Advancing Cleaner Energy

OPTIMIZING THE COSTS OF SOLID SORBENT-BASED CO_2 CAPTURE PROCESS THROUGH HEAT INTEGRATION

Cooperative Agreement
Award No. DEFE0012914

NETL Meeting
March 30, 2016

DE-FE0012914

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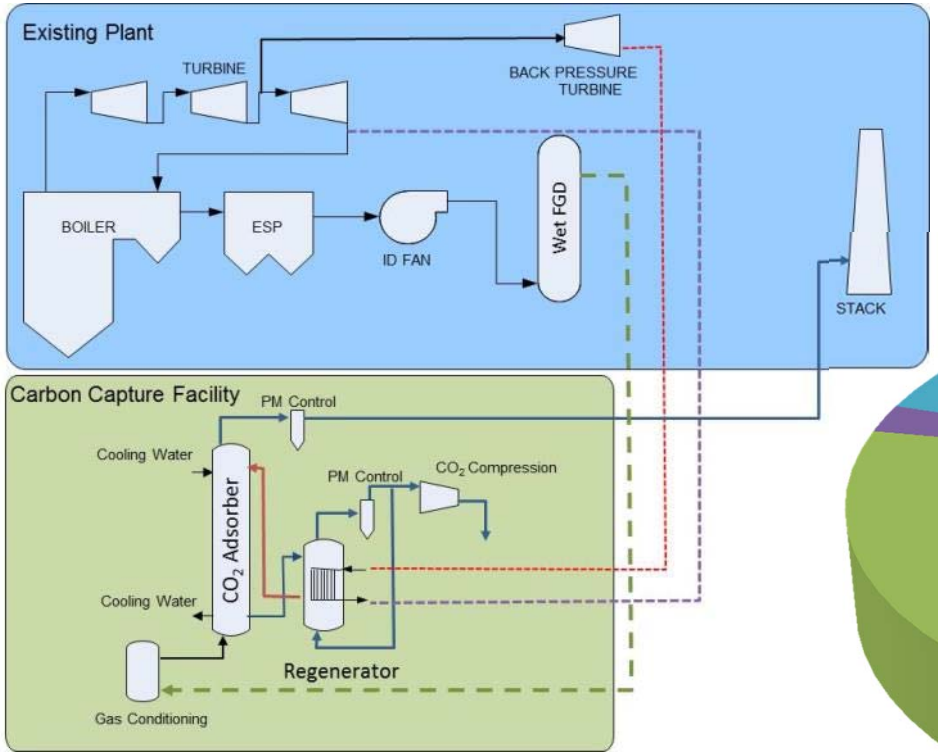
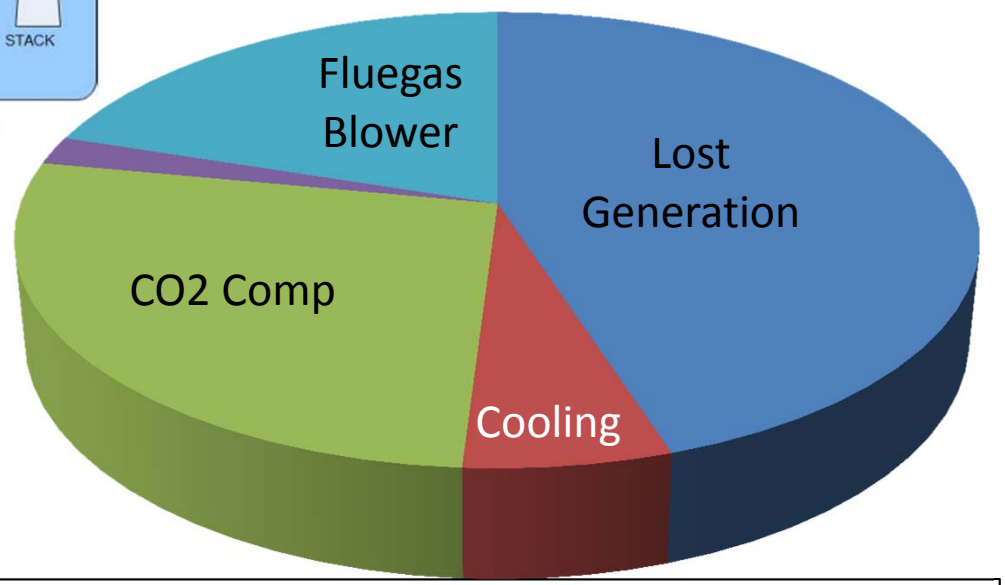
Project Motivation

Reduce the energy penalty of post-combustion CO_2 capture with solid sorbents





Breakdown of Estimated Parasitic Load
DOE Case 10 Analysis, ADAsorb™ without heat integration

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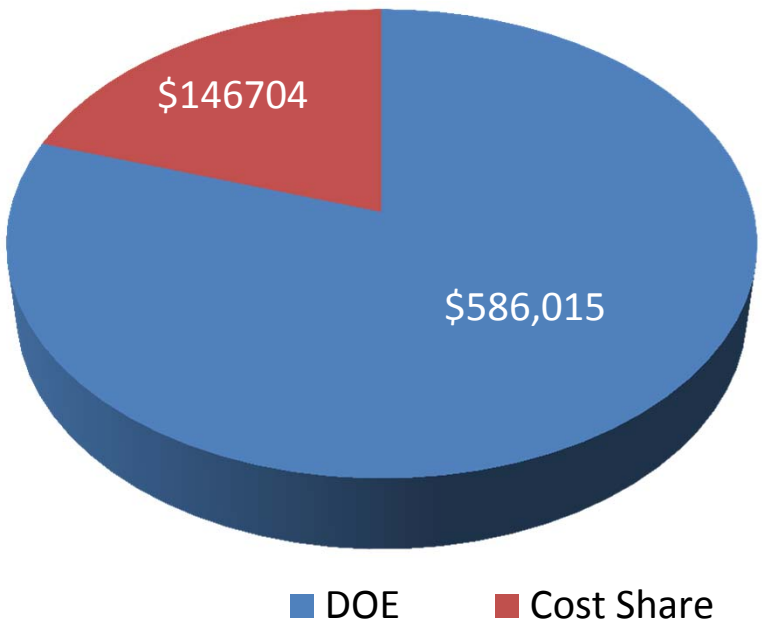
Project Funding, Objective, and Timeline

- The overall objective: reduce the energy penalty and/or the overall levelized cost for solid sorbent-based CO_2 capture
- Outcome: progress towards meeting the overall DOE Carbon Capture Program performance goals



Cooperative Agreement (Award No. DEFE0012914)
Administered by DOE-NETL: Project Manager Bruce Lani
Project Duration: Oct 2013 – Dec 2015

