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Cryogenic Carbon Capture™ Technoeconomic Analysis

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Abstract

The Cryogenic Carbon Capture™ (CCC) process significantly decreases cost and energy demands for CO_2 separation and pressurization to 150 bar compared to alternatives. The process is a post-combustion technology that cools CO_2-laden flue gas to desublimation temperatures (−100 to −135 °C), separates solid CO_2—that forms from the flue gas—from the light gases, uses the cold products to cool incoming gases in a recuperative heat exchanger, compresses the solid/liquid CO_2 to final pressures (100–200 bar), and delivers a compressed CO_2 stream separated from an atmospheric pressure light-gas stream. The overall energy and economic costs are about 30-50% lower than most competing processes that involve air separation units (ASUs), solvents, or similar technologies. In addition, the CCC process enjoys several ancillary benefits, including (a) it is a minimally invasive bolt-on technology, (b) it provides highly efficient removal of most pollutants (Hg, SOx, NO_2, HCl, etc.), and (c) possible energy storage capacity. This report outlines the process details and economic and energy comparisons relative to other well-documented alternatives.

This paper presents the results of a detailed techno-economic comparison of CCC with amine-based systems. The comparison uses identical financial and economic assumptions similar process assumptions as the detailed analyses published by US DOE in the greenfield analysis. Specifically, the comparison assumes power plants that produce the same net output, one equipped with and a second without carbon capture. Separately, the paper compares similar analyses for retrofitting existing systems using typical plant characteristics in the US (initial capital costs have been paid, high plant utilization), though there are no DOE estimates available for direct comparison. Financial and technical assumptions for all comparisons are maintained as close to the DOE reference studies as possible.

The results demonstrate about 30-50% lower costs and energy demands for capture from greenfield coal plants. Natural gas plants produce substantially lower CO_2 concentrations which makes the cost of capturing a ton of CO_2 at the same capture rate as the coal plant higher for all processes while the cost of CO_2 capture per unit of power generation is lower. However, CCC maintains about the same absolute energy and cost advantages for NG as for coal compared to amine systems. Finally, the costs of retrofitting a station are compared to those of building a new station with and without capture. The retrofit costs are comparable to (slightly lower than) new plant costs without capture. In all cases operating and capital cost comparisons show that the CCC process can be retrofitted to a variety of plants to cost effectively reduce CO_2 emissions. Further process integration into the upstream processes and unique process features like water recovery, and integrated energy storage bring the effective cost of carbon capture using the CCC process down further and increase its advantages over alternatives. This technoeconomic analysis shows that the CCC process has the potential to the be lowest cost carbon capture technology under development today.

Keywords: Cryogenic Carbon Capture™; Advanced Carbon Capture;

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1. Introduction

The Cryogenic Carbon Capture (CCC) process developed by Sustainable Energy Solutions (SES) is a post-combustion carbon capture process designed to remove CO_2 primarily from large point sources including coal-fired and natural-gas-fired power plants, cement kilns, steel mills, and other industrial facilities. The CCC process is unique and transformational in several ways, namely it:

- Captures CO_2 at significantly lower energy penalty and cost than competing technologies.
- Uses less water than competing technologies and recaptures water from the flue gas to further decrease water demand.
- Enables large-scale energy storage that greatly increase the usability of renewable power sources and stabilize the grid. [1, 2, 3, 4, 5, 6, 7]
- Is a bolt-on retrofit technology that is minimally invasive and requires no steam. [8, 9]
- Allows for co-capture of ancillary pollutants such as SO_x, NO_x, and Hg.
- Can easily capture above the industry-standard 90% capture efficiency, up to and including direct air capture of CO_2.
- Contains equipment familiar to end users such as power and industrial consumers (e.g. refrigeration systems, heat exchangers, processing vessels).

The CCC process has been recognized by national organizations such as NRG COSIA XPRIZE, R&D 100, and the Edison Awards, as well as area experts like Howard Herzog of MIT, as an innovative and industry-disrupting approach to carbon capture. Howard Herzog asserts in his 2018 book on carbon capture that, “of all these [carbon capture] processes, I regard the CCC process to have the greatest potential” [10].

