U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

DASTUR

US DOE Kick-Off Meeting

Enabling Production of Low Carbon Emissions Steel through CO_2 Capture from Blast Furnace (BF) Gases (FE0031937)

Principal Investigator: Atanu Mukherjee

Project Manager: Abhijit Sarkar

Dastur International, Inc.

Sep, 2021

Outline

Objectives & Key Elements of the Study

PMP & Org. Structure

Research Plan / Project Scope

Technology background and Technical Merits

Preliminary results

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Background and Objectives of the Study

1

The steel industry is responsible for ~7-9% of overall carbon emissions worldwide

2

The Blast Furnace is the most carbon intensive operation in ISPs, emitting 1.6 – 2.1 t CO_2 per t of hot metal.

3

The project aims to reduce CO_2 emissions by up to 70% from the 'available' BF gas (425 MMSCFD), resulting in CO_2 capture of 2.4 to 2.8 mtpa

4

Using a novel Fuel Conversion and Carbon Capture scheme, the project aims to capture and sequester CO_2 at a cost of ~ 42 US$ / tonne CO_2

5

Produce hydrogen for alternative uses in the steel plant in the future

CCU Design Rationale

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1. **Carbon Capture at scale** with BF energy transformation for low carbon H_2 heavy fuel to include multiple downstream consumers

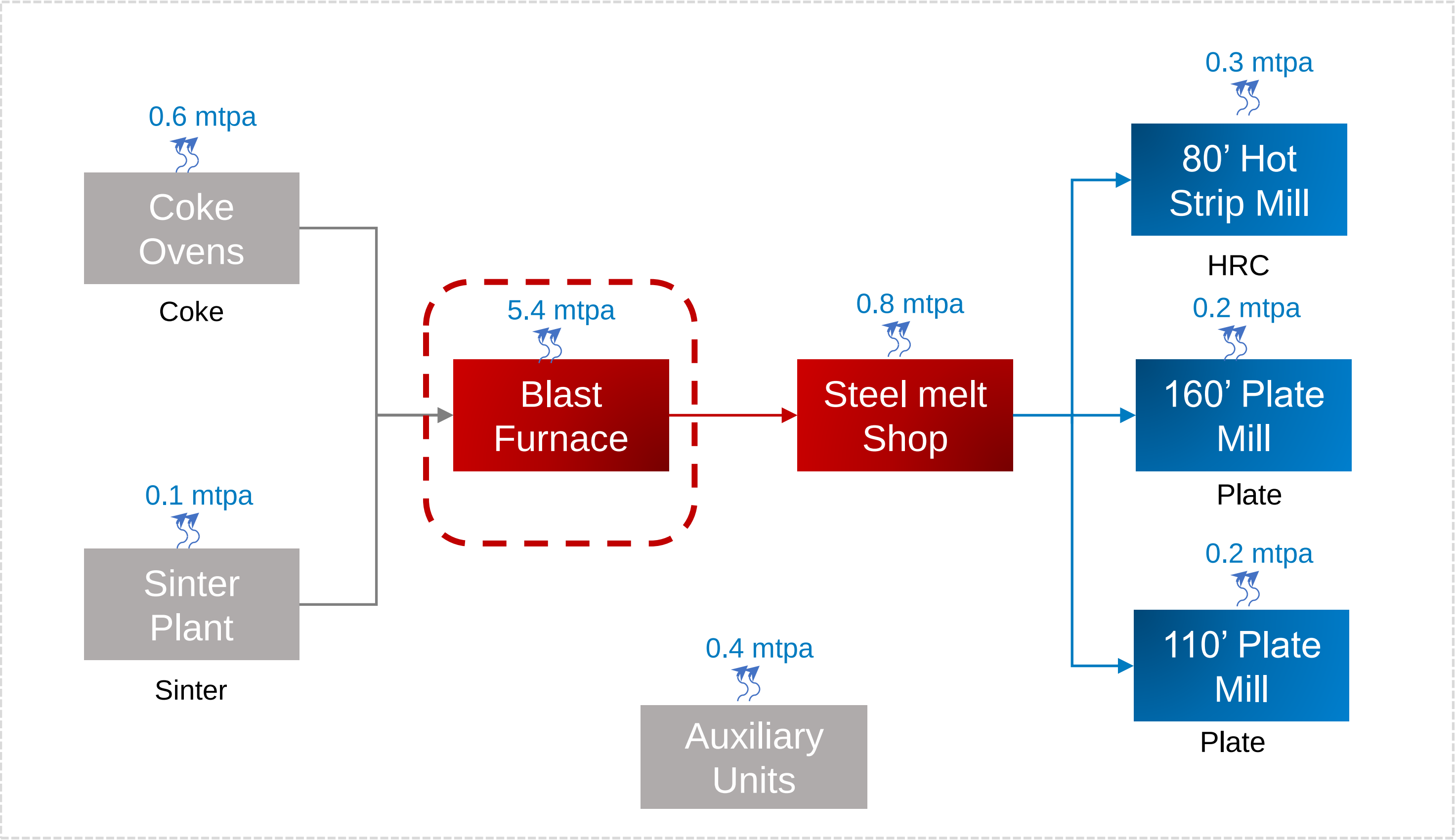
2. **Flexibility of Design** from baseline volume of 2.4 (to 2.8) mtpa CO_2 capture, while optimizing and extracting H_2 heavy fuel for use

3. **Optimizing CO_2 Capture Economics** (Capex and Opex) based on train capacity, CO_2 concentration and related gas conditioning

4. **Flexibility of Design** to route conditioned gas blends to maintain operational flexibility and reliability

5. **Flexible of Design** to extraction of hydrogen for alternative use in steel plant in future

Cliffs Burns Harbor Plant Configuration and Typical CO_2 Emissions (Direct)

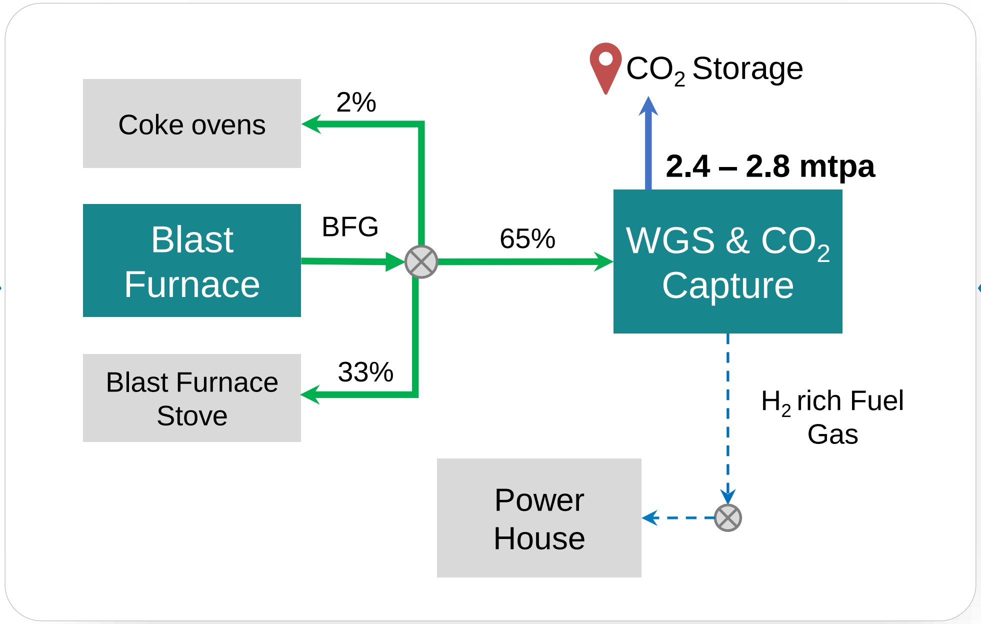


Total CO_2 emissions (direct) is **~ 8 mtpa**

CO_2 figure Based on EPA number

Approach to Design of Carbon Capture Island

- Maximize carbon capture (2.4 - 2.8 mtpa) with single train CCU
- Increasing CO shift through WGS enables higher CO_2 concentration at CCU; minimizes capex



- Cleaner H_2 rich fuel for steam and power generation
- Alternative use of hydrogen in steel plant in future

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Project Organization Chart

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CLIFFS team

CLIFFS CLEVELAND-CLIFFS INC.

- Project Manager
  Lawrence F. Fabina
- Engineering Division Manager
  Von Baum
- Engineering Project Manager
  Brian Brzycki

DASTUR team

DASTUR

- Principal Investigator
  Atanu Mukherjee
- Project Manager
  Abhijit Sarkar
- Process Manager
  Saikat Chatterjee
- Engineering Lead
  Saptarshi Bhattacharya
- Finance Lead
  Arunava Maity

ION Clean Energy

ION CLEAN ENERGY

- Project Manager
  Andrew Awtry

Gulf Coast Carbon Center

GCCC GULF COAST CARBON CENTER

- Project Manager
  Susan D. Hovorka

Engineering Services and Support

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- Project Monitoring
- Document controllers
- Process Engineers
- Process Simulation Experts
- Environment Engineers
- Layout
- Electrical
- Automation
- Utility
- Civil
- Structural
- Cost Analysts

