Potential for Carbon Capture, Utilization, and Storage Technologies in New York State

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Potential for Carbon Capture, Utilization, and Storage Technologies in New York State

Final Report

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Abstract

As part of the Green New Deal, New York State has adopted ambitious greenhouse gas (GHG) emissions reduction targets to achieve a carbon free electricity system by 2040 and transition to a clean energy economy. Carbon capture, utilization, and storage (CCUS) technology may contribute to achieving these targets. This study aims to reduce uncertainties related to the development and potential of such technologies and provide a better view on what CCUS could deliver to the State in terms of climate abatement and economic development. The study compares selected CCS and CCU technologies on costs and abatement potential. CCUS technologies and their energy and low-carbon feedstock requirements are put in the context of wider clean energy development to draw conclusions on what would be required for their deployment in terms policy incentives and innovation effort.

Keywords

Carbon capture, carbon utilization, carbon sequestration, decarbonization, Carbon-to-Value, CCS, CCU, CCUS, DAC, innovation, techno-economic assessment, Green New Deal, carbon dioxide.

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Summary

S.1 Overview and Context in New York State

In 2019, Governor Andrew M. Cuomo signed the Climate Leadership and Community Protection Act (CLCPA), legislation to combat climate change and drive investment in clean energy. Through this legislation, New York State has adopted the following greenhouse gas (GHG) emission reduction targets as part of its goals to achieve a carbon-free electricity system by 2040 and transition to a clean energy economy:

- **2030:** 40% below 1990 levels
- **2050:** 85% below 1990 levels

Governor Cuomo's Carbon-to-Value Innovation Agenda supports selecting technologies that use carbon to create new products as one way to meet these targets. This statewide transformation will help prevent the negative effects of climate change and support New York State in developing a green economy that will stimulate innovation and create new jobs. In addition to private corporations, many NYS agencies including the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Environmental Conservation (NYS DEC) are engaged in efforts to meet these ambitious targets.

Carbon capture, utilization, and storage (CCUS) technology may contribute to achieving these targets. Many CCUS technologies are being developed, but information is scattered and technoeconomic performance not uniformly assessed. Large uncertainties in cost data and potential remain, and the application potential in New York State is unclear. It is also not clear how CCUS may contribute to the climate and innovation agenda and how such technologies compare to other options.

This study aims to reduce these uncertainties and provide a better view on what CCUS could deliver. As a shortlist of CCUS technologies deemed[2] most relevant to NYS, this study assesses carbon dioxide (CO_2) abatement potential, develops cost estimates, and identifies innovation requirements and potential local development partners. The study also explores the potential socioeconomic benefits that may follow from developing these technologies in the State.

S.2 Findings and Recommendations

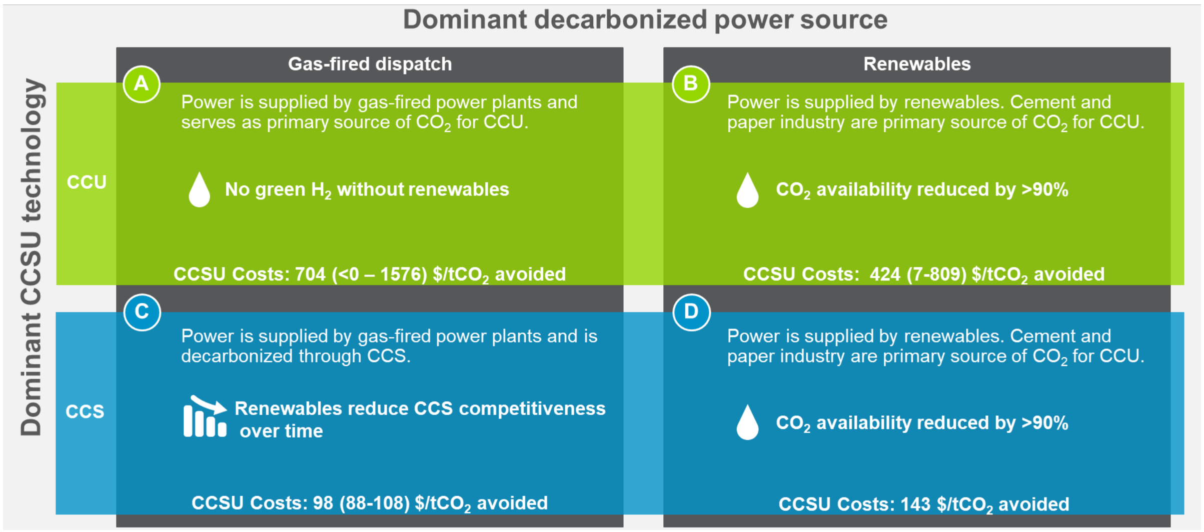
In 2017, power generation was responsible for 94% of CO_2 from the top-33 emitters[3] (top-33) most suitable for carbon capture. This top-33 represents around 12% of total GHG emissions in New York

State. Based on a literature review, the estimated total amount of CO_2 that can be economically stored in the subsurface of NYS is close to 14 $GtCO_2$; this is equivalent to about 70 years of the State's annual emissions in 2017.

Most of these CO_2 emissions can be captured and either stored in the subsurface (carbon capture storage, or CCS) or used as feedstock to create (new) products (carbon capture utilization, or CCU). However, the actual contributions of CCUS to the State's GHG reduction targets depends on the development of renewables. CCS, and to a smaller extent CCU, may decarbonize power generation in NYS, but will face competition from increasingly lower cost renewables. This study developed four pathways to show how increased penetration of renewables will affect CCUS deployment (Figure S-1).

> **Recommendation 1:** Examine and closely monitor how the combination of dispatch power and CCUS will compete against renewables for CO_2 abatement. Data delivered in this study informs complementary modeling and analytics efforts. Defining technology development metrics and their tipping points enables monitoring these developments and supports recognizing timely CCUS deployment opportunities in New York State.

Figure S-1. CCUS Choices versus Decarbonized Power Generation Sources



Note: CCUS costs are total avoidance-weighted average costs. The spread per pathway indicates spread over a selection of technologies within that pathway. Section 7.2 details all four pathways.

The chart of four pathways in Figure S-1 shows a CCUS feedstock conundrum:

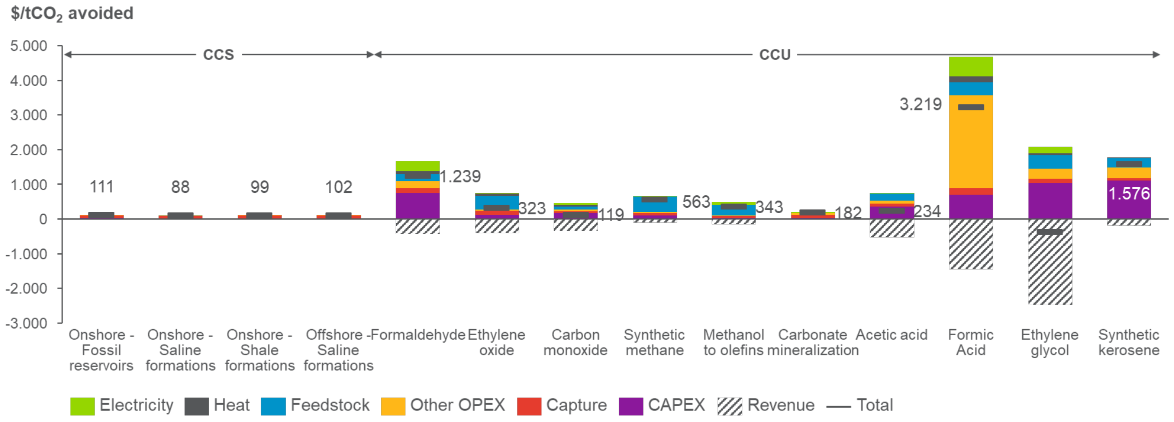
- In a state without renewables, there will likely not be sufficient green hydrogen available to deploy CCU at scale
- In a state with most power coming from renewables, thereby eliminating the main source of CO_2, only smaller manufacturing industries may provide sufficiently large CO_2 sources to deploy CCUS at scale

Despite a low (<1%) contribution, CCUS may prove crucial in sectors such as paper and cement as these sectors may still help in meeting NYS climate targets. Emissions from cement are among the most challenging to abate and CCUS could play an important role this sector. CCU fits a more resilient and circular manufacturing industry. Supporting such industries to lead the way in transforming manufacturing through CCU could prove to be an economic boon by protecting and creating jobs.

> **Recommendation 2:** Focus NYS's innovation agenda on technologies and sectors where renewable options are limited. Investigate CCU deployment to decarbonize selected manufacturing industries such as cement and paper mills where fewer alternatives exist (compared to power generation). Seek technologies that fit these sectors to allow a more resilient and circular manufacturing industry—e.g., concrete curing or aggregate production using CO2 from cement production.

The emissions from NYS's top-33 emitters can be captured for \$26–\$133 per tonne of avoided CO_2,[4] depending on flue gas properties, which is sector specific. Natural gas-fired power, representing 82% of top-33 emissions, has an estimated capture cost of \$78/tCO_2. The estimated transport and storage costs range from \$9 to \$29 per tonne of avoided CO_2 depending on the type of storage formation, distance transported, and annual volume stored. Utilization technology costs show the widest spread, from generating a profit (revenue exceeding projected production costs) to \$3,219 per tonne of avoided CO_2. By 2050, CCS remains much cheaper than most CCU technologies even when considerable cost reductions on energy and feedstock are projected[5] (Figure S-2).

Figure S-2. Projected Abatement Cost of CCUS Technologies by 2050



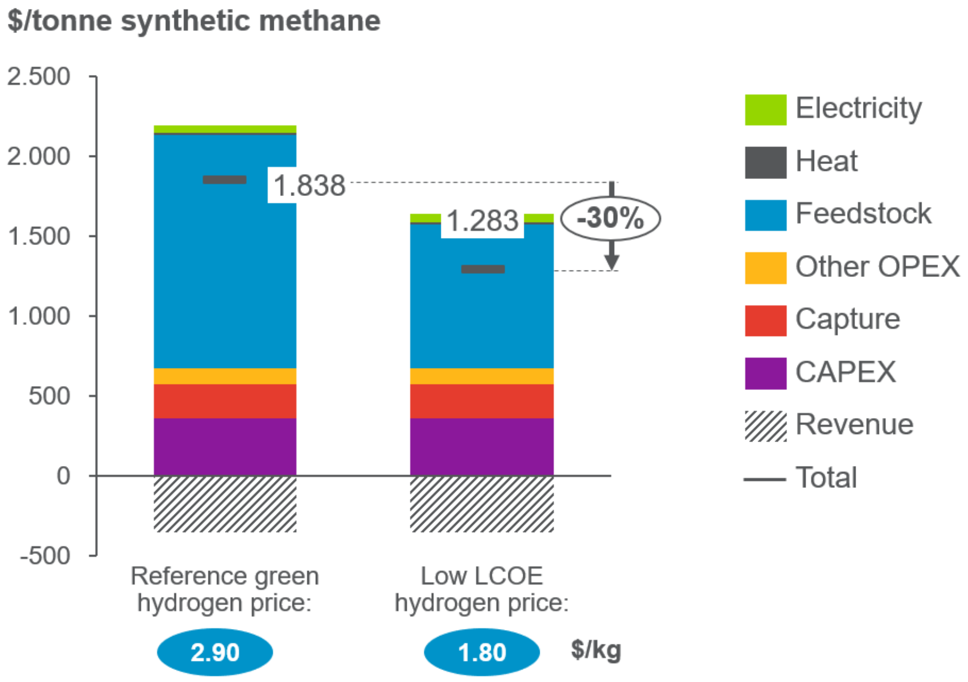
Note: Capture of CO_2 from gas-fired power is assumed. Data labels indicate the total cost when resulting product revenue is taken into account. Technologies projected to have revenue exceeding production cost are not indicated with data labels as the \$/tCO_2 avoided metric fails once it turns negative.

