Energy Storing Cryogenic Carbon Capture

Final Executive Summary

Wyoming Clean Coal Technologies
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Abstract

The Cryogenic Carbon Capture™ (CCC) process is a retrofit, post-combustion technology that desublimates CO_2 in the flue gas and produces a separate liquid CO_2 product. This project focuses on the energy-storing version of this process, CCC ES™. During off-peak hours, CCC ES™ generates more refrigerant than is needed for the process, which is stored in an insulated vessel as a liquid at the low-temperature, low-pressure point in the cycle. During peak demand, the stored refrigerant is used in place of continuously generating refrigerant in a steady-state system. This eliminates nearly all of the energy demand required by CCC for as long as the stored refrigerant lasts.

This project

1. shows that natural gas can be used as effectively as other refrigerants in the CCC process;
2. determines that the stored liquefied natural gas (LNG) refrigerant represents a significant portion of the CCC energy demand;
3. calculates that the LNG energy density suffices to be able to store energy at grid scale;
4. develops heat exchanger technologies that allow LNG flow transients to follow energy storage and recovery transients without damage;
5. simulates grid-level incorporation of energy storage into a realistic system;
6. demonstrates as many of these processes as possible at small scale.

CCC ES™ operates with the carbon capture portion of the process at a constant load, while the LNG generation portion follows power demand. Power demand on grids with intermittent supplies can change significantly within minutes. SES developed dynamic heat exchangers that can follow changes in flowrates without compromising heat exchanger efficiency or inducing thermal stresses.

Detailed analyses demonstrate that a power plantCCC ES™ can manage swings in energy demand on a grid that includes coal, natural gas, wind, and varying daily demands. The revenue generated by storing energy during low-demand, low-cost periods and releasing during high-demand, high-cost periods represents a net revenue that covers 80–90% of the total cost of carbon capture.

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1.1 CCC Process Description

The Cryogenic Carbon Capture™ (CCC) process is a retrofit, post-combustion technology that desublimates CO_2 in the flue gas and produces a separate liquid CO_2 product. Figure 1 illustrates the major process steps. The process (1) dries and cools flue gas, (2) further cools the flue gas in a heat recovery heat exchanger, (3) condenses contaminants (e.g., mercury, SO_2, NO_2, Hg, and HCl) at various stages during cooling, (4) separates the solid CO_2 that forms during cooling from the remaining gas, (5) pressurizes the solid CO_2 to 70–80 bar, (6) reheats the CO_2 and the remaining flue gas to near ambient conditions (15–20 °C) by cooling the incoming gases, and (7) compresses the pressurized and now melted CO_2 stream to final delivery pressure (nominally 150 bar). There is a small external refrigeration loop in the process that transfers the enthalpy of pure CO_2 melting to cooler temperatures to avoid temperature crossover in the heat exchanger.

Two cooling loops are illustrated in Figure 1 that are important in understanding the proposed energy storage concept. Coolant Loop I is used to transfer the heat of CO_2 fusion from the melting point (near −56 °C) to lower temperatures. Coolant Loop II provides cooling for the remainder of the process.