Project Management Plan: Schedule, Milestones & Deliverables

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Tasks	Activities	Months																		
		May '21	Jun '21	Jul '21	Aug '21	Sep '21	Oct '21	Nov '21	Dec '21	Jan '22	Feb '22	Mar '22	Apr '22	May '22	Jun '22	Jul '22	Aug '22	Sep '22	Oct '22	Nov '22
	Deliverables	D1						D2/D3			D4		D5	D6				D7		
Task 1	**Project Management**																			
	Milestone: Project Team Kick-off Meeting	M1																		
1.1	Project Management Plan	D1																		
	Milestone: Updated PMP	M2																		
	Milestone: DoE Kickoff Meeting					M3														
1.2	Technology Maturation Plan							D2												
1.3	Data management Plan							D3												
Task 2	**CO_2 Capture (CC) Island Design**																			
2.1	Preliminary Design																			
	a. Basis of design																			
	b. Process Flow Diagrams																			
	c. System description																			
	Milestone : Preliminary Design Review of CC Island								M4											
2.2	Detail Design																			
	a. Process equipment design																			
	b. Process control description																			
	c. P&IDs																			
	Milestone :Detail Design Review of CC Island												M5							
Task 3	**Balance of Plant & Integration with CC Island**																			
3.1	Preliminary Design																			
	a. Overall Project Design Basis																			
	b. Overall PFDs																			
	c. BOP System Design Description																			
3.2	Detail Design																			
	a. Overall Material & Heat Balances																			
	b. Overall control description & architecture																			
	c. Overall equipment list																			
	d. BOP P&IDs																			
	e. Design of foundation, sitework, ductwork, structural steel and pipe rack																			
	f. Overall General Arrangement Drawings																			

Continued…

Project Management Plan: Schedule, Milestones & Deliverables

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Tasks	Activities	May '21	Jun '21	Jul '21	Aug '21	Sep '21	Oct '21	Nov '21	Dec '21	Jan '22	Feb '22	Mar '22	Apr '22	May '22	Jun '22	Jul '22	Aug '22	Sep '22	Oct '22	Nov '22
		Months																		
	Deliverables	D1						D2/D3			D4		D5	D6				D7		
Task 4	**Studies & Investigations**																			
4.1	Steam and Electricity Sourcing Study																			
4.2	Solvent Disposal Investigation																			
4.3	Waste Water Treatment Study																			
4.4	Permitting Study & Review										D4									
4.5	Hazard and Operability Review (HAZOP)													D6						
4.6	Constructability Review												D5							
Task 5	**Costing**																			
5.1	Capital Cost of Major Equipment incl. Construction Cost																			
5.2	Capital Cost for BoP Facilities incl Construction Cost																			
5.3	Project Indirect Costs																			
5.4	Operating & Maintenance Costs																			
Task 6	**Report Submission**																			
6.1	Initial Engineering Design and Cost Estimate																	D7		
	Milestone : Initial Engineering Design and Cost Estimate																	M6		
6.2	Techo-economic Analysis																			D8
6.3	EHS Risk Assessment																			D9

Milestones		
M1	=	Project Team Kick-off Meeting
M2	=	Updated PMP
M3	=	DoE Kick-Off Meeting
M4	=	Preliminary Design Review of CC Island
M5	=	Detail Design Review of CC Island
M6	=	Initial Engineering Design and Cost Estimate

Deliverables		
D1	=	Updated Project Management Plan (PMP)
D2	=	Initial Technology Maturation Plan (TMP)
D3	=	Data Management Plan
D4	=	Permitting Study & Review
D5	=	Constructability Review
D6	=	HAZOP Review
D7	=	Initial Engineering Design and Cost Estimate
D8	=	Techo-economic Analysis
D9	=	EHS Risk Assessment

Project Milestones

Task / Subtask Number	Deliverable Title	Planned Completion Date
1	Project Team Kick-off Meeting	17 May 2021
1.1	Updated Project Management Plan	31 May 2021
1.1	DOE Kick-Off Meeting	21 Sep 2021
2.1	Preliminary design review of CC island	15 Dec 2021
2.2	Detail design review of CC island	15 Apr 2022
6.1	Initial Engineering Design & Cost Estimate	15 Sep 2022

Funding (DOE & Cost Share)

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Cost type	Total budget	Share
Federal share	US$ 1,497,344	80%
Non-federal share	US$ 377,077	20%
Total	US$ 1,874,421	100%

Cost type	May '21 – Aug '21	Share	Remaining budget	% Remaining
Federal share	US$ 384,356	89%	US$ 1,112,988	74%
Non-federal share	US$ 47,023	11%	US$ 330,054	88%
Total	US$ 431,379	100%	US$ 1,443,042	77%

Objectives & Key Elements of the Study

PMP & Org. Structure

Research Plan / Project Scope

Technology background and Technical Merits

Preliminary results

Project Scope

Task 1 — Project Management

- Project Management Plan
- Technology Maturation Plan
- Data management Plan

Task 2 — CO_2 Capture (CC) Island Design

- Preliminary Design
- Pre-FEED Engg

Task 3 — Balance of Plant Design and Integration with the CC island

- Preliminary Design
- Pre-FEED Engg

Task 4 — Studies and Investigations

- Steam and Electricity Sourcing Study
- Solvent Disposal Investigation
- CO_2 Disposition Study
- A Wastewater Treatment Study, permitting study and review, a hazard and operability review (HAZOP) and a constructability review

Task 5 — Detailed Costing of the Project

- Capital Cost of major equipment & BOP including construction costs
- Project indirect cost
- Operating and maintenance costs

Task 6 — Project Report

- Initial Engineering Design and Cost Estimate
- Techno-Economic Analysis (TEA)
- Environmental Health and Safety (EH&S) Risk Assessment

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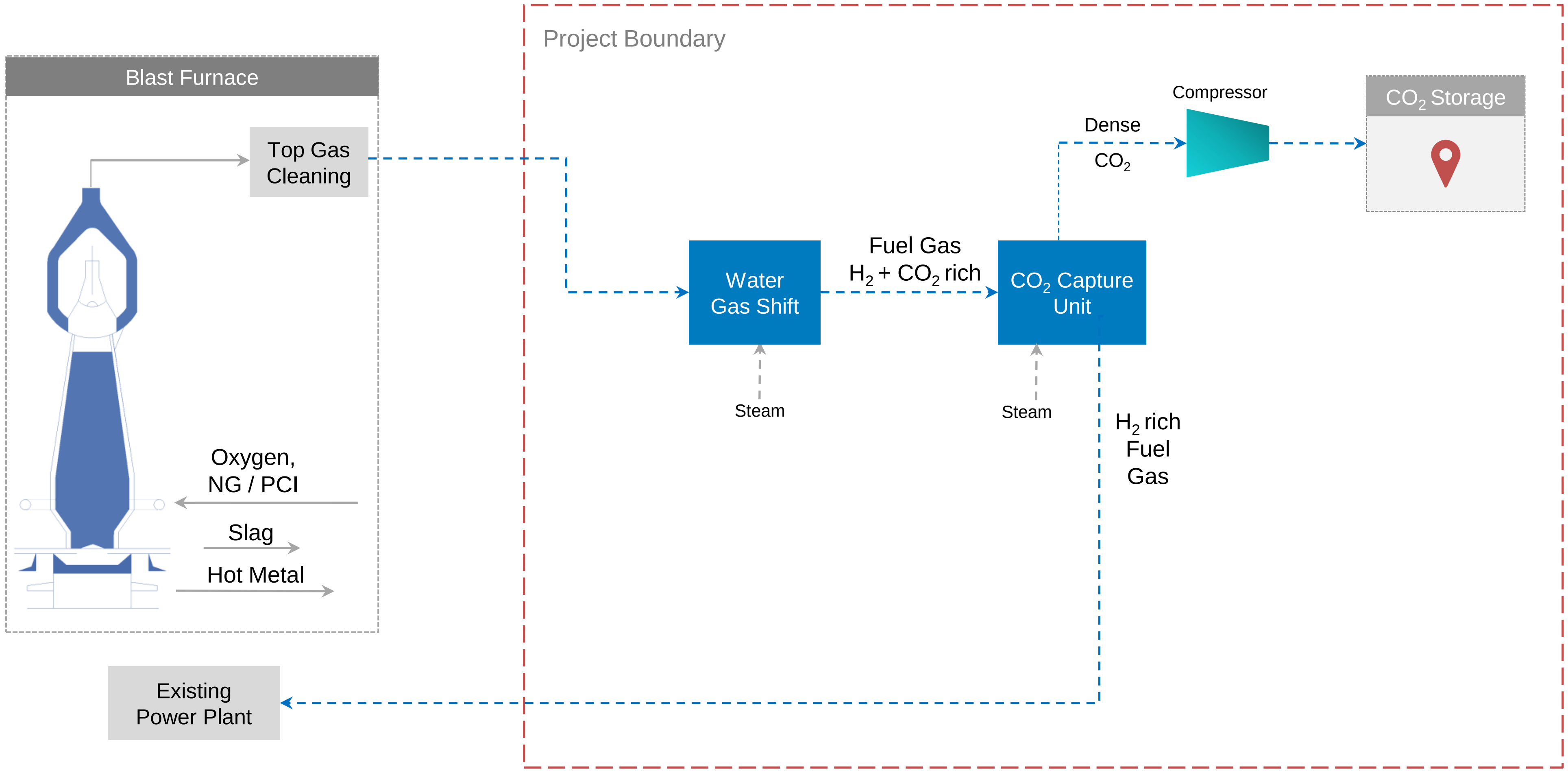
Key Technology Components of the Project



Technical Merits of BF Gas Conditioning through Water Gas Shift

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Process

Exothermic Catalytic Reaction:

$CO + H_2O = CO_2 + H_2 + \Delta$

Feed Gas Preheating / High-quality Steam Generation

Carbon Capture

Facilitates:

- Production of CO_2 rich (> 30 vol.%) gas stream
- Capture of Higher Volumes of CO_2

Lower Equip. sizing & Area Footprint + Lower CapEx & Cost of Capture + Lower Indirect CO_2 emissions

Flexibility

100% Shift
- All CO converted to CO_2
- Enables max. CO_2 capture & H_2 enrichment

Partial Shift
- Allows control over 'H_2/CO'
- Facilitates production of multiple value-added products