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Project Team

- DOE – NETL
  - Project Sponsor
- ADA-ES, Inc.
  - Project Management
  - Technology Selection and Integration
  - Techno-Economic Assessment
  - Project Cost Share
- Technip Stone and Webster Process Technology with Dorr Oliver Division
  - Conceptual Fluidized Bed HX Process
  - Detailed Engineering, Design, and Costing
  - Experience w/ multiple types of FB reactor designs (single, multibed, heat exchanger)
- Solex Thermal Science
  - Experience w/ Moving Bed Heating and Cooling
  - Thermal Modelling & Costing
  - 400 Installations in 23 countries
  - Project Cost Share
- Lehigh University Energy Research Center
  - Broad Process Modelling Capabilities w/ ASPEN
  - Conceptual Process Design
  - Techno-Economic Assessment
  - Project Cost Share

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Project Scope

- Evaluate options to reduce plant heat rate and LCOE associated with ADAsorb™ implementation through:
  - Heat integration with plant
  - Cross heat exchanger
- Assess two different sorbents
  - Preliminary design
  - Preliminary techno-economics
- Assess two cross heat exchanger designs
  - Laboratory testing
  - Preliminary design
  - Preliminary techno-economics

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Project Schedule

Task Description	Schedule
Bench Scale Testing: Moving Bed	April-July 2014
Modeling: Moving Bed	July 2014
Design Integration: Fluidized Bed	July 2015
Heat Integration and Optimization: Economic Sensitivity Analysis	Feb '14 – August'15
Techno-Economic Assessment	July – Dec 2015

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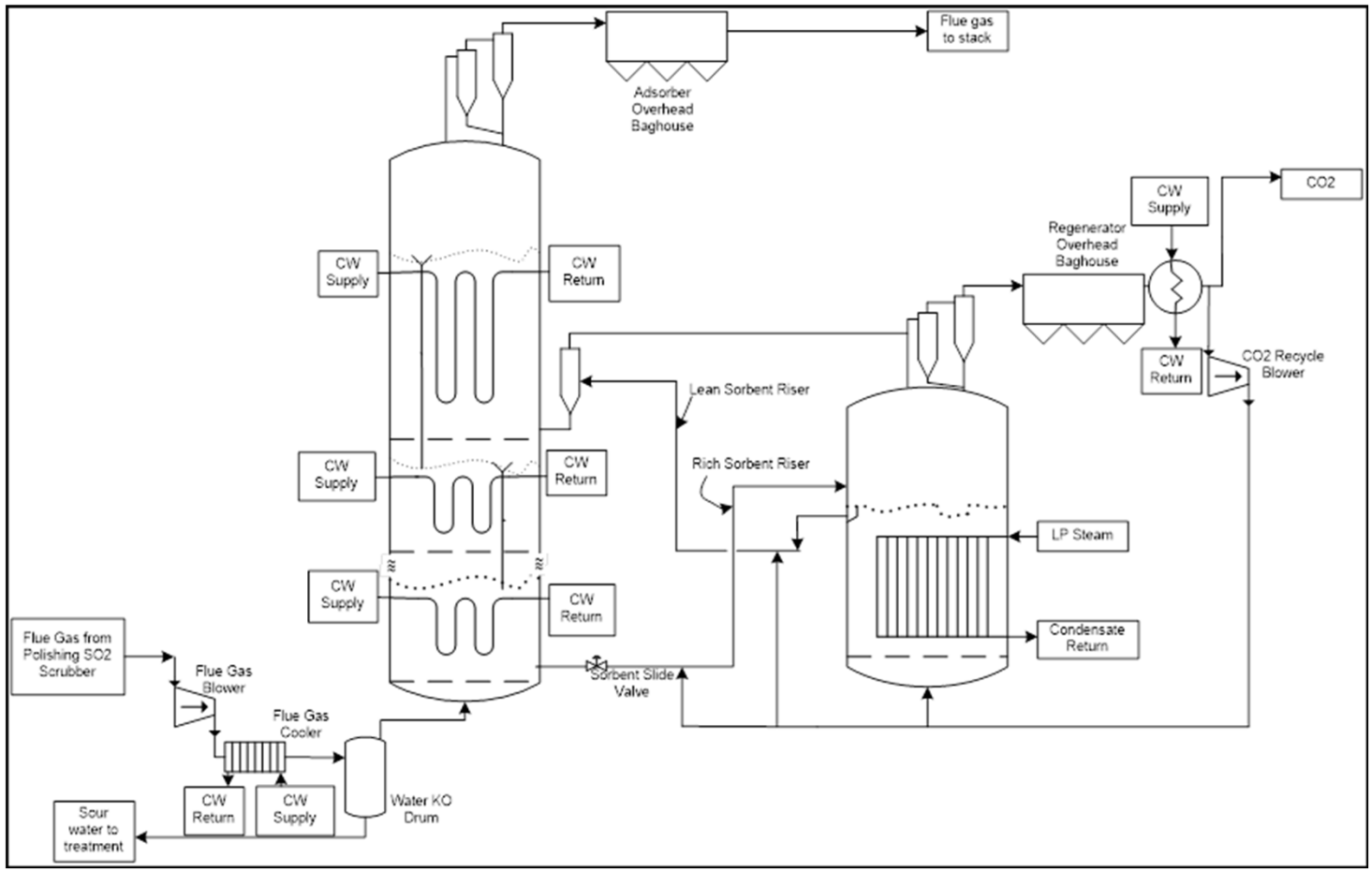
ADAsorb™ Process

- Temperature-swing adsorption process using solid sorbents



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Sorbents for Process Modeling

- Sorbent BN
  - Supported amine sorbent, a version manufactured commercially for a different application
  - Extensively characterized under the ADAsorb™ Pilot Program (DE-FE0004343)
- Sorbent OJ
  - Metal oxide framework (MOF) sorbent under development
  - Lab-scale characterization has been performed

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Key Sorbent Characteristics for Process Modeling

	Unit	Sorbent BN	Sorbent OJ
Equilibrium CO_2 Working Capacity	lbs CO_2/100 lbs Sorbent	7	12
Heat of Reaction	kJ/mol	77	58
Attrition	lbs Sorbent/hour	Negligible	Assumed Same
Sorbent Cost	$USD	5.62	Assumed Same
Moisture Uptake	lbs H_2O/100 lbs Sorbent	0.9	Negligible

