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Field Testing of Cryogenic Carbon Capture

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Abstract

Sustainable Energy Solutions has been developing Cryogenic Carbon Capture™ (CCC) since 2008. In that time two processes have been developed, the External Cooling Loop and Compressed Flue Gas Cryogenic Carbon Capture processes (CCC ECL™ and CCC CFG™ respectively).

The CCC ECL™ process has been scaled up to a 1TPD CO_2 system. In this process the flue gas is cooled by an external refrigerant loop. SES has tested CCC ECL™ on real flue gas slip streams from subbituminous coal, bituminous coal, biomass, natural gas, shredded tires, and municipal waste fuels at field sites that include utility power stations, heating plants, cement kilns, and pilot-scale research reactors. The CO_2 concentrations from these tests ranged from 5 to 22% on a dry basis. CO_2 capture ranged from 95-99+% during these tests. Several other condensable species were also captured including NO_2, SO_2 and PMxx at 95+%. NO was also captured at a modest rate.

The CCC CFG™ process has been scaled up to a .25 ton per day system. This system has been tested on real flue gas streams including subbituminous coal, bituminous coal and natural gas at field sites that include utility power stations, heating plants, and pilot-scale research reactors. CO_2 concentrations for these tests ranged from 5 to 15% on a dry basis. CO_2 capture ranged from 95-99+% during these tests. Several other condensable species were also captured including NO_2, SO_2 and PMxx at 95+%. NO was also captured at 90+%. Hg capture was also verified and the resulting effluent from CCC CFG™ was below a 1ppt concentration.

This paper will focus on discussion of the capabilities of CCC, the results of field testing and the future steps surrounding the development of this technology.

Cryogenic Carbon Capture (CCC)

Since 2008 Sustainable Energy Solutions has developed a process called Cryogenic Carbon Capture (CCC). The CCC process is a true bolt-on technology that can easily be retrofit on virtually any stationary emission source without modification to the boiler, turbine, or steam piping. Using assumptions and modeling techniques from NETL base case 11 the Cryogenic Carbon Capture process is projected to cost

$35/tonne CO_2 avoided (~$30/tonne captured) but because of unique features of the CCC process this cost can be significantly reduced (Figure 1).

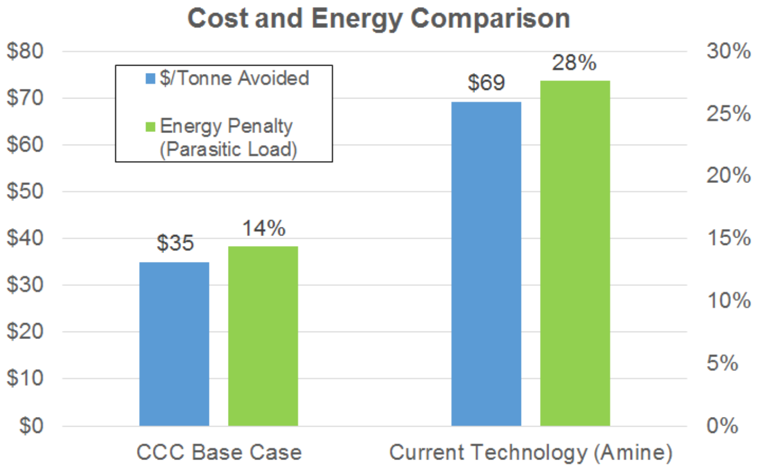

Figure 1. Cost and Energy Comparison

Leveraging existing power plant assets with minimal integration is the most cost-effective way to reduce CO_2 emissions from fossil-fueled power. CCC is an enabling technology that installs on existing infrastructure and greenfield infrastructure alike with no intrusive integration. Using existing infrastructure reduces costs below $30/tonne CO_2 captured. The cost is reduced further as the CCC process removes SO_2, NO_2, Hg, and other regulated pollutants. This offsets the related emission-control costs. The CCC process can also provide efficient large-scale energy storage and demand response capabilities that minimize the parasitic load during peak demand and apply that parasitic load during non-peak demand or when intermittent renewable energy comes online. These unique features make it possible for Cryogenic Carbon Capture to be revenue positive in certain markets.

How CCC™ Works

The CCC process utilizes a large amount of recuperative heat exchange through commercially-available heat exchangers to cool the flue gas to the verge of CO_2 desublimation before it enters a proprietary desublimating heat exchanger which desublimates, or freezes, the CO_2 out of carrier gas stream. The solid CO_2 is separated from the carrier gas and melted for heat recovery then delivered as a high-pressure high-purity liquid. Because the CO_2 is compressed as a liquid rather than a gas the energy input for this step is minimal. The cold light gasses (N_2, O_2 and others) do not condense but they do return through the recuperator for energy recovery. This minimizes the cooling load on the desublimator.

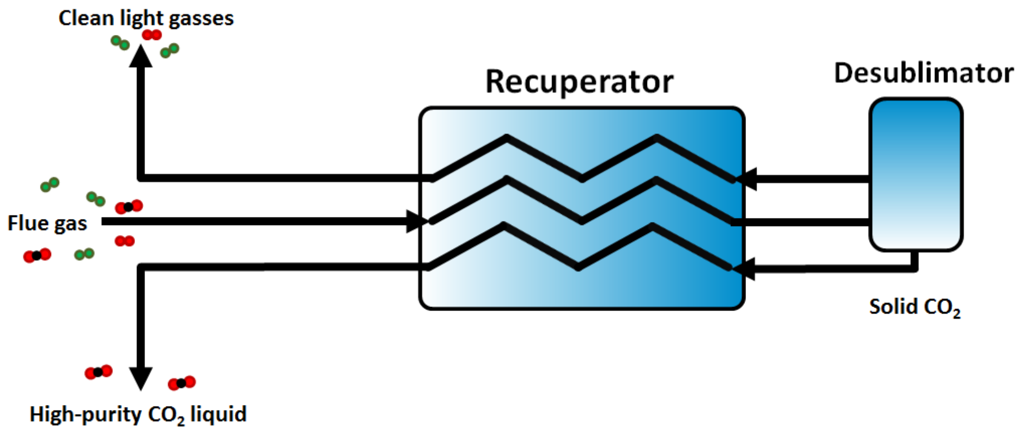

Figure 2. How CCC Works

A frequent mistake people make in energy calculations for this process is to treat the CCC process as a typical refrigeration process. They may look at the energy required to cool the gas from its warmest temperature to its coldest temperature while neglecting the energy that is recovered through recuperative heat exchange. In a typical refrigeration process a stream enters at one temperature and leaves at a lower temperature. In this process the gas is cooled to very low temperatures but most of the energy used to cool the gas is recovered through heat exchange and recuperation so the gas leaving is only slightly colder than the gas coming into it. The energy requirement for the CCC process is the energy required to make up for inherent losses through the process and drive the phase change of the CO_2. The diagram below (Figure 3) represents the conceptual thermal energy to cool the gas stream (T_2), the thermal energy recovered through the recuperator (T_2-T_1), and the thermal energy required to drive the process and make up losses (T_1).

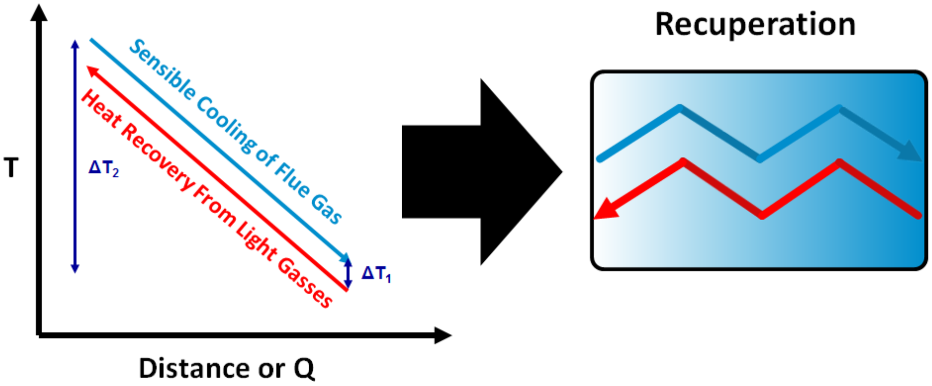

Figure 3. Thermal Energy Recovery Through Recuperator

Pressure loss through the system is an energy load that is not recoverable; it accounts for 10-15% of the total load of the system.