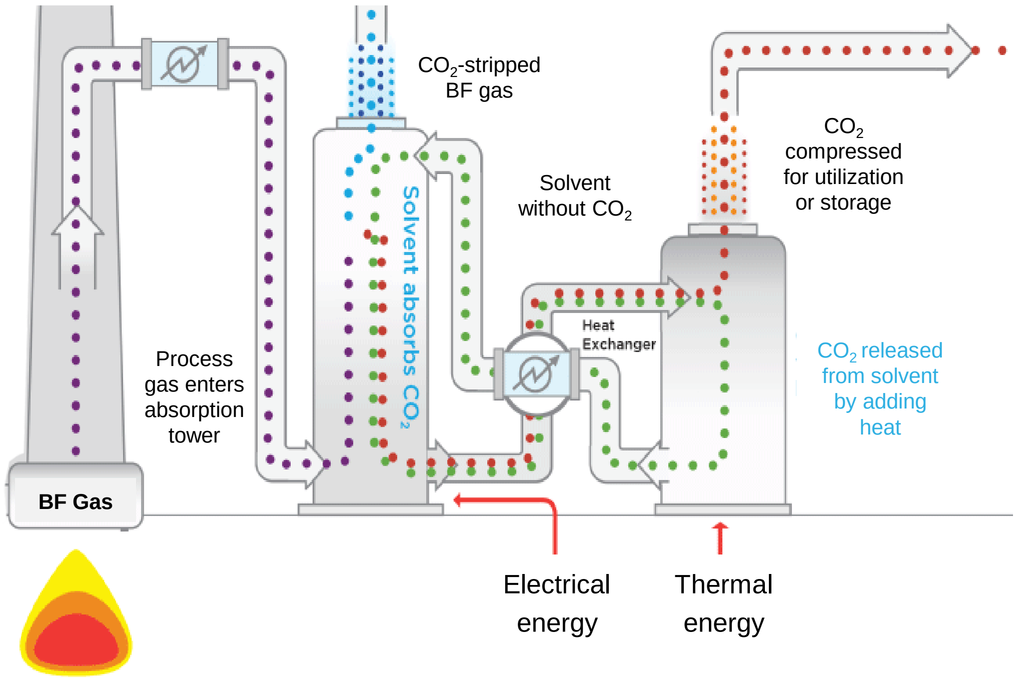
By-Pass
- For maintenance of the shift reactors
- During BF downtimes

Value Creation

Energy Dense H_2-rich Cleaner fuel / Pure H_2 / Dense stream CO_2

CO_2 Capture Technology Overview

- Proprietary Solvent-based Technology
  - Liquid absorbent-based capture
  - Low aqueous
  - World-wide Patents



Performance Attribute	ICE-21 (2017)	Target Commercial Applications
TRL	6	9
Scale (MWe)	12	300
CO_2 in flue gas, vol%	13	11.5
Hours of operation	2,750	> 120,000
L/G, mass/mass	2	1.9
CO_2 Capture Efficiency, %	91	> 95
CO_2 Product Purity, vol%	99	> 95
Corrosion of 304 (mpy)	0	< 0.1

CO_2 Capture Technology Development

Accelerated development path leveraging existing research facilities





2010	2012	2015	2016 - 2017	2018 - 2021
ION-CE Lab-pilot	**EERC**	**NCCC**	**TCM**	**Commercial FEED**
Simulated Flue Gas	*Coal*	*Coal*	*Refinery & Natural Gas*	*Coal*
3 kWe	**0.05 MWe**	**0.5 MWe**	**30 – 60 ktpa**	**2 – 5 Mtpa**
Boulder, CO, USA	*Grand Forks, ND, USA*	*Wilsonville, AL, USA*	*Mongstad, Norway*	*Sutherland, NE, USA*

Differences between Post-Combustion Flue Gases and Cliffs Burns Harbor BFG

Much Higher CO_2 Content

- 30% vs. 4-12% CO_2
- Significantly smaller absorber and ducting
- Change from lined concrete vessel to SS304 vessel
- Maximum train size increases (now limited by stripper/compression equipment)

Higher absorber temperatures

- Intercooling is necessary
- Placement of intercooler is important

Low-oxygen environment

- No oxidative degradation leads to change in solvent management strategies
- Possible contaminant concerns in outlet supercritical CO_2 stream(H_2S, CO)

Gas feeds a powerhouse

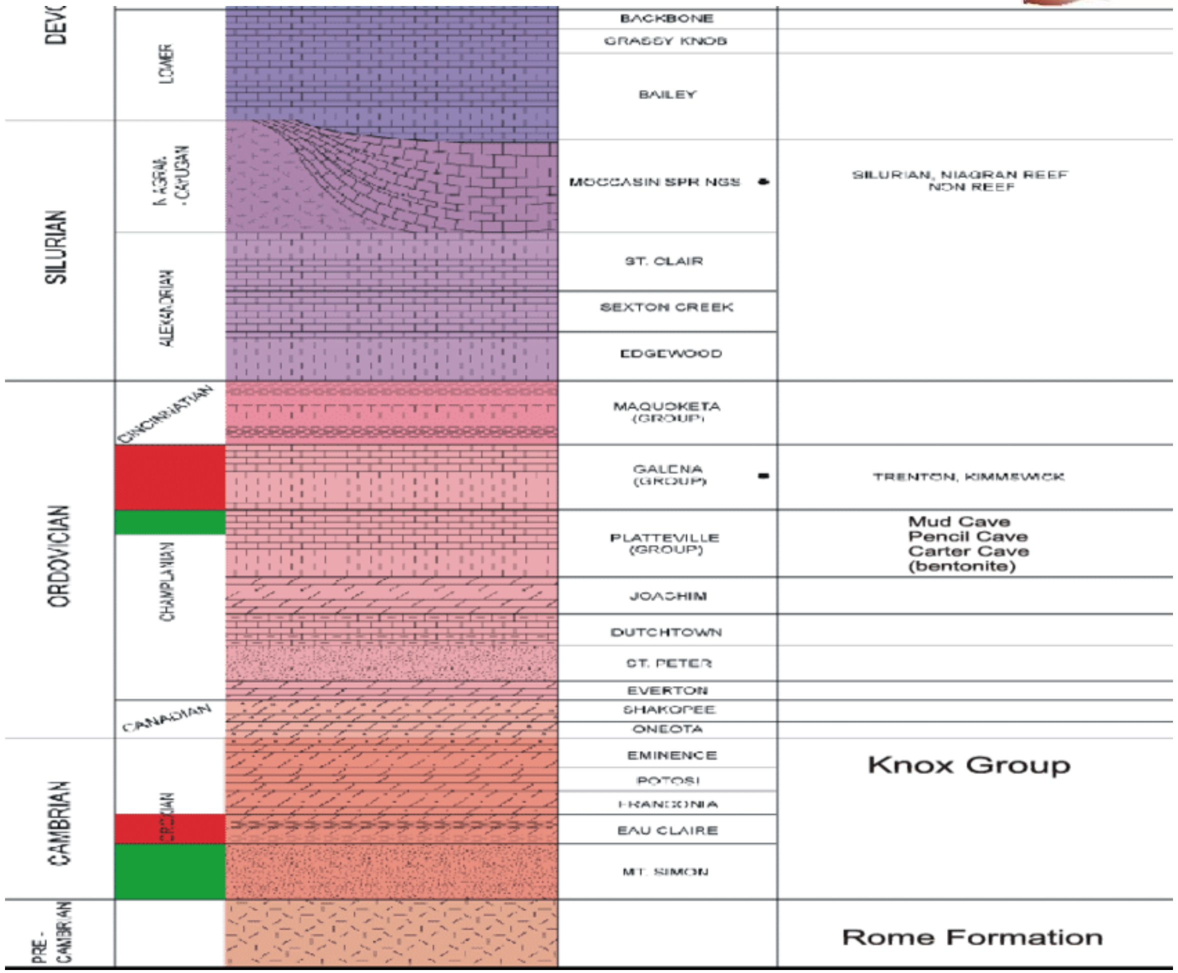
- Low VOC and Nitrogen emissions

CO_2 Disposition Options

- Permeable unit that can accept large volumes of CO_2
- At depth:
  - Below and isolated from (via seal) protected freshwater (>10,000 mgL)
  - >2400 ft below water table (CO_2 dense phase)
- Leasable acreage large enough to accept the rates planned
- Manageable induced seismic risk