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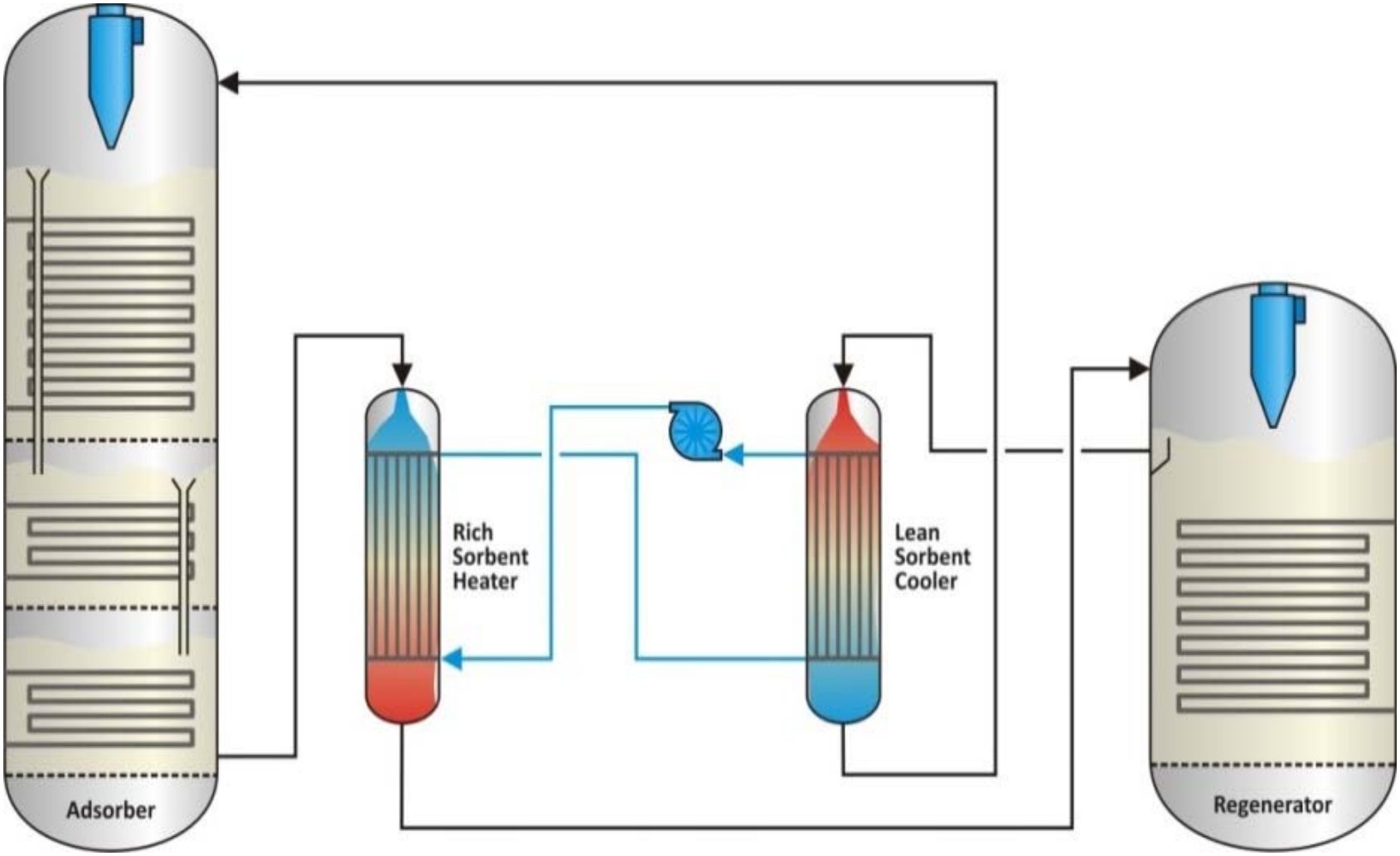
Cross Heater Exchanger Concept



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Benefits of Incorporating a Cross Heat Exchanger

- Sensible Heat Recovery
- Reduced Adsorber Pressure Drop
  - Sorbent is currently cooled in top adsorber bed
  - Reduced cooling requirements → smaller bed → reduced flue gas blower power → reduced thermal regeneration input & cooling duty
- Reduced Regenerator Pressure Drop
  - Sorbent enters regenerator at higher temperature → Less heat transfer surface required

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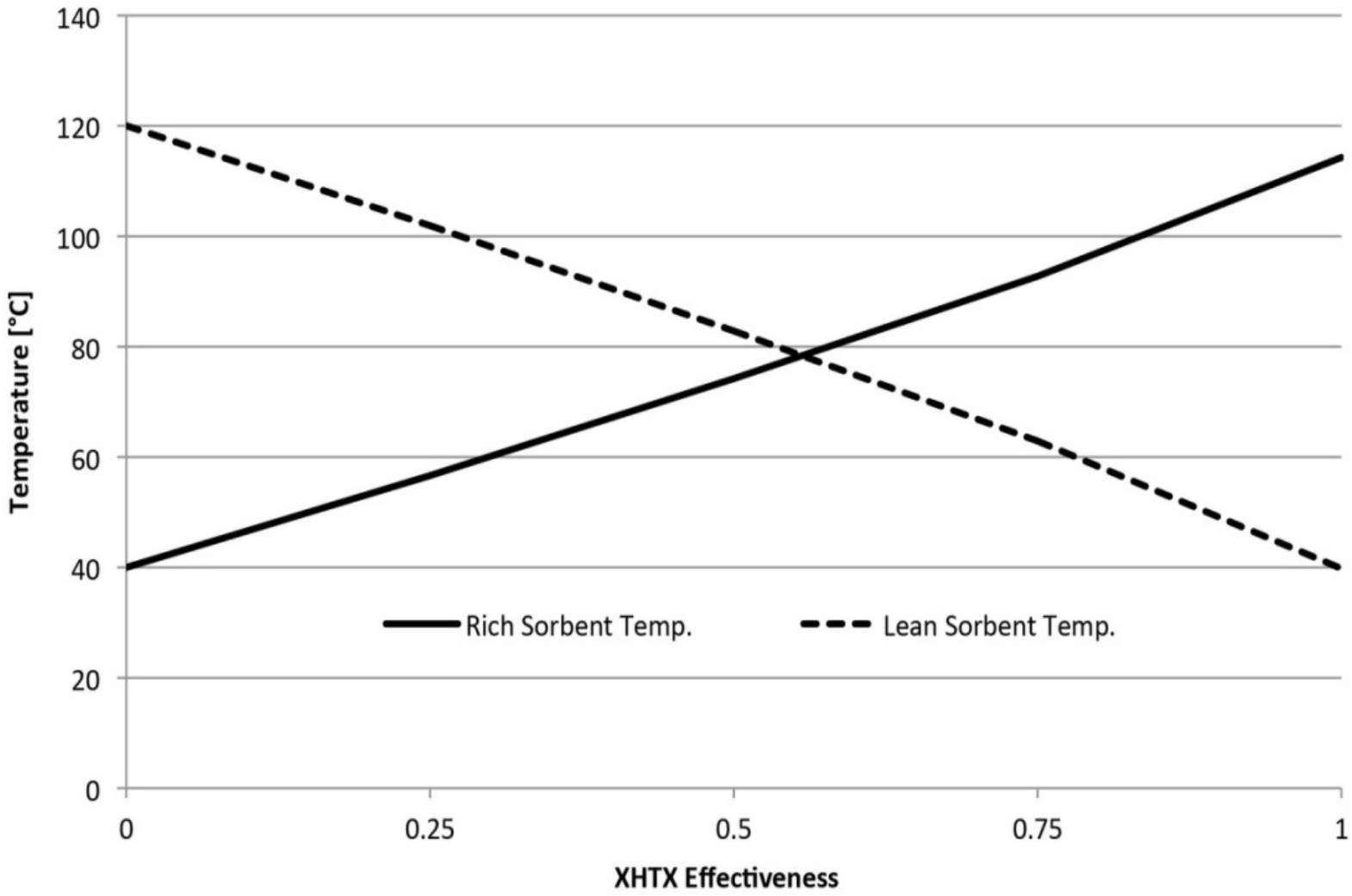
Cross Heat Exchanger Effectiveness (Actual Heat transfer/Max Heat transfer)