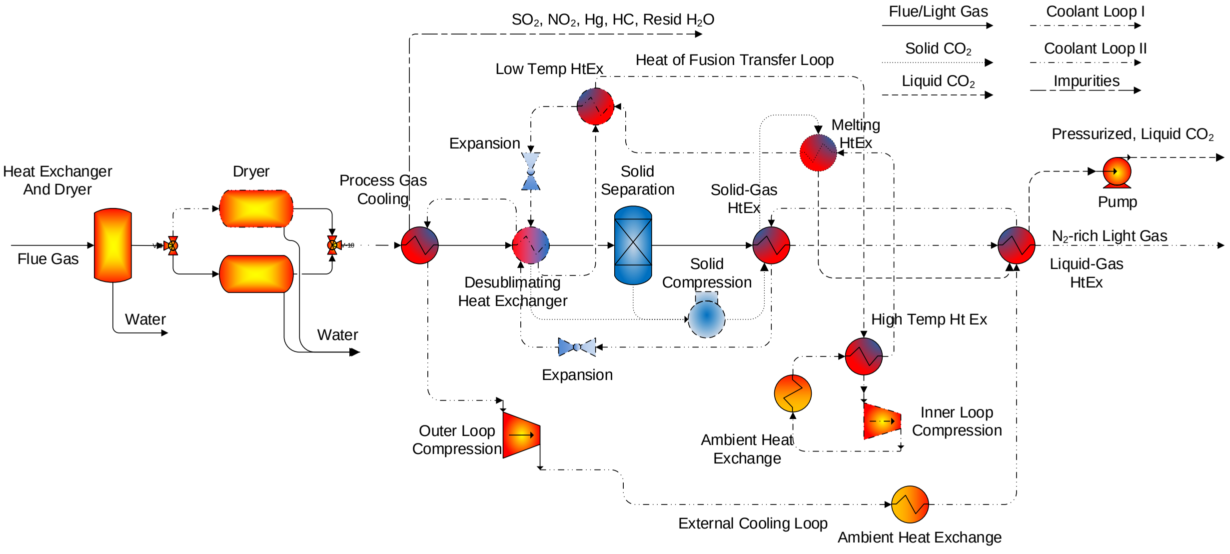

Figure 1. CCC ECL™ version of the CCC process. The distinction between the inner (I) and outer (II) coolant loops is important to the energy storage discussion.

The potential of using natural gas (NG) as the refrigerant in Coolant Loop II is discussed below. NG (i.e., mostly methane) can effectively provide the cooling needed in the external loop, but it is not well suited for internal loop cooling because the critical temperature of NG (methane) is about −83 °C, which is well below the triple-point temperature of CO_2 (−56.6 °C). Therefore, there is no combination of temperature and pressure that would simultaneously condense methane and melt CO_2, rendering NG incapable of going through a phase change in the CO_2 melting heat exchanger. Therefore, using liquefied natural gas (LNG) in a heat exchanger with melting CO_2 would result in very inefficient heat exchange. This inefficiency may represent a tolerable loss compared to the gains from energy storage, but large amounts of energy storage are available without using NG in the inner loop and these will be pursued before revisiting these inner loop issues.

CO_2 purities have been verified as high as 99.95% from the CCC process. Assuming a typical coal flue gas of about 16% CO_2 on a dry basis, most of the potential impurities (e.g., SO_2, SO_3, NO_2, Hg, and As) will be removed prior to the desublimation of CO_2 and will leave in a separate stream. The remainder would include trace amounts of SO_2, SO_3, and NO_2. Some hydrocarbon contact liquid would also be present. None of these species would be present in amounts that would pose any issues if the CO_2 were used for enhanced oil recovery. To our knowledge, no comprehensive standard exists for the purity of CO_2 for carbon sequestration in saline aquifers; the specifications for most CO_2 pipelines require CO_2 purity to be 95–99% [3].

1.2 CCC with Energy Storage

The flow diagram (Figure 1, above) helps illustrate the energy storage concept. After discussing a few of the details, a series of conceptual diagrams (Figures 2–4, below) illustrate this process and may greatly facilitate the understanding of it. The CCC process in the configuration shown in Figure 1 only requires low-temperature refrigerant(s) to operate. During off-peak hours, the CCC ES™ process would generate more refrigerant than is needed for the process, which would be stored in an insulated vessel as a liquid at the low-temperature, low-pressure point in the cycle. Such vessels and processes are common commercially. During peak demand, the stored refrigerant could be used in place of continuously generating refrigerant in a steady-state system. This would eliminate nearly all of the energy demand required by CCC for as long as the stored refrigerant lasts.

The spent refrigerant would then have to be stored at high temperature and low pressure, which would require large storage vessels in comparison to storing the refrigerant at low temperature and pressure.