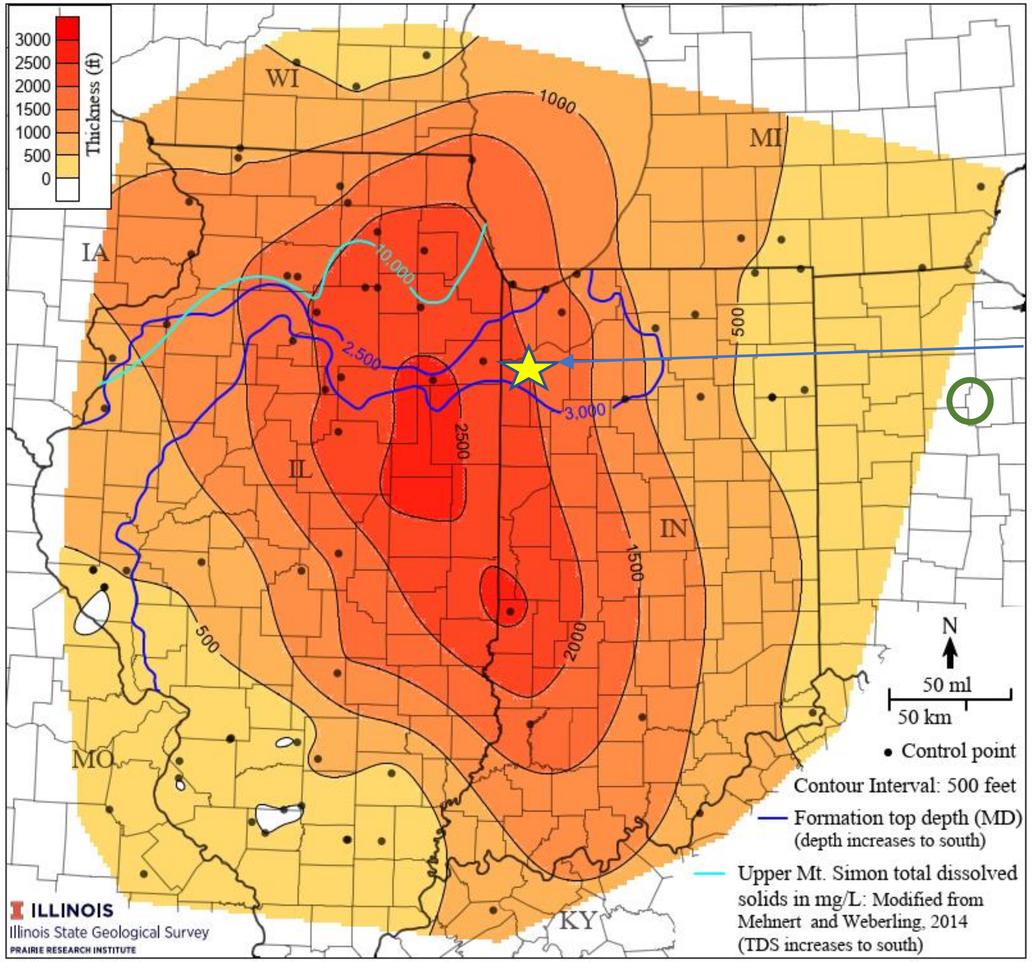
Too shallow

Seals
Mt Simon Target



Generalized Stratigraphic Column of the Illinois Basin

Available Geological Data

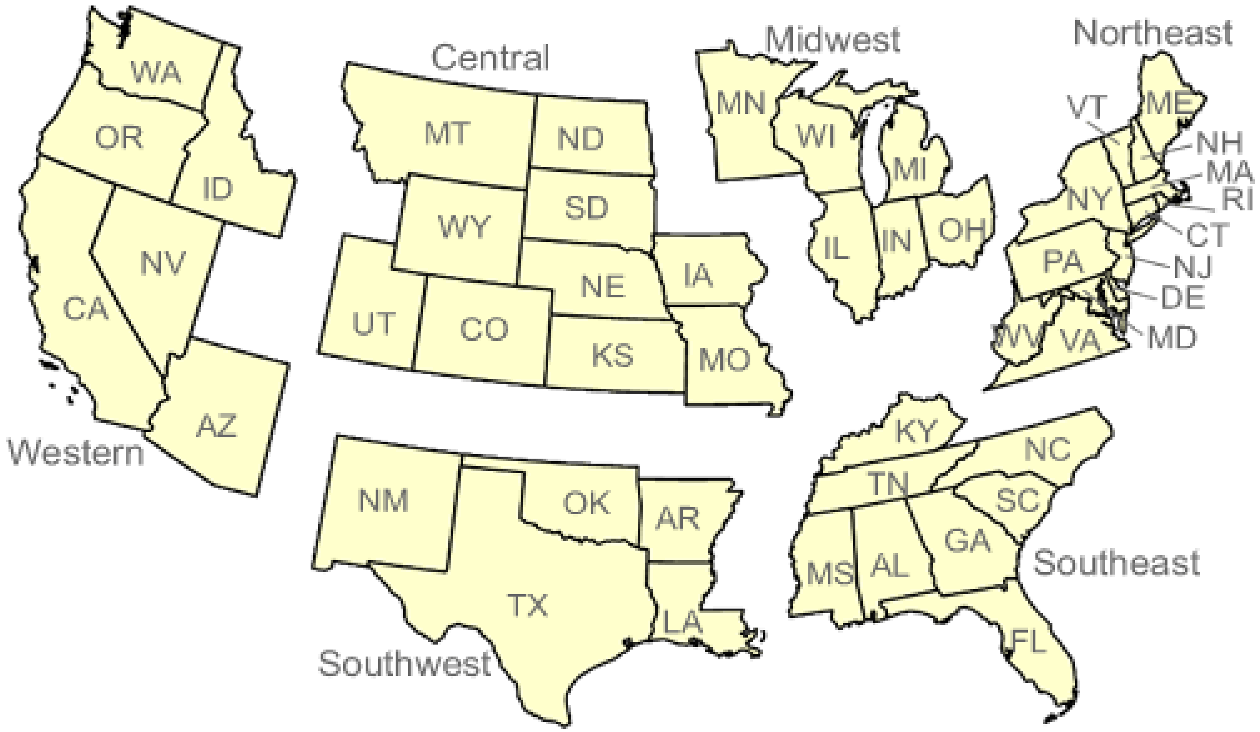


Thickness of the Mt. Simon Sandstone
Preliminary map prepared by Illinois State Geological Survey
03/16/2021

- Existing data compiled by Illinois State Geological Survey
- Subsurface beneath Cliffs BH facility is marginal for storage:
  - Shallow
  - Salinity uncertain
  - High population
- More favorable 15-60 miles to south
- More work required!

Cost of Pipeline

- 2.4 million tonnes per year single source to sink pipeline transport
- National Energy Technology Laboratory FE/NETL CO_2 Transport Cost Model
- 15 Miles = $24M
- 60 miles= $70M
- Savings in scale up (more than one source into pipeline)



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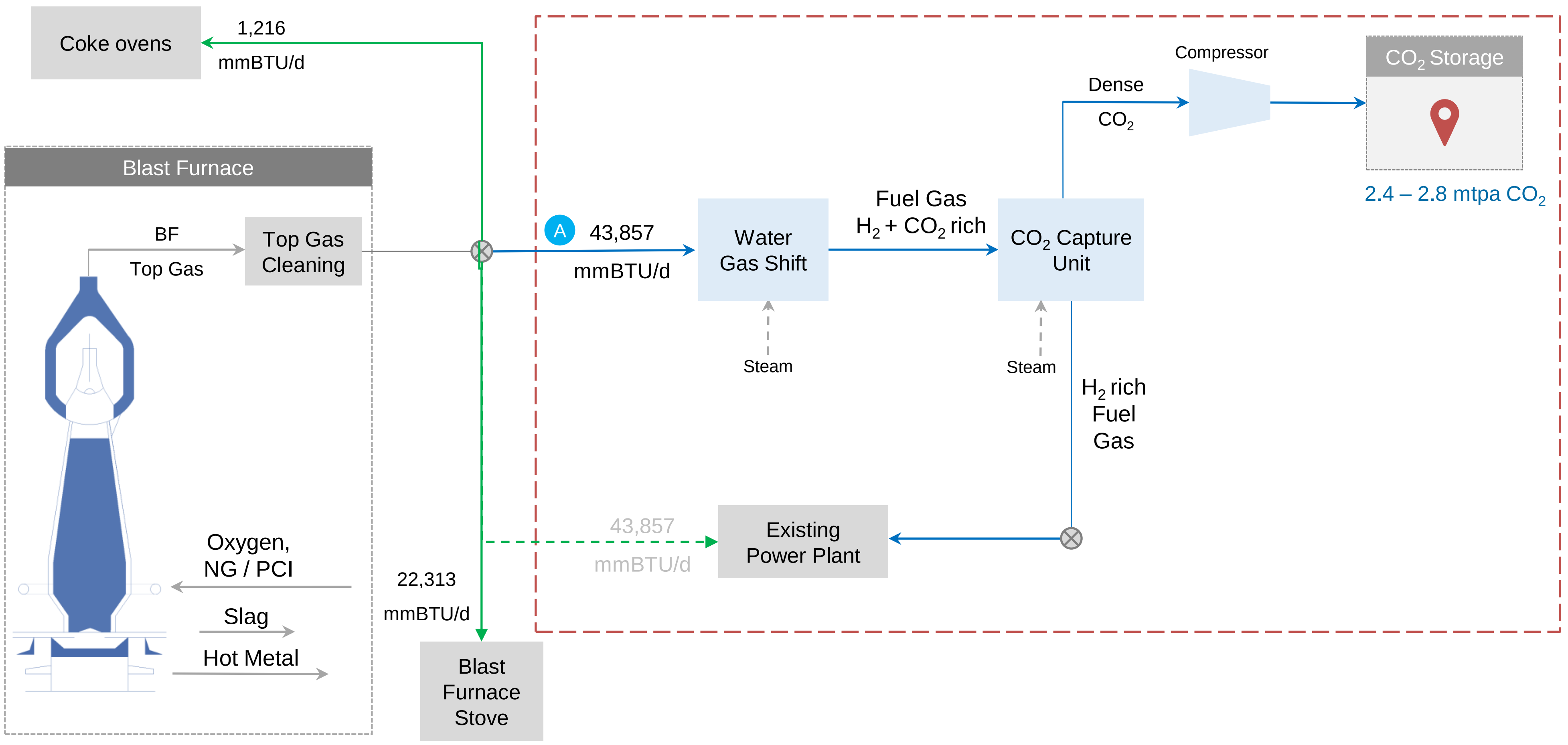
Baseline Architecture with BF Gas Characteristics



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Component	Units	BF Gas (Before Cleaning)
Gas Comp.		
CO	*vol. %*	22.6
CO_2	*vol. %*	22.1
H_2	*vol. %*	9.2
N_2	*vol. %*	45.5
Gas Temp	*°F (°C)*	212 (100)
Gas Pressure	*Psig (Barg)*	13.5 (0.9)
H_2/CO		0.41
Gas CV	*BTU / ft³*	80-110

Available gas for CCUS scheme:

43,857 mmBTU/day

Preliminary Identification of CO_2 Capture Plant Location, Tie-in Points & CO_2 Pipelines to Storage

