From Cryogenic Carbon Capture to Production

SUSTAINABLE ENERGY SOLUTIONS

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Cooler By Design.™

Broad Offering of Highly Engineered Cryogenic Equipment

SES INNOVATION

CHART
Cooler By Design.™

Brazed Aluminum Heat Exchangers

Cold Boxes

Gas Pre-Treatment and Nitrogen Rejection Units

Specialty Pressure & Heat Transfer Equipment

Air Cooled Heat Exchangers

Axial Flow Fans

Integrated Energy Systems

Lifecycle Services

Cryogenic Bulk Storage Tanks

Vaporizers

Cryogenic Storage & Regasification Systems

Packaged Gas Systems

Cryogenic Launch Umbilicals & Storage

Nitrogen Dosing & Food Preservation

Fueling Stations

HLNG Vehicle Tanks

Cryogenic Transport Trailers

LNG Virtual Pipeline Solutions

LNG by Rail

FEMA Valve Portfolio

Servicing & Repairs

Sustainable Energy Solutions

10+ years research and development

50+ patents issued

Platform technology

NG Treating

Carbon Capture

Introduction to Cryogenic Carbon Capture (CCC)

Cryogenic Carbon Capture (CCC)

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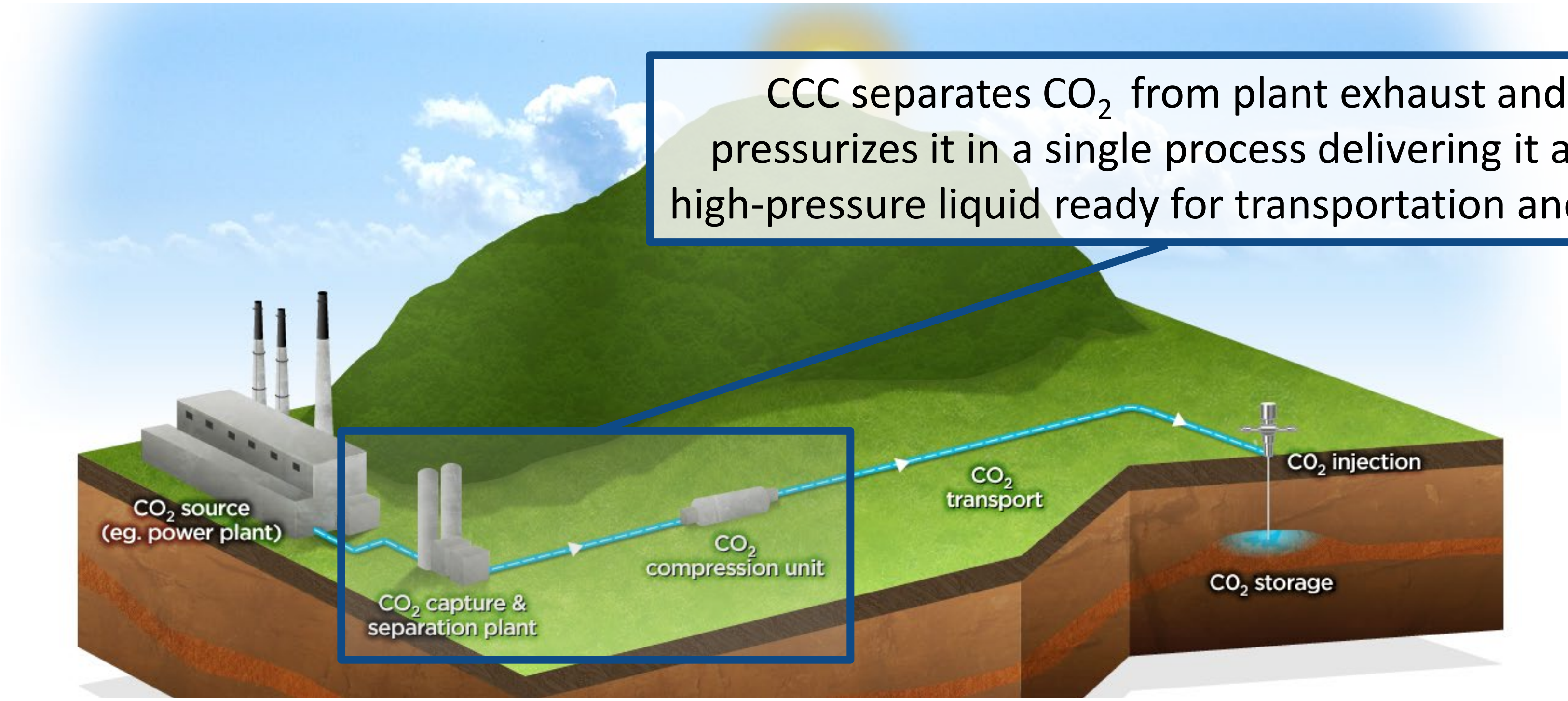
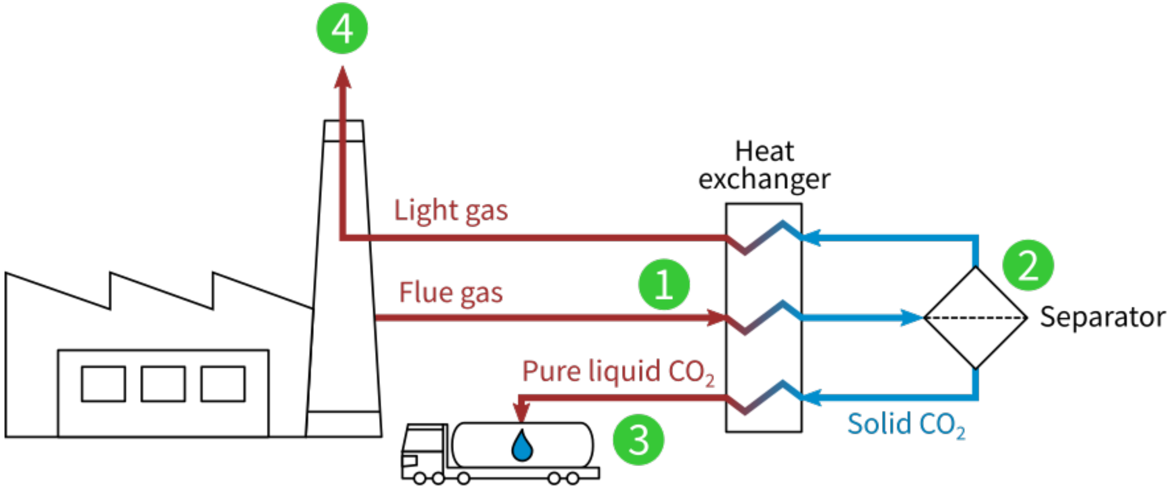
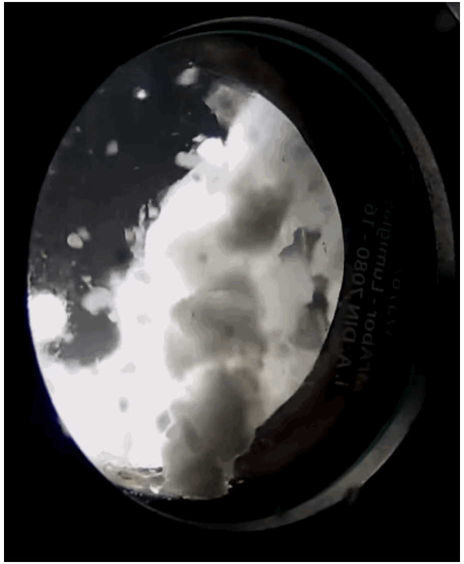
CCC separates CO_2 from plant exhaust and pressurizes it in a single process delivering it as a high-pressure liquid ready for transportation and use