Storing the gaseous refrigerant at low pressure may become prohibitively expensive because of the size of the vessel required. One way to resolve the high-temperature storage issue is to use NG as the refrigerant. The technology for cryogenic refrigeration of methane closely parallels that for LNG, which is typically stored as a liquid at about −164 °C and 2 bar. These conditions are well suited for the stored refrigerant for the CCC ES™ process. At the high-temperature end of the cycle, a gas turbine combusts the methane, which provides additional power and eliminates the storage problem. The effluent from the gas turbine could enter the boiler and contribute to steam generation, providing combined-cycle efficiencies at simple-cycle cost. This energy storage option functionally operates as an LNG plant next to a coal-fired power plant, with the stored LNG driving the CCC process during times of peak demand and being replenished at off-peak times.

The following conceptual diagrams illustrate this process, highlighting only the energy storage aspects. Under normal operation, the CCC process does not involve NG power generation or flow of NG into the system (Figure 2). The coal combustor generates flue gas that is treated by the CCC process and results in a nitrogen-rich effluent stream and a pressurized CO_2 stream. A refrigerant compressor provides most of the energy demand of the CCC process, with energy represented by a lightning bolt into the compressor.

During energy storage (Figure 3), the process differs only in that the compressor load increases (two lightning bolts) so that additional NG can be liquefied and stored in the LNG storage vessel. Nothing flows out of the LNG storage vessel, and the NG turbine set does not operate.

During energy recovery (Figure 4), the process eliminates the parasitic compressor demand and operates only from the stored LNG. The LNG first provides cooling for the CCC process and then—to avoid storage at low-pressure, room-temperature conditions—passes through a NG turbine generation set. The air and NG would not be in the same compressor, as suggested by this simple diagram. However, the compressed NG and air burn in a turbine. This energy storage process minimizes the parasitic load on the coal-fired plant due to carbon capture via CCC. The process also generates additional energy in the form of power from the NG turbine, which is important in

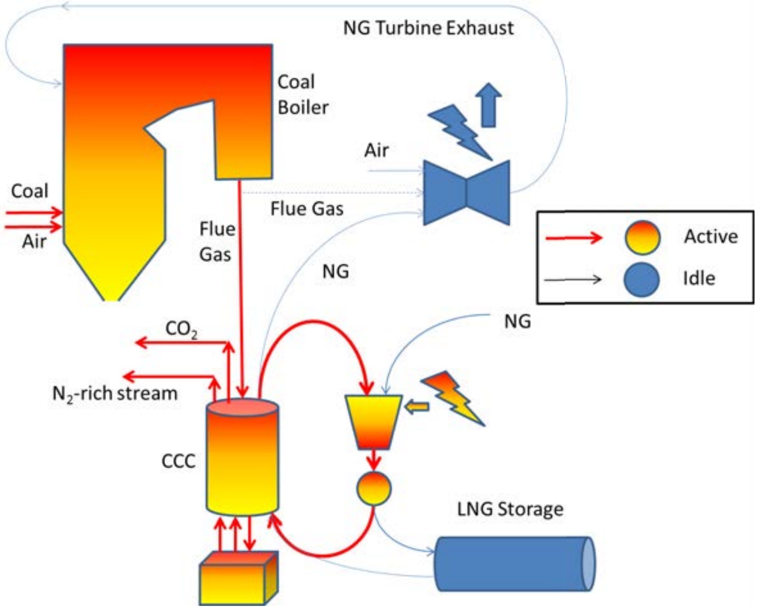

Figure 2. Conceptual CCC ES™ system diagram during normal operation. Idle operations are indicated by solid-colored blue fills, while active operations are shown by yellow/red gradient fills. Compare with Figures 3 and 4.

daily operation. However, the power from the NG turbine should not be included in the energy storage or efficiency calculation because it is a non-regenerative use of NG. The only true energy storage is the loss of the parasitic load from the CCC process.

1.3 Energy Storage Features

The process performance is very good, generally best of class, in the three most important aspects of energy storage: capacity, efficiency, and response time. Each of these is discussed separately.

1.3.1 Capacity

The CCC ES™ process provides energy storage capacity of about 2/3 of the parasitic loss associated with carbon capture if applied only to the outer loop. That represents about 10% of the boiler capacity. In addition, it provides about another 10% of capacity in the form of power generation from the gas turbine during energy recovery. The net effect is that the plant capacity actually increases during energy recovery, relative to the baseline coal boiler rated capacity. These preliminary numbers require more detailed vetting and are conservative estimates.