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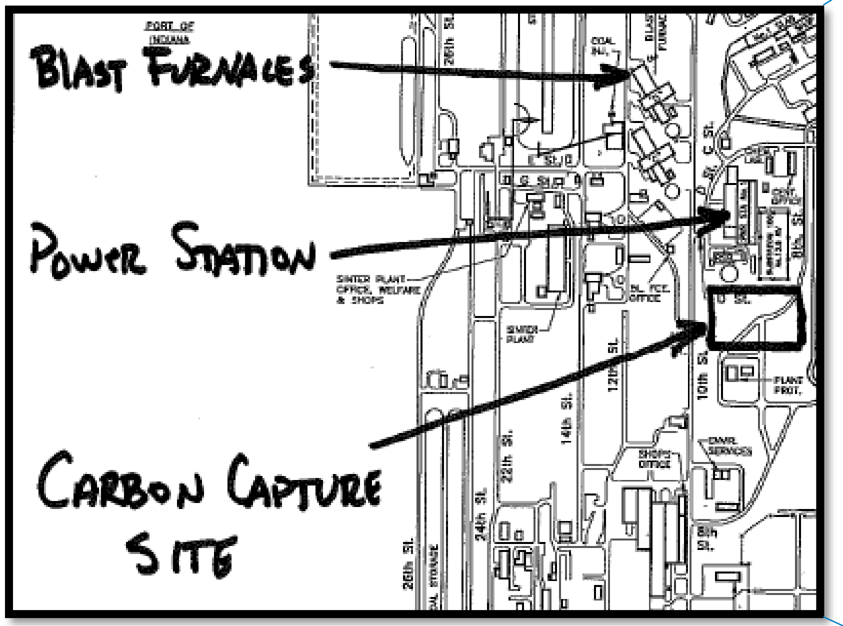
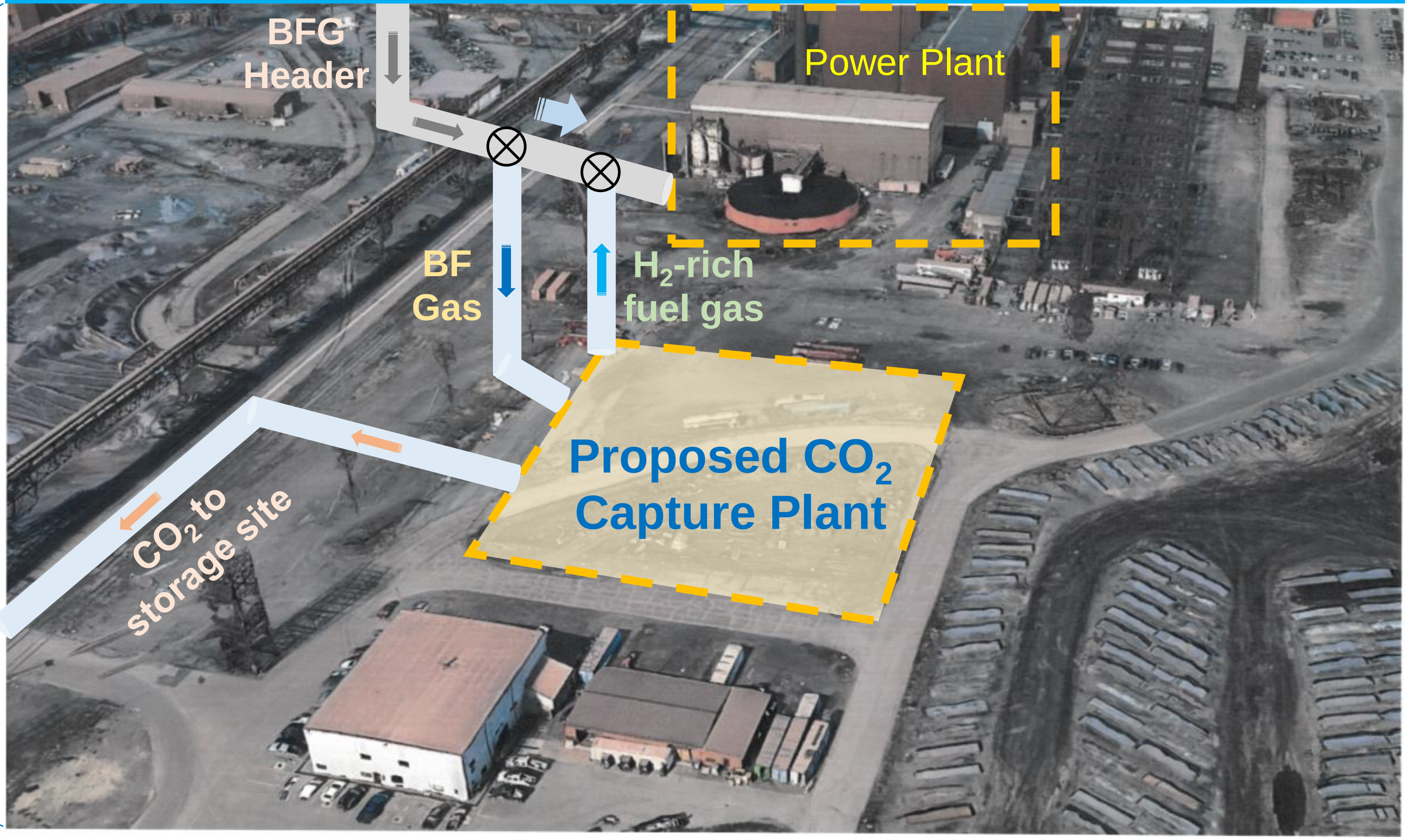
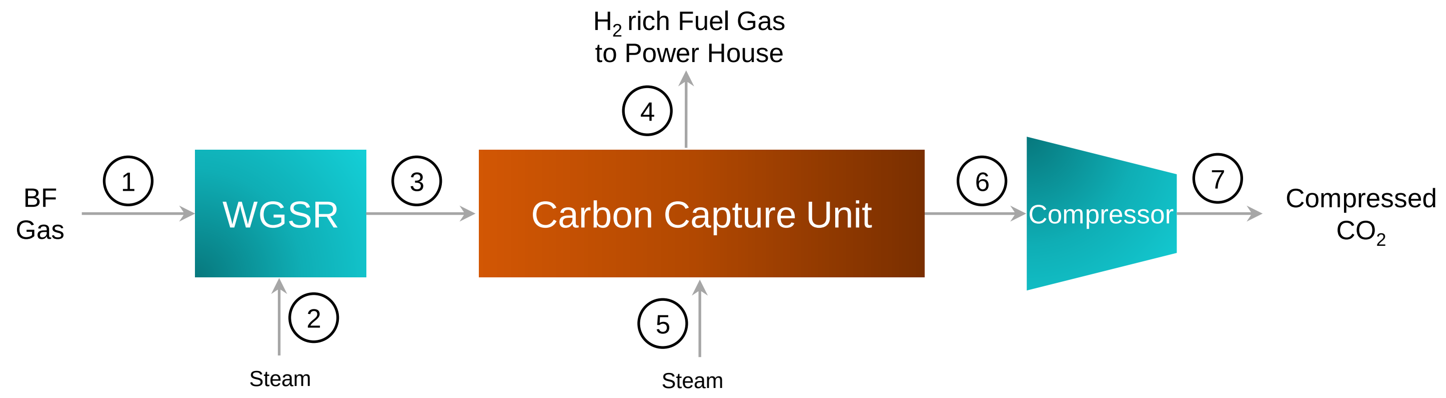


Connectivity with CO_2 Capture plant



BFG Conditioning & CO_2 Capture: Block Flow Diagram and Preliminary Results



Stream description	Units	BF Gas	Steam to WGSR	Shifted Gas from WGSR	H2 rich fuel gas	Steam to CCU	CO_2 into compressor	CO_2 out from compressor
Stream No.		1	2	3	4	5	6	7
Gas Comp. (dry basis)								
CO	vol. %	22.6	0	10	14	0	0	0
CO_2	vol. %	22.2	0	31	2	0	100	100
H_2	vol. %	9.2	0	19	27	0	0	0
H_2O	vol. %	0	100	0	0	100	0	0
N_2	vol. %	45.5	0	41	57	0	0	0
Gas CV	BTU/SCF	103	n/a	92	130	n/a	n/a	n/a
Gas Vol. Flow Rate	mmSCFD	425	n/a	475	337	n/a	138	138