2. Process Description

The CCC technology (Fig. 1) cools and dries flue gas from its outlet temperature to near ambient temperature. The gas is then slightly pressurized in a blower to overcome the pressure drop of the rest of the system. It then proceeds through a direct-contact drying system down to a temperature very close to the frost point, or the temperature at which CO_2 will begin to desublimate from a gas to a solid (approximately −100 °C for a coal-fired flue gas). The gas then enters a proprietary desublimating heat exchanger, where it exchanges heat with a contacting liquid that acts as a heat transfer medium and creates nucleation sites for the desublimating CO_2 particles, creating a contact liquid/CO_2 slurry. The capture efficiency is entirely dependent on the coldest temperature reached by the gas. For a typical coal-fired flue gas at 1 bar, 90% capture occurs at −117 °C and 99% capture occurs at −133 °C. The clean light gases are warmed back to ambient temperatures to recuperate as much cooling as possible and are then released through the stack. The slurry exits the desublimating heat exchanger through a pump that increases the pressure above the CO_2 triple point. The slurry is cooled and then sent through a solid-liquid separations process that increases the mass fraction of CO_2 from about 10% to about 80%. This CO_2 stream is melted, purified in a distillation system to 99.7–99.999+%, pumped to final delivery pressure, and warmed back to ambient temperature. Two cooling loops act as a cascade refrigeration cycle to provide the necessary cooling for the process.

The process consumes minimal energy due to the high amount of heat integration. Nearly all the sensible heating and cooling is provided via recuperation, leaving only the energy of separation and phase change to be provided by the process. The sum of the energy of separation and phase change represent the theoretical minimum energy required for CO_2 separation. CCC is therefore within turbomachinery and heat exchanger efficiencies of the minimum energy possible to affect the separation of CO_2 from any flue gas stream. Additionally, CO_2 compression occurs as a condensed liquid phase, which reduces the equipment cost and energy required for producing a liquid product at typical delivery pressures of 125–150 bar.