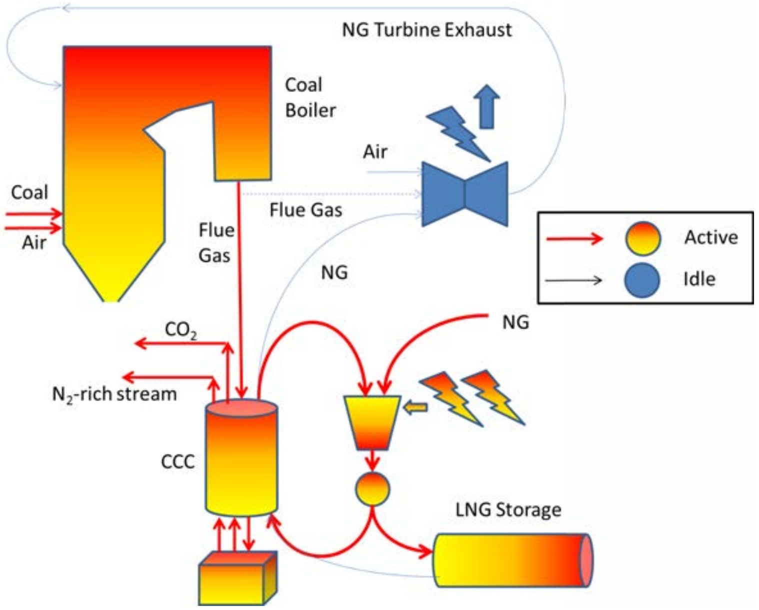

Figure 3. Conceptual CCC ES™ system diagram during energy-storage operation. Compare with Figures 2 and 4. NG enters the system at some stage of the compressor (depending on its line pressure). More power is consumed by the compressor. The excess NG is stored as a liquid at low temperature and modest pressure.

The inner loop could provide similar energy storage capabilities, albeit at a lower overall efficiency or with a refrigerant other than NG. In the latter case, a storage vessel for the room-temperature, low-pressure refrigerant will probably be required. In this scenario, the energy storage capacity increases by about 50% relative to the outer loop only, as illustrated and discussed above.

1.3.2 Efficiency

The effective energy storage efficiency of this process exceeds that of pumped storage or any other large-scale storage system if the plant is committed to carbon capture in any case. A plant committed to carbon capture is most efficient with the CCC option. If the external cooling loop is used, then some refrigerant must necessarily be cooled. The marginal efficiency losses associated with using NG as the coolant only amount to (a) the loss of coolant during storage, and (b) any change in CCC efficiency with NG as the coolant, relative to using a different coolant. Coolant losses during storage are well documented in the LNG industry and amount to about 0.5%/day in a land-based storage tank at −163 °C, and about twice this amount for ship-based storage.