CCC™ Demo Systems

In 2014 SES began field testing two demo systems to gather capture data on flue gas from real sources. One of these systems, called the External Cooling Loop or ECL system, was funded by the Wyoming Advanced Conversion Technology Task Force (Figure 4). This system processes a flue gas stream at about 1.5 bar absolute (about 7 psig). It uses an external refrigeration loop to provide cooling to the desublimator. The second demo system was funded through the Department of Energy's ARPA-E program (Figure 5). Instead of using an external cooling loop this process compresses the flue gas to about 6 bar absolute (about 87 psig) and then expands it to cool it directly; this is sometimes called a self-cooled system. Both demo systems were built in intermodal shipping containers to make them easy to transport from site to site.

Figure 4. 1 tonne/day ECL™ demo system

Figure 5. 0.25 tonne/day CFG™ demo system

CCC™ Field Testing

CCC-ECL Field Testing at BYU

In August of 2014 SES began testing the ECL at Brigham Young University's coal combustion research laboratory on their Burner Flow Reactor (BFR). Using the BFR allowed us to test a variety of coal and biomass mixtures. We tested Wyoming Black Thunder coal as well as other bituminous and subbituminous coal and natural gas. We also co-fired 90% (mass) Black Thunder Wyoming coal with 10% biomass (finely ground hardwood) and captured the CO_2 from the flue gas. Greater than 98% CO_2 was captured. This demonstrated the ability of CCC to produce a negative carbon emission in a realistic scenario. All CO_2 from the coal was captured along with the CO_2 from the carbon-neutral biomass creating a net-negative atmospheric CO_2 emission.

Another highlight from this testing was the measurement of particulate matter in the flue gas stream before and after the CCC™ process. Measurements were taken for particles between 10 μm and 2.5 μm with 98% overall reduction (Figure 7).

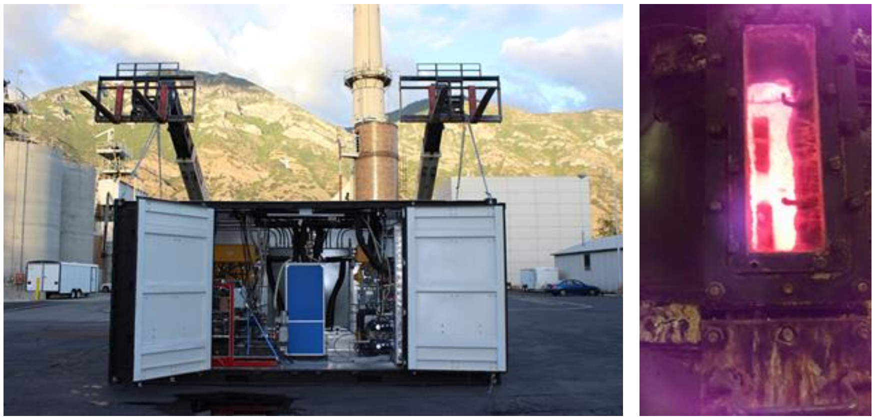

Figure 6. CCC-ECL™ System at BYU (left) Viewport on Burner Flow Reactor (right)

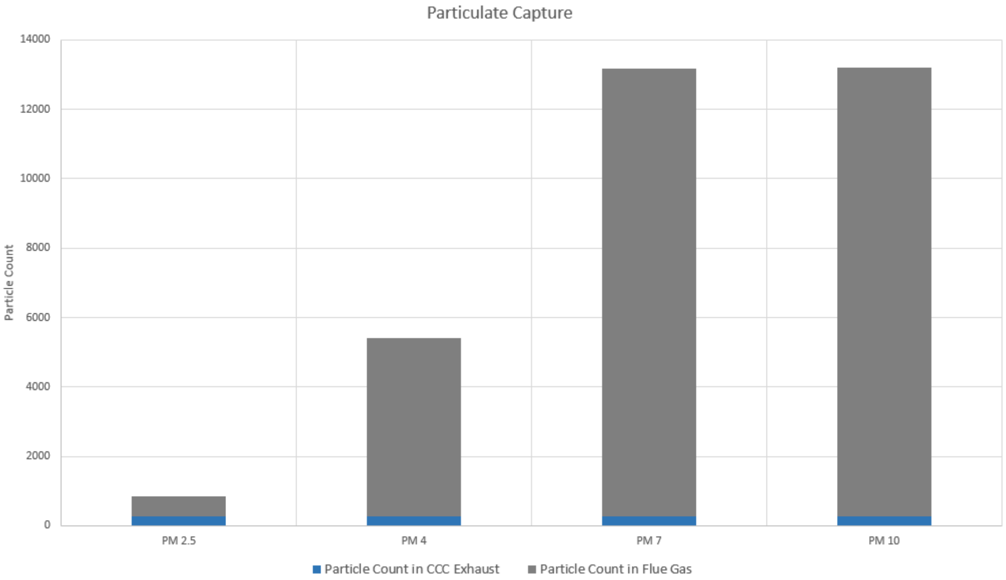

Figure 7. Particulate Capture Data from Initial BYU Testing

CFG Shakedown Testing at BYU

In October of 2014 SES began testing the CFG system at the BYU heating plant. At the time of testing the BYU Heating Plant burned Utah Skyline coal before November 1 and natural gas after November 1 so we set up the system so we could test it on both fuels without changing the setup. Both tests went very well. After tests at the heating plant were completed we moved the skid across the parking lot and continued testing at the Burner Flow Reactor with various coal mixtures. In each case over 90% CO_2 capture was achieved with minimal upsets from source to source.

Figure 8. CCC-CFG™ system being unloaded at BYU Heating Plant

CCC-CFG ™ Testing at a Coal-Fired Power Station in Wyoming

In late November Pacificorp hosted us for testing at one of their coal-fired power stations near Glenrock, Wyoming. At this site they burn a Wyoming Powder River Basin (PRB) coal. We were set up taking a slip stream from unit #3 through a port on the stack. While we were there we completed our first 12 and 24 hour tests with the CCC-CFG system and significantly improved the automation and controls in our process.

Figure 9. CCC-CFG testing at Pacificorp Power Station Near Glenrock, Wyoming

CO_2 inlet concentration varied during runs but outlet concentration was consistent and followed thermodynamically predicted concentrations. Figures 10 and 11 show inlet and outlet concentrations for three 8+ hour runs with moving averages. CO_2 spikes in outlet concentration on 19-Dec-14 are the result of an experimental procedure to mitigate fouling in the system.