An important cost component for CCU technologies is low-carbon hydrogen feedstock. Figure S-3 shows the contribution lower cost hydrogen might deliver to reduce the production cost of synthetic methane. Other important levers to increase competitiveness for CCU technologies are catalyst development[5] and leveling the playing field with incumbent fossil-derived products.

> **Recommendation 3**: Support the economics of CCUS. Support the cost reduction of renewable power and low-carbon hydrogen using subsidies or development grants. Support research and development (R&D) efforts on promising CCU technologies, specifically around catalyst development. Create equal opportunity in CCUS-relevant markets by incorporating externalities from incumbent production processes in such markets.

Figure S-3. Price Impact of Hydrogen Cost Reduction in Overall Costs of Producing Synthetic Methane from CO_2

Sources: See Section 7.1 for details.



Capturing industrial sources of CO_2 is never 100% effective. Removing higher shares of CO_2 from flue gas requires ever higher amounts of energy. Typically, a capture rate of 90% can be achieved at a reasonable cost, while the remaining 10% of emissions are still emitted.[6] In addition, combusting CCU-derived products (such as fuels) means fossil CO_2 is still being emitted. The CO_2, despite being recycled once, still originates from fossil. These factors are important to recognize when considering New York State's long-term carbon-neutrality target.

In a carbon-neutral system, the remaining uncaptured emissions can be offset by either ensuring 10% of total emissions in the flue gas are of biogenic origin—for example, by cofiring sustainably sourced forms of bioenergy—or by ensuring carbon dioxide removal (CDR) technologies are deployed elsewhere in NYS. Direct air capture (DAC) technology or bioenergy combined with CCS (BECCS) could help to achieve these so-called negative emissions—that is, a situation where more GHGs are sequestered or stored than are released into the atmosphere. In this study, DAC typically remains more expensive compared to capturing industrial effluents, but DAC technology providers claim aggressive cost reduction paths.

> **Recommendation 4**: Support reducing the cost of DAC. DAC is a prerequisite to renewable, CO_2-based fuels if biogenic CO_2 is not available and it can be part of a CDR scheme when combined with permanent CCU technologies or CCS. Investigate supporting R&D or deploying a pilot or demonstration-scale DAC plant in NYS to accelerate DAC technology maturation. This study lists several technology developers that could be sought out to deliver this technology.[7]

Uncertainties around CCUS development and integration in NYS remain—it is a dynamic set of technologies that have advanced considerably in science and R&D over the past years and is expected to continue to do so. Beyond the more direct abatement effects CCUS may deliver (as reported here), certain technologies have the potential to act as a balancing solution in a renewable energy grid or as an energy storage medium.

> **Recommendation 5**: Explore the following areas for further study:
>
> - Comparing the cost and grid value of natural gas-fired power with carbon capture and renewable power with balancing solutions such as integrated storage
> - Potential role for selected CCU technology in fuel-based energy storage
> - Revisit CCUS technology readiness and economics periodically over time

1 How Can CCUS Technologies Help to Meet New York State Decarbonization Targets?

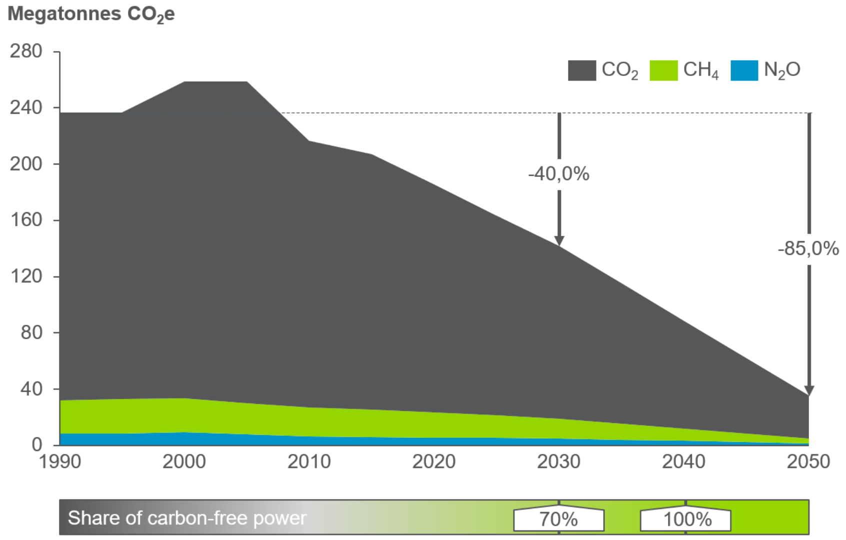
1.1 Introduction and Study Objectives

Carbon dioxide (CO_2) emissions are rising globally at approximately 3% per year, urging countries, jurisdictions, organizations, private investors, and companies to increase efforts and commitments to combat climate change. In response to this crisis, New York State has adopted the Climate Leadership and Community Protection Act (CLCPA), which codifies statewide greenhouse gas (GHG) reduction targets of 40% below 1990 levels by 2030 and 85% by 2050 (Figure 1). The CLCPA also builds on New York's Clean Energy Standard to establish electricity sector targets of 6 gigawatts (GW) of distributed solar photovoltaic (PV) by 2025, 70% renewable generation by 2030, 9 GW of offshore wind by 2035, and 100% carbon free generation by 2040, a nation-leading clean energy agenda. This transformation will not only help in preventing the negative effects of climate change, but it will also create a green economy for NYS that will stimulate innovation and create new jobs. In addition to private corporations, many State agencies including the New York State Energy Research and Development Authority (NYSERDA) and the New York State Department of Environmental Conservation (DEC) are engaged in efforts to meet these targets.

This study aims to identify and analyze suitable carbon capture, utilization, and storage (CCUS)[8] technologies that could be implemented in the State to contribute to GHG reductions and an expanded clean energy workforce. The results of this study will enable NYSERDA to communicate the potential CCUS pathways and technologies that could be implemented in New York State.

Figure 1. Emission Reduction and Clean Energy Targets for New York State

Source of historic data: NYSERDA[9]



1.2 Study’s Relevance: Connection to New York State Policy Context and Innovation Agenda

Policy Context

Governor Andrew M. Cuomo’s State of the State 2019 includes a proposal for the Green New Deal.[10] The Green New Deal is a clean energy and jobs agenda to put NYS on a path to economy-wide carbon neutrality. The Green New Deal would statutorily mandate the State’s power to be 100% carbon-free by 2040. It calls for an emission reduction program that covers all sectors of the economy, including transportation and industry. Systemic changes beyond increasing energy efficiency through using renewables and transforming industrial processes by switching to electrification or bio-based processes are needed to meet these goals. CCUS may be necessary and feasible to further mitigate the consequences of climate change. CCUS may also be interesting from an economic perspective—it could allow emission reductions at comparably low cost or even generate income and create new business models.

Innovation Agenda

Governor Cuomo proposed creating a Carbon-to-Value Innovation Agenda to support the selection of CCUS technologies that use carbon to create new products. Part of this agenda is establishing the CarbonWorks Foundry, a new incubator and accelerator devoted to carbon-to-value technology development focusing on carbon harvesting.

This section addresses how CCUS technologies may contribute to these climate ambitions and the innovation agenda.

1.2.1 How Can CCUS Contribute to New York State Climate Ambitions?

CCUS is an umbrella term for several technologies that share one common trait: they require carbon. To understand where and when in the State’s economy and policy environment CCUS may be necessary and feasible, this study looks at both carbon capture and storage (CCS) and carbon capture and utilization (CCU) technologies to assess their potential in decarbonizing industrial activities and power generation and at what cost.

1.2.1.1 CCS: Capturing and Storing Carbon

Carbon dioxide can be captured from industrial point sources such as a cement plant or a gas-fired power plant or from the atmosphere, in which case the process is called direct air capture (DAC). The captured carbon is then sequestered, or stored, in the subsurface. This is called CCS.

Where CO_2 is industrially sourced, CCS removes much of the produced CO_2 from a plant's exhaust to sequester it permanently. Quantifying the avoided emissions is relatively straightforward: it is the amount of CO_2 captured minus any additional emissions incurred in the capture and storage process.

CCS on industrial facilities or power plants can be put to use to create a carbon neutral State, but it cannot be relied on to fully meet climate targets by itself. Capturing industrial sources of CO_2 is never 100% effective. Typically, a capture rate of 90% can be achieved at a reasonable cost. The remaining 10% of emissions are still emitted.[11] In a carbon-neutral system, this can be offset by either ensuring 10% of total emissions in the flue gas are of biogenic origin—for example, by cofiring sustainably sourced forms of bioenergy—or by ensuring carbon dioxide removal (CDR) technologies[12] are deployed elsewhere in NYS. DAC technology combined with CCS could help to achieve these so-called negative emissions, a situation where more GHGs are sequestered or stored than are released into the atmosphere.

1.2.1.2 CCU: Capturing and Using Carbon

CCU technologies require the same sources of CO_2 as CCS technologies. However, rather than sequestering, these technologies transform this carbon to create useful products. To explain how such technologies may fit a carbon neutral State, the following explains how their abatement potential works.

CCU Abatement: Displacing Emissions from Fossil Fuels and Products

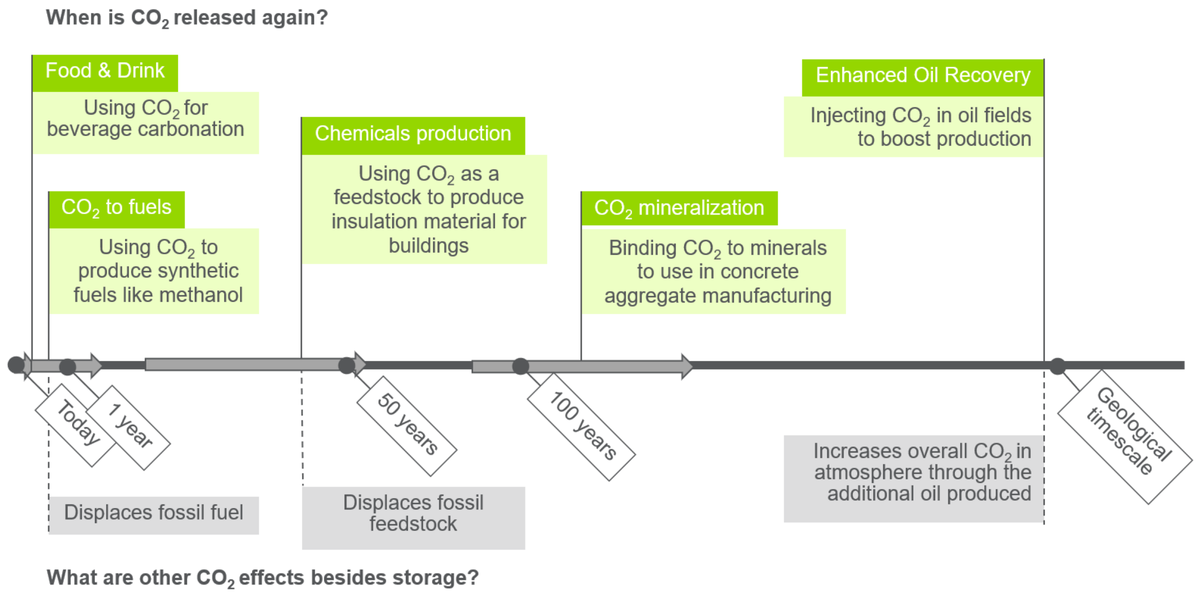
The abatement potential from CCU works altogether differently from CCS. By providing alternative feedstocks to industrial processes, CCU technologies can help keep fossil fuel in the ground. Fossil fuel may also be replaced by synthetic fuel that is derived from recycled carbon. Quantifying avoided emissions for such technologies is more complex compared to CCS as the following must be considered:

- The emissions related to the energy required for the CCU process
- The lifetime of the resulting CO_2-derived product
- The emissions associated with the conventional product that is being displaced
- The potential for circularity in a CCU-based system

All four of these aspects are summarized below. The way these aspects are treated indicates how avoided emissions are calculated in this study.