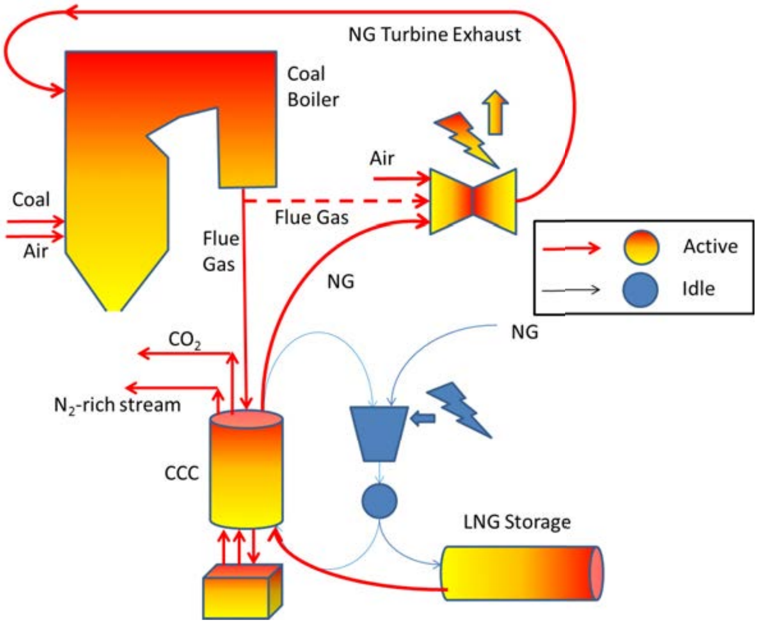

Figure 4. Conceptual CCC ES™ system diagram during energy-recovery operation. Compare with Figures 2 and 3. The main compressor is idled, reducing process energy consumption, and the system runs on the stored liquid NG. In this embodiment, NG enters a turbine generation set after warming to room temperature by driving the CCC system. The NG turbine exhaust enters the boiler at a temperature-matched point and a portion of the cold flue gas from the boiler is used in the NG turbine for turbine inlet temperature control, with only enough air to provide sufficient O_2 for combustion. Most of these latter features are optional, but this system should provide combined-cycle efficiencies at simple-cycle costs (i.e., use of the boiler as a Rankine cycle avoids significant cost), minimal impact on the boiler, and high CO_2 concentrations for efficient CO_2 capture from NG combustion.

The change in process efficiency when using NG as a coolant required both detailed process analysis and experimental confirmation, which occurred as part of this project. However, unlike the CCC process generally, which is a highly innovative process involving several cryogenic processing steps never previously commercialized, LNG processing is a mature technology. Most of the lessons learned and optimization from LNG processing apply directly to this process.

Taking both factors into account, the overall efficiency of CCC ES™ implemented with a 24-hour storage cycle ranges from 99.5% (LNG loss only) to 90% (9.5% cycle efficiency loss and 0.5% LNG loss). This exceeds the efficiency of pumped storage systems (i.e., nominally 76–85%) [1] and can be implemented with CCC on any power plant.

1.3.3 Response Time

The major components of this process involved in energy storage and delivery are compressors, room- or low-temperature heat exchangers at modest pressures (compared to superheater headers), and a NG turbine. All of these components have response times on the order of seconds to minutes. This energy storage response time is well matched to intermittent sources, such as wind turbines and solar photovoltaic cells, and is far more rapid than normal daily power demand cycles. Therefore, this energy storage system enables a coal-based boiler to follow even rapidly changing loads without compromising pressure, part integrity, or efficiency. Indeed, the CCC ES™ process could become the most strategically important component of the much discussed but slowly developing smart grid, providing the most critical part of such a grid: a rapid energy storage/recovery system.

Similar to the efficiency and capacity arguments, this potential rapid response requires detailed analysis and experimental verification, which we accomplished in this project. While the process is similar to LNG processes, most LNG processes operate near steady state and there is less experience available from processes with rapid load changes. We demonstrated heat exchanger configurations that can respond to transients in well under a minute.

2 Conclusions & Recommendations

2.1 Conclusions

The objective of this project was to explore the energy storage capability of CCC. This project

1. shows that natural gas can be used as effectively as other refrigerants in the CCC process;
2. determines that stored liquefied natural gas refrigerant represents a significant portion of the CCC energy demand;
3. calculates that the liquefied natural gas energy density suffices to be able to store energy at grid scale;
4. develops heat exchanger technologies that allow liquefied natural gas flow transients to follow energy storage and recovery transients without damage;
5. simulates grid-level incorporation of energy storage into a realistic system; and

6. demonstrates as many of these processes as possible at small scale.

The following paragraphs summarize the conclusions related to each of these points in turn.

This project demonstrates experimentally and theoretically that natural gas provides essentially identical (very slightly better) refrigeration performance as alternative refrigerants and refrigerant blends. Because the critical point of liquefied natural gas (as low as −83 °C) is well below ambient temperature, it is not possible to compress and then condense liquefied natural gas near room temperature, as is commonly done with traditional refrigerants. However, liquefied natural gas can still be generated efficiently, albeit in a slightly more complex circuit compared with traditional refrigerants.