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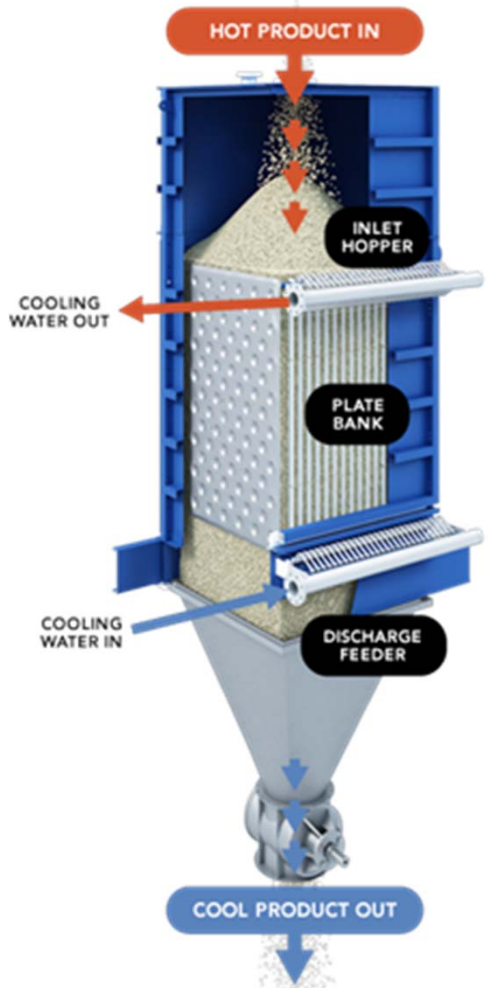
Cross Heat Exchanger Design Options

Moving Bed



Courtesy of Solex

Fluidized Bed

Gas

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Moving Bed Advantages

- Reduced blower requirements: little or no fluidizing gas is necessary
- Counter-Current flow between solids and heat transfer media
  → Possible to achieve an aggressive approach temperature and high heat recovery using only two moving beds per CO_2 capture train (one moving bed for heating and one for cooling)
- *Note: Heat transfer coefficient of a sorbent in a moving bed will be lower than that of the same sorbent in a fluidized bed*

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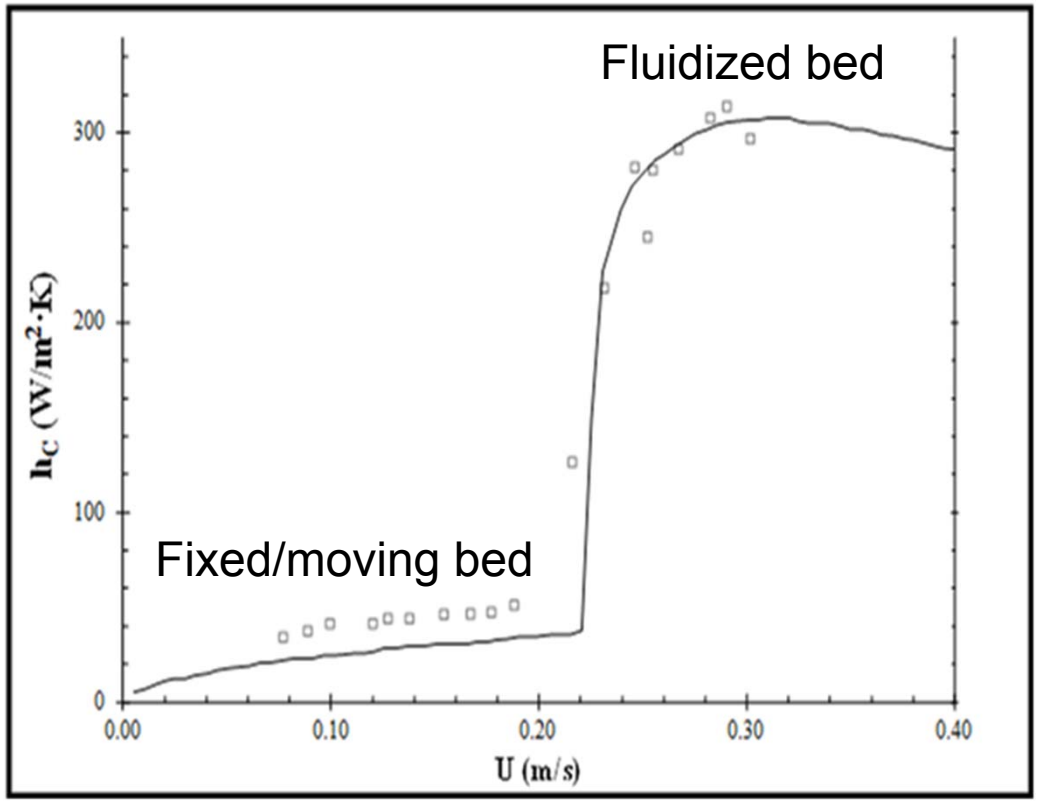
Fluidized Bed Advantages

- ✓ Good heat and mass transfer
- ✓ Equipment components have been demonstrated successfully on the required scale
- ✓ Industry process scalability knowledge



But . . .