Figure 2. Product Lifetime and Other Factors that Affect Abatement Potential for CCU Technologies

Source: Guidehouse, created in collaboration with EIT Climate-KIC



The emissions related to the energy needed for the CCU process must be accounted for in quantifying net emissions reduced through CCU. Carbon dioxide is a thermodynamically stable molecule, so its chemistry often needs a lot of energy as reactions will typically be thermodynamically uphill.[13] The energy required may induce CO_2 emissions. When the CO_2 intensity of the required energy is high, it may eliminate any potential climate benefit of the CCU technology. In this study, reference assumptions on emission intensity of energy are adopted from the United States Energy Information Administration's (EIA's) Annual Energy Outlook (AEO) 2019 (appendix A).

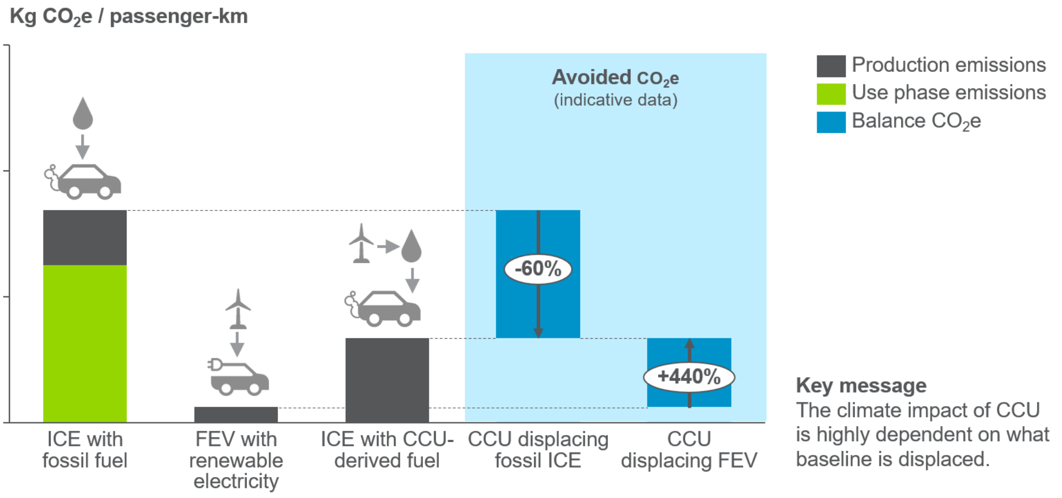
The lifetime of the resulting CO_2-derived product influences the abatement potential of CCU technologies. Products with a long lifetime have a favorable abatement effect, whereas applications which create fuels that are combusted in a few months are typically less favorable (Figure 2). This will be discussed (as relevant) in section 6.2 for selected CCU technologies.

The emissions associated with the conventional product being displaced[14] are key in determining the net abatement potential of CCU technologies. At the bottom of Figure 2, such baseline effects are shown for the examples given. Quantifying the avoided emissions of CCU technologies requires a baseline of emissions to displace. The baseline may change over time and will differ per application, rendering this a complex exercise. The choice of a baseline or reference system will strongly influence the quantification.

Figure 3 explores the effect of an example baseline choice for replacing conventional fossil gasoline in internal combustion engine (ICE) vehicles with CCU-derived synthetic fuel. By using synthetic fuel that was produced through recycling industrial CO_2, there is a displacement of fossil gasoline. The displacement effect can be quantified by accounting for production and combustion (use phase) emissions in both cases, where the latter is equal for both ICE vehicles regardless of how the fuel was produced. Calculated this way, the displacement effect demonstrates a strong reduction of CO_2 emissions as seen in Figure 3. However, the picture is entirely different when full electric vehicles (FEVs) are assumed as the baseline to be replaced by ICEs using synthetic fuel. Because FEVs have a much lower footprint per passenger-kilometer, the climate impact is worsened when using ICE vehicles powered by synthetic fuels.

Figure 3. The Influence of a Baseline on CCU Climate Impact

Source: Guidehouse



Note: Data presented is indicative. Use phase emissions for CCU fuels are assumed zero: CO_2 from DAC or biogenic origin.

Section 6.2 describes potential competing sustainable alternatives for selected CCU technologies. In quantifying avoided emissions, the current incumbent product is used as a baseline; the baseline is assumed 100% fossil fuel. A shifting baseline may have a strong influence on the performance of CCU technologies as the FEV versus ICE example demonstrates.

The potential for circularity in a CCU-based system will affect the overall CO_2 emissions of a CCU technology. The example in Figure 3 also shows that even though there is a climate benefit in the form of a displaced fossil baseline, CO_2 is still being emitted. When considering New York State's long-term carbon-neutrality target, this is important to recognize. The CO_2, despite being recycled once, still has a fossil fuel origin. Ultimately if emitted into the atmosphere, it would mean negative emissions through CDR would need to occur elsewhere in the State to allow for these emissions to take place.

One alternative is to source biogenic, a.k.a. short cycled, CO_2 from industrial processes or to source CO_2 directly from the air through DAC. However, these options are not yet available on a large scale in the short term. Agora Energiewende, a German think tank, published an overview of sustainability aspects in the production of synthetic fuels, where they go as far as to propose only using CO_2 captured from the air or from sustainable biogenic sources to create a closed CO_2 cycle and, if sourcing such CO_2 cannot be achieved, no CO_2 emission reduction is to be recognized.[15]

1.2.2 How Can CCUS Support the Innovation Agenda?

CCUS technologies have the potential to create entirely new industries. To get there, innovation is a necessity. Efforts along the full technology maturation funnel are required—from fundamental materials science to industrial R&D and scaling up through technology pilots and demonstration plants. With these technologies gaining attention around the world, New York State and NYSERDA should aim to identify the strengths they can use to get ahead in what is an increasingly competitive landscape. If successful, CCU could help create jobs in new industries and protect existing jobs by prolonging the license to operate in existing industries. Section 7.1 synthesizes the study's main findings on CCUS and touches on this aspect of job protection and job creation.

Carbon-using technologies fit a vision of a competitive, climate resilient, and circular industry.[16] A future carbon-constrained world will still require carbon in chemicals, construction materials, and other products. CCU may help enable carbon recycling and avoid climate change, achieving the objective of carbon neutrality.

To date, the United States leads the world in the number of patents related to CCS and accounts for most of the top 10 applicants in this category.[17] Maintaining the leading position will likely mean an increasing focus on utilization technologies, specifically on the subset of technologies that have the potential to bring a circular industry closer to reality in sectors where few alternatives exist.

Section 6 describes the technology status and development needs for selected CCU technologies and provides a more detailed assessment of what innovation is required.

1.2.3 How Does CCUS Compete with Other Decarbonization Technologies?

CCS and CCU differ in their ability to curb CO_2 emissions. The magnitude of the role that CCU might play in climate change mitigation is widely believed to be small relative to that played by CCS.[18,19] In specific industries or sectors, CCU may have an important role, however. In identifying how these technologies compete against other decarbonization options, CCS and CCU were treated separately.

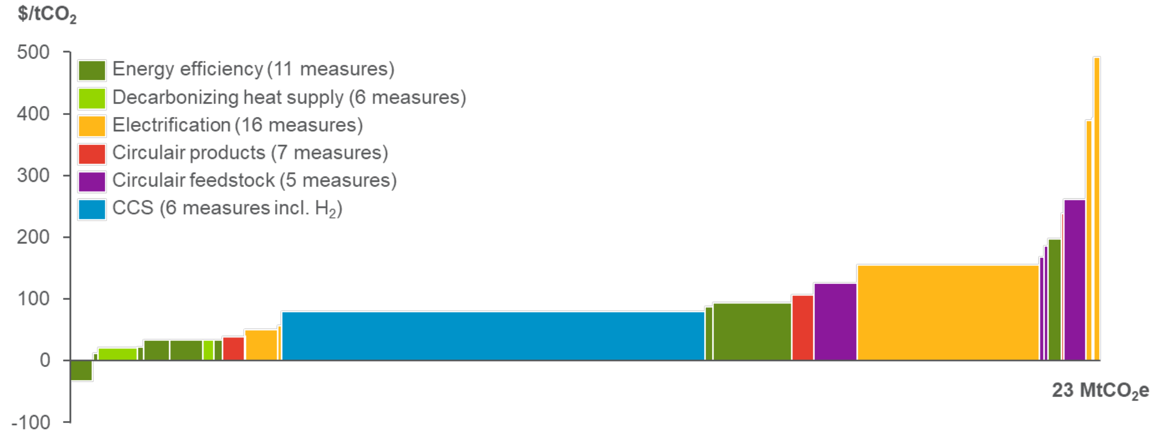
1.2.3.1 CCS is most effective in decarbonizing industrial activities with fewer mature alternatives.

Because capturing industrial effluent CO_2 and storing it underground comes at additional cost and is not necessarily viewed as an attractive GHG mitigation option by society, it needs to be compared to other alternatives to decarbonize a particular activity. As discussed in section 3.1, the largest point source emitters of CO_2 are gas-fired power plants. To produce power, renewable and increasingly affordable alternatives such as wind and solar exist. These are not dispatchable but could be part of a dispatchable power fleet if storage is integrated through, for instance, power-to-gas, pumped hydro, batteries, or mechanical storage technologies. Incidentally, CCU may provide new ways of turning renewable electricity-derived hydrogen into useful products in times of oversupply, essentially balancing the energy grid. Section 6.2.12 shows what this might look like for synthetic methane.

For other industrial activities, such lower cost alternatives are not available yet. In a recent study, Guidehouse compared the industrial decarbonization investment costs needed to meet the Dutch climate target to reduce CO_2 emissions 49% compared to 1990.[20] Figure 4 shows that CCS scores comparatively well economically in meeting this 2030 climate target. This picture may look different for the State. It does show the effectiveness of comparing decarbonization options on a like-for-like basis to select where deploying CCS will be most effective.

Figure 4. Marginal Abatement Cost Curve for Dutch Industry Decarbonization Measures

Source: Adopted from Navigant,[20] converted from Euro.



Key message: CCS measures are on the lower end of the marginal abatement cost curve for Dutch industry to meet its 2030 GHG emissions reduction target

1.2.3.2 CCU is most effective in applications that fit a circular scheme or see few scalable alternatives

The example of powering vehicles in Figure 3 demonstrates that CCU technology should only be deployed in parts of the economy where few economically attractive alternatives exist, even in the longer term. It is possible that CCU may serve to supply carbon through recycling to produce chemical compounds that would otherwise require bio-feedstocks and avoid climate impact. In most transport modes, alternatives to CO_2-derived fuels exist. For aviation, with stringent requirements on gravimetric energy density and limited supply of bio-based fuel, CO_2-based sustainable aviation fuel may have a role to play.[21]

1.2.4 Effectively Deployed CCUS Can Contribute to New York State Climate Targets

As the above considerations show, deciding how to use CCUS needs to be done using a systemic, holistic perspective. Only by understanding alternatives to these technologies (or lack thereof) in a New York-focused context can interested entities such as NYSERDA make an informed decision on where and how to support the development and deployment of CCUS in some form.

CCS shows a larger potential to contribute to achieve climate targets, but CCU holds a larger innovation promise and fits a longer-term circular and green economy. NYS should find its strength and develop and deploy those CCUS technologies that are likely to create the biggest impact.

This study provides an overview of CCUS technologies relevant to New York State, estimates potential and cost, and describes their strengths and weaknesses in the local context. The quantitative, technoeconomic results serve as inputs to a more comprehensive scenario modeling effort by NYSERDA. This model helps explore the role of a broader range of decarbonization options acting on the NYS economy to enable a low carbon 2050 in the State. By establishing this connection, the study provides NYSERDA with the means to evaluate CCUS as part of a bigger set of decarbonization tools that can be considered to meet the State's long-term climate targets.

1.3 Reading Guide

This report starts with an overview of relevant CCUS technologies that could be used to reduce emissions in NYS and provides a concise description of how the most appropriate technologies for further analysis were selected. Section 3 describes the current emissions profile in New York State where relevant for CCUS. Sections 4, 5, and 6 analyze carbon capture (CC) technologies, CCS technologies, and CCU technologies, respectively. All three sections conclude with abatement potential and cost estimates for these technologies. Section 7 takes a broader look at how all three categories of technologies pair up into integrated pathways. Section 8 provides recommendations.