Conceptually Simple Process





1. Flue gas is cooled
2. CO_2 is separated as a solid from the light gases
3. CO_2 is melted and prepared for transport
4. Light gases are reheated and released to atmosphere

CCC Benefits

Lowest energy and cost retrofit technology

Easiest retrofit carbon capture technology

Produces high-purity, liquid CO_2

Very high capture rates, up to negative emissions (99%+)

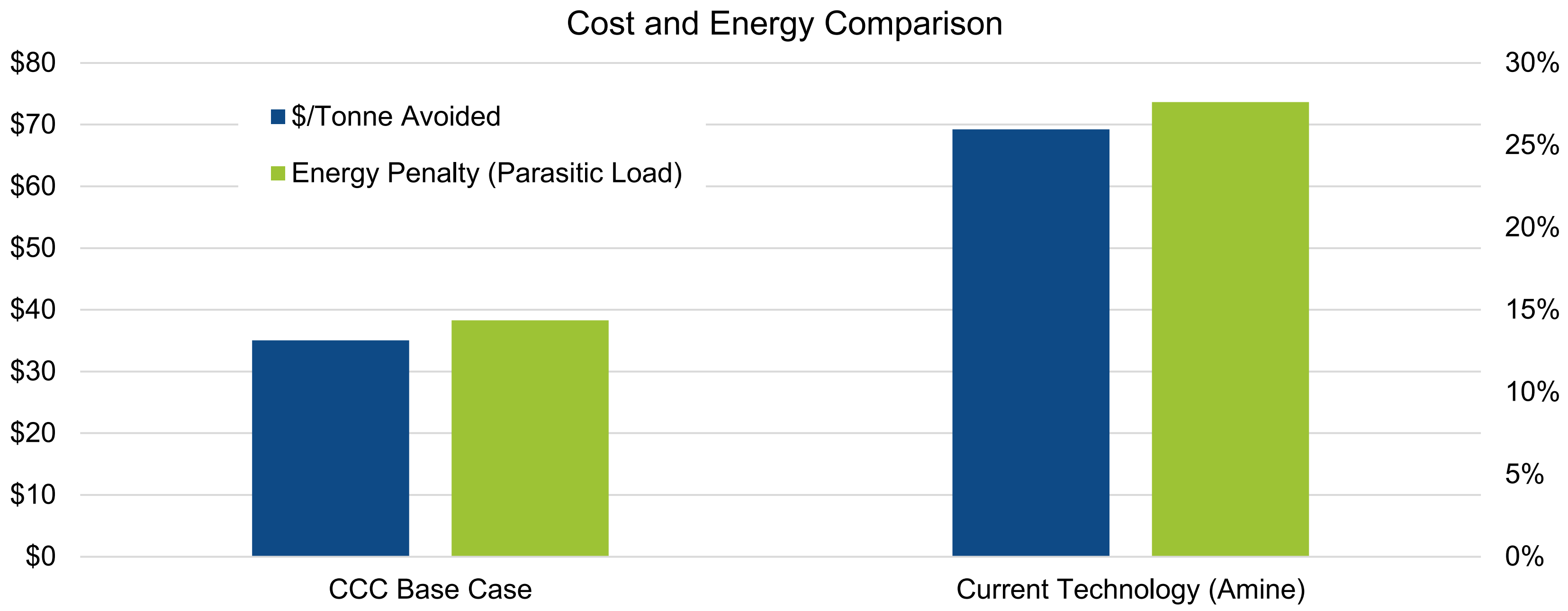
Integrated grid-scale energy storage

Independent Validation

"Of all these [carbon capture] processes, I regard the CCC process to have the greatest potential"

-Howard Herzog, MIT Energy Initiative

CCC Cuts Costs in Half (Large-Scale Coal)



-Numbers based on NETL 2013 net 550 MW super critical pulverized coal plant

-Additional value and revenues could be gained from CO_2 sales and energy storage.

Integrated Energy Storage Example

Energy Storing	Low power prices (surge in renewables or off-peak demand)

CCC generates excess cooling and stores excess refrigerant

Plant output 480 MW

CCC parasitic load ~18%

Energy Release	High power prices (drop in renewables or peak power demand)

CCC runs off stored refrigerant increasing the effective output of the plant

Plant output 560 MW

CCC parasitic load ~5%

CCC cleans up emissions while enabling renewables and providing host plant with near full capacity during peak demand