- ☒ Higher pressure drop
- ☒ More complicated operation

J.F. Davidson, "Fluidization" 1985

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Cross Heat Exchanger Preliminary Assessment

- Solex downward flow moving bed
  - Completed lab tests and modeling using Solex custom software
  - Preliminary design has promising technical and economic potential
- Technip fluidized bed
  - Initial assessment indicates design is not a practical approach

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Solex Bench Scale Testing

- Bench scale moving bed heat exchanger
- Flowability testing showed excellent handling of one sorbent (Sorbent BN)

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ADA and Solex Bench Scale Testing

- Solex moving bed heat exchanger connected to ADA Cold Flow Model
- Sorbent BN heated and cooled with the heat exchanger through process range (40-120^{0}C)
- Sorbent flow smooth and consistent, no bridging between plates observed
- Minor bridging observed at the outlet of the exchanger, which proved to be manageable

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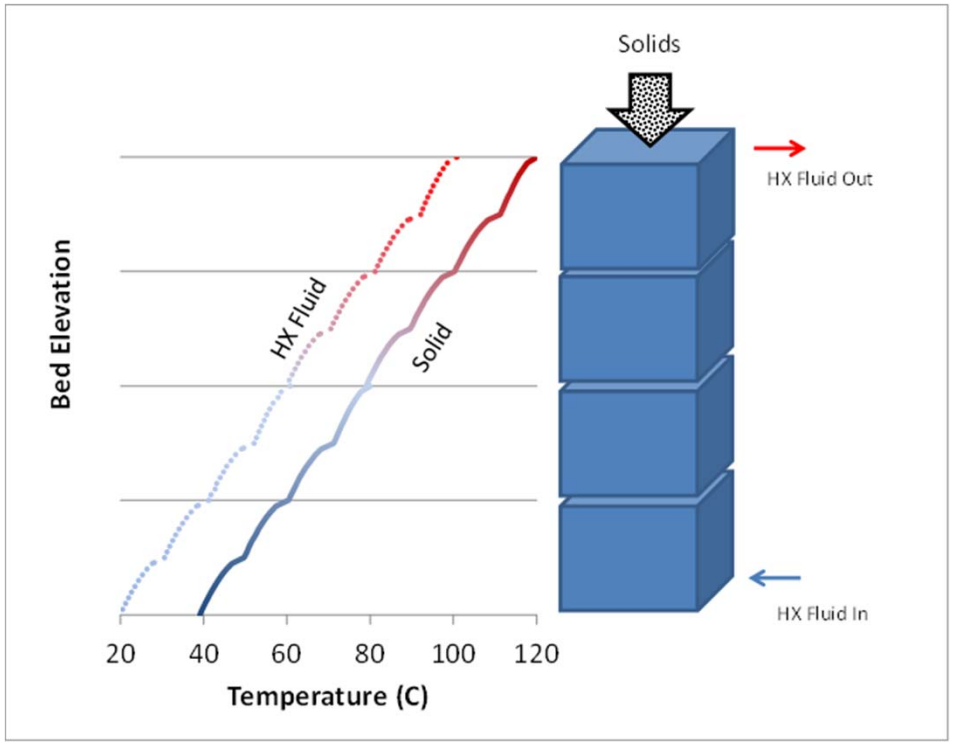
Solex Thermal Modeling

- Solex ThermaPro model of moving bed incorporated into ADAsorb process model
- Approach temperature of 20°C between solid and gas streams
- Sorbent can be cooled from 120°C to 40°C using 4-bed moving bed heat exchanger
- Bench-scale and modeling results used as input for 550 MW_{net} plant model



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Fluidized Bed Cross Heat Exchanger

- Technip modeling of a fluidized heat exchanger showed reduced sensible heat duty in regenerator by 109 MJ/s (372 MMBtu/hr)
- Properties of flue gas and steam based on ADAsorb™ design and pilot scale experience, assumptions included:
  - Steam entering regenerator is 154°C to maintain regenerator temperature of 140°C
  - Steam turbine assumed to be 85% efficient
- Results:
  - Additional electrical load requirements for fluidizing gas blowers and additional water circulation: -28,000 hp
  - Steam savings of 52 kg/s (412,000 lb/hr) could result in Power Plant increased electricity generation of +9,200 hp
  - **Reducing sensible heat duty on regenerator with a fluidized bed heat exchanger by 109 MJ/s (372 MMBtu/hr) increased parasitic electricity requirements equivalent to 18,800 hp**
- Fluidized bed cross heater exchangers were not considered further

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Modeling Heat Integration & Optimization

- Several modifications to ADAsorb™ process were modeled by Lehigh using ASPEN Plus software
- Supercritical PC model, 550 MW_{net}
- Three coals:
  - Illinois No. 6
  - Powder River Basin (PRB) subbituminous
  - North Dakota lignite

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Modeling Heat Integration & Optimization

Several modifications to ADAsorb™ process were modeled:

- Heat integration
  - Cross heat exchanger for heat recovery applied:
    - Between the CO_2 capture process and the power plant
    - Between the CO_2 compression system and the CO_2 capture process
    - Between the CO_2 compression system and the power plant
- Moisture of incoming flue gas
  - The energy penalty and economics of reducing the incoming flue gas moisture content was evaluated
- Adsorber design
  - The design was evaluated to determine if the pressure drop could be reduced
  - The vessel temperature was optimized for varying coals
- Regenerator vessel temperature was optimized for varying coals
- CO_2 compression system discharge pressure