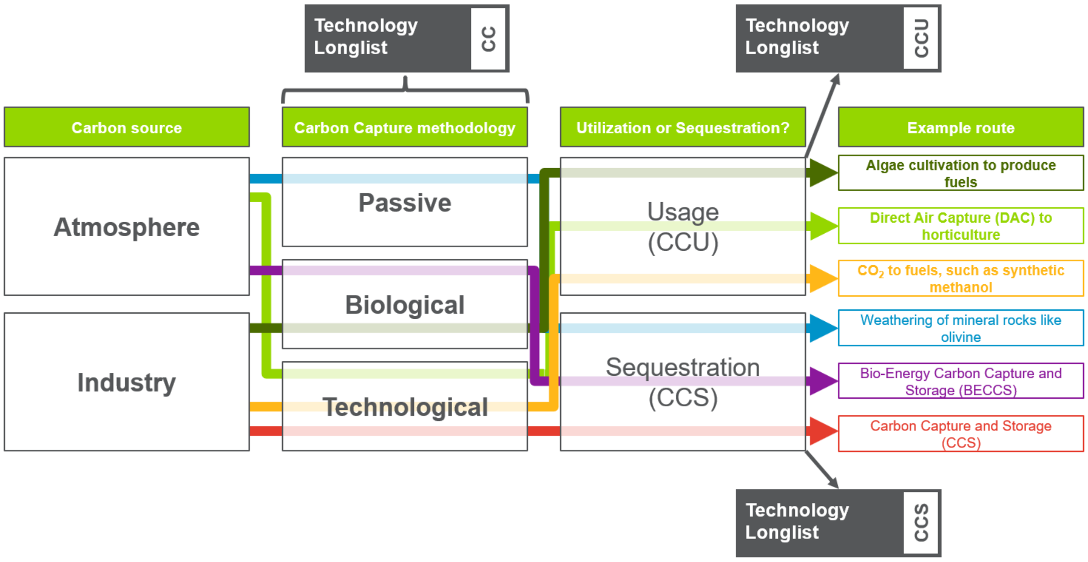
2 Selection of CCUS Technologies for New York State

2.1 Introduction

Numerous technologies allow carbon capture (CC) and subsequent utilization or storage (CCUS). These technologies vary heavily in terms of maturity and relevance for New York State (Figure 5), which makes assessing and describing all technologies in detail not possible as well as not relevant as part of the study.

Figure 5. Selected Routes from CO_2 Sources to CO_2 Sinks

Source: Guidehouse, adopted from a collaboration with EIT Climate-KIC



To provide the most value to NYSERDA and to keep the number of technologies for analysis manageable, shortlisting is required. For this purpose, three comprehensive longlists of technologies for CC, CCS, and CCU, respectively, were developed. The CCU longlist is based on a project[22] funded by the European Commission in 2017 to evaluate the potential of using CO_2 as feedstock for the processing industry, supplemented by previous studies completed by Guidehouse.[23,24] As a next step, a screening and shortlisting approach to develop a shortlist of the most promising CCUS technologies was applied, which were then analyzed in greater detail.

This section describes the longlist of all technologies (section 2.2), the applied shortlisting approach (section 2.3), and the final shortlist of selected CCUS technologies (section 2.4). Sections 4, 5, and 6 focus on the more detailed assessment of the shortlisted technologies only.

2.2 Longlist of Technologies

This section describes all technologies that are part of the longlist for each of the three categories—CC, CCS, and CCU—at a high level. Sources cited in Tables 1–3 and in the description in section 2.1 describe how the longlist was populated to generate a comprehensive overview. The next section details how these technologies were evaluated, for which a larger number of sources were leveraged. These are indicated throughout the text.

Table 1. Longlist of Carbon Capture Technologies

Sources: Global CCS Institute (CCSI), IEA Greenhouse Gas (IEAGHG), John Wood Group, Navigant (now Guidehouse) analysis

Technology	Description	Sub-technology
Post-combustion	Post-combustion involves the capture of CO_2 from the flue gas stream exiting the combustion process. This mode of capture is applicable for most existing power and chemical plants. Since air is used for combustion, most of the flue gas is nitrogen, and CO_2 concentrations are low in the emissions.	Amine-based solvent
		Advanced amine-based solvent (hindered amines)
		Amino-acid salt solvent
		Chilled ammonia process
		Precipitating solvent (K_2CO_3)
		Biphasic solvent
		Catalyzed enhanced solvent (enzyme)
		Ionic liquid
		Temperature swing adsorption (TSA)
		Pressure swing adsorption (PSA)
		Chemical looping (calcium looping)
		Membranes
		Cryogenic distillation
Pre-combustion	Pre-combustion involves gasification of a fossil fuel via oxygen-enriched air to obtain a mixture of CO and H_2. This mixture is converted to a CO_2-H_2 mixture via the water gas shift reaction after which CO_2 is captured.	Physical solvent
		Ionic liquid
		TSA
		PSA
		Sorption enhanced water gas shift
		Sorption enhanced reforming
		Water gas shift reactor
		Membrane
		Cryogenic separation
Oxy-fuel combustion	Oxy-fuel combustion uses enriched oxygen instead of air for the combustion. The flue gas from such a process has minimal nitrogen content, so this CO_2 capture technology involves mere condensation of water from the flue gas.	Atmospheric pressure oxy-combustion
		Ion transport membranes
		Oxygen transport membranes
		Pressurized oxy-combustion
		Oxy-fired circulating fluid bed boiler (coal)
		Oxy-fired pulverized coal boiler
		Oxy-combustion flue gas purification units
		Oxy-fired gas turbine cycles (Allam cycle)
		Oxy-fired gas turbine cycles (CES cycle)
		Oxy-fired gas turbine cycles (Others)
		Chemical looping combustion
Direct air capture	CO_2 is captured from ambient air and can subsequently be either stored underground or used to produce synthetic hydrocarbons. An advantage of this method is that it can be located anywhere and limits the need for the transport of CO_2. Because the concentration of CO_2 in ambient air is low, the energy and land requirements can be considerable.	Amine-based sorbent
		Porous solid-supported amines
		Potassium hydroxide solvent

Table 2. Longlist of Carbon Capture Storage Formations

Sources: Carbon Storage Atlas, Guidehouse analysis

Formation	Description
Depleted oil and gas fields	Depleted hydrocarbon reservoirs that are no longer operational are considered an appropriate location for CO_2 storage. In the depleted field, the CO_2 would occupy some of the pore space that was previously occupied by oil or natural gas. The characteristics of these fields are well-known due to previous exploration and production, and infrastructure such as wells are sometimes still in place, which can reduce infrastructure development cost.
Saline formations	These are geological formations that consist of water-permeable rocks saturated with salt water, called brine. CO_2 can be injected in these sedimentary rocks. CO_2 chemically reacts with salt water to form precipitates that cannot not release the CO_2 to the surface and the atmosphere.
Shale formations	Organic-rich shales can also be used as a reservoir for CO_2 storage. Since through an exchange process between CO_2 and methane (CH_4), additional natural gas production can be realized in natural gas bearing shale formations. This can improve the business case of CO_2 storage.[25]
Enhanced oil recovery (EOR)	CO_2 EOR has been done for decades already in the U.S. Especially in the Permian Basin where natural CO_2 is found, CO_2 has been used to produce oil that was previously economically unrecoverable. In the process, part of the CO_2 remains permanently stored in the oil reservoir.
Unmineable coal seams	Some coal formations are too deep or have other unfavorable geological conditions that prohibit the economic recovery of coal. The extraction of methane gas entrapped in unmineable coal seams can improve this business case and can be done with coal bed methane (CBM) recovery methods. After recovery, the coal seams can be used for CO_2 storage. The injection of CO_2 into a coal seam also releases additional methane, which is called enhanced CBM (ECBM). ECBM, like EOR, is sometimes considered a CO_2 utilization technology, but has fewer commercial developments to date. Sorption of CO_2 to coal adversely effects permeability of the rock, which in coals seams is usually already low.

Table 3. Longlist of Carbon Capture Utilization Technologies

Sources: CarbonNext, Guidehouse analysis

Category	Technology	Description
CO_2 to fuels	Algae cultivation	Algae cultivation using nutrient-rich, typically saline or brackish water in open ponds or closed bioreactors, where CO_2 is bubbled through to accelerate biomass production rates/yield. The lipid (fatty) fraction of the biomass can be used to make biodiesel and other liquid fuel substitutes. Microalgal-derived biofuels are currently developed both through heterotrophic cultivation and phototrophic growth. Non-fuel applications for algae include wastewater remediation, high-value pharmaceuticals, cosmetics, and chemicals.
	Hydrocarbons excreting microorganisms (helioculture)	The cultivation of photosynthetic microorganisms that are circulated in a solution of micronutrients, brackish water and CO_2, which directly excrete hydrocarbons that can be used as fossil fuel substitutes (e.g., ethanol, diesel). The process uses unconcentrated solar energy.
	Formic acid as a fuel	Electrochemical reduction of CO_2 (ERC) combines captured CO_2 and water to produce formic acid (HCOOH) and O_2. The formic acid is used as a hydrogen carrier in fuel cells (for use in transportation, CHP units, etc.); hydrogen is released from the liquid formic acid as required when an aqueous solution of formic acid is exposed to an appropriate catalyst.

Table 3 continued

Category	Technology	Description
CO_2 to fuels	Synthetic diesel	Syngas produced from CO_2 and H_2 undergoes Fischer-Tropsch (FT) reactions to produce linear waxes. Using more H_2, hydrocracking converts to diesel.
	Synthetic kerosene	Gas fermentation of syngas produced from CO_2 by anaerobic bacteria to produce ethanol. This then undergoes oligomerization and, using additional H_2, dehydration/hydrogenation to produce hydrocarbons suitable for use as kerosene-type aviation fuel (LanzaTech–Virgin Atlantic Process).
	Synthetic methane	In an exothermal reaction between hydrogen and carbon dioxide, methane and water are produced. The reaction is typically carried out in the presence of a catalyst, usually nickel.
	Synthetic methanol	The electrolysis of water produces H_2 and O_2, which is combined with CO_2 and compressed and reacted over a metal/metal oxide catalyst to produce methanol and water. The separated methanol can be blended with different grades of gasoline for use as a transport fuel.
Chemical production	Acetic acid	Acetic acid can be produced by the oxidation of methane with CO_2. Current catalysts show selectivity to acetic acid so the development of novel catalysts with higher yields and selectivity is needed. Another route is being explored which involves anaerobic gas fermenting microorganisms that convert CO_2 and H_2 mixture to acetic acid. LanzaTech, in collaboration with the Malaysian oil company Petronas, are developing this technology.
	Acrylic acid	The process involves the reaction of ethylene with CO_2 in the presence of a catalyst. BASF and Dow Chemicals have reported progress on the synthesis of acrylic acid using this route.
	Benzoic acid	Aromatics (e.g., benzene) react with CO_2 to form benzoic acid. The process is currently being tested at lab scale. Using Kolbe-Schmitt reaction, p-hydroxybenzoic acid is produced commercially. The reaction utilizes CO_2 to make potassium phenolate which yields p-hydroxybenzoic acid.
	Butyric acid	It can be produced through gas fermentation of CO_2 by anaerobic bacteria. LanzaTech are leading this development.
	Formic acid	Electrochemical reduction of CO_2 (ERC) combines captured CO_2 and water to produce formic acid (HCOOH) and O_2.
	Oxalic acid	Electrochemical reduction of CO_2 combines captured CO_2 and hydrogen to produce oxalic acid.
	Salicylic acid	In this process, sodium phenoxide is carboxylated with CO_2 in the Kolbe-Schmidt reaction to form salicylic acid. Salicylic acid is currently produced commercially utilizing CO_2.
	Benzene	Methanol can be converted to a range of aromatic compounds simultaneously using a zeolite catalyst. The process is developed by Mobil. High-conversion rates of 95%–100% are achievable with an aromatic(s) yield of 60%–70% of which 80% are BTX, resulting in a total BTX yield of around 56%. The methanol production is the CO_2 utilizing step, see synthetic methanol for more information on this pathway.
	Toluene	
	Xylene	
	Ethylene	First dehydration of two methanol molecules form one molecule of dimethyl ether (DME), prior to conversion to olefins. Referred to as the methanol to olefin (MTO) process. Catalysts include silico-aluminophosphate (SAPO-34 or MTO100) or zeolite systems. Several MTO technologies are licensed; UOP LLC & Norsk Hydro; ExxonMobil; Lurgi & Statoil; SYN Energy Technology Co. & Lummus Technology. MTO has started to enter commercialization with several plants built in China. The methanol production is the CO_2 utilizing step (see synthetic methanol for more information on this pathway).
	Propylene	