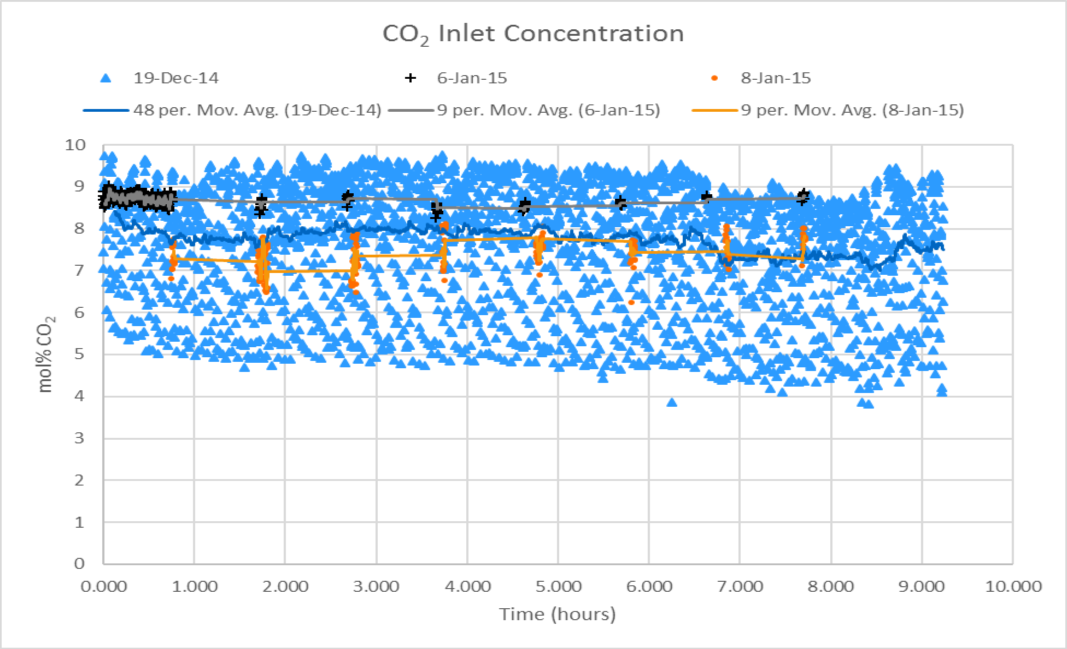

Figure 10. CCC-CFG Inlet CO_2 Concentrations

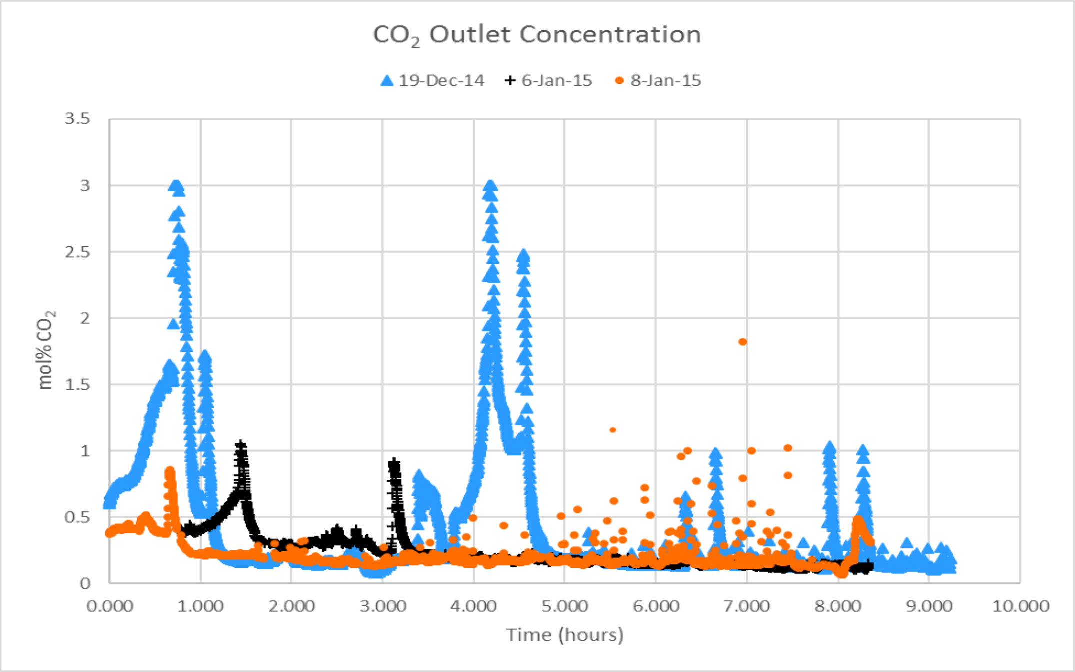

Figure 11. CCC-CFG CO_2 Outlet Concentrations

The CCC process captures pollutant species that condense at CO_2 desublimation temperatures. The capture of CO_2, SO_2, NO_2, and Hg have been measured by SES. The system also captured over 99% of the NO during a run in January.

		1/6/2015	**1/8/2015**
NO In	ppm	57.825	23.941
NO Out	ppm	0.311	1.834
NO Capture	%	99.5%	92.3%

Table 1. NO Capture Data at PacifiCorp Site

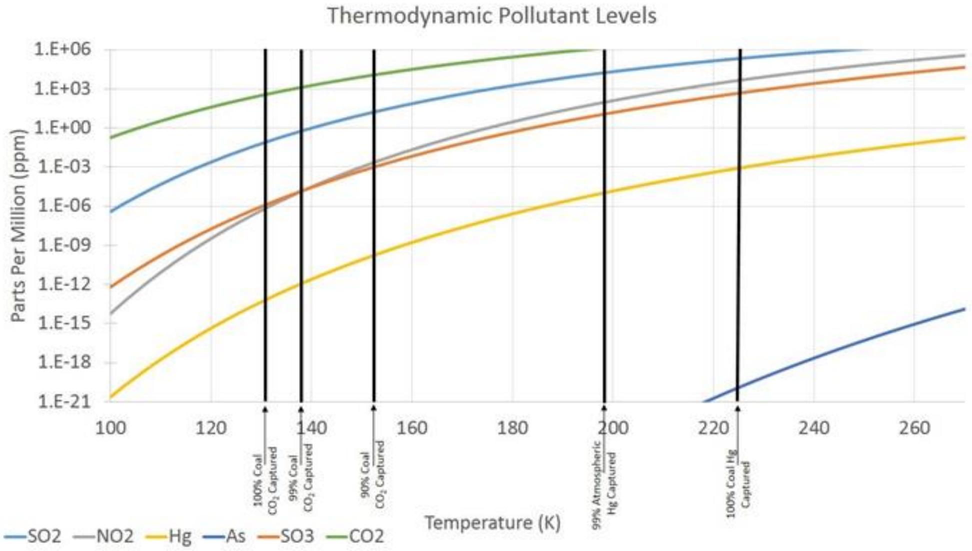

Figure 12. Theoretical Pollutant Capture at Various Temperatures

NO capture was somewhat unexpected when we we first measured it because it condenses at temperatures that are lower than the desublimation temperatures of CO_2. After further research, testing, and collaboration with industry experts we found that NO reacts with O_2 at low temperatures to form NO_2

which then condenses and is captured by the CCC process. This reaction is especially favorable at higher pressures in the CFG-CCC process but both CFG-CCC and ECL-CCC systems have demonstrated NO capture. Since our first NO capture observation we have run additional tests in the ECL system and additional laboratory experiments which repeatedly show NO capture in the CCC process.

During tests in Wyoming we contracted a 3rd party emissions testing company to measure Hg emissions before and after the CCC process. Hg emissions from the stack were recorded at 735 pptv or 5.77 µg/m^3. After the CCC unit, Hg emissions were below the detection limit of 1 pptv or 0.01 µg/m^3. This means that Hg levels after the CCC process are lower than atmospheric Hg levels.

CCC-ECL Testing at a Coal-Fired Power Station in Wyoming

In February of 2015 we brought the CCC-CFG back to Orem for additional closed-loop testing with simulated flue gas and we took the CCC-ECL system out to the same power station where we had previously tested the CCC-CFG unit. One of the highlights of these tests was demonstrating the demand response capability of the CCC-ECL. During non-peak demand the CCC-ECL process can liquify extra refrigerant then use that refrigerant at peak demand times while keeping the compressors and other refrigeration equipment turned off. This reduces the energy requirement of the process by about 85%.

Figure 13. Testing Energy Storage at SES Research Lab

We liquified extra natural gas and nitrogen as sample refrigerants during test runs and then turned off all powered equipment in the refrigeration loop and continued to run at >90% CO_2 capture with minimal load from the process. Burning the spent refrigerant gives an additional benefit because during peak demand times after the natural gas refrigerant has been vaporized to provide cooling it can be burned in a quick-response simple-cycle natural gas turbine to supplement power need. If the simple-cycle turbine is integrated into the power station, its flue gas could be reinjected into the boiler giving the response time of a simple-cycle turbine with the efficiency of a combined-cycle gas turbine.