Refrigeration in general represents about 80% of the total energy demand for CCC, depending on the amount of CO_2 in the flue gas, over half of which can be incorporated into the liquefied natural gas loop. Therefore, CCC ES™ can store and release most of its energy consumption in the form of stored refrigerant, or liquefied natural gas.

The energy density of liquefied natural gas suffices to store several hours' worth of refrigeration in tanks that are on the smaller end of commercially available storage tanks. Therefore, CCC ES™ has the capacity to store enough energy to supply refrigerant for the entire peak demand time of a typical power plant.

CCC ES™ operates with the carbon capture portion of the process matching boiler load, which is typically essentially constant, while the liquefied natural gas generation portion follows power demand. Power demand on grids with intermittent supplies can change significantly within minutes. Transient analyses and experiments showed that heat exchangers may be able to keep up with such rapidly changing demands, but that they experience rapid internal temperature changes that may exceed thermal stress limits. SES-developed (patent-pending) dynamic heat exchangers remove or greatly reduce these thermal stresses. This project demonstrated that such heat exchangers can follow even step changes in flow rates without compromising heat exchanger efficiency or inducing thermal stresses.

Detailed analyses of CCC ES™ demonstrate that, for example, an 800 MW power plant with this technology can manage ± 400 MW swings in energy demand on a grid that includes coal, natural gas, wind, and varying daily demands. The data include actual demand variations and corresponding costs of power production. The revenue generated by storing energy during low-demand, low-cost periods and releasing during high-demand, high-cost periods represents a net revenue for the CCC ES™ system of slightly over $20/MWh [4], which would cover 80–90% of the total cost of carbon capture. This large economic benefit can only be realized for a load-following power station, so it is not included in the economic analyses included in this project. However, CCC ES™ allows the power plant to follow load while the boiler remains at a constant firing rate, so nearly every power plant should be able to benefit from this technology.

SES has demonstrated at small scale (up to one tonne of CO_2 per day) the essential components of CCC ES™, including using liquefied natural gas as a refrigerant, energy storage, and energy recovery.

2.2 Recommendations

Sustainable Energy Solution's CCC ES™ process separates CO_2 from flue gases and other CO_2-laden streams and pressurizes the resulting liquid in preparation for transport and storage. Some of the distinguishing characteristics of CCC ES™ compared with the leading alternatives (i.e., advanced amine systems [2]) include:

1. consumes about half of the energy;
2. costs less than half;
3. stores energy in a highly efficient, grid-scale, rapidly responding process;
4. retrofits to existing coal, natural gas, biomass, cement kiln, and other systems;
5. captures most pollutants (CO_2 , SOx, NOx, Hg, PMxx, VOCs, etc.) in a single multipollutant platform;
6. recovers flue gas moisture, reducing water demand; and
7. is capable of very high capture rates at modest costs.

The energy and cost advantages are the most important on this list and combine to make CCC ES™ a very promising alternative to other processes. The energy and costs associated with this technology and all other carbon capture technologies exceed those of technologies used for mitigating other pollutants. A modern coal-fired power plant, for example, consumes 11–14% of the power plant output to capture and store CO_2 using this technology. By comparison, less than

5% of a non-capture plant provides the energy for all of the parasitic losses. The capture plant increases electrical power generation costs by about 2.5 ¢/kWh, and possibly much less if the energy storage option is used. For comparison, the US national average residential electricity price is about 13 ¢/kWh. CO_2 abatement requires more energy and more money than all traditional pollutant reductions combined. However, the CCC process costs less than other widely analyzed options and is in any case well within the regional variation of power costs within the US.

This project focuses on the energy-storing version of this process (CCC ES™). During off-peak hours, the CCC ES™ process generates more refrigerant than is needed for the process and stores the excess in an insulated vessel as a liquid at the low-temperature, low-pressure point in the cycle. Such vessels and processes are common commercially. During peak demand, the stored refrigerant could be used in place of continuously generating refrigerant in a steady-state system. This would eliminate nearly all of the energy demand required by CCC for as long as the stored refrigerant lasts.