Table 3 continued

Category	Technology	Description
Chemical production	Ethylene oxide	The carboxylation[26] of ethylene results in ethylene oxide. The reaction is mediated by metal oxide catalysts. Ethylene oxide is mainly used in the production of ethylene glycol. Currently, it is commercially produced by the direct oxidation of ethylene.
	Ethylene glycol, Propylene glycol	Electrochemical reduction of CO_2 can result in polyols. A highly efficient catalyst is needed that can yield glycols without producing unwanted by-products.
	Sodium bicarbonate	The CO_2 gas stream is passed through an aqueous solution of sodium hydroxide to produce sodium carbonate. This follows bicarbonation of sodium carbonate to sodium bicarbonate.
	Ethylene carbonate	It is commercially produced using CO_2. The process involves carbonation of ethylene (or propylene) oxide to ethylene (or propylene) carbonate.
	Dimethyl carbonate	Carboxylation of alcohols (e.g., methanol) produce dimethyl carbonate. The two most studied catalytic systems for these reactions are tin oxides and ceria-zirconia oxides.
	Polyethylene carbonate	The CO_2 can be made to react with an epoxide such as ethylene (or propylene) oxide resulting in polyethylene (or polypropylene) carbonate. These low-molecular weight polycarbonates can be used as replacements for polyether polyols which are a component of polyurethanes. These polycarbonates also find their applications in ceramics, adhesives, biomedical as well as packaging materials.
	Polypropylene carbonate	
	Ammonium carbamate	The inorganic compound ammonium carbamate is produced as an intermediate in the production of urea when CO_2 reacts with ammonia. This production process using CO_2 is the current commercial route to making urea.
	Methyl carbamate	The organic carbamates are generally synthesized by reacting an alcohol (which in case of methyl carbamate can be methanol) with urea. Both methanol and urea can be produced using CO_2. Methyl carbamate is produced by reacting methanol with urea using boron trifluoride or cupric acetate as a catalyst. Methyl carbamate is used as a reactive intermediate in textile and polymer industries.
	Ethane diol dicarbamate	Dicarbamates (ethane diol dicarbamate) are formed by the reaction of CO_2 with diamines (ethylene diamine) and an alcohol (methanol) in the presence of a basic catalyst. They are also formed by the reaction of CO_2 with diamines in the presence of a basic catalyst and the subsequent reaction of the product with an organic halide. The potential market for dicarbamates is large as it relates to the substitution of diisocyanates which are currently used in the manufacturing of polyurethanes.
	Polyurethane	Conventionally, polyurethane is produced by reacting an isocyanate (R-N=C=O) with a polyol (HO-ROH) to form polymer chains of these two monomers which are joined together using carbamate links. Polyurethanes can also be produced using CO_2 based polyols such as polyether polycarbonate polyol which is reacted with isocyanate to produce flexible polyurethane foam (Covestro process).

Table 3 continued

Category	Technology	Description
Chemical production	DME	DME is conventionally produced by condensing two methanol molecules. For this process to be a CCU process, methanol needs to be produced via a CO_2-based route. However, DME can also be produced by dry reforming of methane and CO_2 to make syngas. This syngas is reacted with more H_2 over a Cu-ZnO-Al_2O_3/zeolite catalyst in a FT type reaction to make DME. In an alternative lab development, DME can also be produced in a single-step CO_2 hydrogenation process using a bifunctional catalyst which produces methanol and causes its dehydration in the same reactor.
	Formaldehyde	Formaldehyde can be synthesized from CO_2 via hydrogenation. Hydrogenation results in formic acid which is an intermediary that undergoes reduction to formaldehyde.
CO_2 mineralization	Carbonate mineralization - natural minerals	Carbon mineralization is the conversion of CO_2 to solid inorganic carbonates using chemical reactions. Mineral carbonation occurs naturally and is a slow process. For carbonate mineralization to be a viable method to capture and reuse CO_2 from anthropogenic sources such as coal-fired power plants, this process must be accelerated considerably. The carbonates that are produced are stable over long timescales and can be used for construction, mine reclamation or disposed of without the need for monitoring or the concern of potential CO_2 leaks that could pose safety or environmental risks.
	Carbonate mineralization - industrial waste streams	Similar as above but applied to industrial waste streams such as fly ash, bauxite residue, and steel slag.
	Concrete curing	Concrete curing using CO_2 is reported to achieve superior strength and hardness compared to conventional curing. This happens after the concrete has been placed. Cement requires a moist, controlled environment to gain strength and harden fully. The cement paste hardens over time, initially setting and becoming rigid though weak and gaining in strength in the weeks following. Instead of using the traditional energy intensive steam curing methods this alternative method using CO_2 can be used. Commercial applications on a relatively moderate scale have been reported by Solidia Technology and CarbonCure.
Enhanced commodity production	Methanol yield boosting	The yield of methanol from conventional methanol synthesis can be increased (estimated by up to 20%) by the injection of additional CO_2 upstream of the methanol reformer.
	EOR	The injection of CO_2 into partly depleted oil reservoirs to boost production. Part of the CO_2 stays in the reservoir, the remainder is produced with the oil and re-injected.
	Enhanced coal bed methane (CBM) recovery	The injection of CO_2 into coal seams to produce methane. Part of the CO_2 stays behind.
	Supercritical CO_2 power cycles	The use of supercritical CO_2 in closed loop power cycles as a replacement for steam (e.g., in fossil fuel-fired or nuclear power plants). Benefits include increased electricity conversion efficiency and less thermal fatigue and corrosion.
	Urea yield boosting	Urea yield boosting is a well-known application of CO_2 and is used to produce fertilizers (urea granules and other fertilizer derivatives).

Table 3 continued

Category	Technology	Description
Food and drink	Beverage carbonation	Captured (food-grade) CO_2 may be utilized directly in food-related applications, such as beverages. This replaces the use of industrial CO_2.
	Food freezing, chilling, and packaging	CO_2 may be utilized directly in food-related applications, such as freezing food using dry ice. In packaging applications, CO_2 is used in modified atmosphere packaging with products such as cheese, poultry, snacks, produce, and red meat, or in controlled atmosphere packaging, where food products are packaged in an atmosphere designed to extend shelf life. This replaces the use of industrial CO_2 (see also refrigerant gas in the other industrial applications category).
	Horticulture (glasshouses)	Growth rates of several plant species increase with elevated CO_2 levels if all other nutrients, water, and sunlight are available in abundance. Greenhouses often employ gas engines or buy technical CO_2. In case of a gas engine, a CO_2 vaporizer collects CO_2 from the flue gases and distributes it inside the greenhouse via diffusers. External CO_2 supply reduces energy costs for greenhouse farmers.
Other industrial applications	Metal working	The mold for CO_2 casting is made of a mixture of sand and liquid silicate binder which is hardened by passing CO_2 gas over the mold. The equipment of the molding process includes CO_2 cylinder, regulator, hoses, and handheld applicator gun or nozzle. CO_2 molding delivers great accuracy in production. CO_2 is also used in welding as a shrouding gas to prevent oxidation of the weld metal.
	Refrigerant gas	CO_2 is used as the working fluid in a refrigeration plant, particularly for larger industrial air conditioning and refrigeration systems. It replaces more toxic refrigerant gases that also have significantly greater global warming potential.
	Electronics	Printed circuit board manufacture uses small quantities of CO_2 in niche applications predominantly as a cleaning fluid.
	Water treatment and pH control	CO_2 is used for remineralization of water following reverse osmosis and for pH control (reduction). CO_2 is used for pH control in swimming pools.
	Supercritical CO_2	Supercritical CO_2 can be used in a wide range of applications. These include coffee decaffeination, extraction of aromas or flavors and plant substances, pharmaceutical processes, and as a solvent in dry cleaning. Benefits of using CO_2 compared to other chemicals traditionally used are that it is inert and non-toxic. Furthermore, because of its low-critical temperature and moderate pressure requirements, natural substances can be treated particularly gently.

2.3 Technology Shortlisting Approach

The shortlisting approach used in this study was designed to help select the most relevant and promising technologies for New York State by screening the longlist of technologies on several key criteria. The criteria applied to the different technologies include technology maturity, global and domestic or local (State) production of certain products, and the presence of geological formations in New York State. The team selected these criteria in collaboration with NYSERDA because the criteria provides a good view on relevance for the State. In addition, the information and data required to assess these criteria is available, and the criteria allows the team to sufficiently differentiate to select the most relevant technologies.

Table 4 describes the selected criteria and shows the relevant technologies and application.

Table 4. CCUS Technology Shortlisting Criteria

Sources: market research, CarbonNext, Carbon Storage Atlas, Guidehouse analysis

Criterion	Description	Applied to
Global product demand (in tCO_2/yr)	Most CO_2-based products are produced for a global market. The existence of a large global market is an indicator for how much CO_2 could potentially be used through a CCU route and how much of that demand could be met by NYS.	CCU
Technology readiness level (in TRL 1-9)	An indicator for the maturity of the CCUS technology and whether it will realistically play a role in NYS in the coming decades. For CC, the top five most mature technologies were selected. For CCU, two buckets were created: TRL ≥6 or TRL <6 to ensure that mature technologies were selected as well as promising technologies that are still in need of innovation and development where NYS could play a role.	CC CCU
Local production demand (yes or no)	The existence of local production of a reference product indicates that there are companies present where the CCU technology could be trialed or implemented and that there is infrastructure available to handle and trade the product. U.S. production data was used primarily. The production of the compound in NYS was assessed qualitatively only.	CCU
U.S. product demand (in $MtCO_2$/yr)	Top five applications by U.S. demand were selected for each TRL <6 and TRL ≥6 groups of technologies selected to ensure relevance.	CCU
Geology presence in NYS (yes or no)	Only the geological formations that are available in NYS are selected.	CCS

The resulting technology shortlist was adjusted in consultation with NYSERDA to absorb more qualitative considerations and ensure the most relevant technologies were included in the final shortlist.

The process is outlined in Figure 6 for all CCUS technologies. For CC and CCS only one criterion was used to shortlist the most relevant technologies. For CCU, more criteria were applied subsequently to generate the list of the most promising technologies.