Figure 14. Unloading the ECL system at the PacifiCorp Power Station in Wyoming

Figure 15. Testing the ECL on Unit #3 at the Power Station

CCC-ECL Testing at a Commercial Cement Plant in Morgan, Utah

In June of 2015 a cement producer hosted our CCC-ECL system at their plant in Morgan, Utah. Cement plants produce CO_2 in higher concentrations than most sources because CO_2 is released in the cement production process and added to the CO_2 from the fuel used to heat the process. Consequently, cement plants can produce flue gas streams with upwards of 30% (mol) CO_2. In our tests CO_2 concentrations were typically around 22% (mol) and were sometimes higher. The plant we tested at set us up at a port near the bypass baghouse. In addition to burning coal at their site they also burn shredded tires and municipal waste. It provided a great opportunity for testing because we tested the CCC process on flue gas with high concentrations of CO_2 from unique fuel sources. The CCC process easily separates CO_2 in both low and high concentrations. Table 2 shows flue gas inlet and outlet concentrations from various runs as measured using a MKS fourier-transform infrared spectroscope (FTIR).

Figure 16. CCC-ECL System at the Cement Plant in Morgan, Utah

	Temp			CO2 in			CO2 out			CO2 capture			Start	End	Total
Date	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max	Avg	Min	Max			Hours
6/12/2015	-138.6	-140.9	-127.2	20.2	18.4	20.9	0.62	0.27	1.04	97.5	95.9	99.0	15:30	17:04	1.57
6/16/2015	-137.8	-142.9	-120.7	16.9	13.9	18.1	0.63	0.15	1.45	96.9	93.0	99.1	9:44	12:25	2.68
6/17/2015	-133.8	-137.4	-128.8	21.0	17.0	22.1	0.40	0.24	0.72	98.5	97.3	99.1	10:11	14:06	3.92
6/18/2015	-135.7	-140.5	-122	19.2	16.8	20.8	0.58	0.22	1.54	97.5	93.4	99.0	12:10	16:25	4.25
6/19/2015	-134.7	-138.4	-123.1	21.2	18.9	23.6	0.57	0.25	0.95	97.9	96.5	99.0	10:15	16:19	6.07
6/22/2015	-132.7	-137.6	-111.2	21.1	19.3	22.4	0.74	0.29	1.69	97.2	93.4	98.9	12:31	16:45	4.23
6/23/2015	-132.9	-137.7	-113.5	21.8	14.7	23.1	0.70	0.30	1.33	97.5	95.4	98.9	12:54	16:15	3.35
6/25/2015	-127.7	-135.7	-114.4	20.7	18.2	21.5	0.57	0.25	1.39	97.8	94.8	98.9	8:53	15:28	6.58
6/30/2015	-132.9	-137.4	-128.6	17.6	13.0	19.8	0.50	0.23	0.68	97.6	96.5	98.7	10:09	11:35	1.43
6/30/2015	-127.0	-136.6	-122	20.1	7.3	21.6	0.73	0.29	0.95	97.1	95.1	97.7	13:18	13:36	0.30
6/30/2015	-128.2	-140.9	-116.1	21.4	16.1	24.3	0.67	0.21	1.66	97.5	93.7	99.1	14:52	17:10	2.30
7/1/2015	-128.1	-135.4	-113.6	20.4	16.5	22.8	0.61	0.25	2.31	97.6	90.6	99.0	11:16	20:33	9.28
7/2/2015	-127.8	-132.4	-122.3	18.4	16.9	19.9	0.57	0.32	1.12	97.4	94.8	98.7	10:12	12:35	2.38
7/7/2015	-130.1	-136.3	-120	21.6	19.9	22.5	0.65	0.25	1.16	97.6	95.8	99.0	11:35	13:23	1.80
7/8/2015	-127.1	-134.4	-122.3	21.7	12.9	23.5	0.51	0.18	1.21	98.1	95.4	99.2	10:15	15:08	4.88
7/9/2015	-126.5	-131.3	-124.9	19.9	18.4	20.6	0.62	0.35	0.76	97.5	96.9	98.5	9:50	13:40	3.83
7/10/2015	-126.3	-134.2	-118.5	20.5	17.2	21.6	0.77	0.24	1.79	97.0	93.0	99.0	7:26	11:26	4.00
7/15/2015	-128.7	-136.5	-111.2	21.0	18.3	23.3	0.76	0.34	1.69	97.1	93.3	98.7	10:27	19:26	8.98
7/16/2015	-126.5	-136.8	-116.3	20.0	17.8	21.3	0.70	0.19	2.17	97.2	91.2	99.1	9:11	12:57	3.77
7/18/2015	-125.3	-136.9	-114.8	19.7	17.2	21.6	0.81	0.18	1.54	96.7	93.5	99.1	12:24	13:21	0.95
7/21/2015	-126.6	-128	-120.6	20.5	19.0	21.9	0.82	0.64	1.14	96.8	95.4	97.5	15:59	19:37	3.63

Table 2. Run Data from Various Runs at The Cement Plant

CO_2 outlet concentration can be predicted using the pressure and temperature in the desublimator. Figure 17 shows agreement between measured CO_2 capture data and predicted capture at the cement plant.

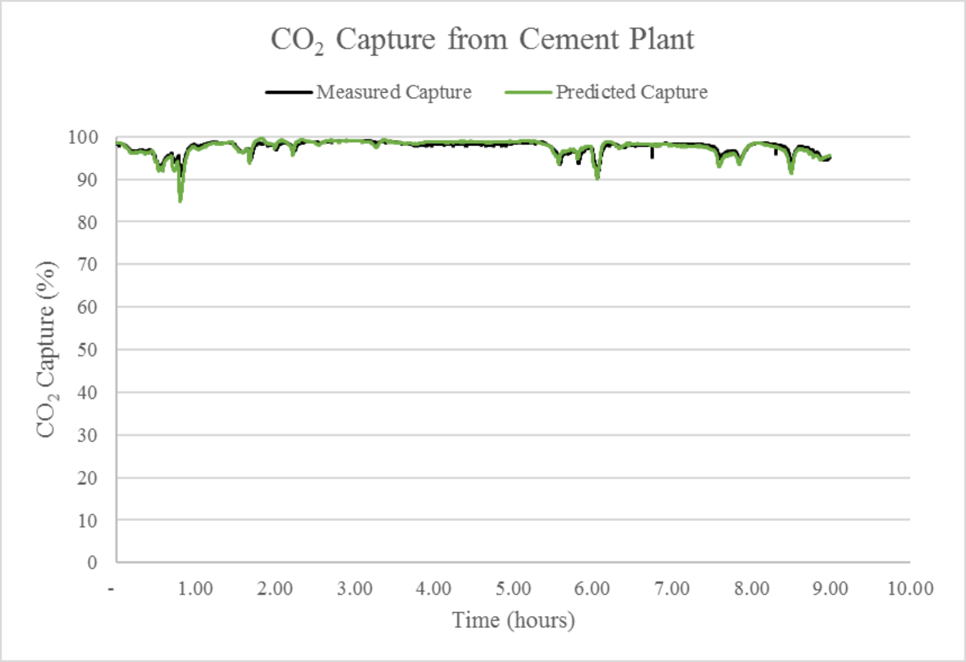

Figure 17. Measured and Predicted CO2 Capture Data

Current Testing and Future Plans

In 2015 and 2016 SES demonstrated the CCC-CFG system at other sites in Utah and Wyoming. We continue to do closed-loop and unit-operations testing daily at our lab in Orem, Utah. These tests focus on improving process reliability and efficiency and developing intellectual property around the process.

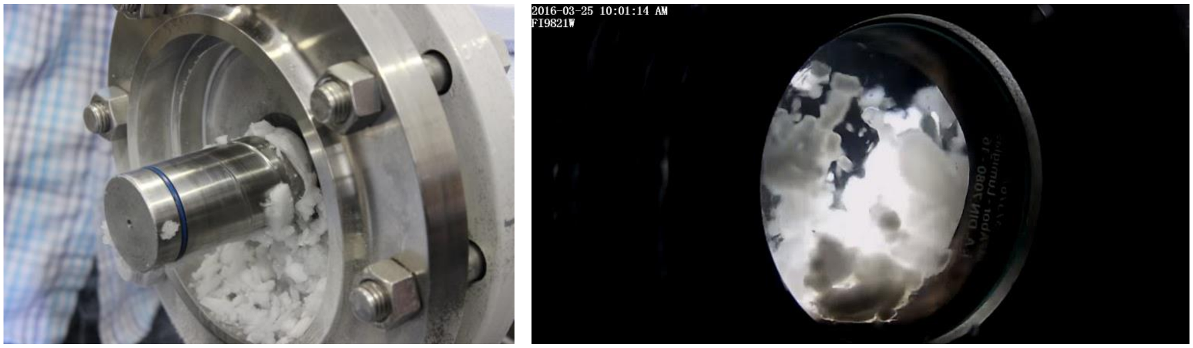

Figure 18. CO2 filtration (left) Solid CO2 Melter (right)

We are developing CCC technology for small commercial deployment. We are currently working under funding from NETL, Rocky Mountain Power, and others. Our current work will culminate in long-term testing and demonstration at a commercial coal-fired power station next year. We are interested in working with anyone interested in partnering or assisting in the scale up and deployment of this technology. Additional information can be found at https://sesinnovation.com/.

