SUSTAINABLE ENERGY SOLUTIONS

Cryogenic Carbon Capture Development Progress and Field Test Data

August 26, 2019

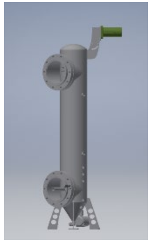
Larry Baxter

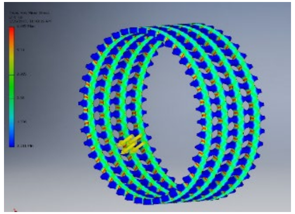
DE-FE0028697; $3.7M DOE/$4.7M total;
10/01/2016 – 06/30/2019

CCC-Dev Project Timeline

Phase 1

De-Risking Individual Unit Operations

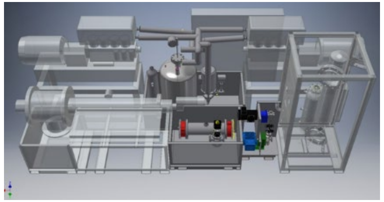


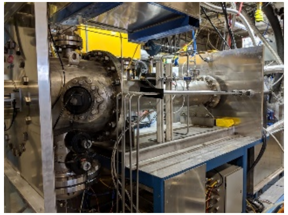


Oct 2016 – Sept 2017

Phase 2

Field Test Skid Modification





Oct 2017 – Dec 2018

Field Test at Hunter Power Plant

Jan 2019 - Jun 2019

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Overview

High-level review of CCC technology

Full-scale techno-economic discussion

Detailed discussion process and subsystems

Testing data from field tests

Current Carbon Capture Technology Challenges

Expensive	\$70/tonne CO_2 (more for existing plants) 25%-30% Parasitic Load
Difficult to retrofit	Require an entirely new plant in some cases or significant modifications/integration with the steam cycle and turbine in others
Produce CO_2 gas	Requires additional compression and purification for transportation and many uses

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CCC Provides the Solutions

Half the cost and energy	Even greater advantages in retrofit scenarios
Easily retrofits to any stationary emissions source	Applicable to NG and coal power plants, cement plants, NG burners, etc. without plant modifications
Produces CO_2 ready for use	Produces high-purity (>99.9%), high pressure CO2 ready for transportation and sale

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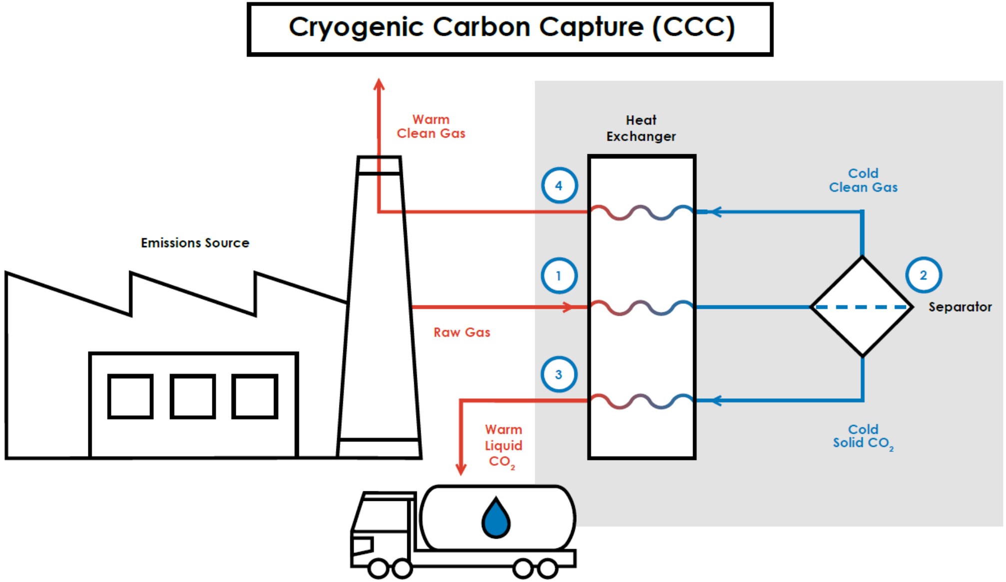
CCC has Additional Unique Advantages

Robustly handles SO_X and NO_X	With development may be able to replace SOX, NOX, and mercury treatments
Option of Grid-Scale Energy Storage*	Integrates with intermittent renewables on the grid, allows for 80% reduction in parasitic load during peak demand

*See appendix for more details

CCC is a Simple Process



The CCC process (1) cools a dirty exhaust gas stream to the point that the CO_2 freezes using mostly heat recuperation, (2) separates solid CO_2 as it freezes from the clean gas, (3) melts the CO_2 through heat recuperation and pressurizes it to form a pure liquid, and (4) warms up the clean, harmless gas releasing it to the atmosphere. See appendix slides for more detailed flow diagrams.

Independent Validation

Of all these processes [CCS technologies], I regard the CCC process to have the greatest potential by a significant margin.