Figure 6. CCUS Technology Shortlisting Process

Source: Guidehouse

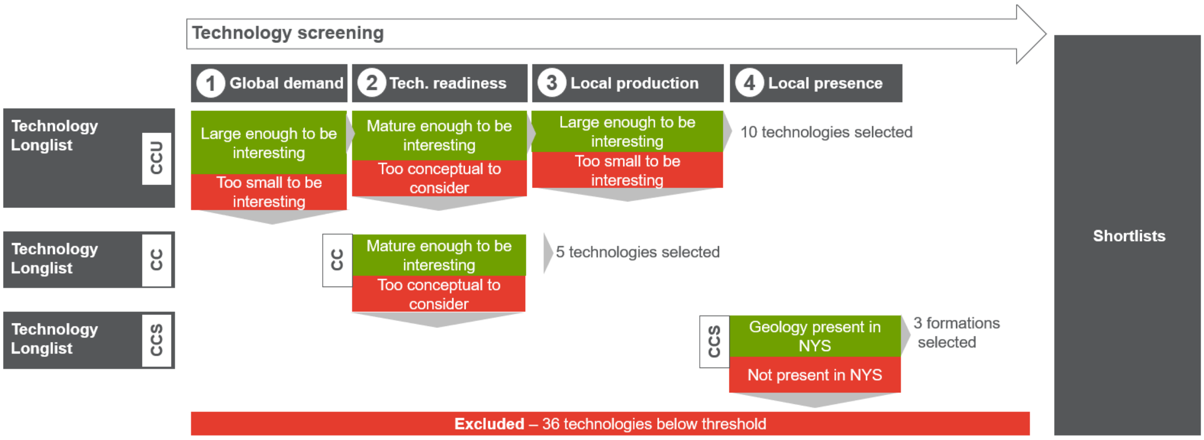
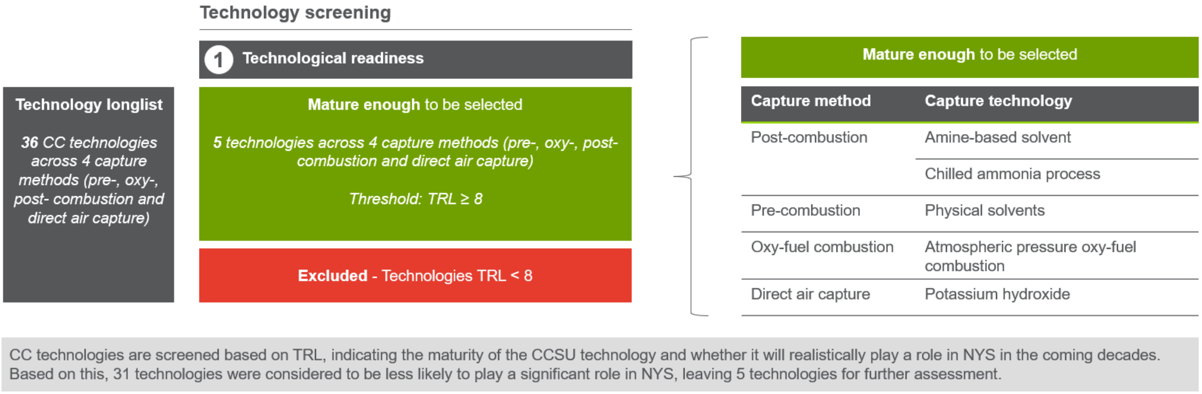


Figure 7 shows the process to select relevant capture technologies for New York State. By applying a technology maturity threshold, five capture technologies were shortlisted. Within the DAC capture technologies, supported amines were investigated as well, but given certain data limitations, the level of detail provided for this technology was not to the same level as the other technologies. Section 4.3.5 provides an explainer box with further analysis.

Figure 7. Technology Screening of Carbon Capture Technologies

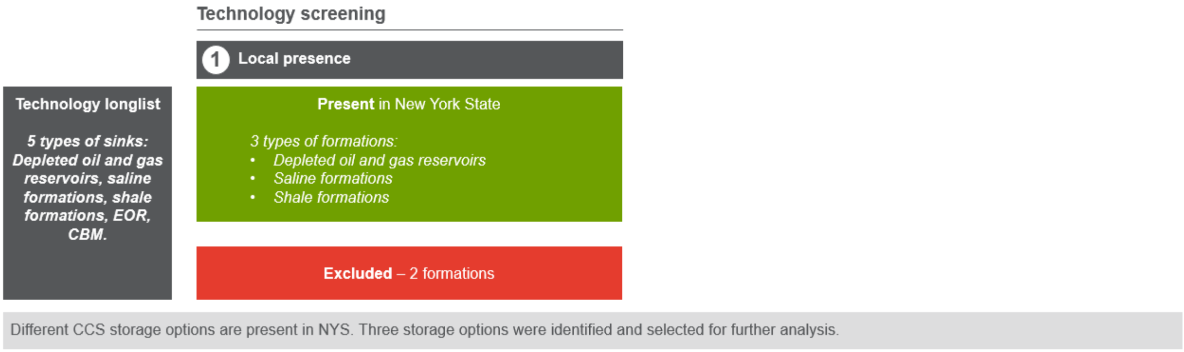


Capture method	Capture technology
Post-combustion	Amine-based solvent
	Chilled ammonia process
Pre-combustion	Physical solvents
Oxy-fuel combustion	Atmospheric pressure oxy-fuel combustion
Direct air capture	Potassium hydroxide

CC technologies are screened based on TRL, indicating the maturity of the CCSU technology and whether it will realistically play a role in NYS in the coming decades. Based on this, 31 technologies were considered to be less likely to play a significant role in NYS, leaving 5 technologies for further assessment.

Figure 8 shows the process to select relevant geological storage options for New York State. By identifying which formations are present, the shortlist was constructed.

Figure 8. Technology Screening of Carbon Capture Storage Formations

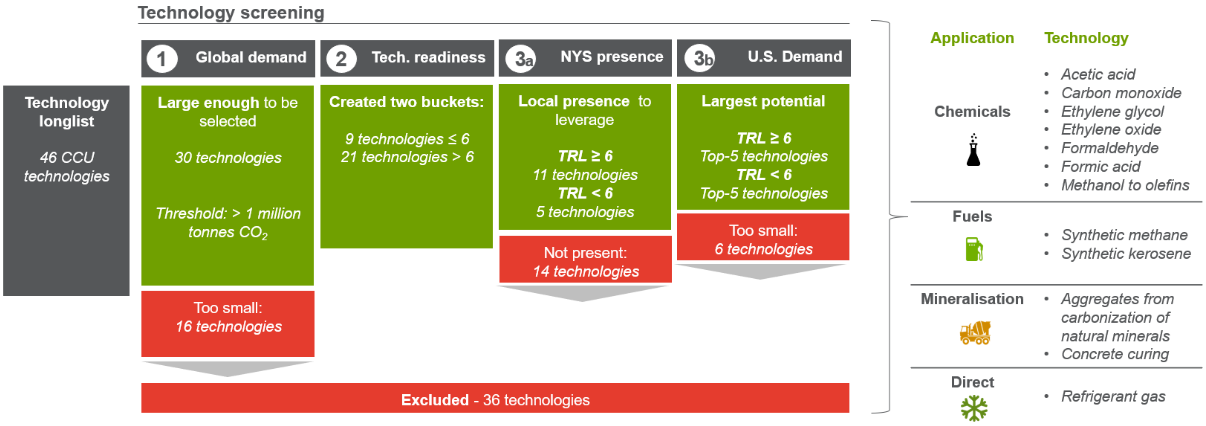


Different CCS storage options are present in NYS. Three storage options were identified and selected for further analysis.

Figure 9 shows the process used to select relevant utilization technologies for NYS. First, the global demand to eliminate technologies were estimated that, even on a global scale, are likely to not deliver sufficient CO_2 demand for these technologies to be interesting from an end-of-pipe abatement solution point of view. The second step did not eliminate any technologies but instead categorized all technologies in one of two buckets: one for relatively mature technologies and the other for technologies that will require considerable research and development to mature. For these two buckets, a local presence of existing producers was confirmed, who sell the same product, produced in the traditional way. Where no producers were identified, the technology was omitted from further analysis. For the remaining technologies, the top 10 technologies were selected in terms of their largest potential to serve the U.S. market. Finally, in consultation with NYSERDA, two technologies originally identified as shortlisted technologies based on the process outlined in Figure 8 were replaced with four different technologies. These technologies were added to align better with New York State’s innovation agenda and climate ambitions:

- Formic acid to test if this could fit the potential local development of battery technology.
- Refrigerant gas to replace existing industrial gases that are known for their significant global warming potential, such as fluorinated gas (F-gases) .
- Concrete curing to be applied in existing cement and concrete industries as it is a relatively mature technology reported to reduce cement consumption in concrete due to the strengthening effect of CO_2-based curing.
- Synthetic kerosene to replace fossil kerosene in aviation. Airports in the State are large consumers of aviation fuels for which limited sustainable alternatives exist compared to other forms of transport.

Figure 9. Technology Screening of Carbon Capture Utilization Technologies



The first screening filtered out the **16** technologies that are not significant in terms of the volume of a global market which could potentially absorb CCU products. The second and third screening filtered out **14** applications that are less likely to play a significant role due to less developed technology. The final screening filtered out **6** applications for which insufficient domestic demand exists. **2** applications were added at a later stage from the excluded set for reasons explained in the main text.

2.4 Shortlisted Technologies

The selected final shortlists of technologies representing the most relevant set of technologies for New York State are described in section 2.3. This is no guarantee, however, that the selected technologies will materialize locally or even globally. It may be that none or only a subset of selected technologies will be deployed locally. That said, it is still valuable and interesting to consider the selected technologies in greater detail because, besides the merit to consider the selected technologies themselves, the analysis can be used to draw conclusions that are likely to be robust—even if not all technologies will play a role in New York State.

The final selection represents several technologies, which based on the screening analysis followed in the study, have a reasonable chance of materializing and are, therefore, explored further in sections 4, 5, and 6.

Table 5. Shortlisted Carbon Capture Utilization and Storage Technologies for New York State

Source: Guidehouse

Selected CC technologies	Selected CCS formations	Selected CCU technologies
Pre-combustion—physical solvents	Depleted oil and gas reservoirs	Acetic acid
Oxy-fuel combustion at atmospheric pressure	Saline aquifers	Carbon monoxide
Post-combustion—amine-based solvent	Shale formations	Ethylene glycol
Post-combustion—chilled ammonia process		Ethylene oxide
DAC—potassium hydroxide solvent		Formaldehyde
		Formic acid
		MTO
		Synthetic methane
		Synthetic kerosene
		Aggregates from carbonization of natural minerals
		Concrete curing
		Refrigerant gas

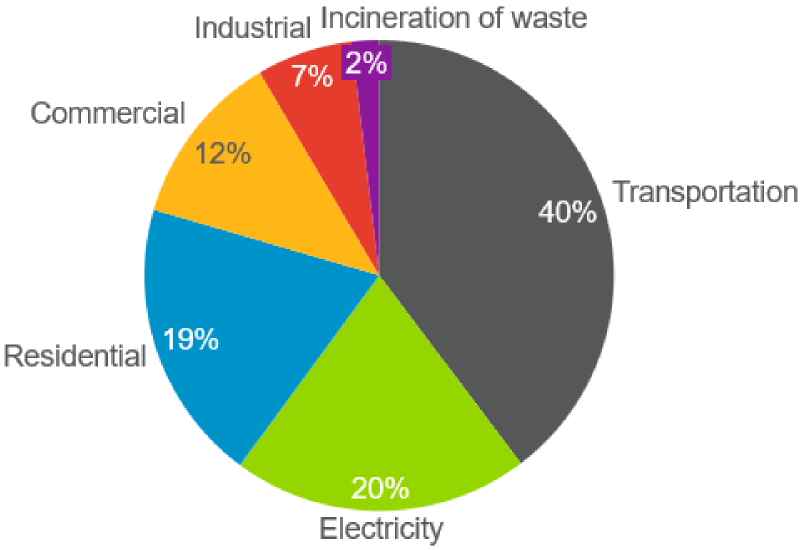
3 Carbon Dioxide Emissions in New York State Today

3.1 GHG Emissions in New York State

To understand the potential scale required for the CCUS technologies in this study and to quantify the cost of capture, this section provides an overview of annual emissions of all stationary point sources in the State. CCUS technologies are only relevant for relatively large stationary point sources. In NYS, these types of sources are mostly found in the electricity, industrial, and incineration of waste sectors. Of the total CO_2 emissions in NYS (Figure 10), these specific categories of CO_2 emissions are relatively small (in 2015, 20%, 7%, and 2%, respectively[27]). Smaller sources and mobile sources (emissions from transport) are not in scope for CCUS technologies and this study.