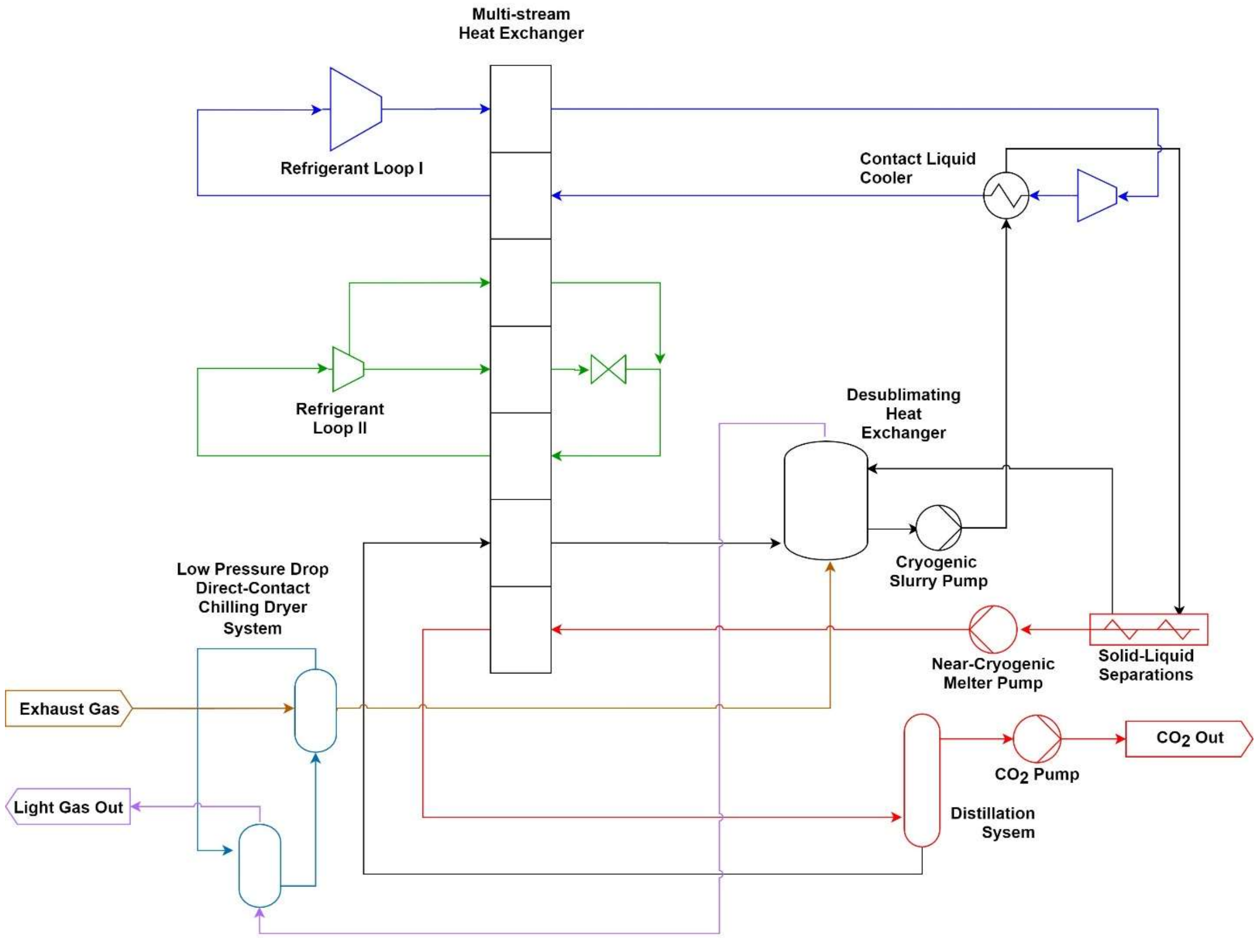

Fig. 1. High-level PFD of the CCC process showing to main sub-systems of the process.

3. CCC Technology Advantages

3.1. Flue Gas Water Recovery

The CCC process decreases its water demand in two substantial ways. First, the process creates a bone-dry light gas stream at slightly below ambient temperatures. This gas can generate cooling water because of both its low temperature and its lack of humidity. Second, the CCC process requires the flue gas to be cooled from its exit temperature to ambient temperature, condensing and recovering substantially all the moisture in the flue gas, which further decreases the CCC water demand.

3.2. Pollutant Capture

As the flue gas cools to near-cryogenic temperatures, any molecule that has a vapor pressure greater than the vapor pressure of CO_2 will be captured along with the CO_2. This includes heavy metals such as Hg, As, Pb, etc. as well as other criteria pollutants such as SO_x, NO_2, and particulates. CCC captures these pollutants so efficiently that it has the capacity to replace flue gas desulfurization (FGD) units for SO_x reduction, activated carbon beds for Hg removal, and selective catalytic reducer (SCR) units for NO_x reduction. Carbon monoxide (CO) as well as any other compounds lighter than CO_2 will not be captured by the CCC process. Table 1 shows the concentration of pollutants in the effluent gas for a coal-fired flue gas exiting a CCC system that captured 90% of the CO_2.

Table 1. Pollutant composition in the clean flue gas exiting the CCC process when capturing 90% of the inlet CO_2.

Pollutant	ppm
SO_2	32.7
SO_3	0.002
NO_2	0.007
Hg	4.80E-10
As	7.31E-37

3.3. Energy Storage

CCC presents a unique opportunity for large-scale, inexpensive, high-efficiency energy storage. The CCC process operates in a temperature regime that enables it to use natural gas as a refrigerant. The refrigerant can be generated and stored in condensed liquid form as liquefied natural gas (LNG) during times when electricity is inexpensive, supply is high, or demand is low and then utilized during times when electricity is expensive, supply is low, or demand is high. Most of the parasitic load comes from the refrigerant compressors, so using stored LNG offsets most of the energy penalty. The excess warm vaporized natural gas can either be returned to the pipeline or burned in a natural gas turbine whose effluent CO_2 will also be captured. SES estimates that the potential for energy storage is about 7–12% of the total power plant capacity. This version of the process is referred to as CCC with energy storage or CCC-ES. CCC-ES allows the carbon capture system to act as a spinning reserve for the grid, enabling greater utilization of renewable resources and replacing the most expensive electricity generated with reliable, CO_2-free reserve power.

3.4. Retrofit Capability

Most carbon capture technologies require significant infrastructure to run properly, even in a retrofit application. For example, the amine carbon capture plant installed at the Boundary Dam power plant required significant integration with the plant's steam cycle. This proved more difficult than expected and contributed to the project going over budget and experiencing delays. The Petra Nova project required the installation of a brand-new cogeneration combined heat and power plant to provide the electricity and steam needed for the amine system. The CCC process requires only electricity and cooling water and can therefore be easily retrofitted onto existing power plants and industrial facilities. If water is unavailable, using air-cooled compressors can make the CCC process a net positive source of water. This slightly decreases the efficiency of the system but results in the only bolt-on retrofit carbon capture technology that requires only power to operate.