-Howard Herzog, MIT Energy Initiative

MIT Energy Initiative

ELECTRIC POWER RESEARCH INSTITUTE

nrg | cosia CARBON XPRIZE

EDISON AWARDS GOLD 2016 WINNER

R&D 100 55 Years of Invention

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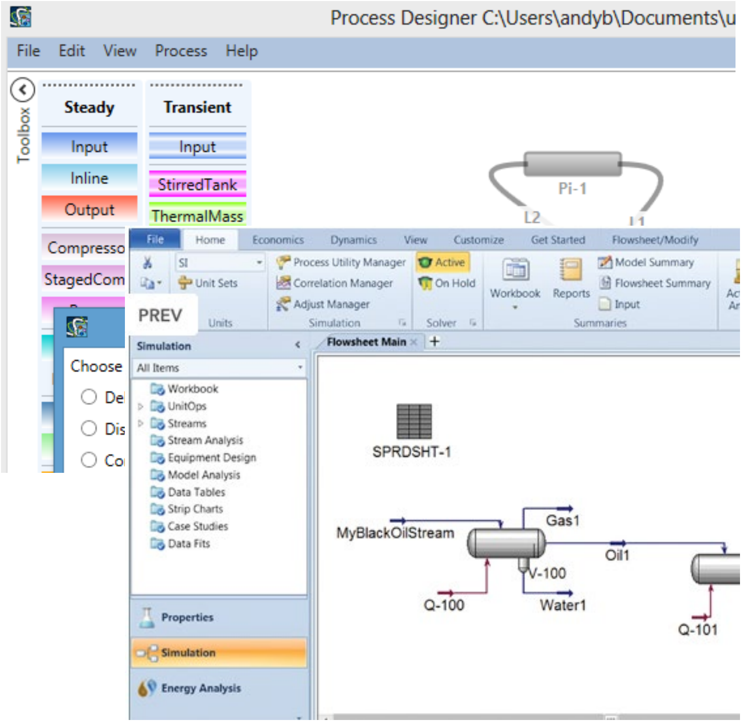
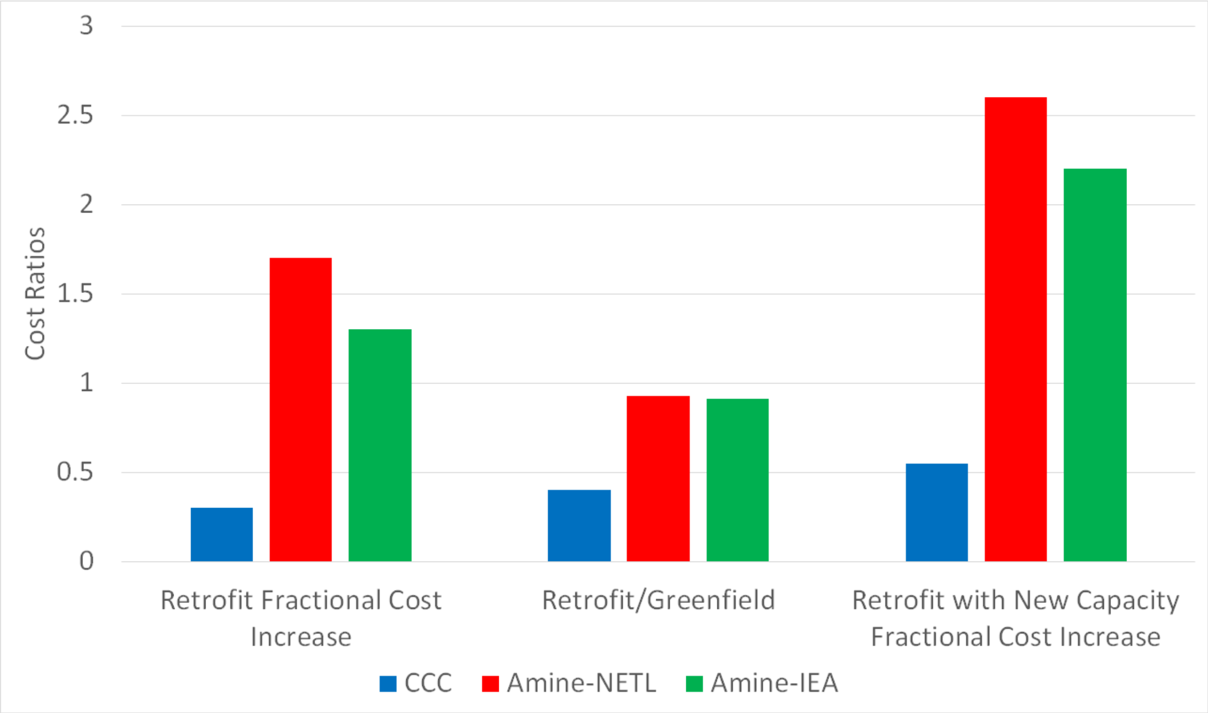
FULL SCALE TECHNO-ECONOMIC DISCUSSION

Process Simulation and Modeling

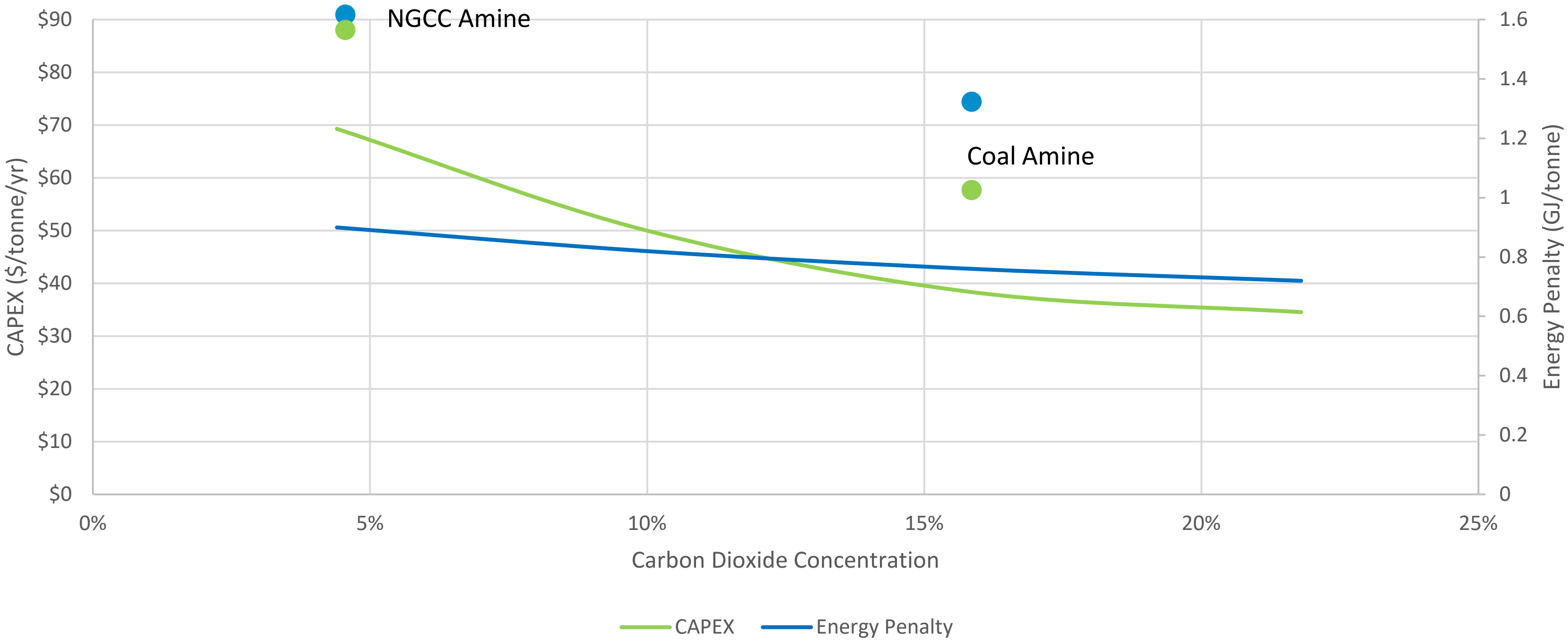
- Robust in-house process simulation software developed specifically for CCC
- Capable of simulating various sizes and applications ranging from our skid-scale system to full-scale
- Thermodynamically rigorous calculations
- Results comparable to Aspen simulations
- Vetted and checked by various project partners and third-party contractors