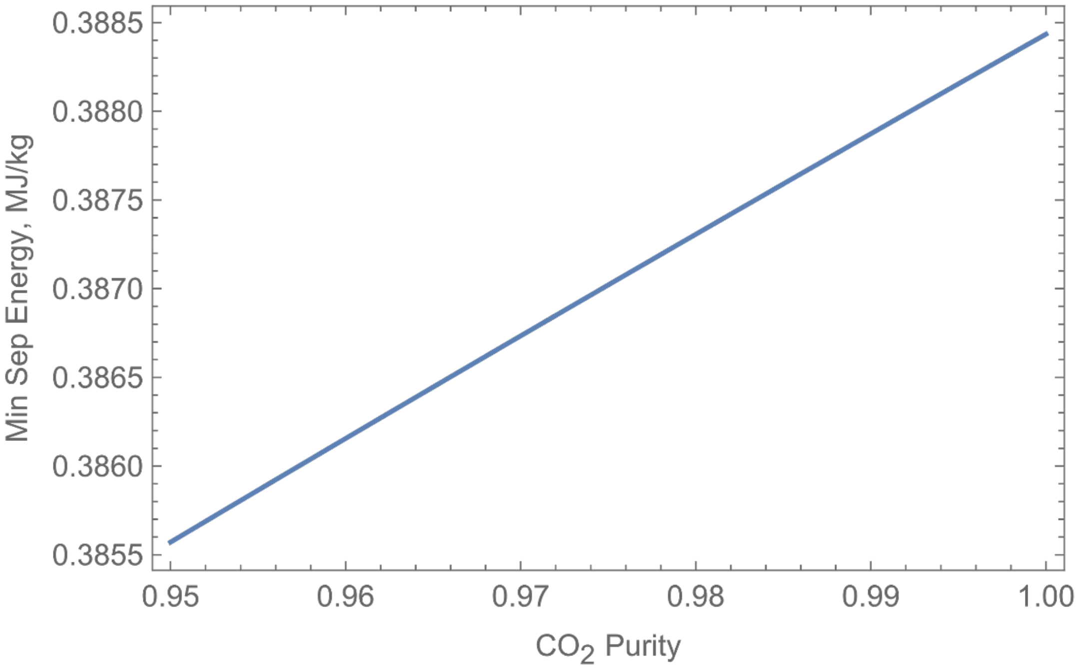
CCC and Chart

A Winning Combination

Energy Demand Dependencies

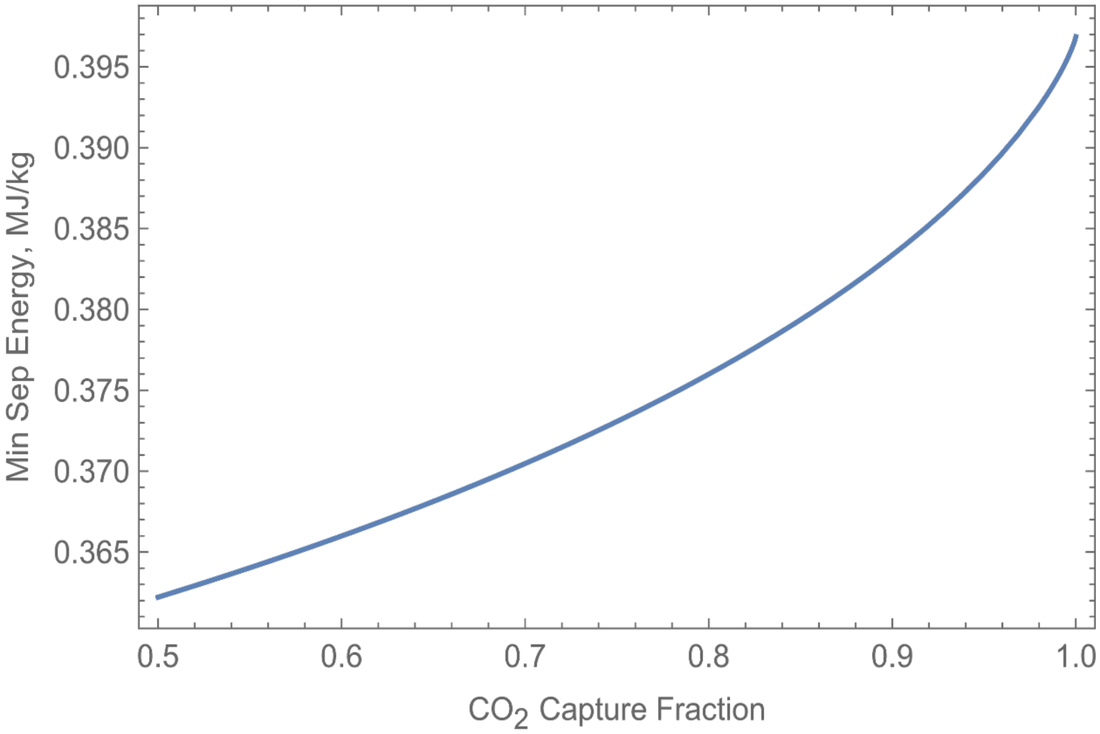
- Carbon capture specific energy demand (energy/mass captured) depends primarily on three process variables
  - Initial composition
  - Capture fraction
  - Product purity
- Efficiency and especially costs also have significant economies of scale
- CO_2 compression requires additional energy comparable to the separation energy demand for those systems that require it (nearly all systems except CCC).
- Variations in minimum specific energy indicates sensitivity to the process variables
- Actual systems always require more energy and generally have greater sensitivity
- The following plots pertain to any carbon capture system and assume initial mole fractions, capture fractions, and purities of 15%, 95%, and 100%, respectively, unless otherwise indicated.