4. Technoeconomic Baseline

The National Energy Technology Laboratory (NETL) has performed detailed technoeconomic analysis of carbon capture in the "Cost and Performance Baseline for Fossil Energy Plants" [11]. It is, to our knowledge, the most complete and comprehensive set of publicly available cost and performance data available for comparison of carbon capture technologies. The NETL study provides detailed guidelines for process assumptions and economic modeling, allowing for rigorous one-to-one comparison of carbon capture technologies. The baseline studies selected for this report are Case 11 and Case 12 in the cited report. Case 11 is a greenfield 550 MW_e net supercritical pulverized coal (SC PC) power plant with no carbon capture. Case 12 is a greenfield 550 MW_e net SC PC plant with an amine capture unit with 90% CO_2 capture. SES performed detailed modeling of the CCC process to simulate a 550 MW_e net SC PC plant that uses the same process and economic assumptions as specified in the NETL report. While CCC can easily achieve higher capture efficiencies at low marginal cost, the system was designed for 90% capture to match the NETL study. For both the amine and CCC case studies, the size and cost of the base power plant must be scaled to achieve 550 MW_e net output. Therefore, a carbon capture system with a higher parasitic load requires a larger base plant to achieve the same net electricity output. Results of these studies are presented for both energy and economic performance below.

5. Energy Performance of Carbon Capture Systems

Each CCS technology requires energy to perform the separation and compression of the CO_2. This analysis will present the energy penalty of the case studies in two ways. First, the energy penalty will be presented as an intensive value in terms of the electric power required per mass of CO_2 captured in MJ_e/kg. This presents a scalable value that can be applied to other flue gases that are similar in terms of pressure and composition. The energy penalty will also be expressed extensively in terms of the high heating value (HHV) heat rate of the power plant. This is a key parameter identified in the NETL report and it is also used in the costing simulations. The HHV heat rate is the amount of thermal energy from the combusted fuel required per unit of electricity produced. The NETL report presents this value in the units of BTU/kWh, and the same units are used in this publication.

5.1. Energy Performance of NETL Cases

Case 11 is a non-capture SC PC power plant and therefore has no energy penalty. The net HHV heat rate for Case 11 is 8,687 BTU/kWh. The energy penalty of Case 12 is not stated explicitly in the NETL report in terms of MJ_e/kg. This is because a large amount of the energy penalty of the amine process is a result of the redirection of steam from the steam turbine to the amine process. The potential electricity that could have been generated from this steam is the electric energy penalty for this redirection. This lost potential electricity can be easily calculated based on the difference in the steam flowrate and electric output of the steam turbine between the capture and non-capture cases. The energy penalty of the Case 12 amine system using this calculation is 1.376 MJ_e/kg. The HHV heating rate is stated in the report as 12,002 BTU/kWh. This means the parasitic load of the amine capture plant for Case 12 is 27.6%.

5.2. Energy Performance of CCC Cases

Detailed thermodynamic simulations of the CCC process were performed in accordance with all requirements of the NETL baseline report. CCC simulations have been verified by third parties including American Air Liquide, General Electric, Booz Allen Hamilton, EPRI, Chart Industries, and several others. The vast majority of the energy penalty of the CCC process comes from the electricity required to drive the refrigeration compressors. For this report, the refrigerant compressors have an assumed efficiency of 90%, which is in line with vendor quotes that have been received at this scale. The flue gas blower has an 85% efficiency, condensed phase pumps have an 80% efficiency, and slurry pumps have a 72% efficiency, which are all well within commercial specifications.

Table 2. Power requirements for each sub-system in the CCC process.

Energy Source	Work (MW_e)
Refrigerant Compression	113.8
Flue Gas Compression	2.5
Separations Compression	1.0
Condensed Phase Pumping	3.3
Total	120.5

In addition to the large amount of power needed for the refrigerant loops, the other power requirements are shown in Table 2. The flue gas compression shown is simply the amount of work required in a blower to overcome the pressure drop of the CCC system. A small compressor is required in the distillation system, and condensed phase pumping of the slurry and liquefied CO_2 has also been accounted for. As stated previously, these electric loads represent the entirety of the CCC parasitic load, as there is no steam or other energy inputs required.

A marked difference can be seen when we interpret this parasitic load into the two established metrics. The CCC process requires only 0.894 MJ_e/kg of CO_2 captured. This corresponds to a HHV heat rate of 10,584 BTU/kWh and an energy penalty of 17.9%. The CCC energy penalty of the CCC process is only about two-thirds of what an equivalent amine process would require while achieving the same capture efficiency.

CCC can also capture pollutants and can replace other pollutant equipment such as an FGD, SCR, activated carbon beds, and even baghouses or electrostatic precipitators. To illustrate the significant advantage this offers to the CCC technology, a separate case is included for CCC with pollutant removal (CCC-PR). This case is identical to the other CCC case but removes the capital cost, operating cost, and electric load of the ancillary pollutant systems that can be replaced by CCC. For the NETL report in question, this includes an FGD, SCR, and a baghouse. This does have a small effect on the energy penalty of the system, but a more significant effect on the economics, as will be seen later in the report. Table 3 summarizes the energy penalty of all the cases presented here, including the CCC-PR case.