Retrofit Costs

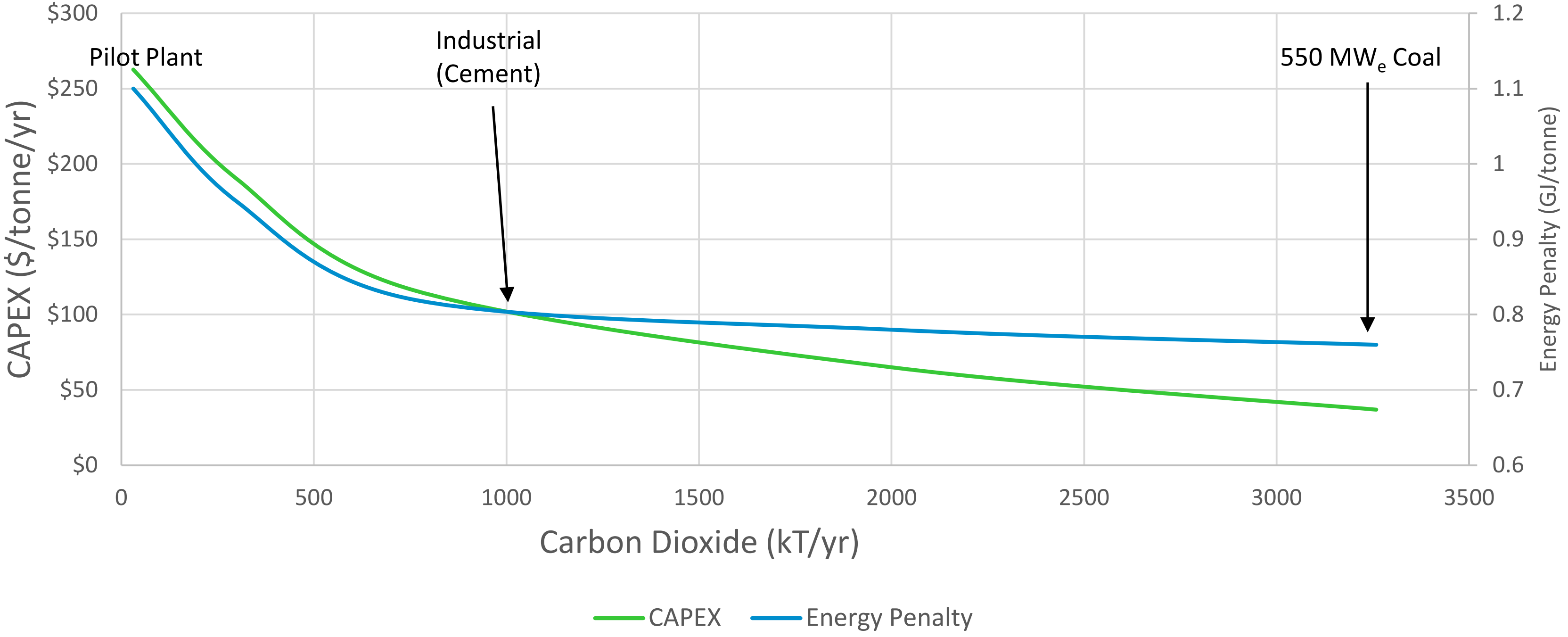


Cost and Energy with Composition

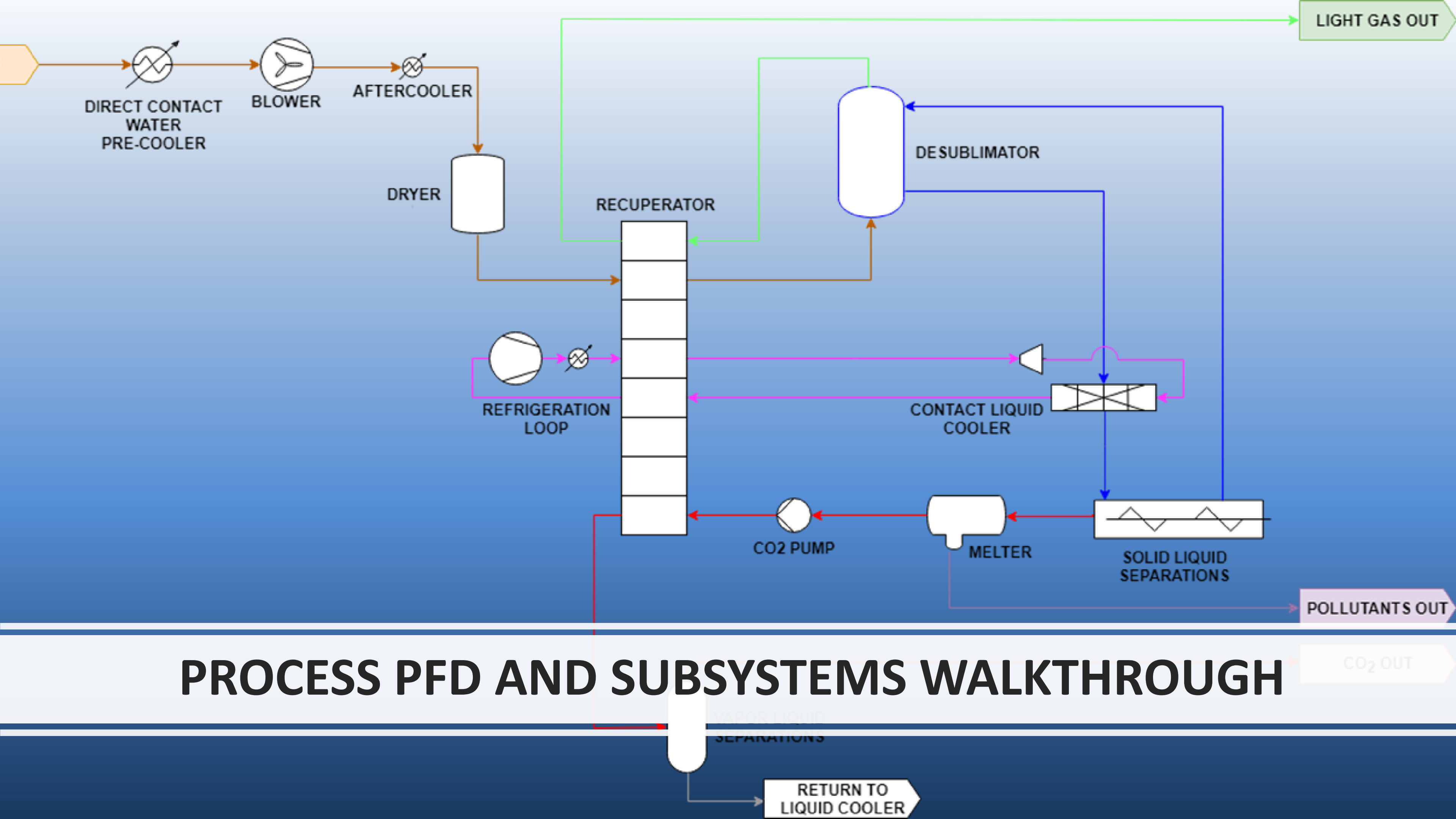


CAPEX numbers is the total equipment cost, not depreciated over any timeframe, and it does not include operating costs. These numbers assume large installations on the order of a power plant