Figure 10. Share of CO_2 Emissions in New York State in 2015

Source: New York State Greenhouse Gas Inventory



To obtain an exhaustive list of large stationary CO_2 point sources in NYS two databases have been utilized:

1. The New York State Emission Inventory,[28] which was used as the leading[29] data source
2. The EPA GHG emission database,[30] which was used as a supporting data source

The emissions of the majority of larger stationary CO_2 sources were obtained from the New York State Emission Inventory (2017 data). A preselection was made to select only the large CO_2 emitters, as large emitters are the most relevant sources for significant CCS or CCU application. A cut-off of 220,000[31] tonnes CO_2 emissions was used to select the larger CO_2 emitters.

For some specific facilities that do not meet the cut-off of 220,000 tonnes CO_2 emissions, the CO_2 concentration in the flue gases is relatively high (>35%[32]), rendering these facilities more cost-effective when applied to a CCUS technology. In New York State, these facilities are ethanol and hydrogen production plants. As these specific facilities were not in the New York State Emission Inventory, these have been added from the United States Environmental Protection Agency's (EPA) emissions database.

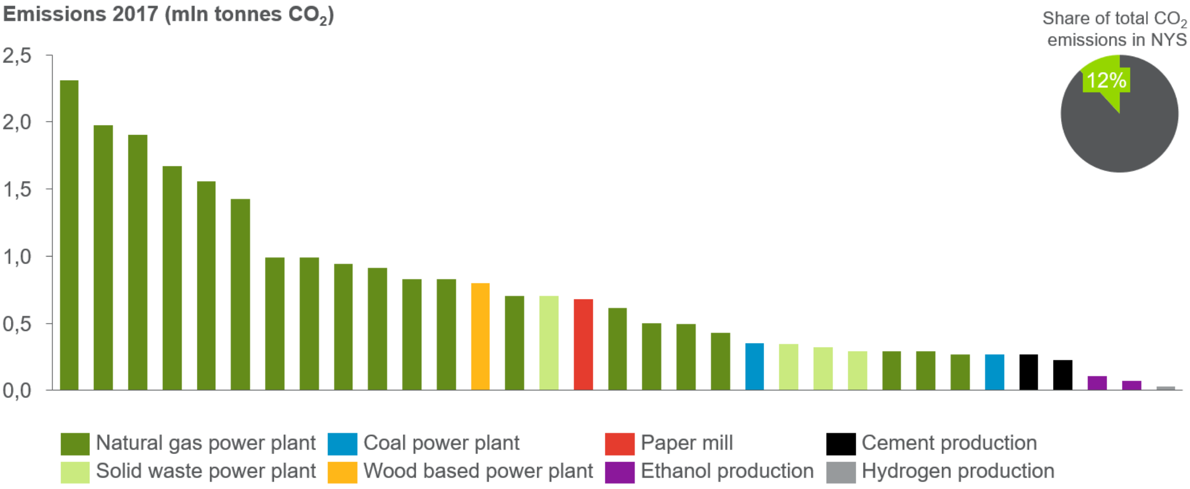
Based on the above-mentioned selection criteria, 33 stationary CO_2 sources were within scope of the analysis.

3.2 Carbon Dioxide Emissions Overview: Stationary Point Sources

The emission sources in scope of the analysis range between approximately 2.3 million tonnes and 27,000 tonnes. Most of the sources and total emissions are related to natural gas-fired power plants.

Figure 11. Overview of Largest CO_2 Point Sources in New York State by Type of Facility

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



The presented data in Figure 11 is from 2017. The CO_2 emissions from the largest point sources shown are not expected to remain stable and, following policy ambitions, should decline. For every relevant sector in the sections that follow, a brief outlook shows how these emissions might change toward 2030 and 2050.

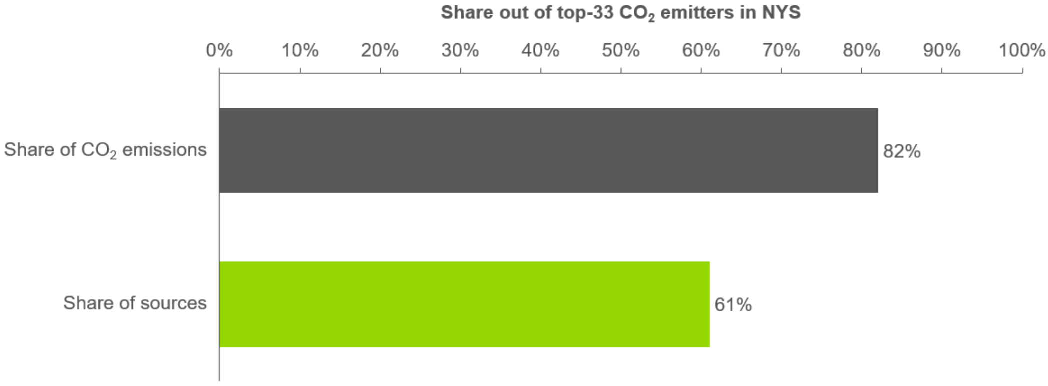
3.2.1 Natural Gas-Fired Power

Natural gas-fired power plants have both by far the highest share of total emissions and the highest number of total sources in the analysis. The total emissions of natural gas-fired power plants in scope is approximately 20 million tonnes CO_2.

Figure 12 shows the share of natural gas power plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 12. Share of Natural Gas-Fired Power Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



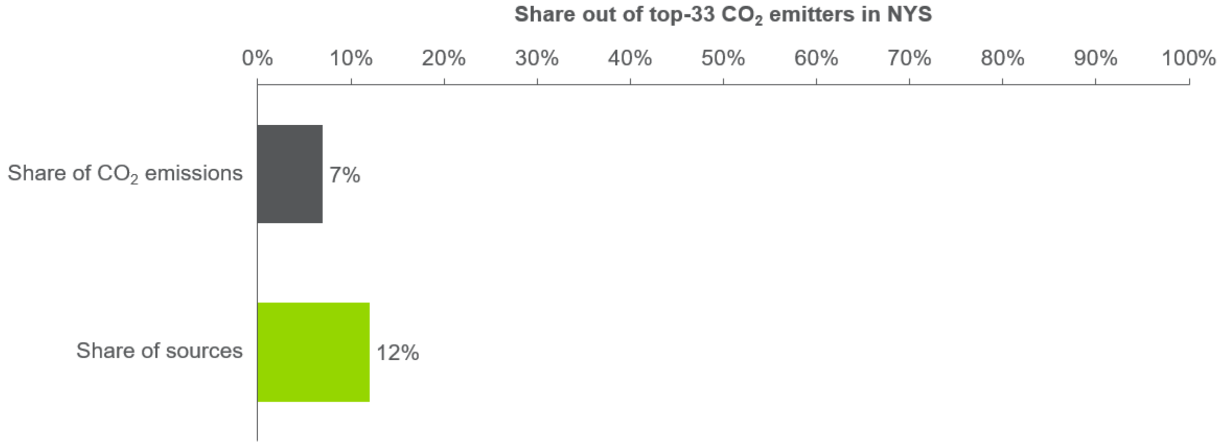
Natural gas-fired power is considered one of the least CO_2-emitting fossil power sources per unit of power produced. However, in an emission-constrained world the role of fossil energy for power is limited, including that of natural gas. The International Energy Agency (IEA) foresees a stable U.S.-wide trend when it comes to natural gas-fired power generation in a 2°C scenario but sees power output decrease after 2035, although installed capacity remains stable. Natural gas power with CCS also overtakes unabated natural gas power in the 2040s. Such developments are in line with a zero-emission power sector by 2050.

3.2.2 Solid Waste-Fired Power

Of all large stationary CO_2 emitters in scope of the analysis, the second largest emitter type is solid waste-fired power plants. These power plants produce in total 1.66 million tonnes CO_2. Figure 13 shows the share of solid waste-fired power plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 13. Share of Solid Waste-Fired Power Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis

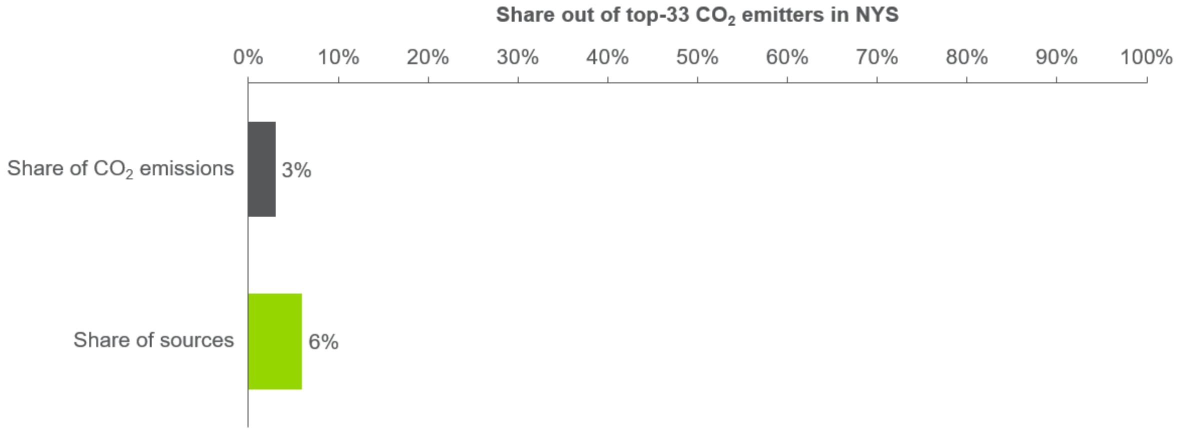


3.2.3 Coal-Fired Power

Coal-fired power plants are a significantly smaller part of New York State power generation both in terms of total emissions and the number of plants in scope of this analysis. The total emissions of coal-fired power plants in scope is around 618,000 tonnes CO_2. Figure 14 shows the share of coal-fired power plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 14. Share of Coal-Fired Power Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



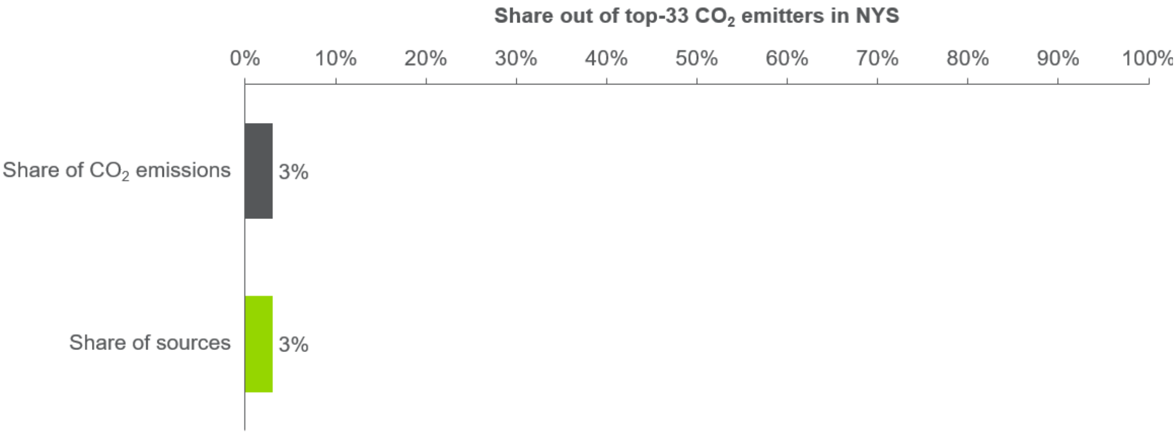
Whereas some coal-fired power stations operate in New York State today, the competitiveness of coal-fired power has decreased significantly over the last decade, especially in jurisdictions that are subject to a CO_2 pricing as is the case for NYS. U.S.-wide there may be some coal-fired power stations left in the 2030s but considering the low-carbon alternatives available, this is unlikely in the State.