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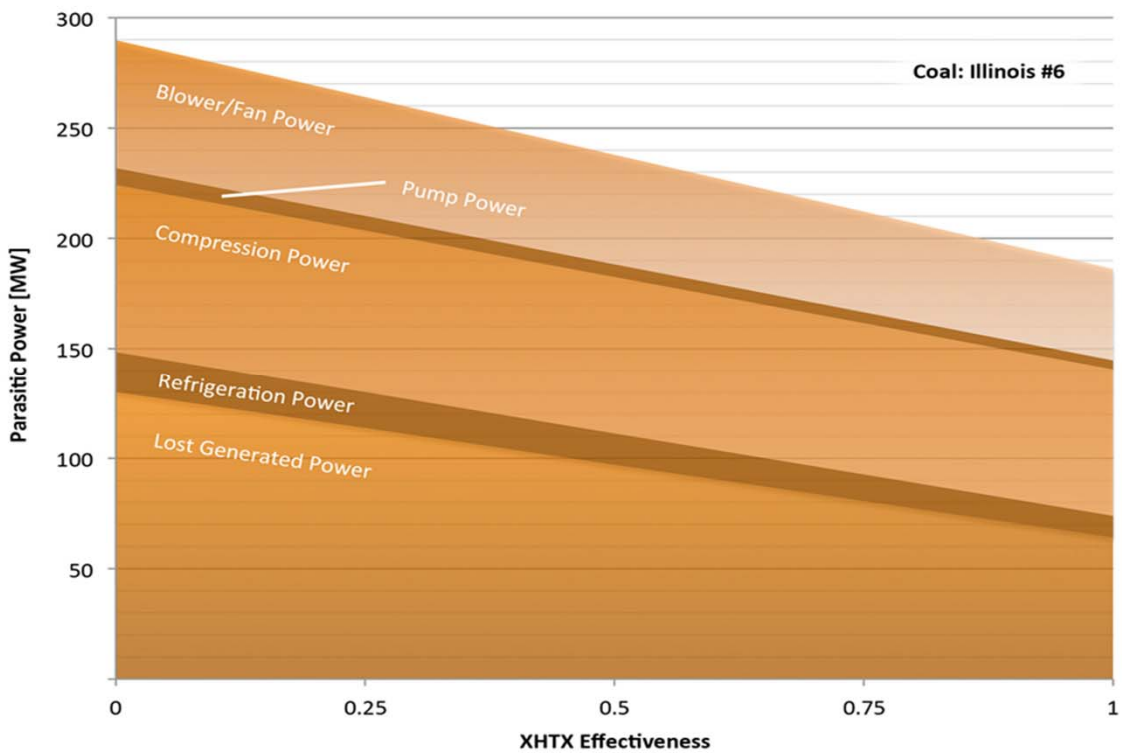
Effect of Cross Heat Exchanger Effectiveness on Parasitic Power Losses

- Largest contributor to parasitic power is lost electrical generation
- Other significant contributors: compression power and the blower or fan power
- Pump and refrigeration power only account for a small percentage of the total parasitic power



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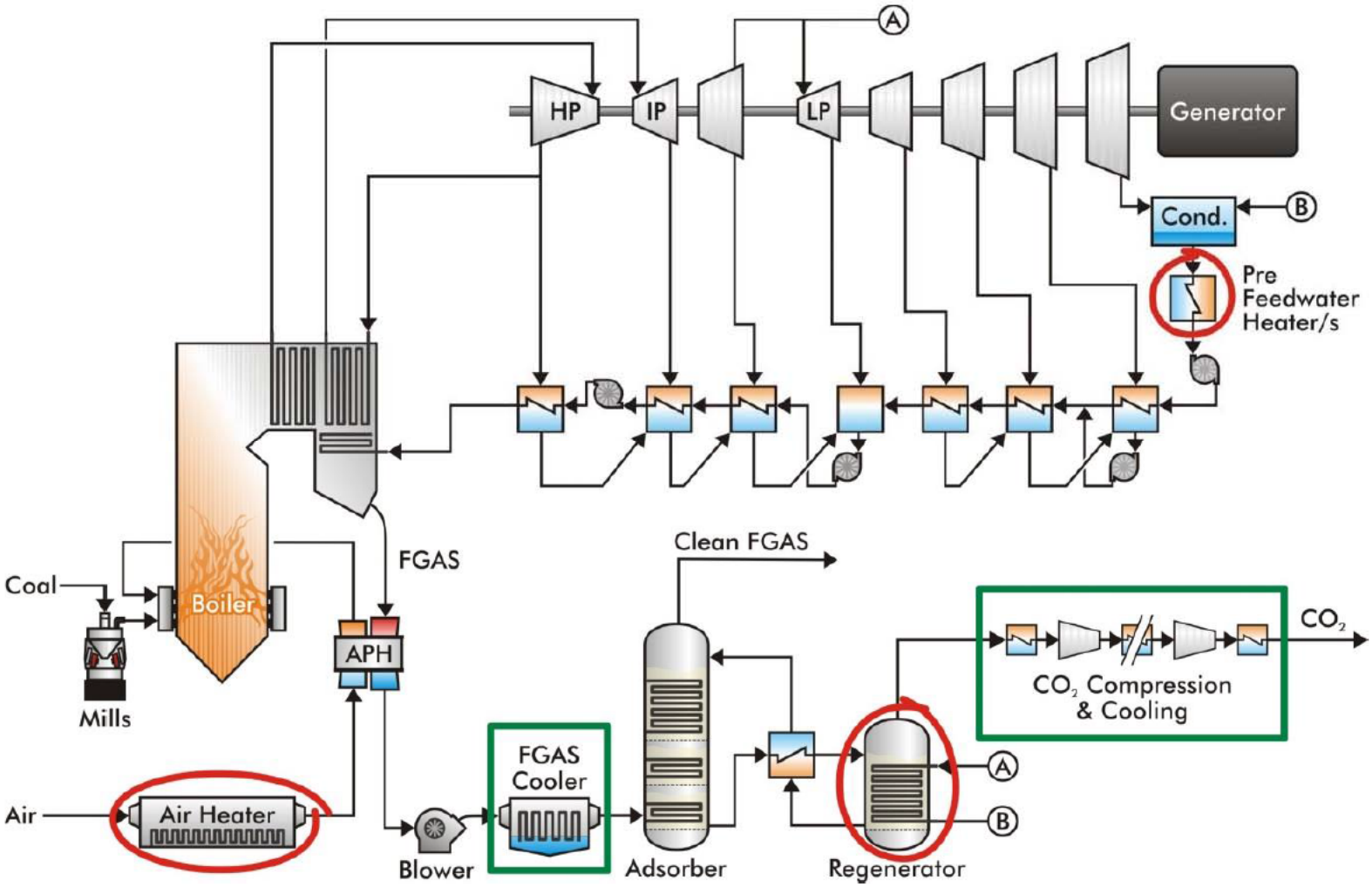
Effect of Sources and Sinks for Waste Heat



Lehigh Model

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Effect of Sources and Sinks for Waste Heat

- Cases examined for Sorbent BN and Sorbent OJ:
  - HI REG – Heat from the compressors used to heat sorbent entering the regenerator
  - HI FWH – Heat from the compressors used to heat steam cycle feedwater
  - HI FG AIR – Heat from the flue gas cooler used to heat boiler combustion air
  - HI FG FWH – Heat from the flue gas cooler used to heat steam cycle feedwater
  - XHTX 0.75 eff – Cross heat exchanger with a 75% effectiveness
  - OPTI – Case without a cross heat exchanger or heat integration at optimal adsorber and regenerator operating temperatures