Energy Demand vs Purity



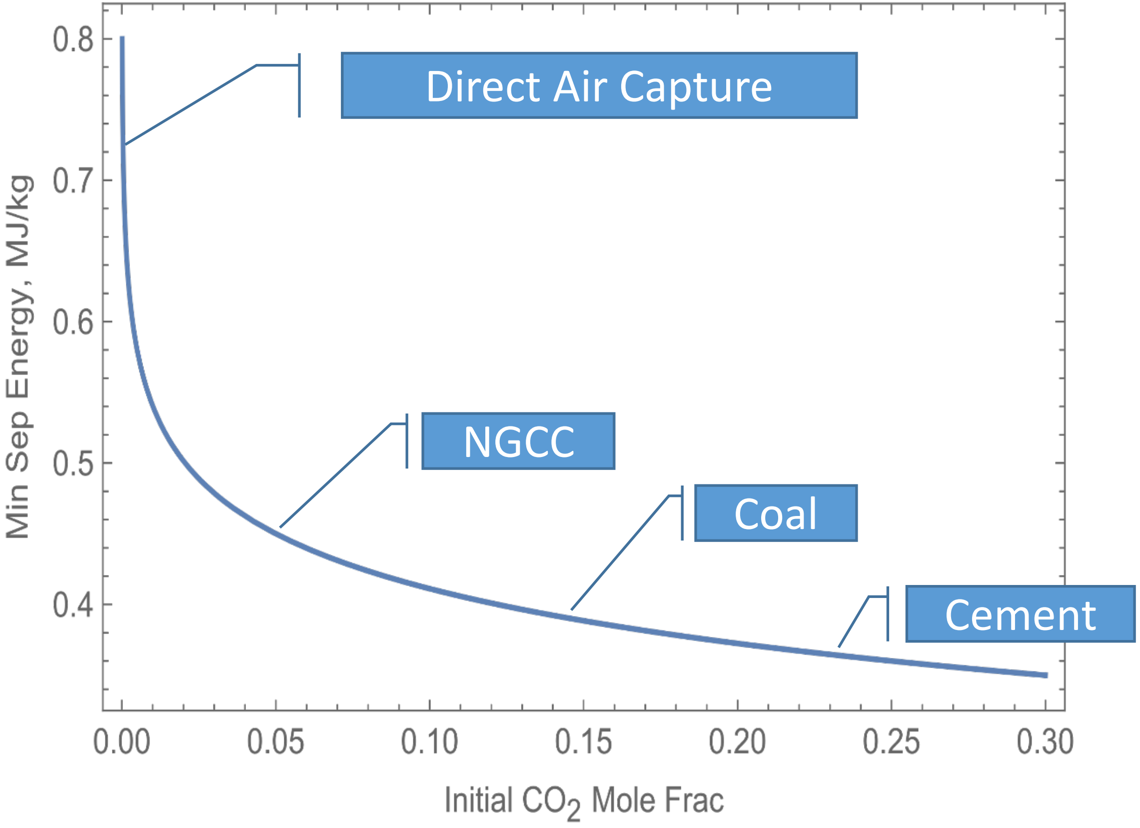
- Min. specific energy depends on product purity in linear and modest ways.
- Real systems depend on purity in stronger and more nonlinear ways.
- Real system separate water, O_2, and other species in addition to CO_2.

Energy Demand vs Capture Fraction



- Min. specific energy demand depends significantly and nonlinearly on capture fraction
- Energy and energy dependence increase with increasing capture fraction
- Min. specific energy remains finite as capture fraction becomes 1.

Energy Demand vs Init. Composition

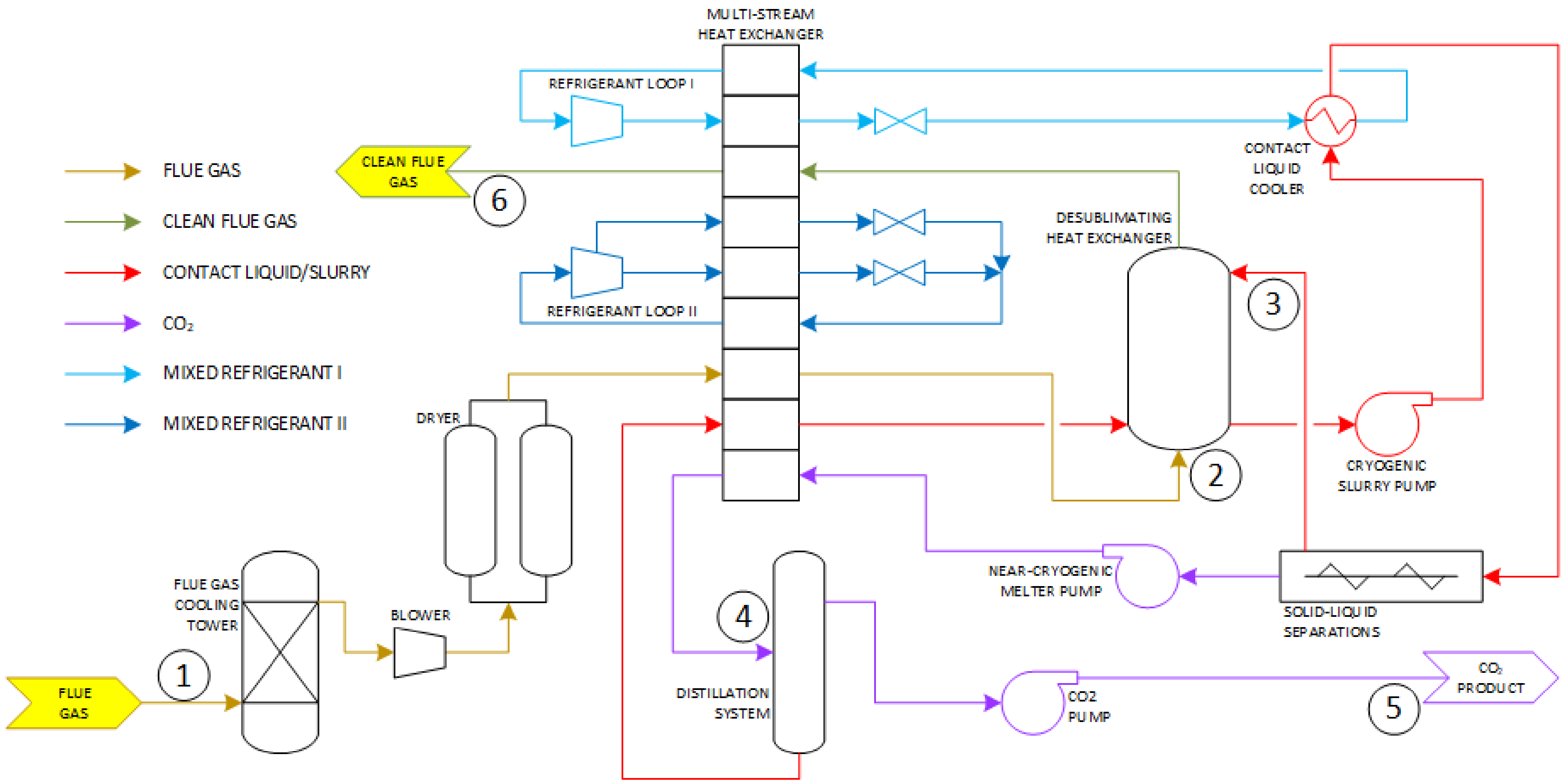


- Min. specific energy demand depends on initial composition in extreme and nonlinear ways.
- Min. specific energy becomes infinite as initial composition approaches zero.
- Differences in real systems exceed these minimum energy differences.