Acknowledgements

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Disclaimer

Works Cited

US Department of Energy, N.E.T.L., Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Revision 2a, September 2013.

Field Testing of Cryogenic Carbon Capture

CMTC

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July 19, 2017

Thank You

CARBON MANAGEMENT

Wyoming

arpa·e

CHANGING WHAT'S POSSIBLE

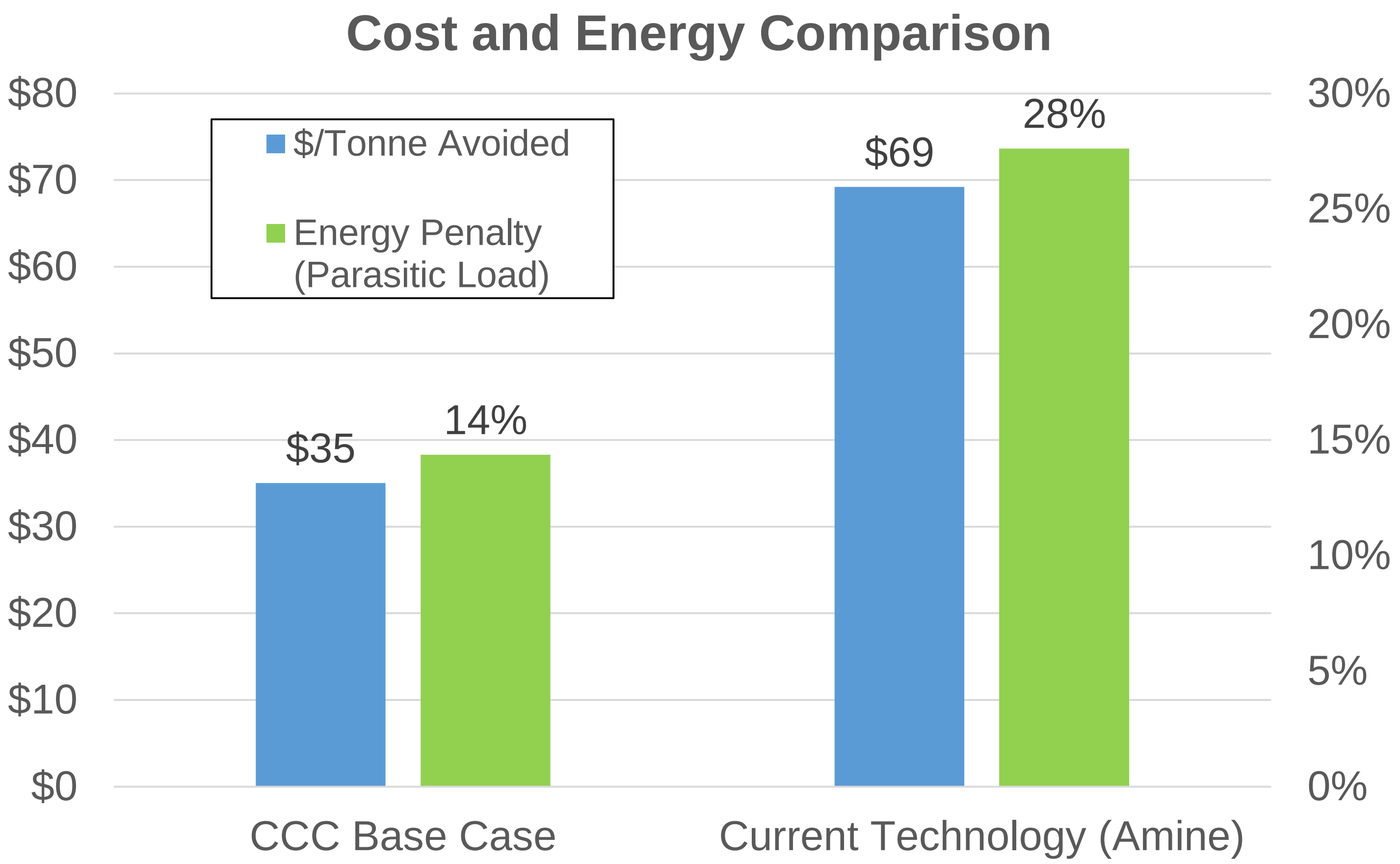
CCEMC

Climate Change & Emissions Management Corporation

PACIFICORP

SES INNOVATION

CCC Cuts Costs in Half



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

In a base-case, greenfield comparison CCC is half the cost of alternatives (~$30/tonne captured)

Even more savings are possible

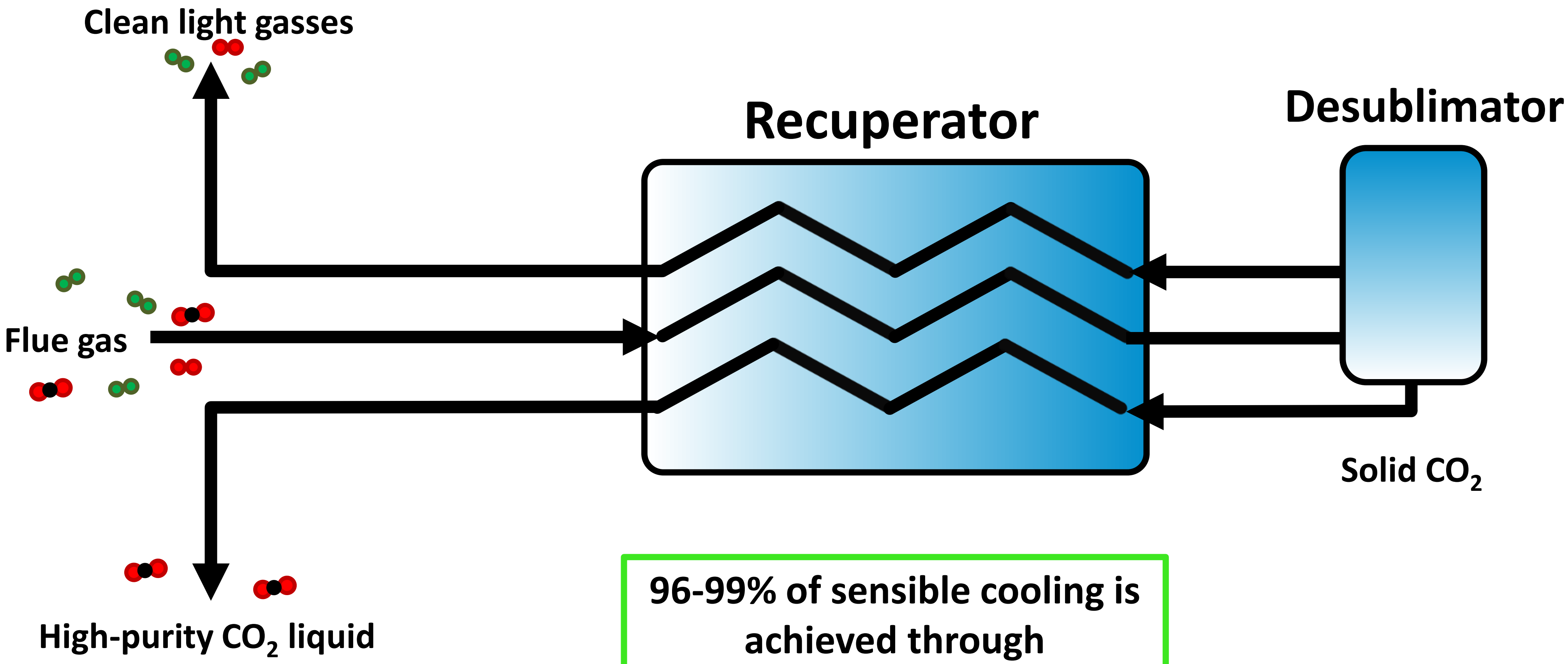
SES INNOVATION

Negative Cost Carbon Capture is Possible

Additional, unique benefits being developed by SES reduce the cost of CCC even further