Table 3. Energy penalties for non-capture, amine, CCC, and CCC with pollutant removal cases.

Energy Source	Case 11 (no capture)	Case 12 (amine)	CCC	CCC-PR
Power Needed (MJe/kg)	0.000	1.376	0.894	0.854
HHV Heat Rate (BTU/kWh)	8687	12002	10584	10480
Parasitic Load	0.0%	26.7%	17.9%	17.1%

5.3. Other Baseline Studies

To ensure the NETL study is representative of a true amine process, other carbon capture studies are presented here [12]. These studies occurred in the USA, Europe, China, and Australia and have similar assumptions to the NETL study (flue gas pollutant removal systems, amine-based post-combustion process, compression of the product CO_2 stream). They show that the NETL study is representative of a typical amine system.

Energy Source	CMU	EPRI	TNO	TPRI	CSIRO
Power Needed (MJ_e/kg)	1.42	1.41	1.52	1.44	1.42
Base Plant HHV Heat Rate (BTU/kWh)	8687	8979	7982	8257	8868
Plant with Capture HHV Heat Rate (BTU/kWh)	11402	12342	11586	11439	12053
Parasitic Load	23.9%	27.3%	31.1%	37.8%	26.4%

6. Cost of Carbon Capture

The NETL report utilizes cost of electricity (COE) as its main metric for economic comparison. The cost of electricity is influenced by the capital, operating, and fuel costs, as well as the cost for transportation, storage, and monitoring (TS&M) for the capture cases. It considers all capture plants to be higher risk than a non-capture plant, resulting in higher contingencies and a higher cost for capital for the capture cases (Case 12 and the CCC cases) than the base non-capture case (Case 11). As with the energy studies, the CCC cases have been rigorously performed to fall in line with all economic assumptions inherent to the NETL study to allow for a one-to-one comparison of the CCC technology with the amine technology. Also included will be the cost of CO_2 avoided (Eq. 1) and cost of CO_2 captured (Eq. 2). Cost of CO_2 captured is a standard metric. Cost of CO_2 avoided is less prevalent and is defined as the costs to avoid emitting a unit of CO_2. Avoided cost incorporates the parasitic load of the capture plant into the cost by taking into account the additional fuel, and therefore additional CO_2 emissions, required to generate the same net

550 MW of electricity. It is important to note that per NETL specifications, the cost of CO_2 captured uses the COE excluding the TS&M costs, since these are not included as part of the capture system. However, the cost of CO_2 avoided uses the COE including TS&M costs.

$$\text{Avoided Cost} = \frac{\left(\text{COE}_{\text{CCS with TS\&M}} - \text{COE}_{\text{Non CCS}}\right)\frac{\$}{\text{MWh}}}{(\text{CO2 Emissions}_{\text{Non CCS}} - \text{CO2 Emissions}_{\text{CCS}})\frac{\text{tonne}}{\text{MWh}}} \tag{1}$$

$$\text{Captured Cost} = \frac{\left(\text{COE}_{\text{CCS w/o TS\&M}} - \text{COE}_{\text{Non CCS}}\right)\frac{\$}{\text{MWh}}}{(\text{CO2 Captured}_{\text{CCS}})\frac{\text{tonne}}{\text{MWh}}} \tag{2}$$

6.1. Economics of the NETL Cases

Case 11 and Case 12 cost details can be found in the NETL report. Case 11 has a COE of $58.90/MWh and no avoided cost or captured cost since there is no CO_2 capture. Case 12 has a total COE of $106.50/MWh. For this study, that corresponds to a cost of CO_2 captured of $42.06/tonne and a cost of CO_2 avoided of $68.92/tonne. A greenfield amine capture plant results in a COE that is $47.60/MWh greater than a greenfield non-capture plant, a 80.8% increase. This accounts for the increased fuel, capital cost both for scaling the base plant and for the amine system, increased operating costs, and the transportation, storage, and monitoring of the CO_2. A more detailed breakdown of the cost of electricity will follow the CCC cases below.