CCC ES™ makes the CCC technology as strategically important for renewable fuels as it is for fossil fuels. The energy-storage version generates excess refrigerant at night or at other times when there is excess and inexpensive power available on the grid. During peak demand, the stored refrigerant drives the capture process, decreasing the normal energy demand to near zero and increasing power plant output by the amount by which the parasitic load decreases. On utility-scale power plants, this energy storage scheme can absorb intermittent power from large wind or solar sources and deliver during peak demand times, typically the next afternoon. This makes renewables much more effective than they otherwise can be and decreases the need to build additional power plants to compensate for carbon capture.

The retrofit importance of carbon capture systems is difficult to overstate. The great majority of the current growth in CO_2 emissions and the majority of total CO_2 emissions come from developing economies completing new power plants with very high opportunity costs. If carbon capture technologies cannot retrofit these relatively new power systems at reasonable costs, the prospects for carbon capture in such economies are very low. Global climate change mitigation cannot be successful without active participation from these developing economies. Independent of the importance of retrofitting new plants in developing countries, future CO_2 emissions from the

US and other mature economies are also projected to overwhelmingly come from currently existing plants.

The multipollutant capture facet of CCC makes it ideally suited for current and essentially all future environmental regulations. CCC removes every gas less volatile than CO, which includes nearly all current and foreseeable pollutants, except CO. In addition, the recovery of flue gas moisture to decrease water demand from power plants addresses some of the most critical power plant siting and operation issues.

Finally, managing global temperature increases to less than 2 °C requires capturing more CO_2 than the sum of all CO_2 currently emitted from all electrical power sources. This means that significant amounts of CO_2 from residential and commercial and mobile sources also must be captured. The costs associated with capturing CO_2 from intermittent, dispersed, small, and mobile sources will greatly exceed those from stationary continuous large sources, such as power generation. Therefore, capture systems operating on large stationary sources must remove as much CO_2 as possible (99%+) for successful climate management to succeed.

CCC addresses all of these issues. SES has demonstrated CCC up to skid scale (i.e., with flow rates that produce up to 1 tonne of CO_2 per day) processed through modular systems housed in a series of shipping containers. These demonstrations include flue gases containing CO_2 from subbituminous coal, bituminous coal, biomass, natural gas, and municipal waste and at locations that include utility power plants, heating plants, cement kilns, and pilot-scale combustion facilities.

2.2.1 Next Steps

The modeling and testing performed under this project resulted in the first significant analysis and demonstration of the CCC ES™ process. The next steps in the commercialization plan of this important technology include a market analysis that will provide a detailed model of the value of the technology in different markets, the most applicable markets for the technology, and the markets where the technology could be adopted first. The next steps in the technology development plan are to increase the scale and duration of CCC ES™ testing to the same level as the CCC skid demonstrations, demonstrate the CCC ES™ technology in a field test, and integrate CCC ES™ into the next scale up of the Cryogenic Carbon Capture™ technology. Specifically, SES will be seeking funding to integrate the CCC ES™ process into a field demonstration of the carbon capture technology in one of several potential applicable markets.

To fully realize its potential, the CCC ES™ process needs to be installed at a full-scale commercial plant where it can have significant positive effects on the plant and the surrounding grid. The first demonstration of this scale will cost hundreds of millions of dollars and will be a major engineering project. To accomplish this, SES will need to partner with a commercial engineering firm that has the reach and capability to scale the technology and take it to a global market. SES will do this by engaging in a long-term contractual or equity agreement with one of these potential partners. SES will engage with at least one such partner in the next stage of development to initiate important technical and business collaboration.

SES has secured letters of support from host-sites for the next scale of development in Europe and the United States and is currently pursuing relationships with similar entities in Canada. In addition to these host sites, SES has a bid from a global engineering contractor to build the pilot facility and is pursuing more permanent relationships with other engineering firms. SES is actively seeking funding for a pilot demonstration of the technology. Within the next two years, SES anticipates forming a formal relationship with a commercialization partner and securing funding for a pilot demonstration of the technology.

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