- **No steam, plant integration, or modification for retrofit**
- Demand response or grid-scale energy storage
- Improved efficiency through power plant heat integration
- SO_x, NO_x, Hg, and other pollutants removed in addition to CO_2
- High-purity, liquid CO_2 ready for utilization

How CCC Works

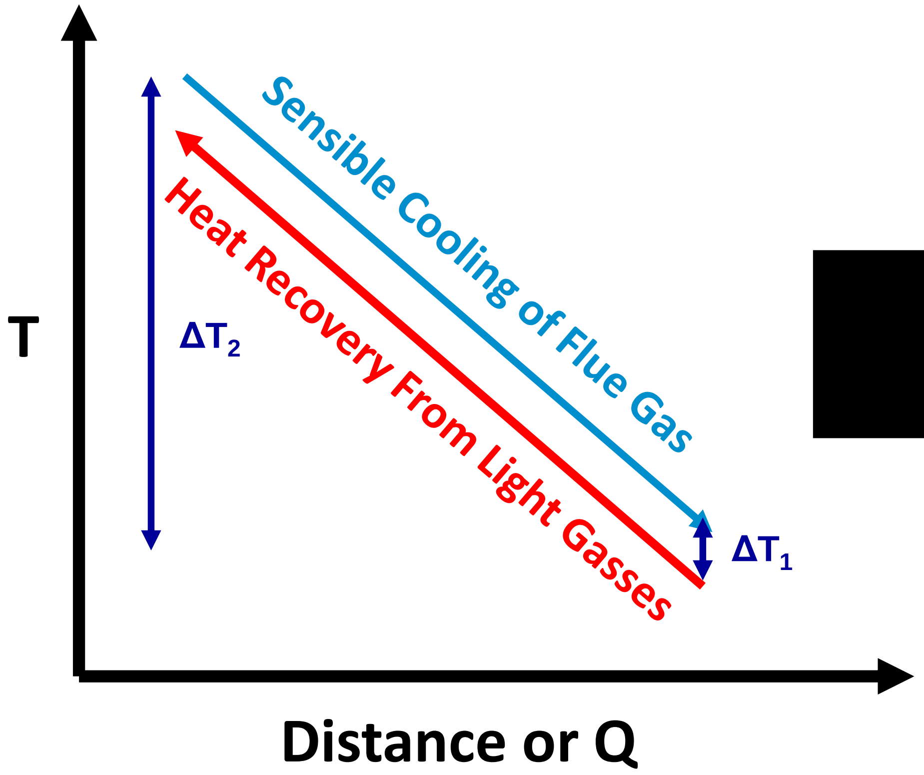


96-99% of sensible cooling is achieved through recuperation

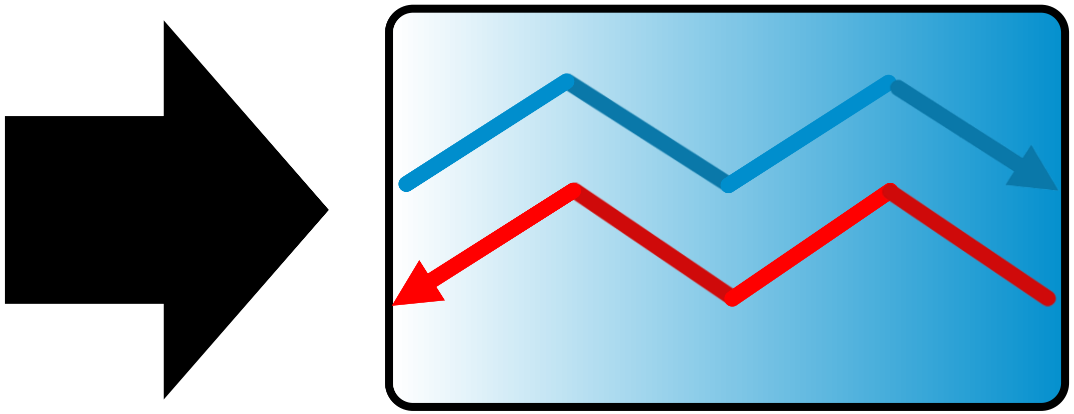
Heat Recovery

T_2 represents the energy required in a traditional refrigeration system.

T_1 is the analogous energy required for the CCC process because of energy recuperation



Recuperation



SESinnovation.com

CO_2 Melting in CCC Process

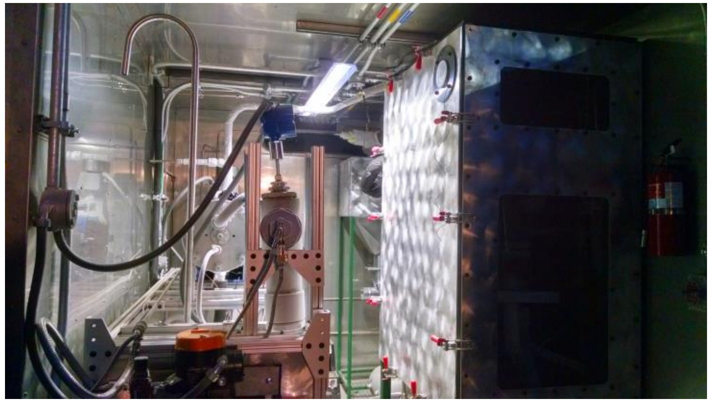
CCC™ Skid-Scale Prototype Systems

External Cooling Loop ECL™

- Operating pressure 1.5 bar
- 1 tonne CO_2/day capacity
- External refrigeration

Compressed Flue Gas CFG™

- Operating pressure 6 bar
- 0.25 tonne CO_2/day
- Auto-refrigeration



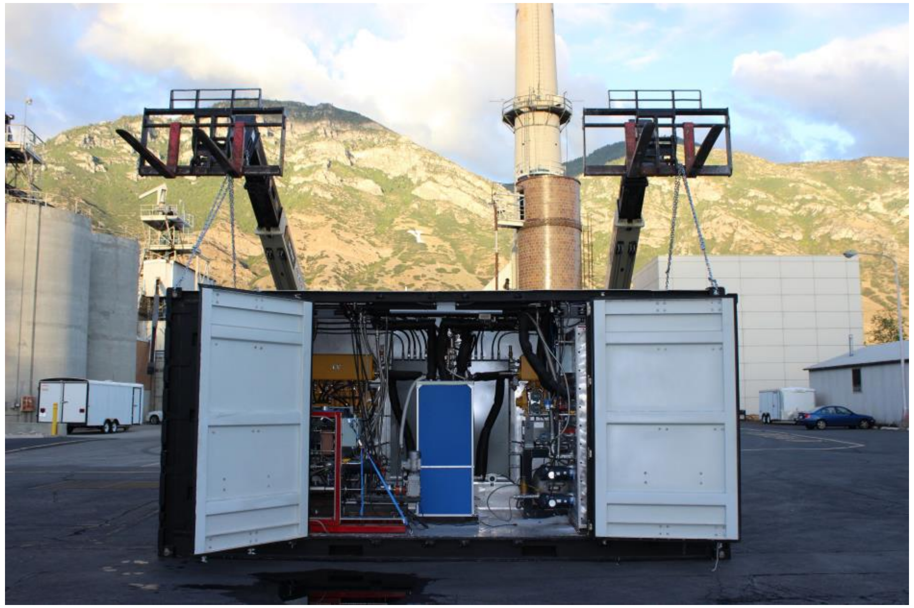
ECL Testing at Brigham Young University

Tested at BYU in August of 2014

Fuels included coal, biomass, natural gas and blends of these.

Co-fired 90% (mass) Wyoming Black Thunder coal with 10% biomass at >98% capture rate for a carbon negative test.