CCC Process

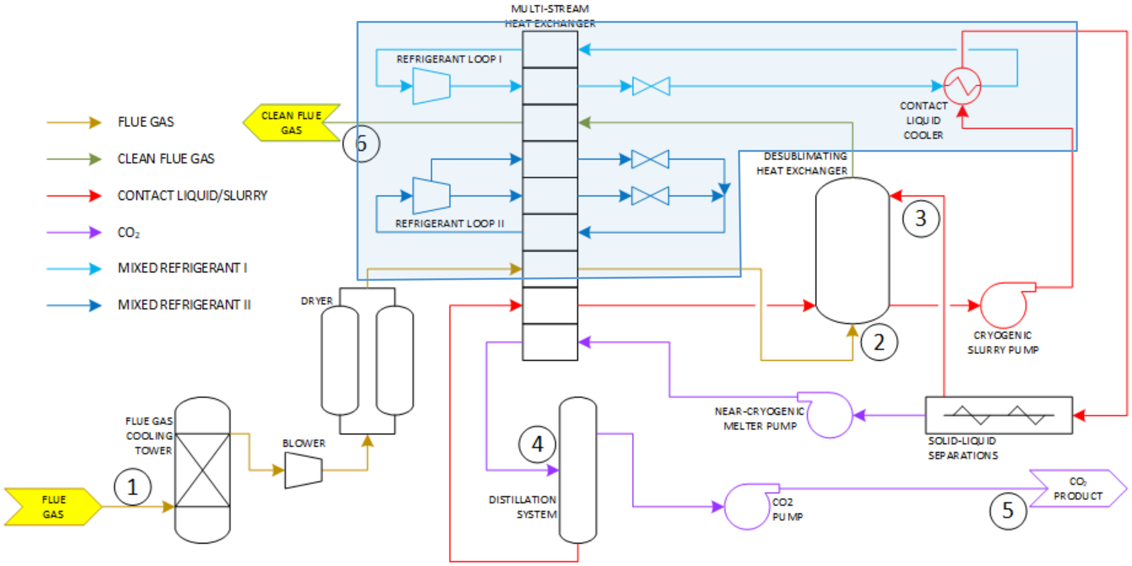
- The CCC process involves four steps
  - Cool stream to condensation point
  - Condense (desublimate) CO_2
  - Pressurize condensate
  - Warm via heat recovery
- Capital-intensive components are commercially available
  - Compressors/turbomachinery
  - Largest heat exchangers
- Some innovative, non-commercial equipment
  - Desublimating heat exchanger
  - Drying technology

PFD



MULTI-STREAM HEAT EXCHANGER
REFRIGERANT LOOP I
REFRIGERANT LOOP II
CLEAN FLUE GAS
6
FLUE GAS
CLEAN FLUE GAS
CONTACT LIQUID/SLURRY
CO_2
MIXED REFRIGERANT I
MIXED REFRIGERANT II
CONTACT LIQUID COOLER
DESUBLIMATING HEAT EXCHANGER
3
2
CRYOGENIC SLURRY PUMP
DRYER
NEAR-CRYOGENIC MELTER PUMP
SOLID-LIQUID SEPARATIONS
FLUE GAS COOLING TOWER
BLOWER
4
DISTILLATION SYSTEM
1
FLUE GAS
CO2 PUMP
CO_2 PRODUCT
5

Refrigeration System Leverages Chart IPSMR Expertise



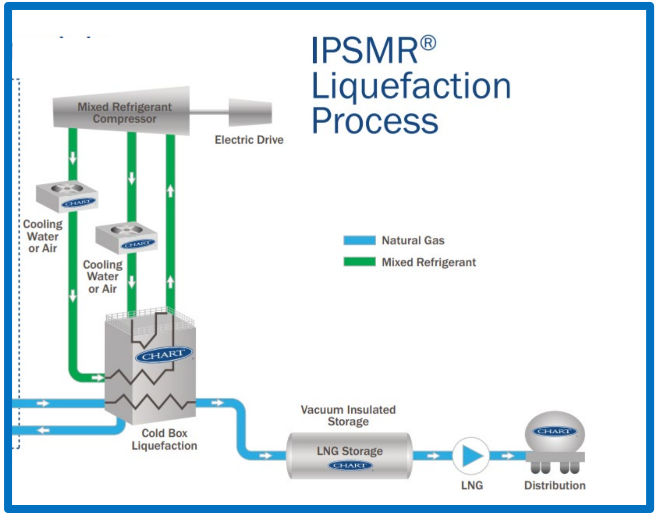
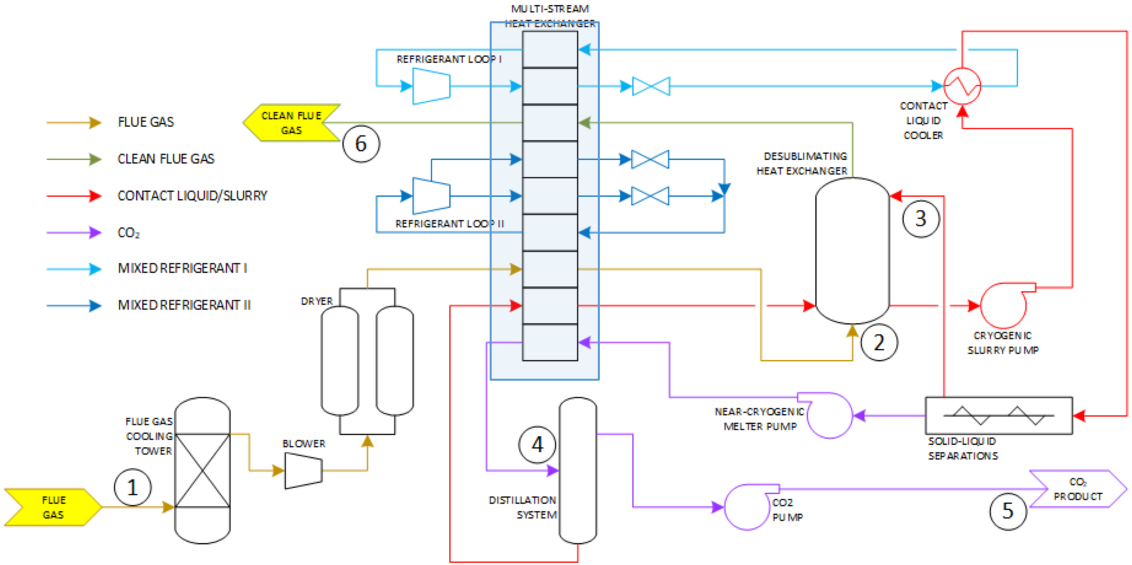
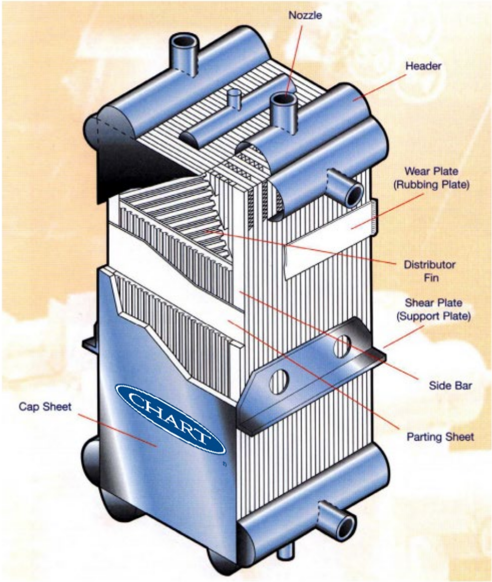
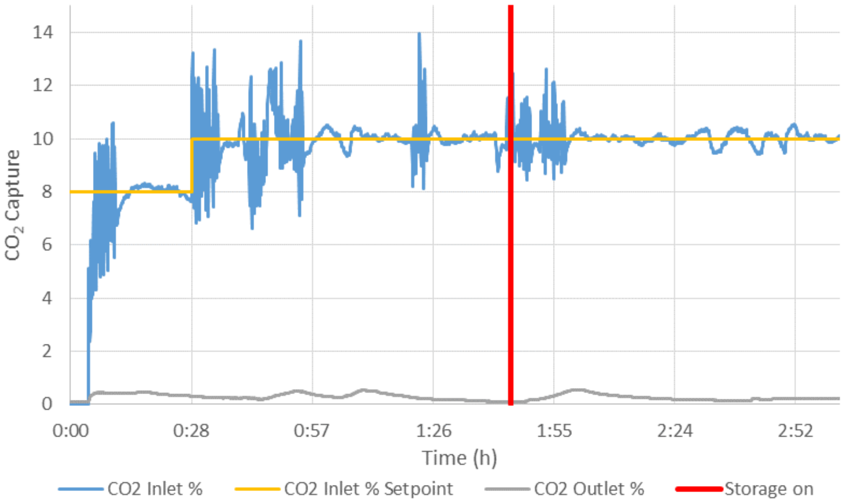