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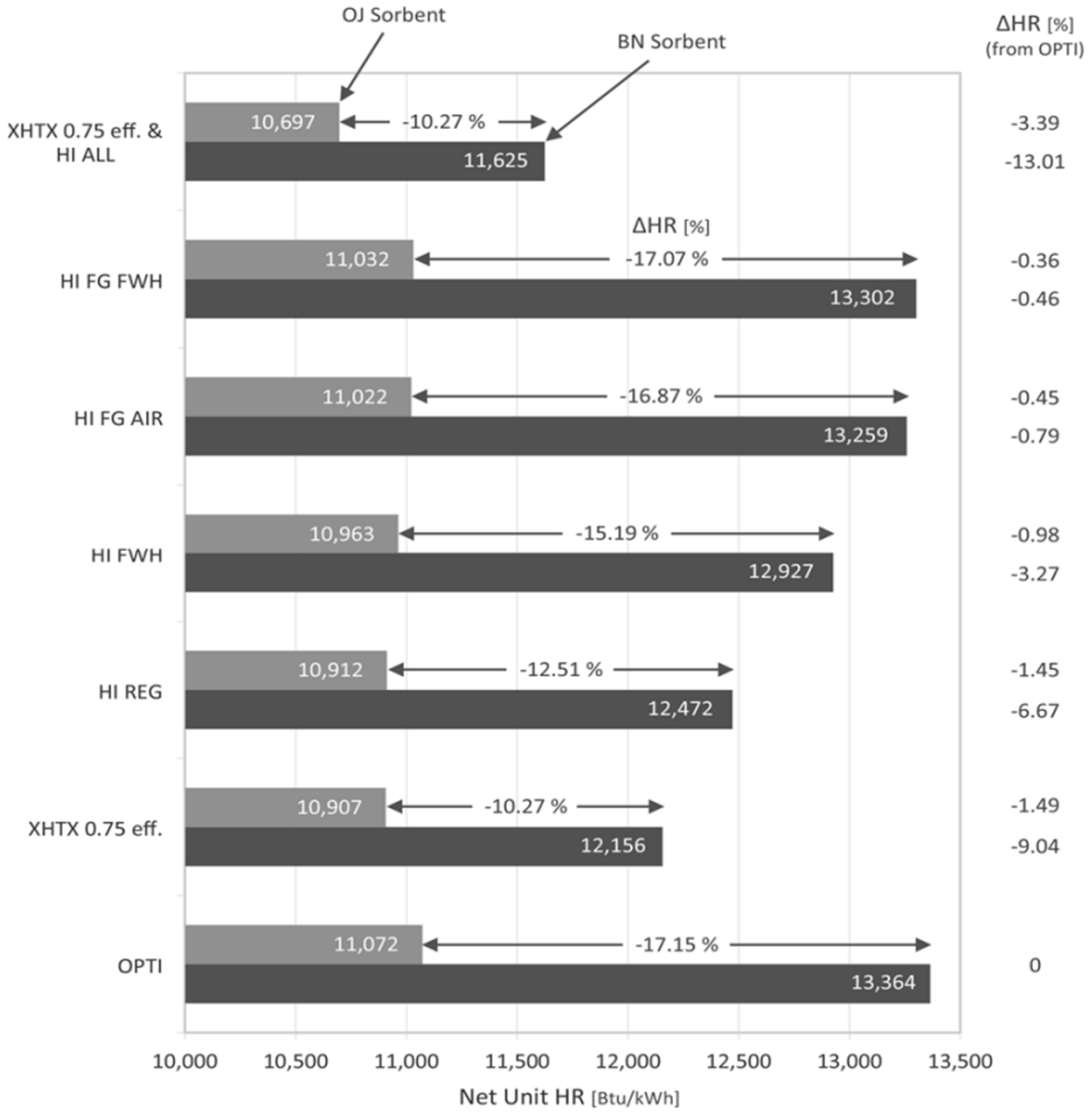
Effect of Sources and Sinks for Waste Heat on Net Heat Rate



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Effect of Increasing (Decreasing) Moisture in Flue Gas for Sorbent BN

- Sorbent BN is known to adsorb moisture from flue gas
- Effects of flue gas moisture content significant for Sorbent BN
- Sorbents that adsorb more than 1%-2% moisture from flue gas not cost-competitive unless CO_2 working capacity is high

	Illinois #6		PRB		ND Lignite	
Water Multiplier	Net Unit HR [Btu/kWh]					
0	12,595	-5.7%	13,836	-6.9%	14,223	-6.6%
0.25	12,792	-4.2%	14,098	-5.1%	14,481	-4.9%
0.5	12,978	-2.8%	14,348	-3.4%	14,728	-3.3%
0.75	13,165	-1.4%	14,602	-1.7%	14,978	-1.7%
1	13,358	-	14,855	-	15,233	-
1.25	13,477	0.9%	14,997	1.0%	15,382	1.0%
1.5	13,521	1.2%	15,051	1.3%	15,438	1.3%
Water Multiplier	Sorbent Flow Rate [Mlb/hr]					
0	16.7	-22.6%	19.4	-23.0%	18.3	-23.1%
0.25	17.8	-17.5%	20.8	-17.7%	19.6	-17.8%
0.5	19.0	-11.9%	22.2	-12.0%	20.9	-12.1%
0.75	20.3	-5.9%	23.8	-5.8%	22.4	-5.9%
1	21.5	-	25.3	-	23.8	-
1.25	22.2	3.2%	26.0	3.0%	24.6	3.1%
1.5	22.5	4.6%	26.4	4.4%	24.9	4.6%

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Effect of Reducing System Pressure Drop with Illinois No. 6 Coal, 550 MW_{net} plant

	Units	Base Case – no PCCC	ADAsorb™ PCCC	ADAsorb™ PCCC 1 psi reduction	ADAsorb™ PCCC 2 psi reduction
Case		1	2	6	7
Unit heat rate [HR]	Btu/kWh	8,796	13,002	12,932	12,863
Unit efficiency	%	38.8	26.2	26.4	26.5
ΔHR from Case 1	%	0	48	47	46
ΔHR from Case 2	%	(32)	0	(0.5)	(1.1)

- Decrease in pressure drop does not affect heat rate significantly
- Pressure affects CO_2 adsorption characteristics enough to require higher sorbent circulation rate at lower ΔP

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Operational Process Improvements

- Based on process modeling, determined:
  - Quantify the tradeoffs between the capital and operating costs of a cross heat exchanger
  - Impacts on net unit heat rate and on the cost of carbon capture
  - Optimal configuration, approach temperature, and number of heat exchangers
- Optimal operating temperatures for the adsorber and regenerator for ADAsorb™ system operating at a supercritical PC power plant burning an Illinois #6 coal were:
  - Sorbent BN: 40°C (104°F) and 120°C (248°F), same as the base case temperatures
  - Sorbent OJ: 38°C (100°F) and 59°C (140°F)