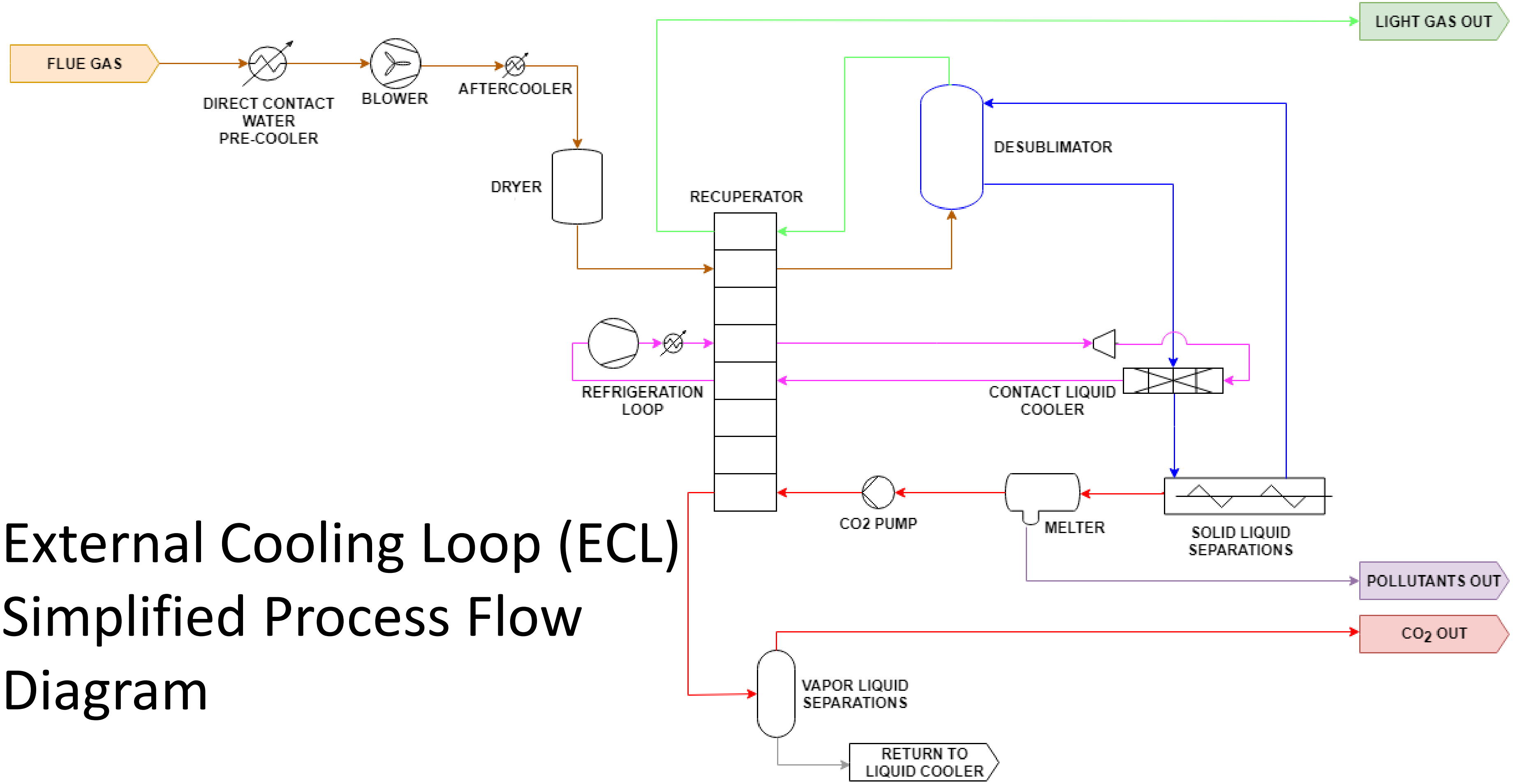
Cost and Energy with Plant Size



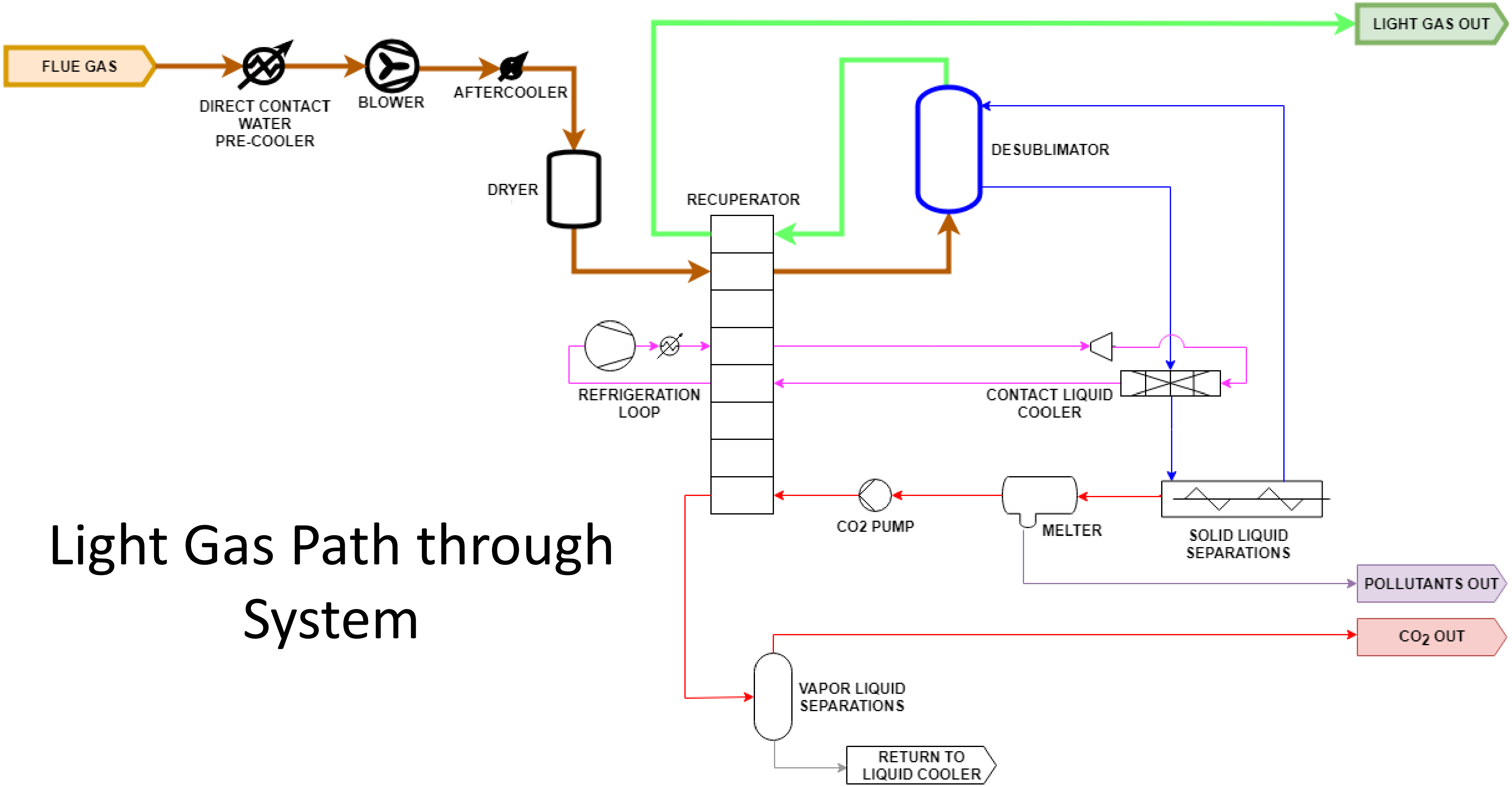
CAPEX numbers is the total equipment cost, not depreciated over any timeframe, and it does not include operating costs. These numbers assume a CO_2 composition of approximately 16% on a dry basis.