6.2. Economics of the CCC Cases

Detailed economic modeling of the CCC process has been performed many times and has been updated again for this paper. Capital cost of all major equipment comes from vendor quotes tailored to the designs produced by the thermodynamic simulations of the process. Most quotes have been updated within the last year and are current as of this publication. This includes quotes for the most expensive items, the refrigerant compressors and multi-stream heat exchanger. Installation factors and other economic considerations mimic those in the NETL study, including line-by-line estimation of operating costs. Using these parameters and quotes, the COE for the base CCC case is $87.46/MWh, representing a 48.5% increase over Case 11. The cost of CO_2 captured is $26.88/tonne and the cost of CO_2 avoided is $40.57/tonne. The incremental cost of CCC over Case 11 is $28.56/MWh, which is 40% less than the incremental cost of Case 12 over Case 11. CCC-PR has a COE of $74.54/MWh, a captured cost of $12.36/tonne, and an avoided cost of $22.19/tonne. The CCC-PR costs are decrease because the capital and operating costs of the FGD, SCR, and baghouse are removed since they become redundant, leading to significant economic savings.

6.3. Economics of Energy Storage

The energy storage aspect of CCC was covered briefly above, but bears mention again during the economic discussion here. The ability to time-shift the parasitic load of the process has significant economic benefits, in addition to contributing to other less quantifiable metrics such as grid stability. While a detailed study of the CCC-ES system is beyond the scope of this work, previous rigorous analyses have placed the value of energy storage at utility scale at about $24/MWh [7, 3, 6]. This includes the small increase in capital cost of the LNG storage tank that differentiates CCC-ES from the base CCC process. This places the COE of CCC-ES at $63.46/MWh, which is only marginally above the COE for NETL's non-capture case. The corresponding cost of CO_2 captured is −$0.42/tonne and the cost of CO_2 avoided is $6.48/tonne. The negative capture cost is a result of the TS&M costs being slightly more than the difference between the COE of Case 11 and the CCC-ES case. This case does not assume the advantages of the CCC-PR case, and including the benefits of pollutant removal, the COE would be less than a non-capture plant.

6.4. Importance of Retrofit

All the case studies included up to this point assume a greenfield installation of a coal-fired power plant. While this is instructive and important for creating comparisons, it does not accurately reflect the reality of the status quo. It is highly unlikely that any such plants would be built in the current market environment. Most opportunities in the current market would be retrofits of existing plants. As discussed earlier, CCC is ideal for retrofitting existing utilities and industrial plants, as only electricity and water are required, and in some cases, only electricity. Amine systems, in contrast, would need more water in addition to a very large steam source, necessitating significant integration with the existing plant or a construction of an additional plant to provide the steam and electricity required. Retrofitting also allows companies to utilize their existing capital resources and infrastructure rather than replacing existing plants. In the United States, for example, most coal-fired power plants have already paid off their initial capital investments, and so their COE is based almost entirely on operating and fuel costs.

To illustrate the economic advantage of retrofitting existing plants, one additional CCC retrofit case (CCC-Ret) has been included. This case assumes that a 670 MW plant exists that has the same operating and fuel costs on a per MW basis as the 550 MW plant of Case 11. This 670 MW plant has already paid off its capital costs for the existing power plant. This plant is then retrofitted with CCC, derating the plant to 550 MW, and capturing 90% of the CO_2 emissions. The new capital expenses of the CCC plant and slightly expanded cooling water system are included in the cost estimates, but there are no additional capital expenses for the existing plant because of the bolt-on nature of the technology. This retrofitted plant has a COE of $49.43/MWh, which is less expensive than the COE of new but non-capture Case 11, which is $58.90/MWh. Even though the operating and fuel costs are higher for this plant than a new 550 MW plant, and even with the capital costs and additional operating costs of the newly installed CCC system, the total cost to the utility is still lower than Case 11. This illustrates an important point: that retrofitting an existing plant often results in a power plant that includes CO_2 capture at a lower cost to the utility than building a new non-capture plant.

6.5. Economic summary

Table 4 below contains a breakdown of each of the cases presented in this study. This includes the two NETL cases, Case 11 and Case 12, as well as all 4 CCC cases (CCC, CCC-PR, CCC-ES, and CCC-Ret). CCC technology, in all cases, significantly outperforms amine technology. In the CCC-ES and CCC-Ret cases, COE comes close to or outperforms the non-capture base case. Fig. 2 presents this same information. In the NETL and all but the retrofit SES/CCC computations, the capital and operating costs include both replacing the lost capacity associated with adding carbon capture and the costs associated with the carbon capture system itself. That is, the analysis assumes greenfield plants with the same net output but with and without carbon capture. Most carbon capture processes require substantial modification or replacement of the upstream process. However, the CCC process requires virtually no such modifications and represents a bolt-on retrofit option. The last column indicates the costs of such an option. The same investigations cited in the energy penalty discussion above also did economic simulations of the amine capture plant to generate a COE. Table 5 summarizes the results.