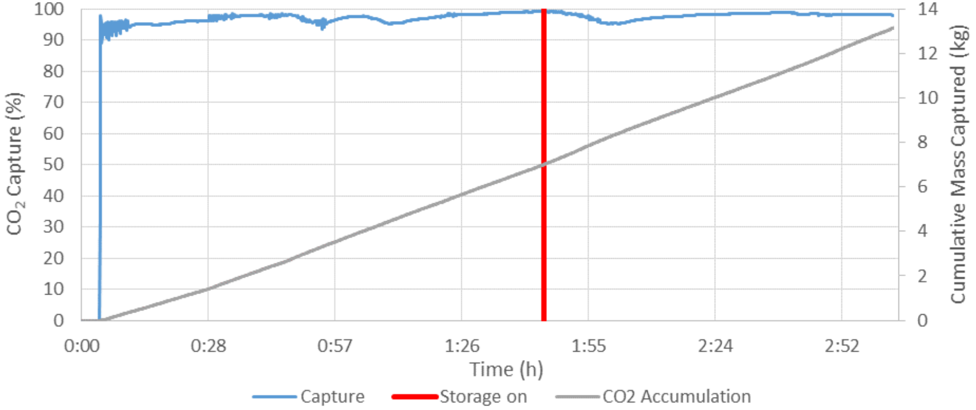
Chart World-Leading BAHX Technology is at the Heart of the CCC Process





Energy Storage





CCC Advantages

- CCC has many compelling ancillary advantages
  - Low cost
  - Low energy demand
  - Easy to retrofit
  - Enables cost effective and efficient grid-scale energy storage
  - Multipollutant and robust to contaminants
  - Recovers water from flue gas
  - Capable of net-negative emissions
  - Scalable
  - Can produce high-purity product (99.99+%)