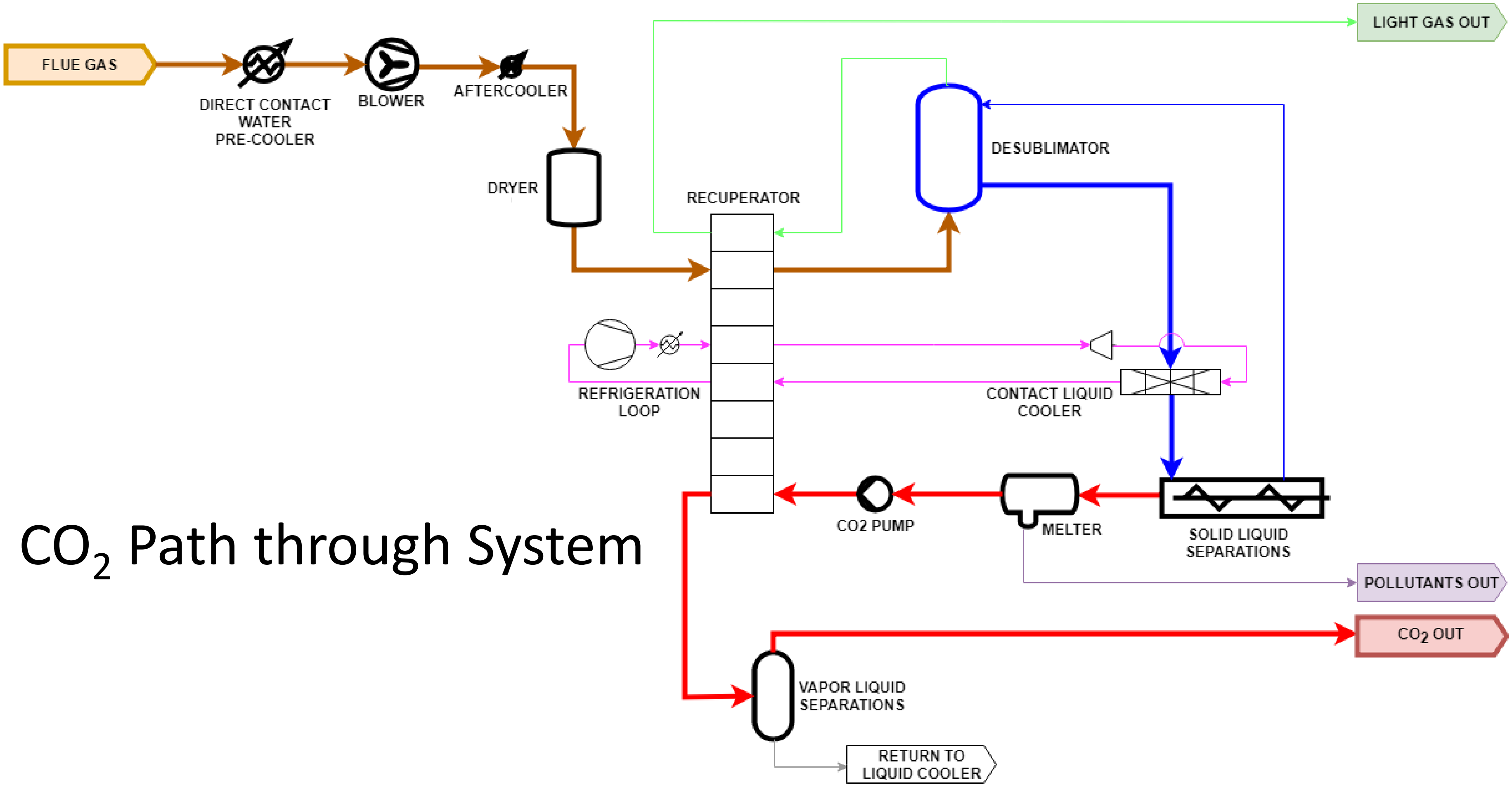
PROCESS PFD AND SUBSYSTEMS WALKTHROUGH



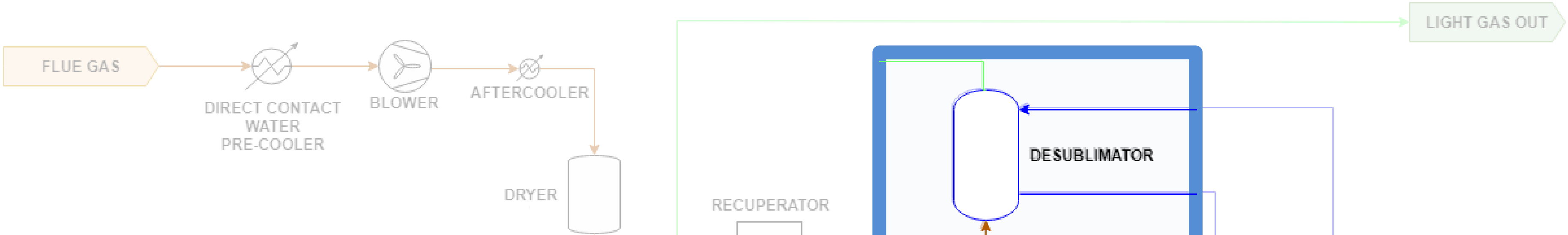
External Cooling Loop (ECL) Simplified Process Flow Diagram