Table 4. Cost breakdown for each case compared in this work. CCC-Ret does not have a reported avoided or captured cost since it would have a different base case than the other cases in this table.

	Case 11	Case 12	CCC	CCC-PR	CCC-ES	CCC-Ret
COE ($/MWh)	58.90	106.50	87.46	74.54	63.46	49.43
TS&M ($/MWh)	0.00	5.60	4.93	4.88	4.93	4.93
Fuel ($/MWh)	14.20	19.60	17.29	17.11	17.29	17.29
Variable OPEX ($/MWh)	5.00	8.70	7.53	4.81	7.53	7.53
Fixed OPEX ($/MWh)	8.00	13.00	10.59	10.49	10.59	10.59
CAPEX ($/MWh)	31.70	59.60	47.12	37.25	47.12	9.10
Energy Storage Value ($/MWh)	0.00	0.00	0.00	0.00	-24.00	0.00
COE Increase ($/MWh)	0.00	47.60	28.56	15.64	4.56	-9.47
Difference from Case 11	0.0%	80.8%	48.5%	26.6%	7.7%	-16.1%
Avoided Cost ($/tonne)	0.00	68.92	40.57	22.19	6.47	n/a
Captured Cost ($/tonne)	0.00	42.06	26.88	12.36	-0.43	n/a

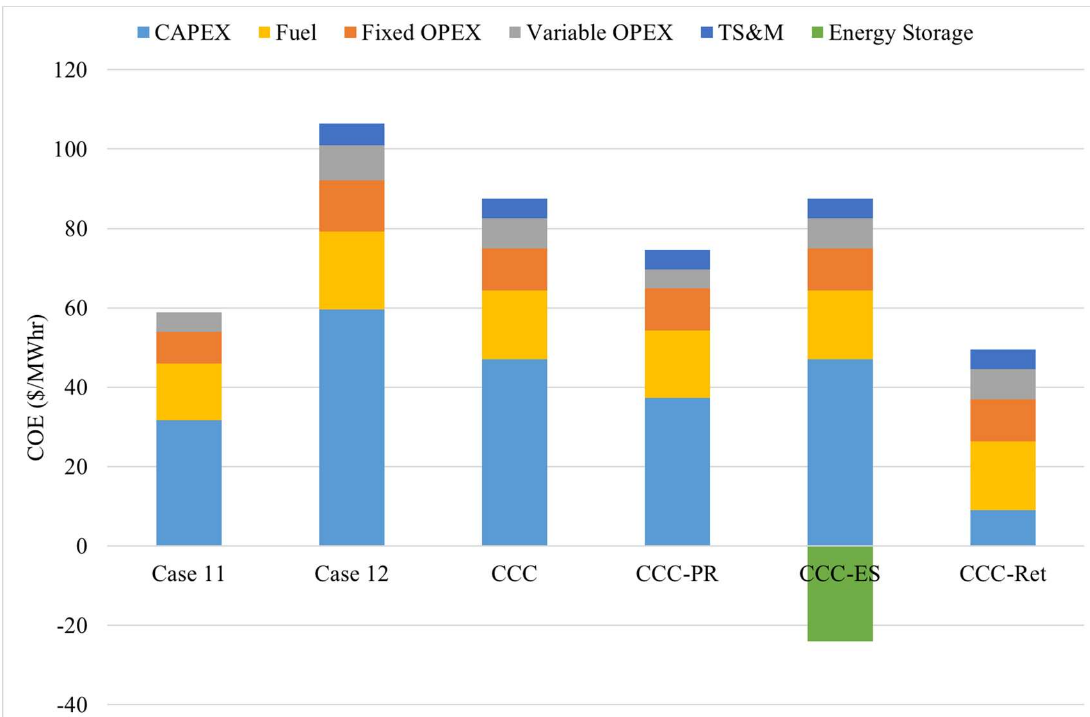

Fig. 2. Plot showing costs for each case compared in this work. COE is the sum of all bars, both positive and negative

Table 5. Comparison of NETL and literature review of costs of amine CO_2 capture on coal plants [12].

