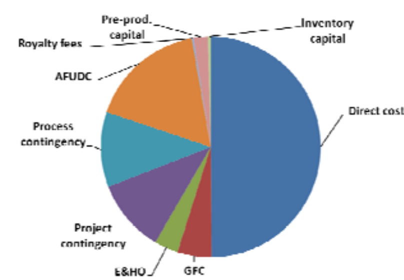
Case study cost results: CaL system total capital requirement

Cost component	$/kW$_{net}$ (FOAK)
PFC	2,041
General Facilities	204
Eng'g & Home Office	143
Project Contingency	437
Process Contingency	451
AFUDC	699
Royalty Fees	10
Pre-production Capital	87
Inventory Capital	16
Total Capital Reqm't	**4,088**



Estimated cost for FOAK plant based on current state of the CaL technology

All costs in constant 2012 US dollars

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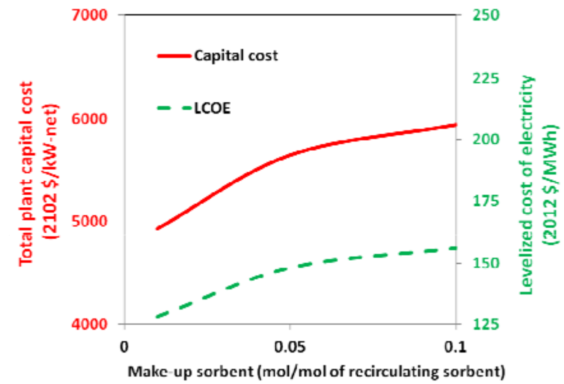
Case study cost results: Total power plant costs (FOAK)

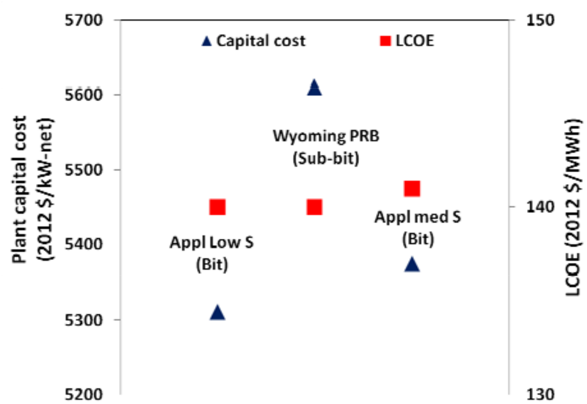
Parameter	No CCS	CaL (FOAK)
Net plant power output (MW)	608	1,056
Total plant capital cost ($/kW-net)	1,970	5,374
Levelized cost of electricity ($/MWh)	61	141
Cost of CO_2 captured ($/tonne)	-	83
Cost of CO_2 avoided ($/tonne) *		105

*Based on reference plant CO_2 flow rate of 0.82kg/kWh and LCOE of $59/MWh; Includes cost of transport and storage. All costs are in constant 2012 US dollars

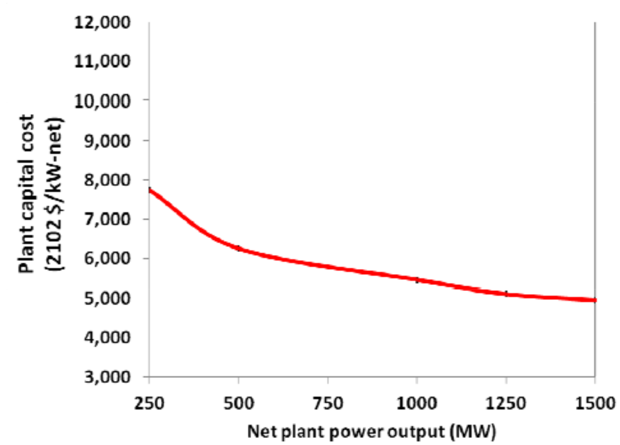
Effect of make-up sorbent fraction (FOAK case)



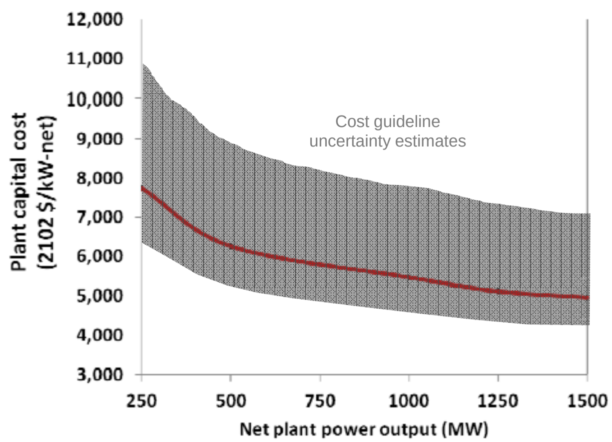
Effect of coal type (FOAK case)



Economy of scale (FOAK)



Economy of scale (FOAK)



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Case study cost results: FOAK vs. NOAK cost assumptions

Parameter	CaL (FOAK)	CaL (NOAK)
Net plant power output (MW)	1,056	1,056
CaL system total capital reqm't. ($/kW-net)	4,088	3,089
Total plant capital cost ($/kW-net)	5,374	4,231
Levelized cost of electricity ($/MWh)	141	103
Cost of CO_2 captured ($/tonne)	83	44
Cost of CO_2 avoided ($/tonne)	105	56

*Based on reference plant CO_2 flow rate of 0.82kg/kWh and LCOE of $59/MWh; Includes cost of transport and storage. All costs are in constant 2012 US dollars

To achieve Nth of a kind cost you have to build N plants!

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Conclusions

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Conclusions

- Power plant with CaL-based CO_2 capture has a lower energy penalty compared to current post-combustion CO_2 capture processes
- Based on preliminary case study assumptions, efforts are needed to reduce the capital cost of the CaL process for it to better compete with alternative post-combustion processes

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