Light Gas Path through System



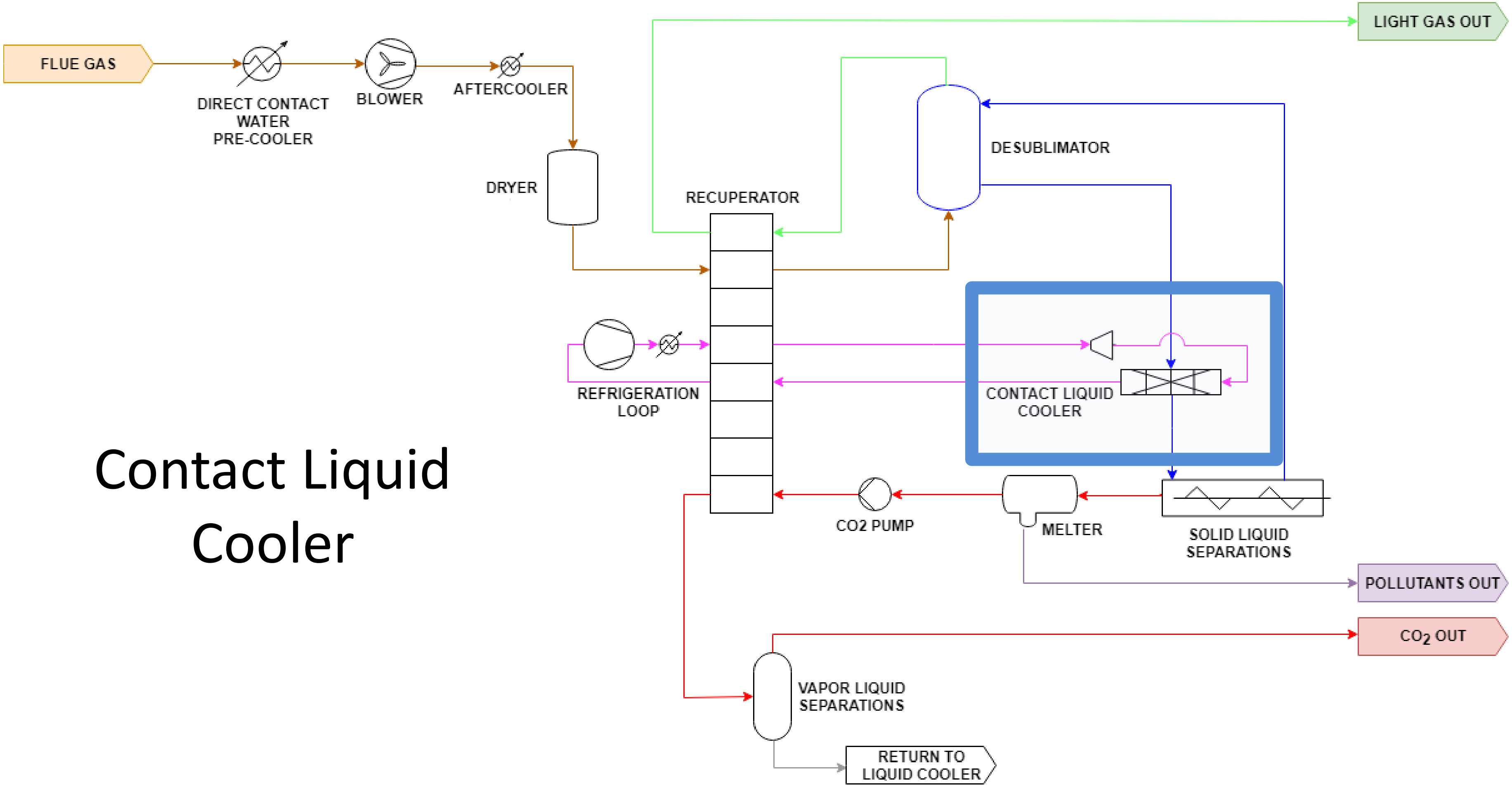
CO_2 Path through System



Direct Contact Desublimating HX

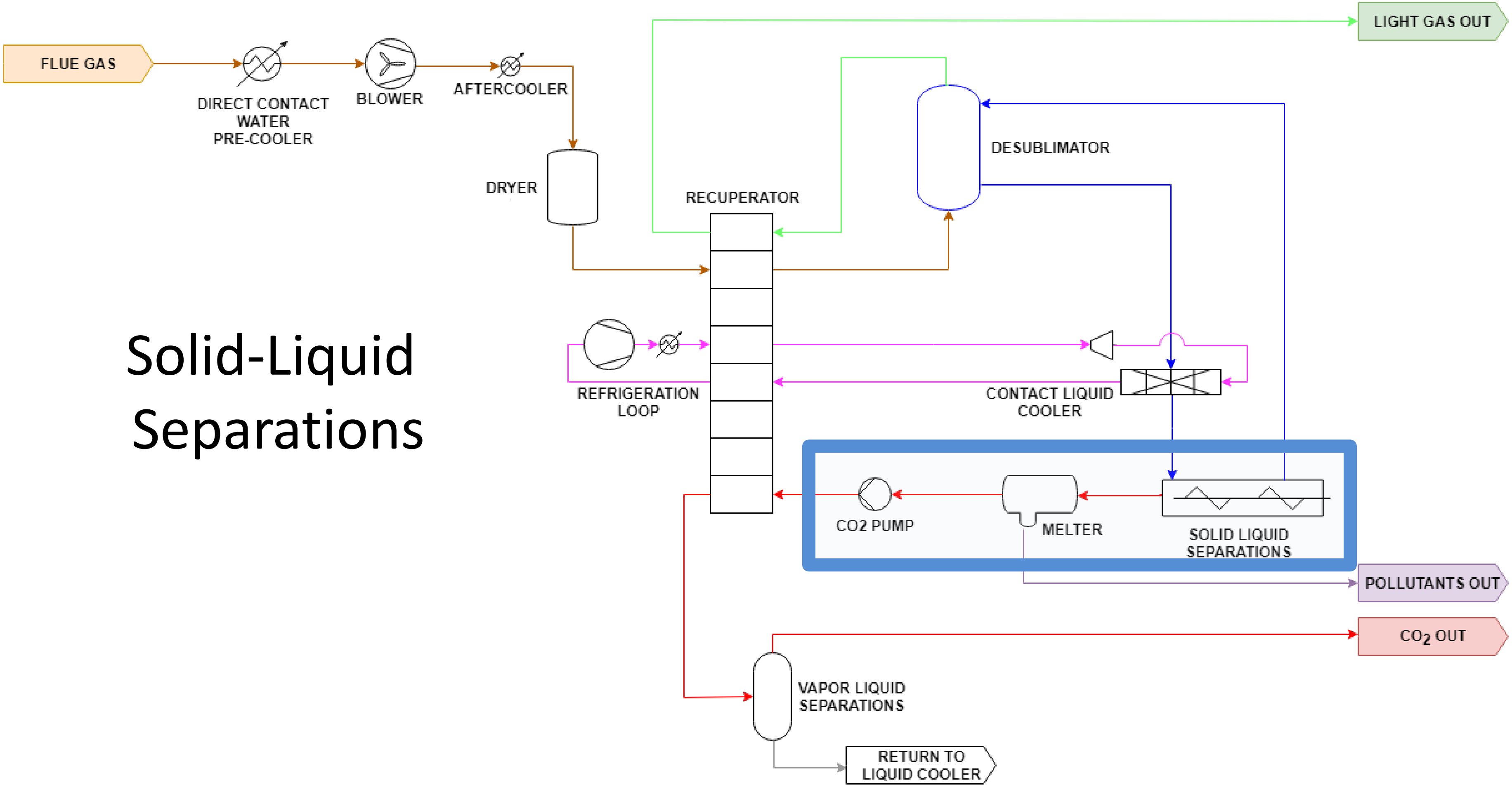
Multiple heat exchangers developed

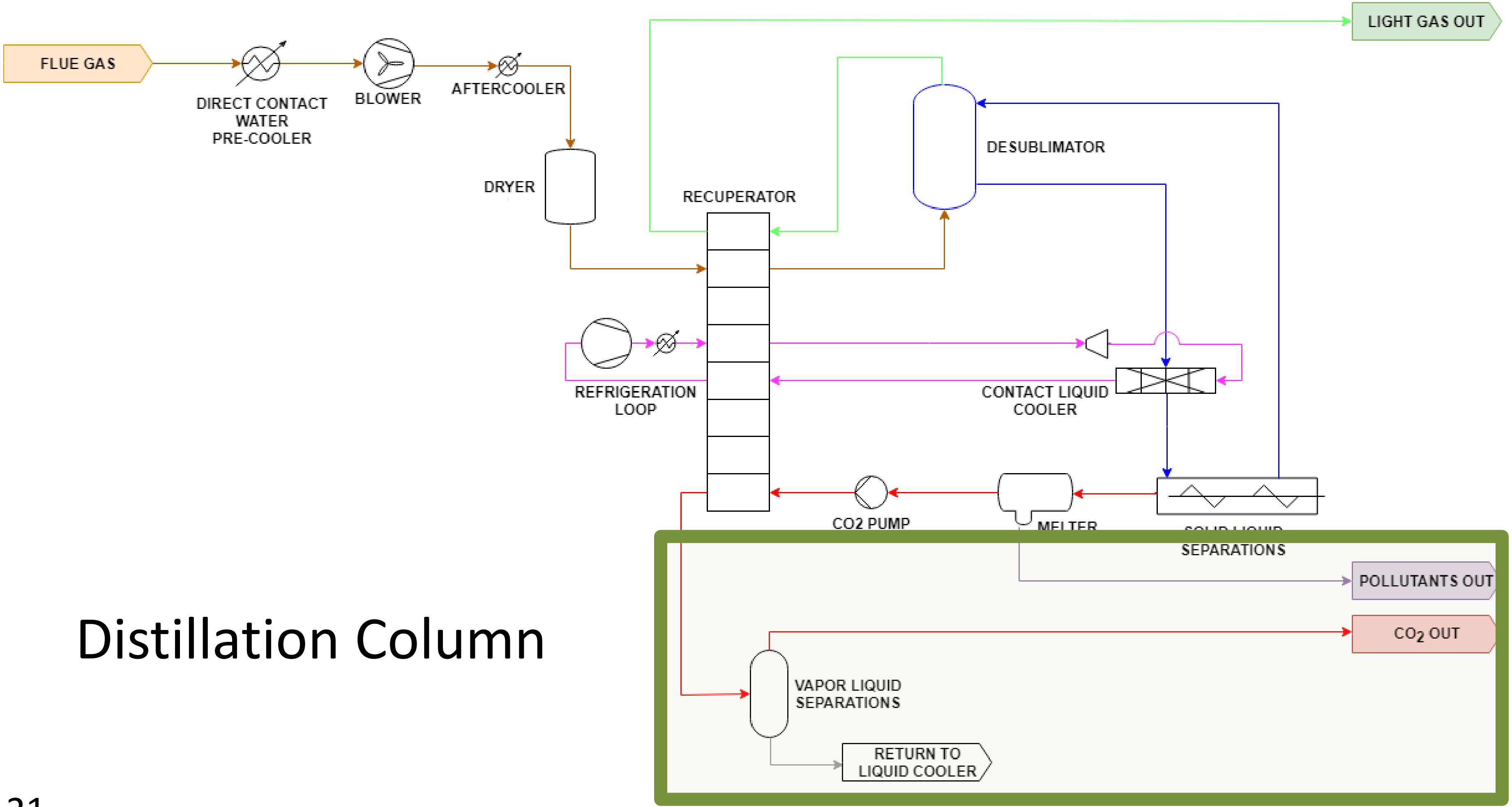
- **Spray tower (skid selected HX)**
  - **Easiest to scale**
  - **Similar to commercial processes**
  - **Most tested**
- Multi-stage bubbler
- Fluidized bed
- Combined spray and bubbler systems