Measured particulate matter from 10 µm to 2.5 µm at the inlet and outlet and recorded 98% overall reductions.

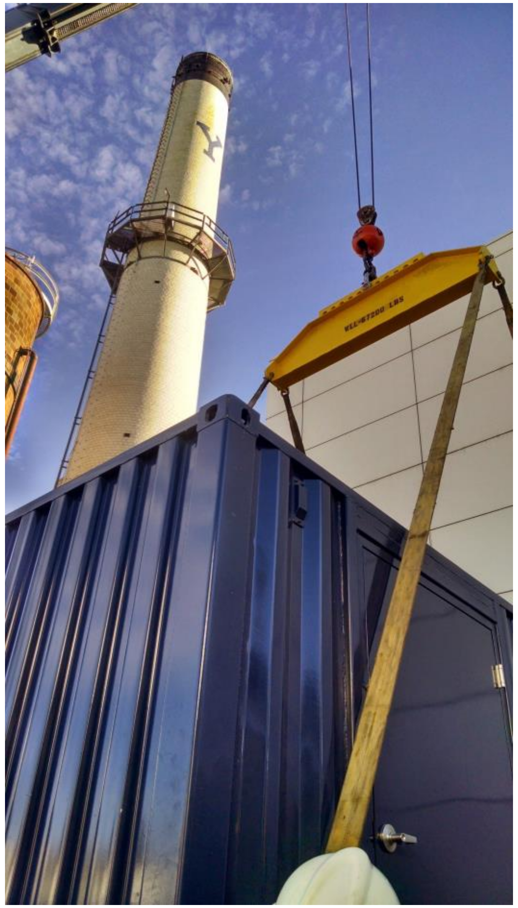


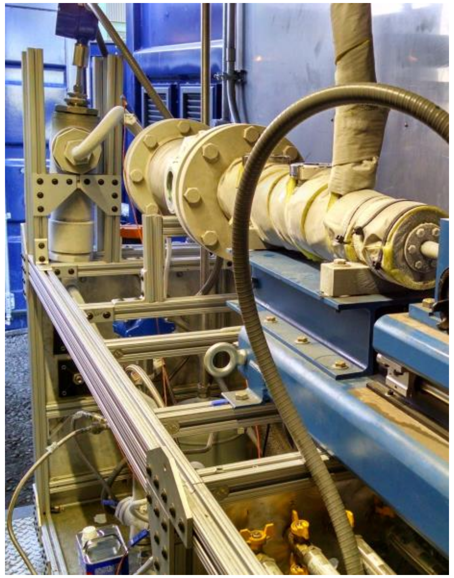
CFG Shakedown Testing at BYU

CFG shakedown testing at BYU in October of 2014

Field tested at the BYU heating plant burning Utah Skyline coal followed by natural gas.

Tested on a separate pilot-scale burner flow reactor fired with several coal, biomass, natural gas, and blended fuels.





CFG Tests at a Wyoming PacifiCorp Power Station

Testing at a Wyoming PacifiCorp Power Station November of 2014
Slip stream from boiler unit 3 burning Powder River Basin (PRB) coal

- **Plant had a FGD and a PRB coal, so almost no SO_x in flue gas**
- **CO_2, NO_x and Hg capture measured**
- **First distant (450 miles) field test**

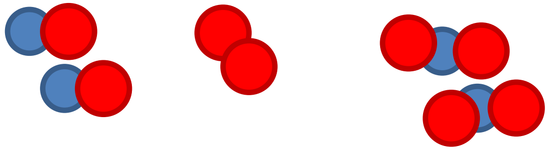


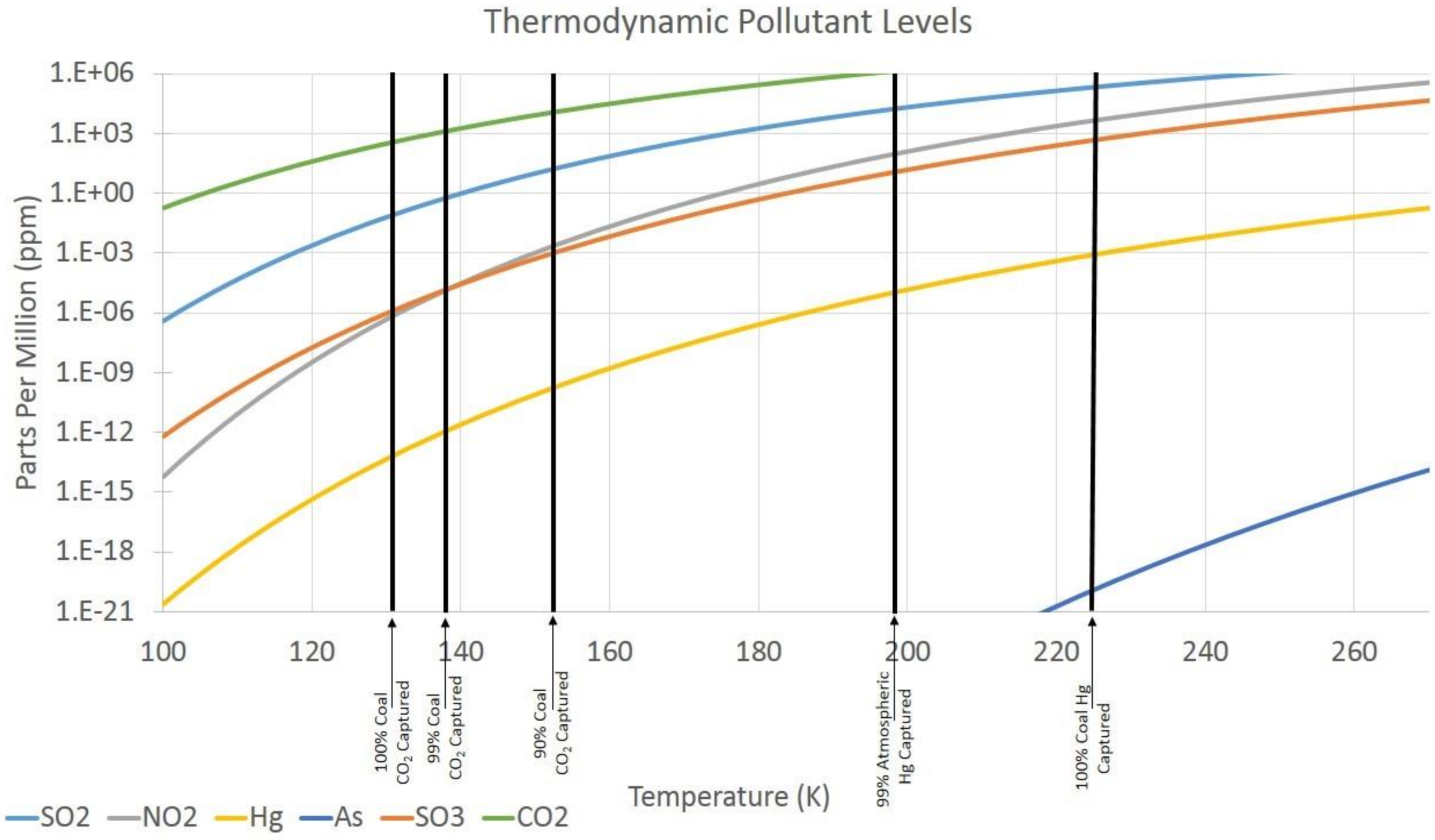
NO_x Capture in CCC Process

CCC captures a wide array of pollutants including SO_2, NO_2, and Hg.