Small Pilot Field Demonstrations

Natural Gas, Coal, Cement, Biomass Exhaust Gas Sources

Capture at Cement Plant

Small Pilot Operated by SES

Use in Concrete

CarbonCure Utilization Partner

Demonstration

SES INNOVATION

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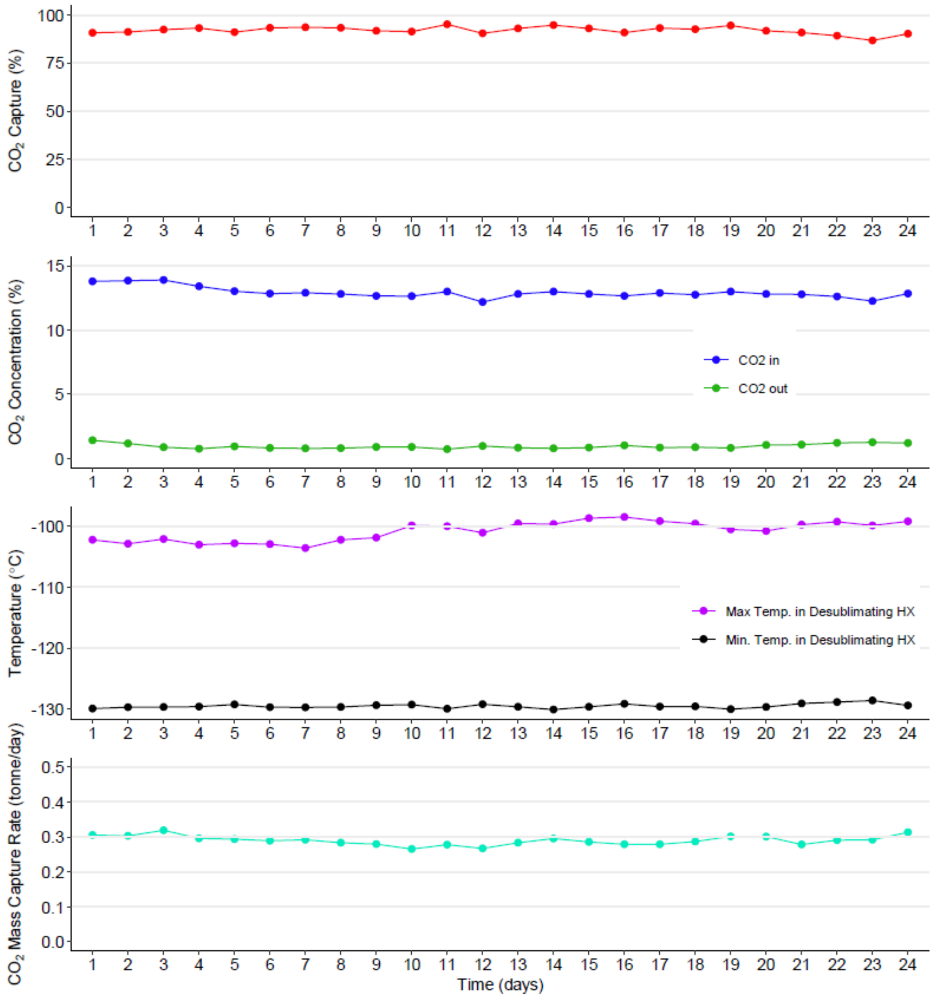
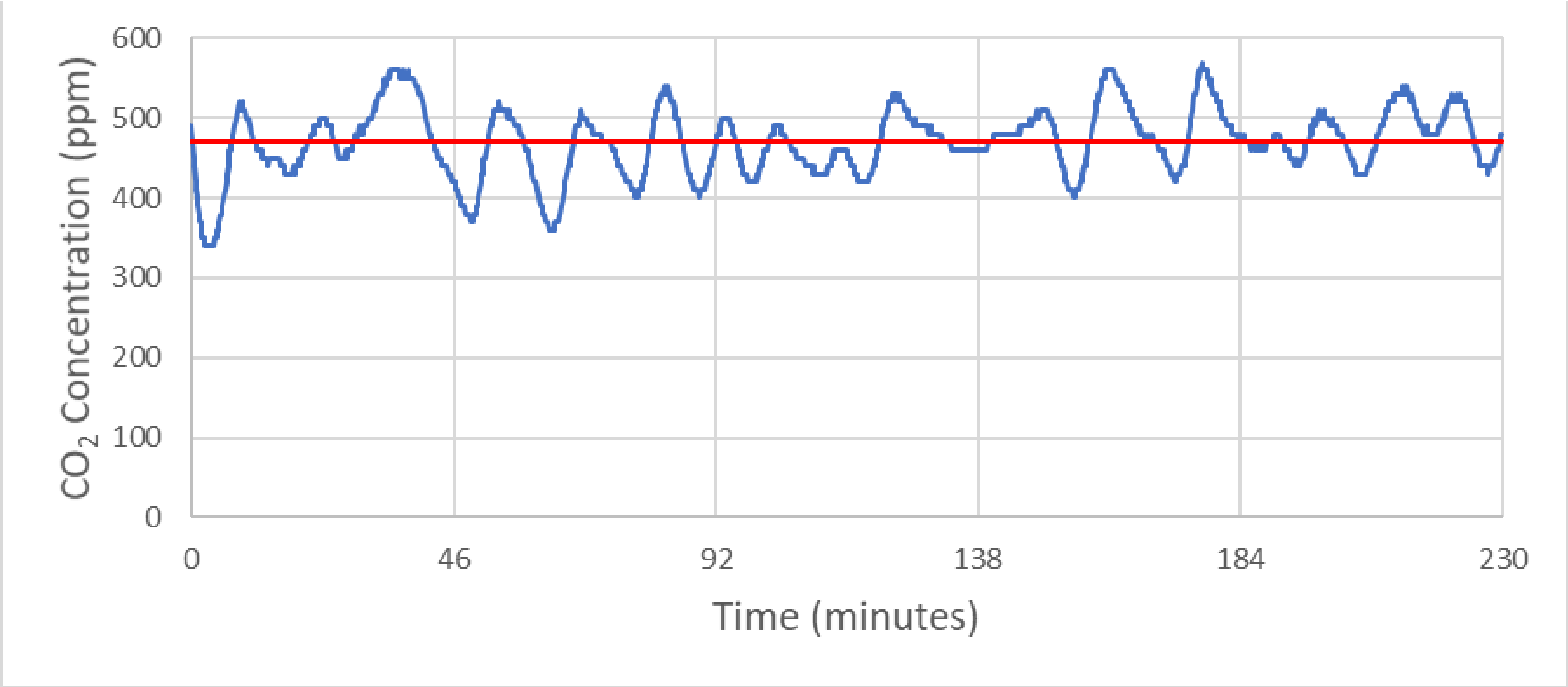
25 days continuous operation – actual data