Contact Liquid Cooler

Solid-Liquid Separations





Distillation Column

Distillation Column

Skid Scale

Sulzer assisted with design

Built by SES

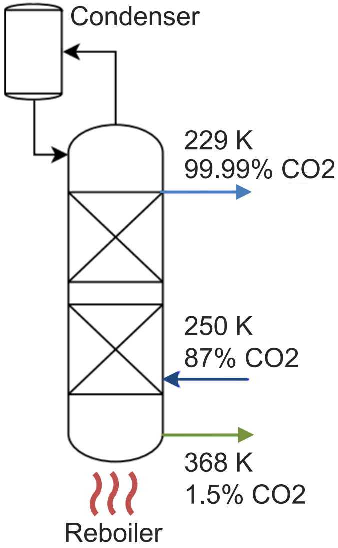
Packed bed with 7 theoretical stages

Operated for 8+ months at Hunter power plant

99.99% CO_2 design spec exceeded in actual operation

Sized for 1 tonne/day CO_2

Pilot/Full Scale



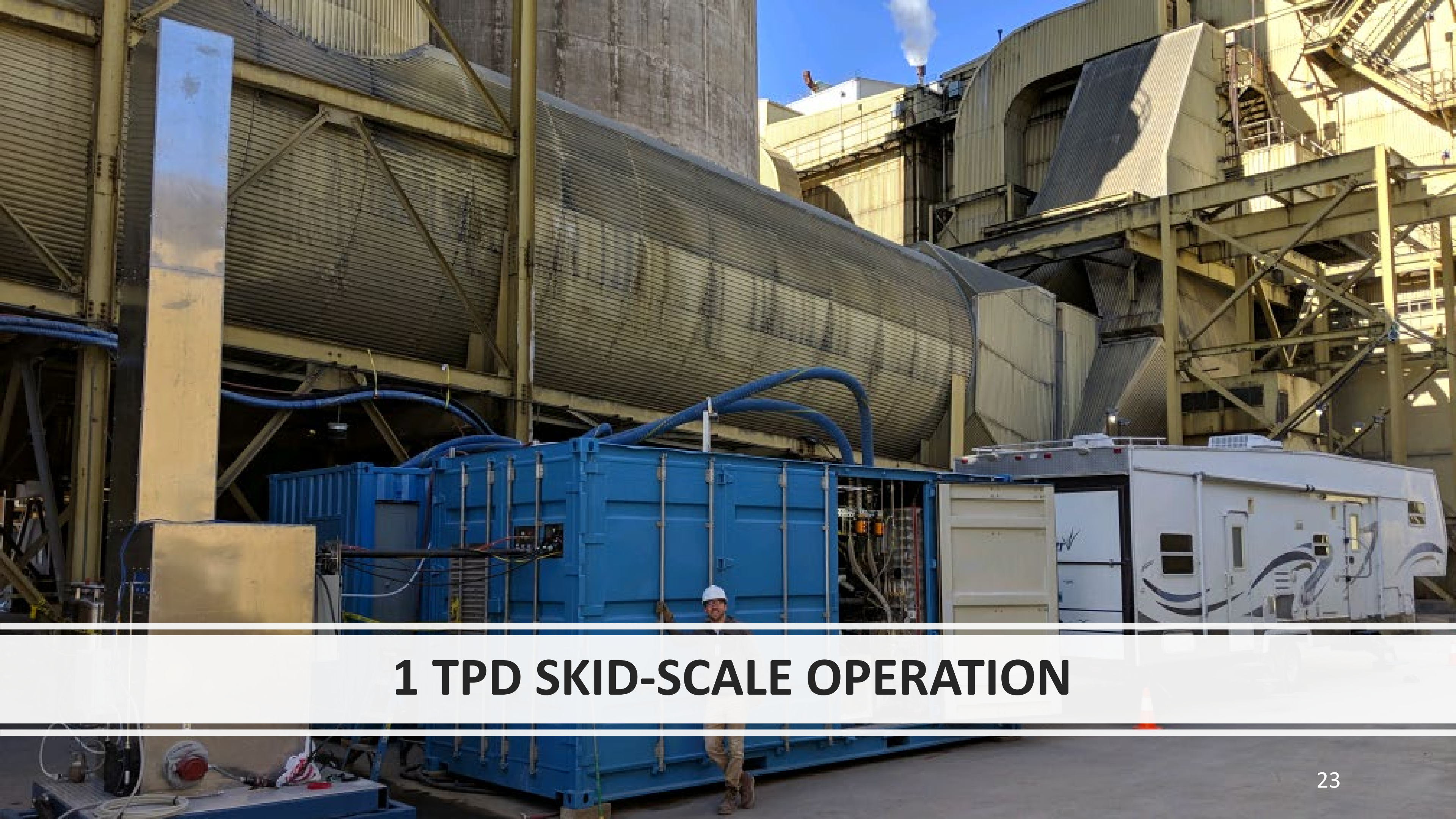
Direct scale up from skid-scale

>99.99% CO_2 design spec

Condenser cooling provided by heat of melting CO_2—no additional utility required

Reboiler utility can be provided by low pressure steam, natural gas burner, or electric heater

Alternative designs with no/reduced reboiler load



1 TPD SKID-SCALE OPERATION

Objectives of Skid System

- Objectives
  - Proof of concept of the CCC process
  - Develop and test most innovative unit operations
  - Improve reliability, efficiency, and scalability of overall process
  - Extended tests with real flue gas
- Not intended to
  - Achieve representative energy and cost numbers
  - Use same equipment design as full scale

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Selected Skid Instrumentation

Parameter	Instrument	Purpose	Location
Inlet Flue Gas Composition	Fourier transform infrared spectroscopy (FTIR), Nondispersive infrared (NDIR)	Measuring the concentrations of CO2 and other pollutants	(2)
Flue Gas Temperature	Thermocouples (TC)	Validating thermodynamic models	(1)(2)
Cooling Load	TC's, Coriolis Meter	Measure the cooling obtained from the Stirling Coolers	LN2 Tank, CL Cooler
Clean Gas Composition	FTIR, NDIR	Determine capture rate	(6)
Slurry Composition	Coriolis Meter	Monitor thickness of slurry	(4)
Melter Liquid Composition	Coriolis Meter	Monitor efficiency of screw press system	(5)
Spray Tower Recirculation Rate	Coriolis Meter, Turbine Meter	Monitor flow into spray tower	(3)
Liquid CO_2 Composition	FTIR	Monitor liquid CO_2 purity	Clean CO_2 Out