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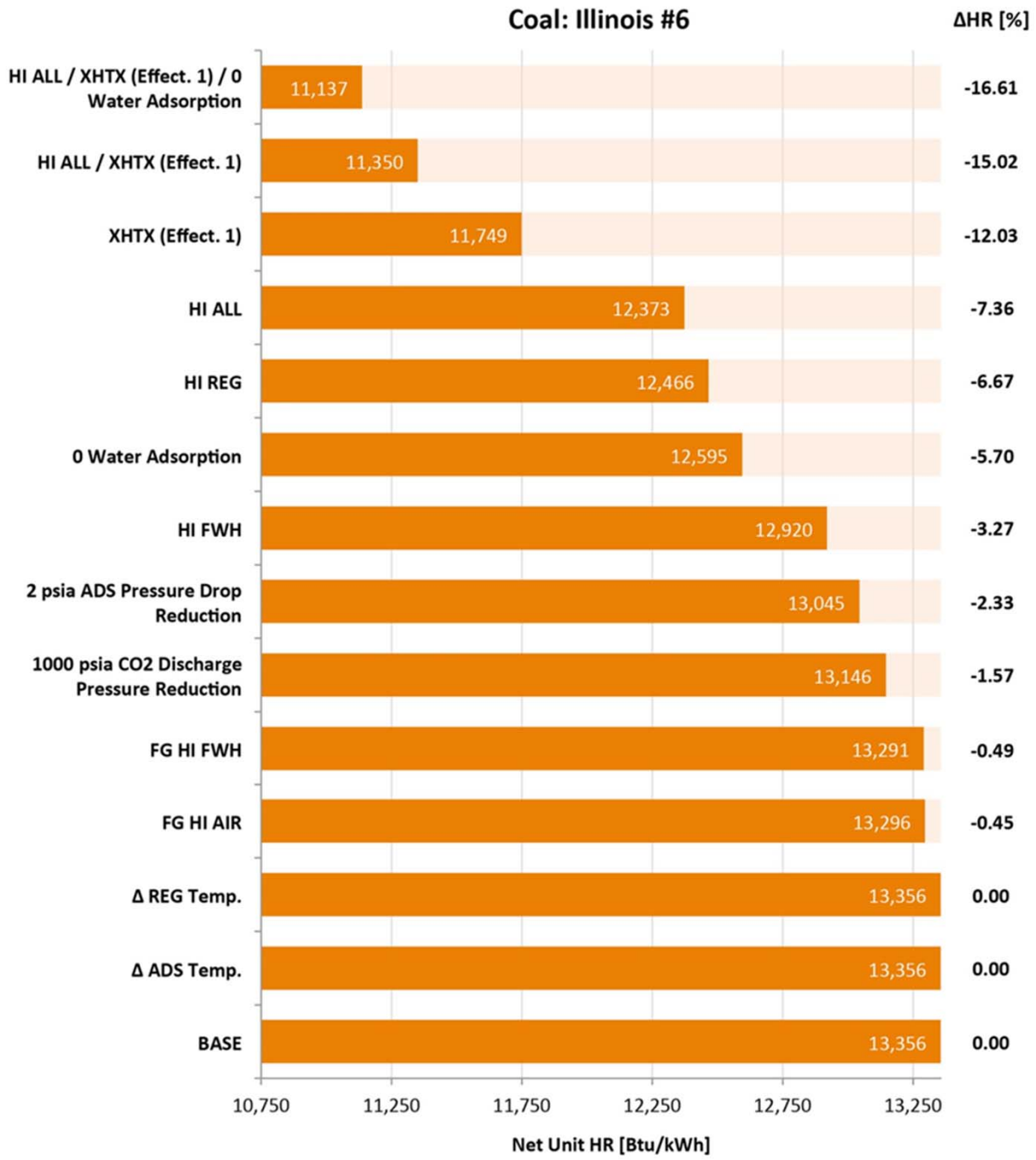
Operational Process Improvements :

Heat Rate Improvements for Sorbent BN



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Techno Economic Analysis Results

- Sorbent BN with cross heat exchanger alone or in conjunction with waste heat from the compressor used for supplemental regenerator heating had lower COE than without
- Without heat integration, sorbent OJ had improved performance over the MEA process

	Sorbent BN		Sorbent OJ	
Case	COE	LCOE	COE	LCOE
ADAsorb™ without heat integration	$154.4/MWh	$194.8/MWh	$126.2/MWh	$159.2/MWh
Cost increase from no CO_2 capture	66%		36%	
Comparison to 90% CO_2 capture with MEA	15% higher		6% lower	
ADAsorb™ with 75% cross heat exchanger	$148.4/MWh		$125.9/MWh	
ADAsorb™ with 75% cross heat exchanger with waste heat	$147.4/MWh			

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Summary

- Two cross heat exchanger designs were evaluated for use between the adsorber and regenerator: moving bed and fluidized bed
  - Fluidized bed approach was not feasible because the additional electrical load associated with fluidization was too high
- Process modeling showed:
  - The largest contributor to parasitic power was lost electrical generation, followed by power for CO_2 compressor and power to fluidize adsorber and regenerator
  - Sorbents which adsorb more than 1-2% moisture are unlikely to be cost competitive unless they have > 15% CO_2 working capacity
  - Reductions in adsorber pressure drop could negatively affect the CO_2 adsorption characteristics for certain sorbents and, thus, do not provide the efficiency benefits expected

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Summary

- Techno-economic assessment showed:
  - Addition of a cross heat exchanger and heat integration was found to significantly improve net unit heat rate
  - Additional equipment costs required to realize these improvements almost always outweighed the improvement in performance
  - Sorbent BN with cross heat exchanger alone or in conjunction with waste heat from the compressor used for supplemental regenerator heating had lower COE than without
- Sorbent characteristics critical to techno-economics:
  - Sorbent OJ with cross heat exchanger alone only lowers the COE by $0.3/MWh, or 0.2%.
    - Given this very small difference in COE it is suggested that it would be best not to include a cross heat exchanger for this sorbent. The additional complexity of adding such a system will most likely outweigh the minimal improvement in COE.
  - Sorbent OJ has shown clear thermodynamic benefits over sorbent BN
    - For the OPTI cases, the OJ sorbent is seen to result in a COE $28.2/MWh (18%) lower than the COE for the BN sorbent,
    - When comparing the lowest-cost OJ and BN cases, the OJ case comes in $21.4/MWh (15%) lower.
    - The primary reason for this is the improved CO_2 loading capacity of the OJ sorbent.

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Questions?

Sharon Sjostrom
sharons@adaes.com

Jayson Denney
Jayson.Denney@adaes.com

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