Observed 99.5% capture of NO (from 57 ppmv to <1 ppmv) at this Wyoming PacifiCorp power plant.

$$2\,NO + \,O_2 \rightarrow 2NO_2$$

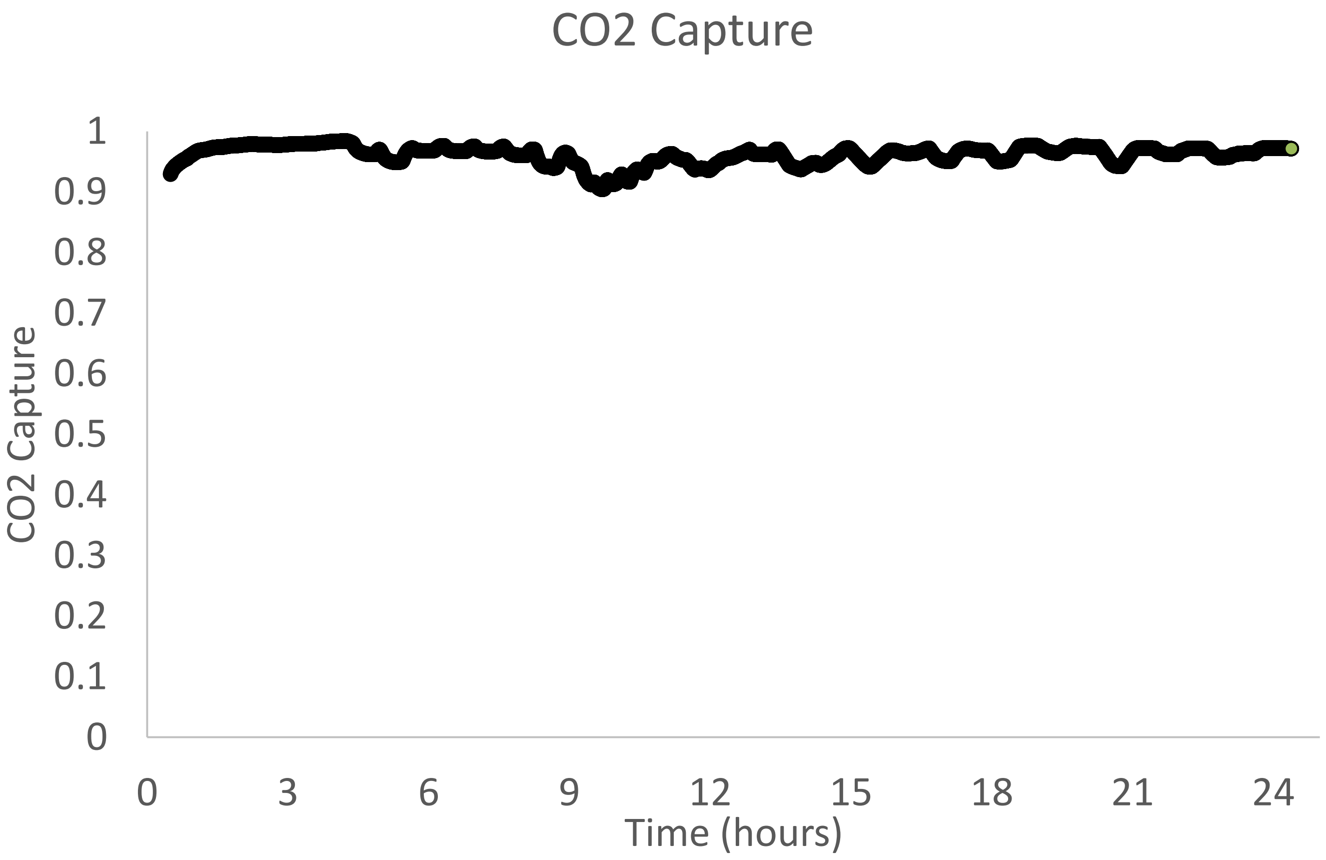




Power Plant Tests

Tests averaged over 97% CO_2 capture

Over 99.8% of mercury was captured with the outlet mercury content being less than atmospheric levels. The outlet concentration was less than the detectible limit of the instrument or lower than 1 pptv or 0.01 µg/m^3



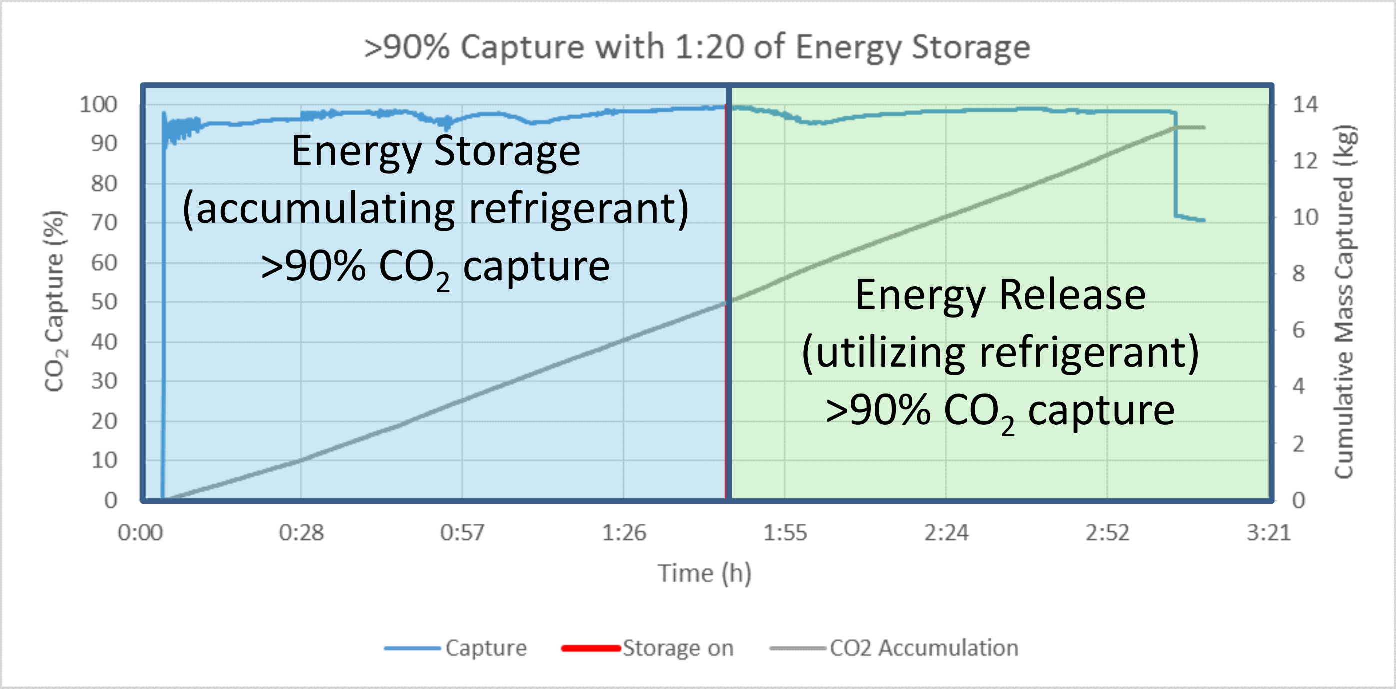
ECL at a Wyoming PacifiCorp Power Station

February 2015 test of the CCC-ECL system at the same power station where we had tested the CFG. The ECL system demonstrated energy storage in addition to capture tests similar to the CCC-CFG.

Capturing CO_2 with Refrigeration Turned Off

CCC offers demand response or energy storage by liquifying excess refrigerant at non-peak times or when surplus energy comes onto the grid from renewables or other sources.

This stored refrigerant drives the process during peak demand, nearly eliminating CCC energy demand and increasing net output by this amount.



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ECL Testing at a Utah Cement Plant

CCC-ECL™ field test at the Holcim Cement plant in Morgan, Utah. The cement plant burns coal, shredded tires, and municipal waste.

Daily tests for two months with a 97% average capture for the set
25-45% NO capture.

20%+ CO_2 in flue gas. CCC successfully captures CO_2 from streams with 4-26% CO_2.

Other CCC Demonstrations

SES has run several additional system demonstrations over the past two years

Small-Commercial Opportunities

The CCC process produces high-purity, liquid CO_2 that is ready for transport and utilization

Some promising utilization markets

Fertilizer production

Concrete curing

Food processing

Enhanced oil recovery

Etc.

Continued CCC Testing

Currently preparing for 500+ hour test at another Pacificorp Power Plant.

Designing 100 TPD system for 2018 tests

100 TPD is commercial scale for non-power applications, pilot scale for utility power plant.

Thank You

Please contact me for more information or if you are interested in discussing project opportunities

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