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OVERALL TEST RESULTS

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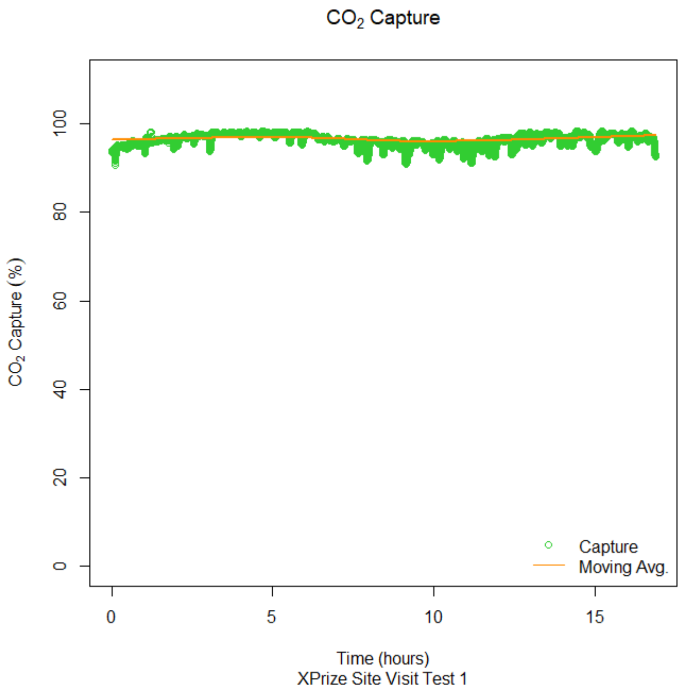
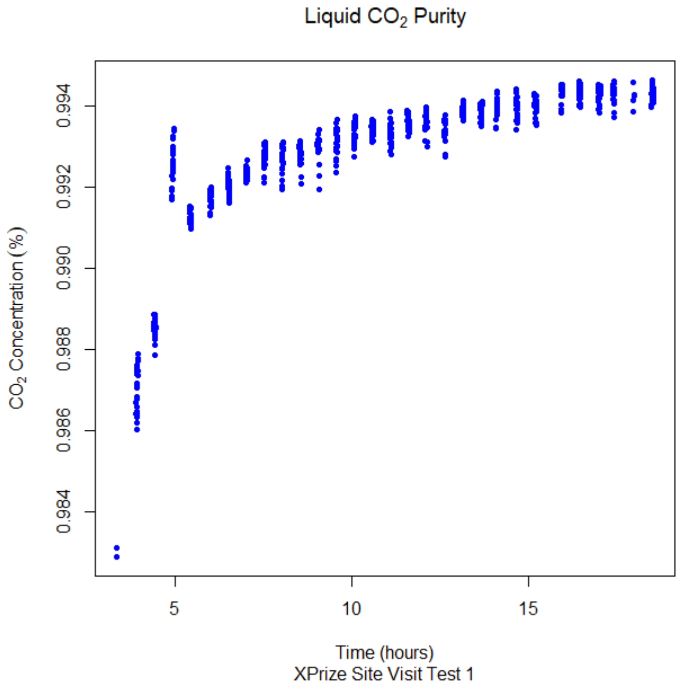
High Capture and Purity





Hunter Plant Test Results

- Testing was delayed due to delays with equipment construction and unexpected equipment failures
- Over 450 cumulative hours of testing
- Typical test results
  - 90-98% CO_2 capture
  - Tests reached 1 tonne/day, but overall capacity and test duration missed targets

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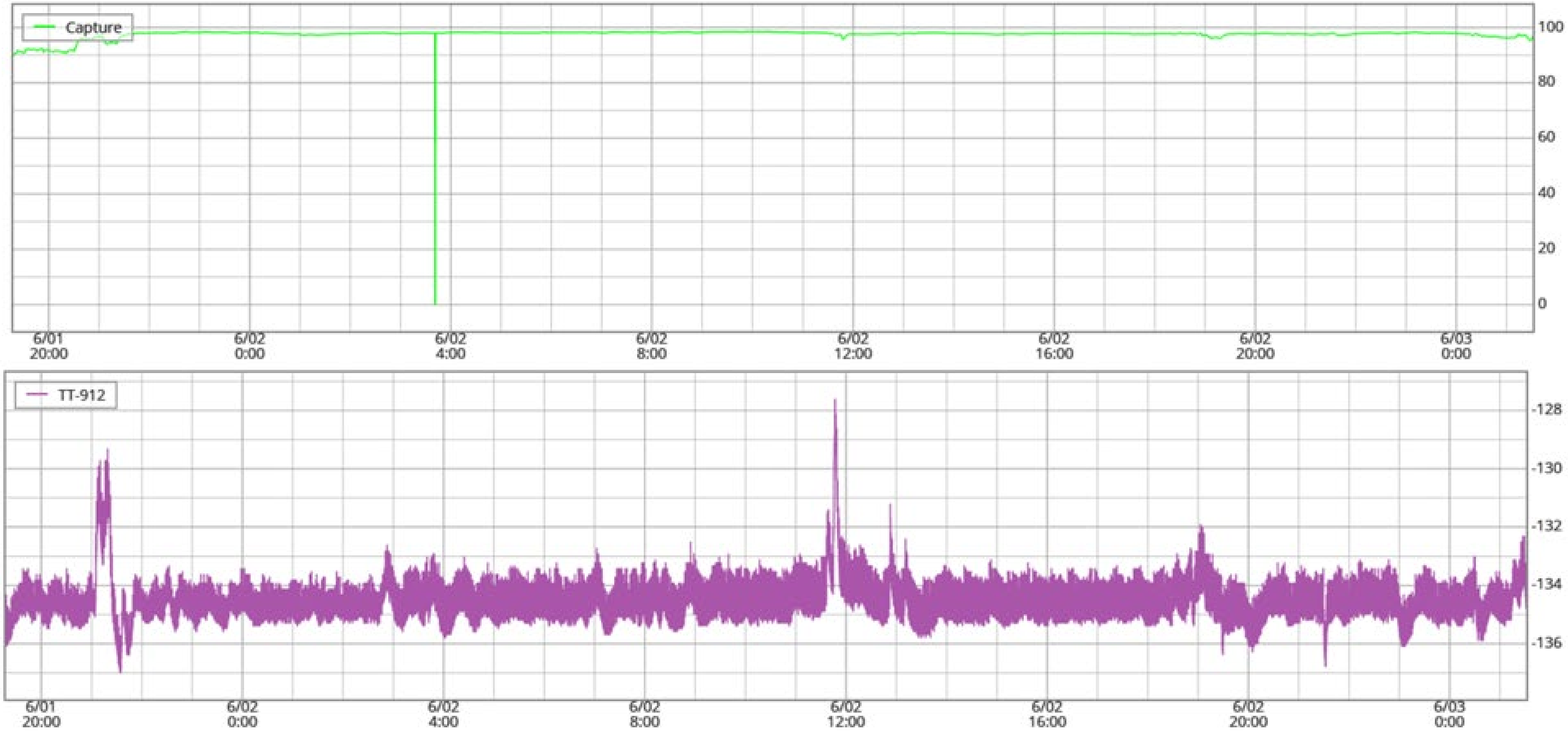
Test Run (1-3 June 2019)

98% avg. CO_2 capture

−135 °C avg refrigerant T



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