considering 2.4 mtpa CO_2 capture capacity

Water Gas Shift Process Modeling: PFD & Gas Stream Characteristics

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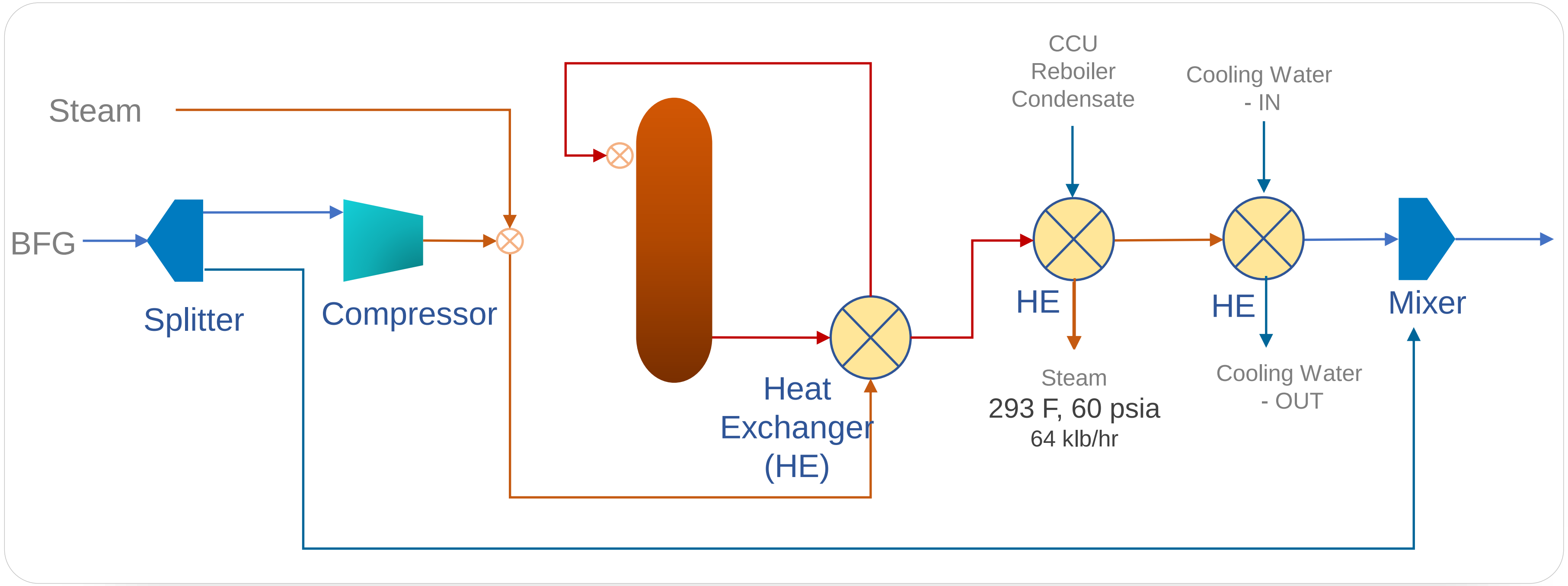
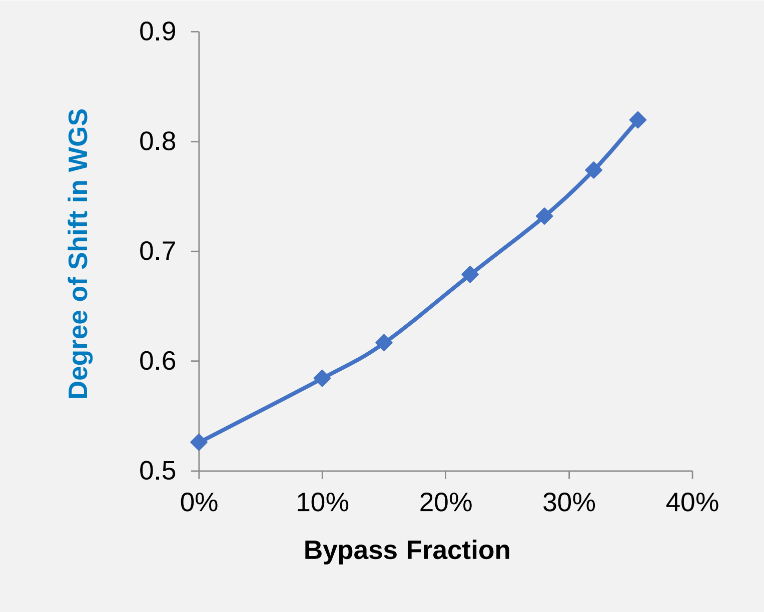
Considerations

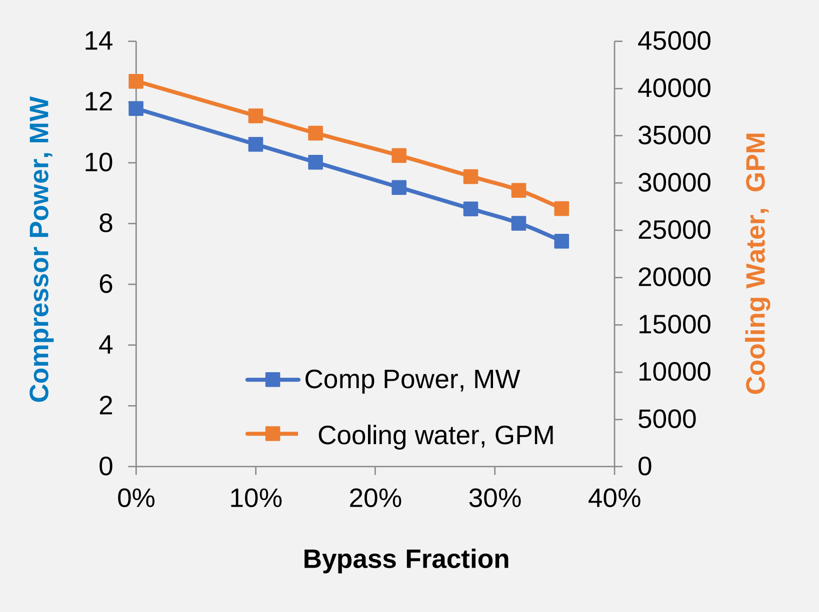
- Feed steam is available at 257 °F (145 °C) and 14.5 psig
- Feed BFG need to be compressed to 14.5 psig to account for the overall pressure drop
- Mixture of BFG and Steam need to be heated to 660 °F (350 °C) for the required catalytic activity in the WGSR
- 36% BFG is by-passed to get optimum result and desired H_2/CO in the outlet

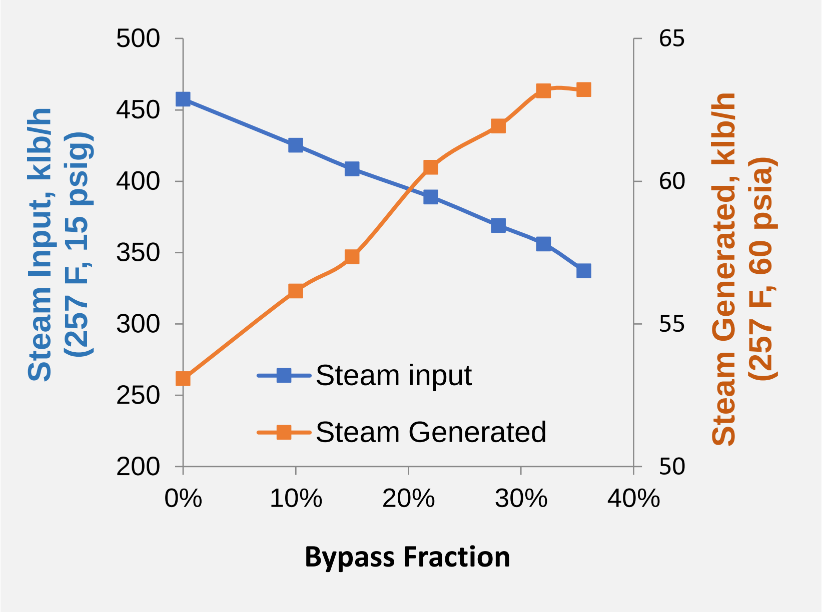


considering 2.4 mtpa CO_2 capture capacity

Water Gas Shift Process Modeling: Preliminary Results ($H_2/CO = 2$)







Increasing Bypass fraction → Decreasing gas volume to be shifted

- Needs more shift in the reactor
- Decreasing compression duty
- Decreasing cooling duty
- Decreasing steam for reaction

- Increasing degree of shift→ Increasing exothermic heat → Increasing steam generation (293 F, 60 psia)

Favorable Conditions

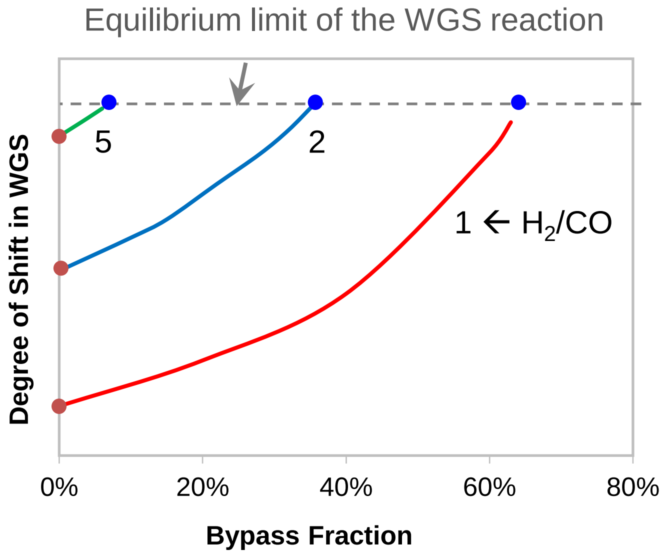
- Maximizing the bypass fraction, until the equilibrium limit † of the WGS reaction, results in most favorable conditions

† determined by feed gas composition and temperature

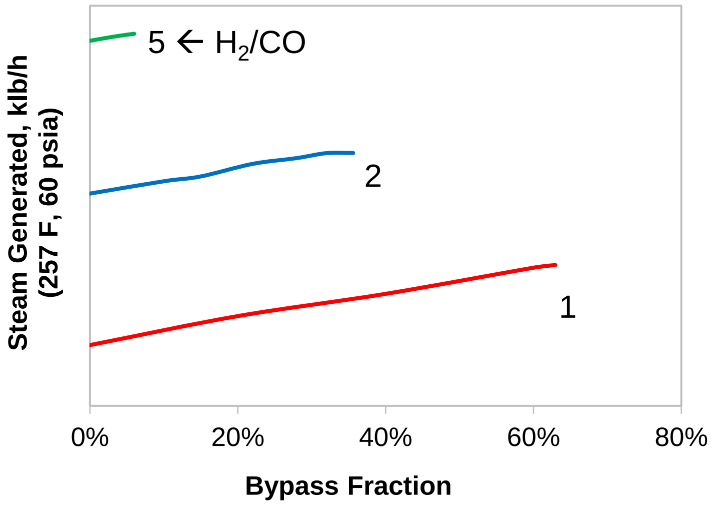
36%
Bypass Fraction

660 ºF
Reactor Inlet temperature

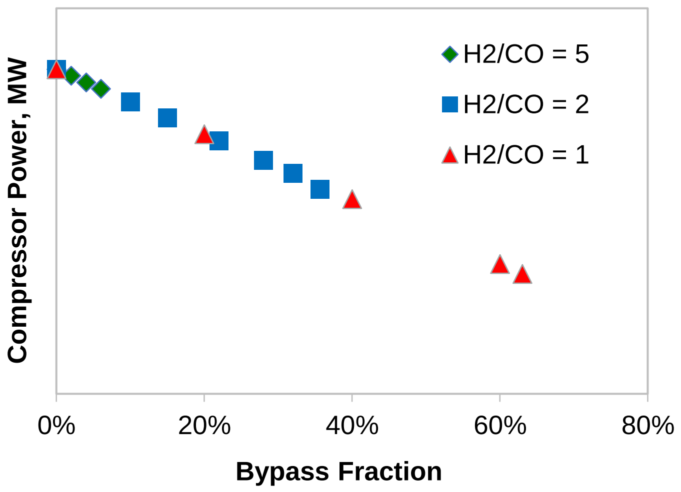
63 klb/h
293 F, 60psia
Steam generated



- Minimum degree of shift – at 0% bypass – increases with H_2/CO
- Maximum degree of shift – bound by the equilibrium limit of WGS reaction
- Maximum bypass – occurs at maximum degree of shift – decreases with H_2/CO