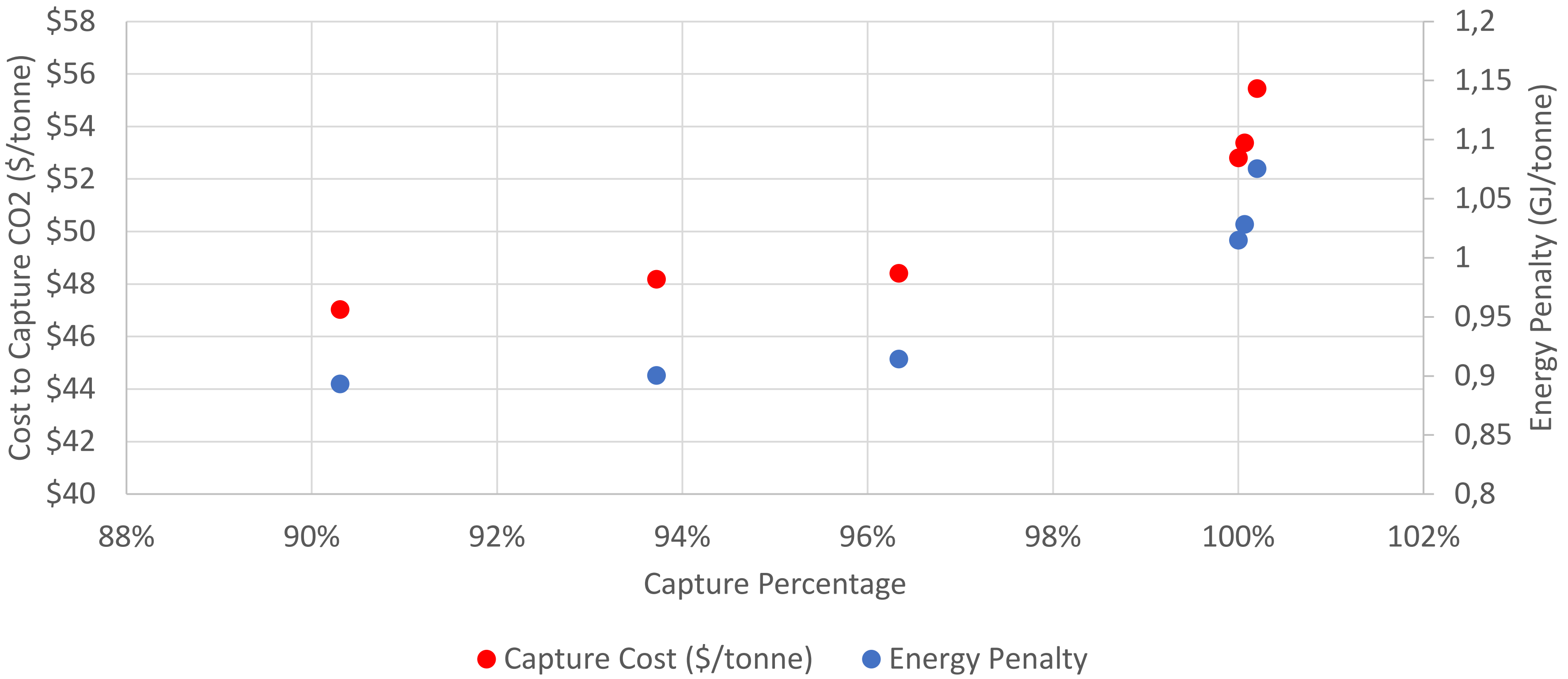


Skid-scale Demonstration



DAC threshold is greater 410 ppm because most O_2 has been removed as CO_2 and H_2O

PS DAC Costs



$58
$56
$54
$52
$50
$48
$46
$44
$42
$40
Cost to Capture CO2 ($/tonne)
1,2
1,15
1,1
1,05
1
0,95
0,9
0,85
0,8
Energy Penalty (GJ/tonne)
88%
90%
92%
94%
96%
98%
100%
102%
Capture Percentage
Capture Cost ($/tonne)
Energy Penalty

Next Step:

Small-Commercial Project to Begin 2021

Currently Building 30 TPD System

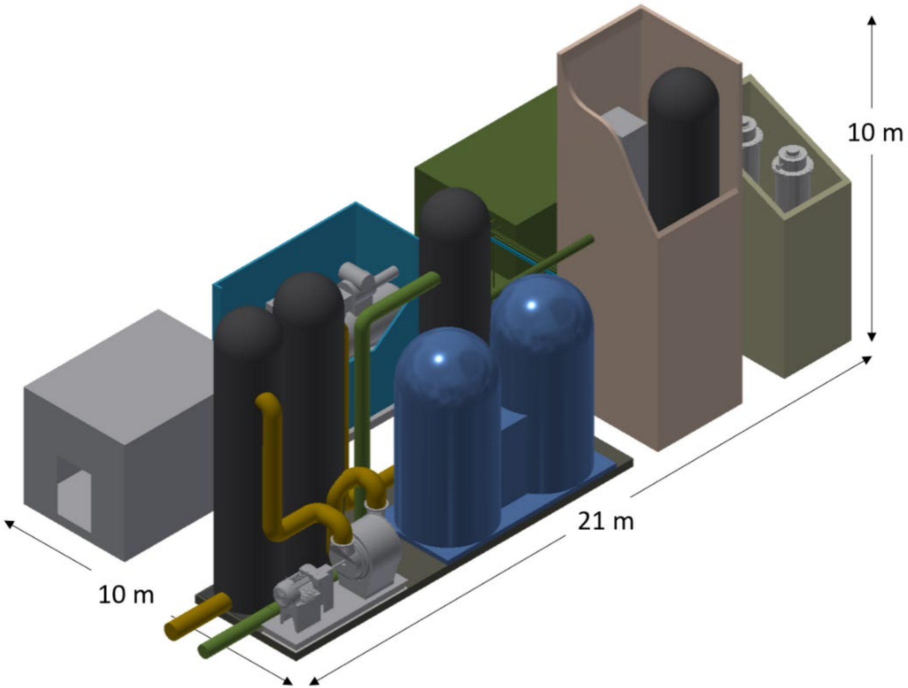


Chart Industries, Inc. SES Cryogenic Carbon Capture™ Technology Selected for Funding from the U.S. Department of Energy

October 07, 2021 07:30 ET | Source: Chart Industries, Inc.

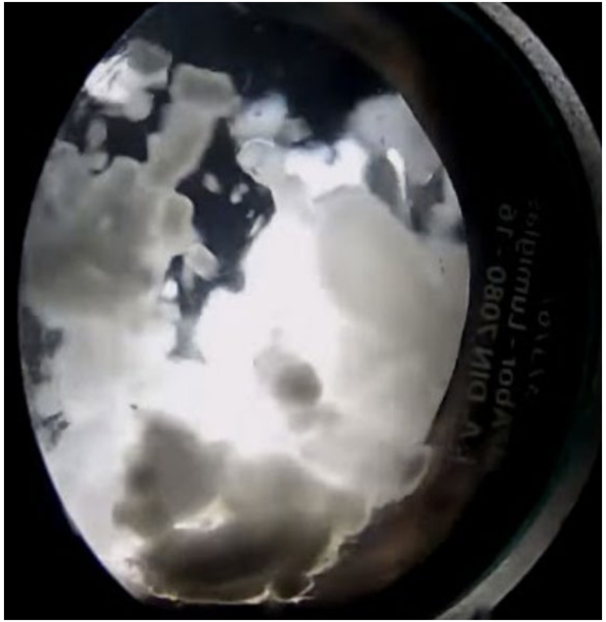
Demonstrate industrial reliability and validate commercial-scale economics

Full-scale for near-term markets, pilot demonstration for utility-scale system

Preliminary design finished

Acknowledgements

- Project sponsors/partners: Chart Industries, State of Wyoming, Department of Energy, Pacificorp, King Abdula University of Science and Technology (KAUST), State of Utah, Air Liquide, General Electric, Province of Alberta, Dong (now Ørsted) Energy
- SES Employees (12 engineers, 1 MBA/economist/EIT)
- Brigham Young University



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