	NETL	CMU	EPRI	TNO	TPRI	CSIRO
Reference Non-capture Plant COE ($/MWh)	58.90	59.10	73.40	43.90	42.00	53.40
Amine-based CCS Plant COE ($/MWh)	106.50	99.20	121.10	79.20	62.00	114.50
Increase in COE ($/MWh)	47.60	40.10	47.70	35.30	20.00	61.10
Difference from Base Case	80.8%	67.9%	65.0%	80.4%	47.6%	114.4%

7. Conclusion

Current energy infrastructure still relies heavily upon fossil fuels for power generation, although there is an increasing trend towards using renewable resources. Other sectors, such as cement and steel, will continue to produce CO_2 even if fossil-based utilities are replaced. Climate change issues become more pronounced each year and carbon capture and sequestration is an essential part of climate management. Cryogenic Carbon Capture™ is a viable alternative to current technologies such as amines. CCC has the following advantages:

- A lower parasitic load, 30-50% lower than absorption technology depending on the reference study and application.
- Lower cost of electricity, about 40-50% lower using established metrics.
- Bolt-on retrofit to any existing utility or industrial plant, increasing economic benefits.
- Ancillary pollutant removal that can replace or improve existing systems.
- Easily captures above 90% of outlet CO_2.
- Enables large-scale energy storage that stabilizes the grid, enables renewables, and gives utilities additional savings.

In terms of both cost and energy, CCC outperforms competing carbon capture technologies. It is a potential paradigm-shifting technology that offers a solution to the current questions facing the energy industry.

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9. References

[1] S. M. Safdarnejad, J. D. Hedengren and L. L. Baxter, "Dynamic optimization of a hybrid system of energy-storing Cryogenic Carbon Capture and a baseline power generation unit," *Applied Energy,* vol. 172, pp. 66-79, 2016.

[2] F. Fazlollahi and L. L. Baxter, "Modeling and analysis of natural gas liquefaction process: Energy storage of cryogenic carbon capture (CCC-ES)," *EM: Air and Waste Management Association's Magazine for Environmental Managers,* vol. 65, no. August, pp. 28-35, 2015.

[3] F. Fazlollahi, A. Bown, E. Ebrahimzadeh and L. L. Baxter, "Design and analysis of the natural gas liquefaction optimization process-CCC-ES (energy storage of Cryogenic Carbon Capture)," *Energy,* vol. 90, pp. 244-257, 2015.

[4] M. J. Jensen, D. Bergeson, D. Frankman and L. L. Baxter, "Integrated rapid response energy storage with CO2 removal," in *PowerGen International*, Orlando, FL, 2012.

[5] S. M. Safdarnejad, J. D. Hedengren and L. L. Baxter, "Effect of Cryogenic Carbon Capture (CCC) on smart power grids," in *Proceedings of the American Institute of Chemical Engineers (AIChE) Conference*, Austin, TX, 2015.

[6] S. M. Safdarnejad, J. D. Hedengren and L. L. Baxter, "Plant-level dynamic optimization of Cryogenic Carbon Capture with conventional and renewable power sources," *Applied Energy,* vol. 149, pp. 354-366, 2015.

[7] F. Fazlollahi, A. Bown, E. Ebrahimzadeh and L. L. Baxter, "Transient natural gas liquefaction and its application to CCC-ES (energy storage with Cryogenic Carbon Capture)," *Energy,* vol. 103, pp. 369-384, 2016.

[8] M. J. Jensen, C. S. Russell, D. Bergeson, C. Hoeger, D. J. Frankman, C. S. Bence and L. L. Baxter, "Prediction and validation of External Cooling Loop Cryogenic Carbon Capture (CCC-ECL) for full-scale coal-fired power plant retrofit," *International Journal of Greenhouse Gas Control,* vol. 42, pp. 200-212, 2015.

[9] S. M. Safdarnejad, L. Kennington, L. L. Baxter and J. D. Hedengren, "Investigating the impact of Cryogenic Carbon Capture on power plant performance," in *2015 American Control Conference (ACC)*, Chicago, IL, 2015.

[10] H. J. Herzog, Carbon Capture, Cambridge, MA: MIT Press, 2018.

[11] J. L. Haslbeck, N. J. Kuehn, E. G. Lewis, L. L. Pinkerton, J. Simpson, M. J. Turner, E. Varghese and M. C. Woods, "Cost and Performance Baseline for Fossil Energy Plants Volume 1: Bituminous Coal and Natural Gas to Electricity. Revision 2a," United States Department of Energy, 2013.

[12] M. Zhao, A. I. Minett and A. T. Harris, "A review of techno-economic models for the retrofitting of conventional pulverised-coal power plants for post-combustion capture (PCC) of CO2," *Energy & Environmental Science,* vol. 6, no. 1, pp. 25-40, 2013.