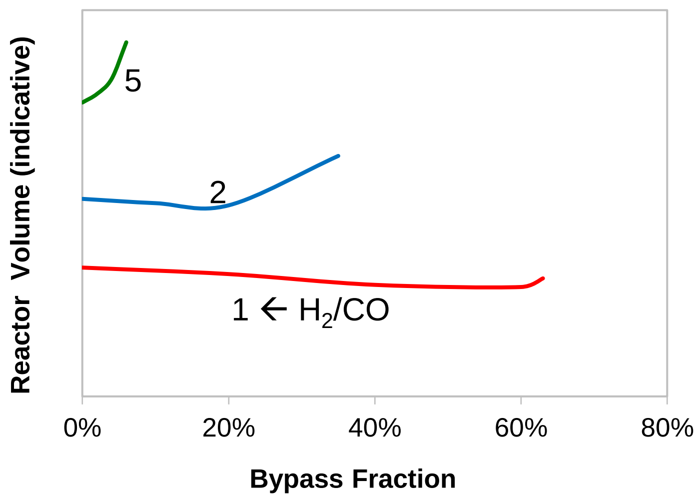


Increasing H_2/CO → increasing degree of shift → increasing steam generation



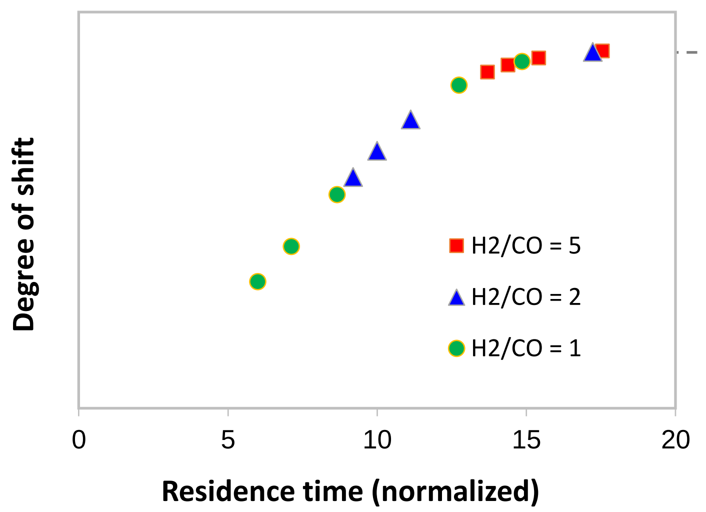
- Increasing Bypass → decreasing Vol. of gas for compression → decreasing compression duty
- Independent of H_2/CO ratio

Water Gas Shift Process Modeling: Guiding Principles for Optimization



- Reactor size strongly depends on the H_2/CO – higher H_2/CO requires higher degree of shift.

- No *one-size-fits-all* for reactor size. Fixing one reactor size may result in over sizing of reactor or insufficient shift when targeting various H2/CO cases



Residence time (deduced from Reactor volume and bypass fraction) plotted against the degree of shift for various cases, collapses all points along one curve. This proves that the overall WGS model is internally consistent

Effect of H_2-rich fuel on Fuel Mix and Gas Pipeline to Power House

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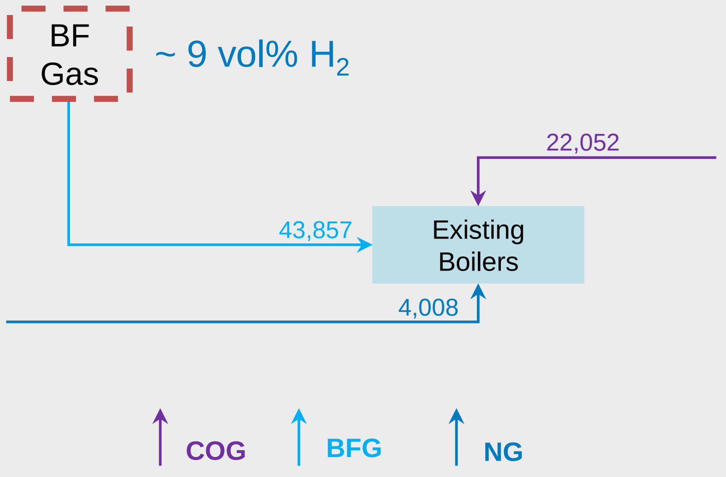
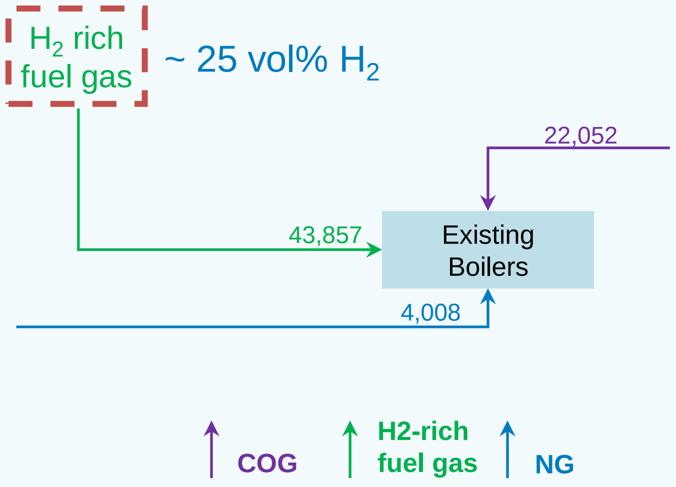
Present Scenario



Sl. No.	Fuel	Energy content (mmBTU/day)	% (energy basis)	Volume Flow Rate (ft³/day)	% (VFR basis)	Heat Value (BTU/ft³)
1.	COG	22,052	31%	40,837,037	9%	540
2.	**BFG**	43,857	63%	402,357,798	90%	103
3.	NG	4,008	6%	3,891,262	1%	1030
	Total	69,917		447,086,097		

Envisaged scenario for 2.4 mtpa capture



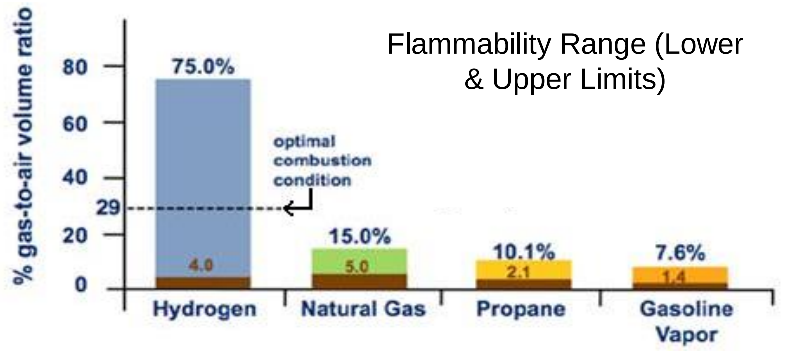
Sl. No.	Fuel	Energy content (mmBTU/day)	% (energy basis)	Volume Flow Rate (ft³/day)	% (VFR basis)	Heat Value (BTU/ft³)
1.	COG	22,052	31%	40,837,037	11%	540
2.	**H2RF**	43,857	63%	337,361,538	88%	130
3.	NG	4,008	6%	3,891,262	1%	1030
	Total	69,917		382,089,838		

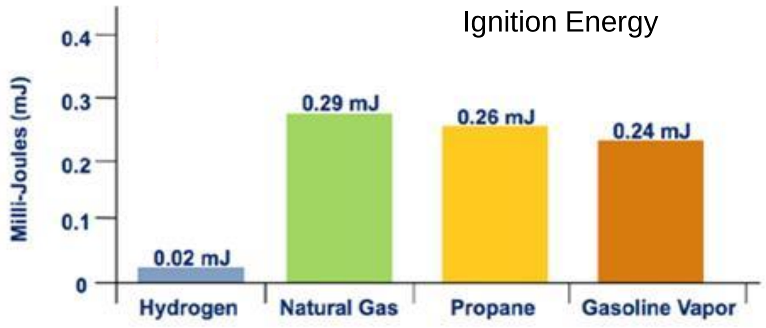
No change is envisaged in the NG, COG & H2RF (originally BFG) pipeline sizing

Powerhouse Boiler: Effect of H_2-rich fuel on burners

H_2 Combustion Characteristics

Combustion Parameter	Unit	Methane	Hydrogen
Molecular Weight	*kg/kmol*	16	2
Energy Density	*kJ/Nm³*	0.716	0.09
Flame Speed	*m/s*	0.55	7.7
Air to fuel ratio	*kg/kg*	20.78	41.2
Higher Heating value	*MJ/m³*	39.8	12.7
Lower Heating value	*MJ/m³*	35.8	10.8





CFD Modeling

Fluid flow pattern

- Temperature fields
- Velocity fields

Flame Characteristics

- Flame Temperature & Velocity
- Flashbacks
- Air/Fuel Ratio
- Flame Appearance

Combustion Products

- NOx, SOx, SPM, etc.
- Extant emission norms to be considered

H_2

Maximum H_2 limit

+

New 'low-carbon' fuel-mix design

Site Visit Highlights

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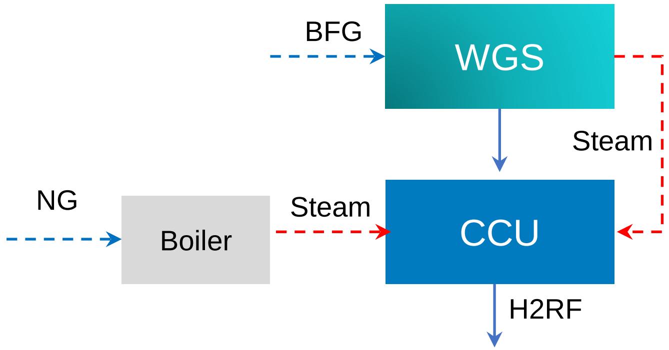
Host	Attendees
CLIFFS	DASTUR, ION CLEAN ENERGY, GCCC GULF COAST CARBON CENTER

1. No overground and underground facilities other than 132 KV transmission line - needs to be relocated during the site work
2. Space available for installation of CHP/boiler to source steam and power
3. BFG tapping can be taken from nearby pipe-rack beside power house
4. 15 PSI.g saturated steam available from power house for the project
5. New NG pipeline to be laid for additional natural gas requirement

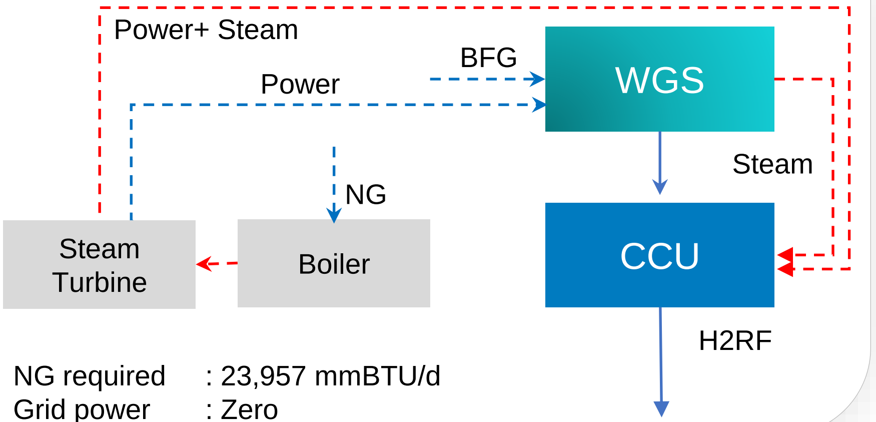
Power and Steam Sourcing Options

1 With Boiler



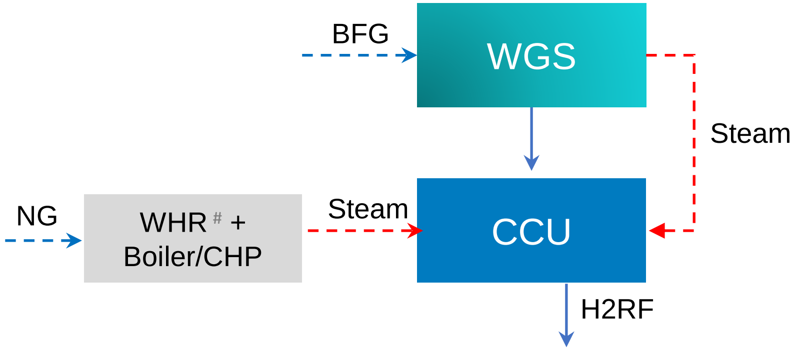
NG required : 19,337 mmBTU/d
Grid power : 40 MW

2 With CHP



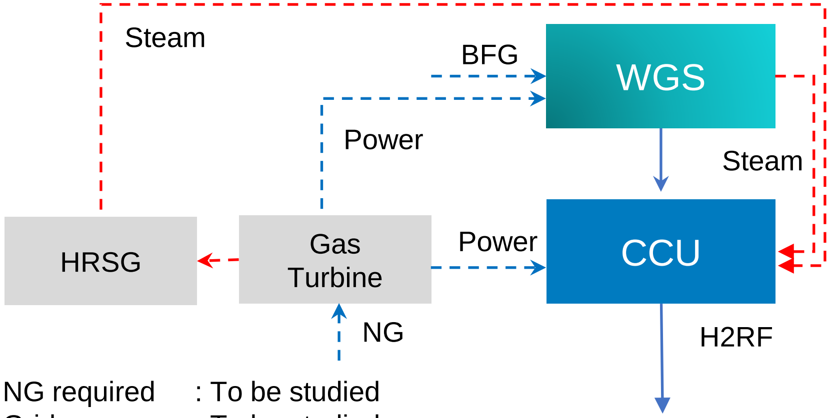
NG required : 23,957 mmBTU/d
Grid power : Zero

3 With WHR +Boiler/CHP



NG required : To be studied
Grid power : To be studied

4 With Gas turbine + HRSG



NG required : To be studied
Grid power : To be studied

Potential steam generation from CDQ, BOF gas recovery system and other options

* Numbers are based on 2.4 mtpa capture

Cost of Capture at Burns Harbor – Preliminary Techno-Economic Analysis

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BFG volume considered: 43,857 MMBTU/d

Parameter	Option 1 – With CHP	Option 2 – with Boiler	Unit
CO_2 Captured	2.4	2.4	$MTCO_2$/year
Total CAPEX	450	430	$MM
Annualization Factor	0.0944	0.0944	-
Amortized CAPEX	**17.7**	**16.9**	**$/tonne CO_2**
Annual OPEX	42.0	60.5	$MM/year
OPEX/Cash Cost	**17.5**	**25.2**	**$/tonne CO_2**
Capture cost incl. CAPEX	**35.2**	**42.1**	**$/tonne CO_2**
Transport, Sequestration & Monitoring (TSM)	10	10	$/tonne CO_2
Total Cost	**45.2**	**52.1**	**$/tonne CO_2**

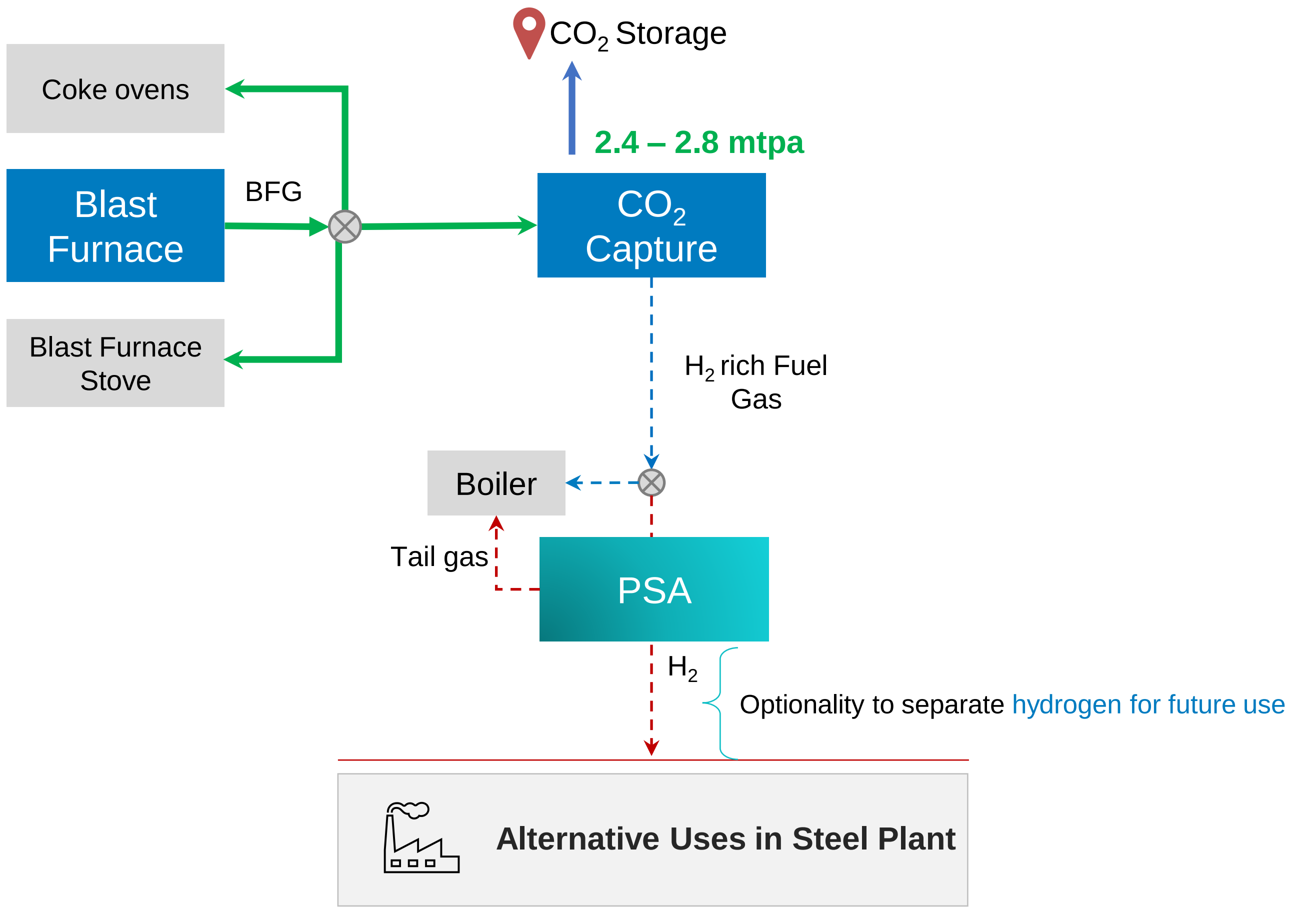
Assumptions @ $70/MWh electricity cost at BH, 90% uptime, 95%+ capture

Goal of ~$32 $/t by commissioning

- Increase in CO_2 volume will amortize same capex over higher volumes
- Onsite wells being explored as an alternative to off site sequestration.
- Steam generation from WGS and other waste heat schemes can complement the net steam requirement of CCU reboiler

*Includes capital cost of Water Gas Shift, CHP for carbon capture needs, NG fuel costs at 3$/Mmbtu
**Includes cost for carbon capture, carbon compression up to 2215 psia

Opportunity to Extract H_2 for Alternative Uses in Steel Plant in Future



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