3.2.4 Wood-Fired Power

The last power plant type in scope of the analysis is the wood-fired power plant. There is only one of these plants in scope, emitting a total of 803,000 tonnes CO_2. Figure 15 shows the share of wood-fired power plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 15. Share Wood-Fired Power Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis

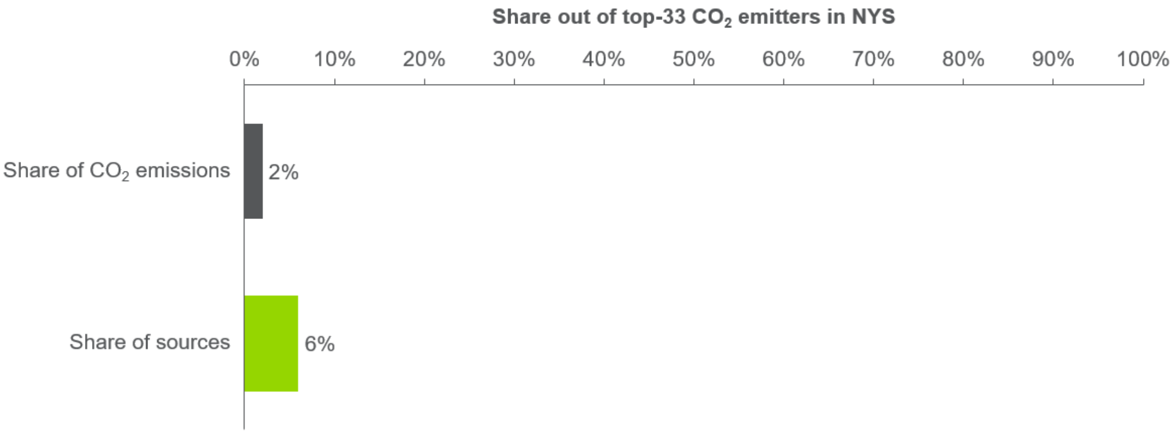


3.2.5 Cement

Two cement production facilities exceed annual emissions of 220,000 tonnes CO_2. The total emissions of these two locations is 494,000 tonnes CO2. Figure 16 shows the share of cement production facility emissions and the number of sources as part of the total emissions and number of sources in scope.

Figure 16. Share Cement Production Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



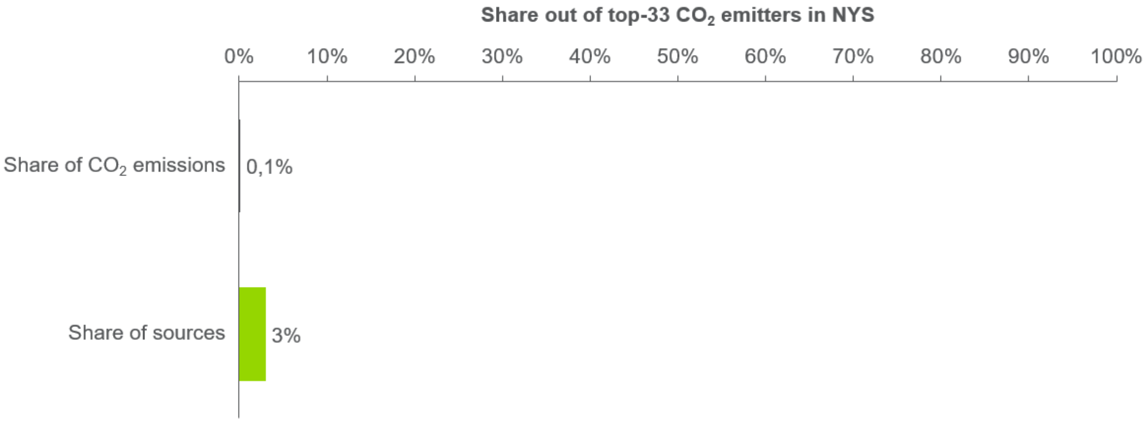
The cement sector has limited options available that fully mitigate their manufacturing emissions. Conventional emission reduction measures such as energy efficiency, fuel switching, or reducing the clinker to cement ratio only marginally affect the overall emissions, which are led by process emissions from carbonate decomposition in the limestone production process. On average, about two-thirds of the emissions are process-related—that is, not related to the combustion of fuels. A measure that makes a significant impact for the cement sector is CCS, so unless this is deployed on a large scale, emissions in the sector are likely to remain stable or decrease relatively slowly over the next couple of decades.

3.2.6 Hydrogen

Hydrogen production only makes up a small fraction of NYS emissions. However, a single plant was added, despite modest annual CO_2 emissions below the selection threshold, due to the relatively high CO_2-concentration in the flue gases. The total emissions of the plant in scope is 27,000 tonnes CO_2. This makes the hydrogen production plant in scope the smallest emission source in the analysis by a large margin. Figure 17 shows the share of hydrogen production plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 17. Share of Hydrogen Production Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



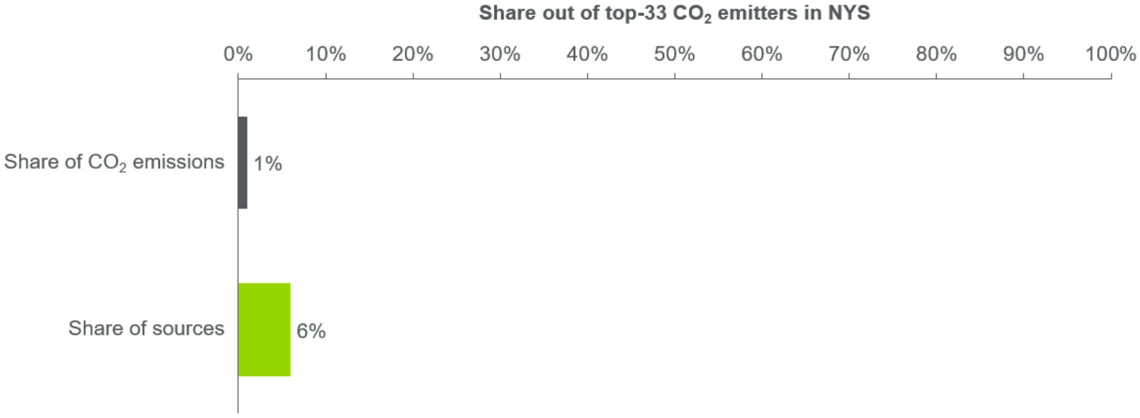
The chemical sector shows significant production growth from an increased demand for chemical products globally. As such, it will be a challenge for the chemical sector to decarbonize simultaneously. However, sustainable alternatives exist to produce hydrogen, such as water electrolysis—though this is expected to remain the costlier option for the coming decades compared to conventional hydrogen or hydrogen production with CCS. Green hydrogen could become available at a lower cost if sufficient, otherwise curtailed, wind or solar power become available. Unless CCS or wind power are deployed at a large scale, emissions from hydrogen production are expected to remain stable until green hydrogen production becomes more cost competitive.

3.2.7 Ethanol

Similar to hydrogen, two ethanol production facilities have been added to the analysis due to their high-CO_2 concentration in the flue gases. Both emission sources are relatively small compared to all other sources in scope, with total emissions of 177,000 tonnes. Figure 18 shows the share of ethanol production plant emissions and number of sources as part of the total emissions and number of sources in scope.

Figure 18. Share of Ethanol Production Related CO_2 Emissions

Sources: New York State Emission Inventory, EPA emissions database, Guidehouse analysis



Since ethanol plants that use biomass feedstock produce biogenic CO_2, this is generally not a sector that is targeted for emissio reduction. However, it is one of the first opportunities for CC as it is emitted at near 100% purity. The biogenic CO_2 makes this source suitable for CDR or circular CCU-derived products, such as fuels. Hence, despite a relative smaller level of annual emissions, these types of sources could be used in the coming decades for CCUS applications.

3.3 Concentration Profiles of CO_2 Emissions

The concentration of CO_2 in different flue gas streams is an important parameter to consider when evaluating the costs of CO_2 captured. Bains et al. (2017) showed that if the concentration of CO_2 in a flue gas or process stream is low, then the costs for CO_2 capture and concentration would be high and vice versa due to the additional energy required.[33] In this section, the CO_2 concentration from flue gases originating from the point sources identified in section 3.2 are presented. The concentration of CO_2 from different point sources were mainly obtained from the Bains et al. (2017) paper, completed with other reference reports, and were cross-checked with literature where necessary. In Figure 19, the amount of CO_2 emitted by point source has been represented, listing the percentage of CO_2 in each flue gas stream. Table 6 lists each percentage used for reference purposes. The top three sectors for emissions are natural gas power plants, ethanol production, and solid waste power plants. Each account respectively for 879,000, 192,000, and 183,000 tonnes of CO_2 per year. Of these three, ethanol production has a relatively high-CO_2 concentration of 98.5%.

With natural gas production as the major source of CO_2 emissions, the weighted average concentration of CO_2 is on the low side. This means that capture costs are expected to be on the higher end of the spectrum. Section 4.4 provides a more detailed analysis of the cost of capture of stationary point sources in the State.

Figure 19. Amount of CO_2 Emitted by Sector in New York State and CO_2 Concentration of Flue Gas

Sources: New York State Emission Inventory, EPA emissions database, Bains, [33]*Guidehouse analysis*

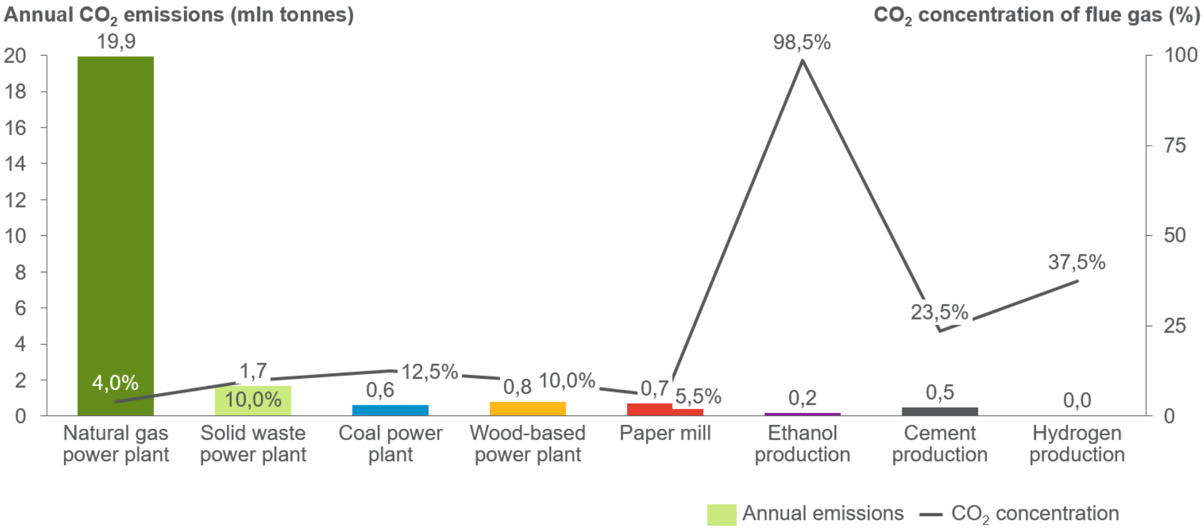


Table 6. Carbon Dioxide Concentration of Flue Gases by Point Source

Sources: Bain,[33]*Guidehouse analysis*

Point source	CO_2 concentration (% mol)
Natural gas	4.0
Solid waste	10.0
Coal	12.5
Wood	10.0
Paper mill	5.5
Ethanol production	98.5
Cement production	23.5
Hydrogen production	37.5

4 Carbon Dioxide Capture and Concentration

This section describes the shortlisted CC technologies following the assessment framework outlined in section 4.1. It concludes with an overview of the associated capture cost, tying back to the most important power and industrial point sources of CO_2 in New York State. Throughout this section, different developers working on carbon capture technology are mentioned. Appendix C provides an overview of these organizations.

4.1 Assessment Framework Introduction

The following is a list of aspects that are explored per technology as part of the shortlisted technology assessment.

- **Technology description and stage of development:** A description of the CCUS technology, as delivered as part of the longlist assessment; a description of maturity with a technical readiness level (TRL) indicator; and information on research efforts to advance the technology.
- **Physical, environmental, and co-location requirements:** A description of criteria for deployment such as availability of feedstock and low-carbon energy for CCU or presence of relevant geologic formation for CCS and how these criteria apply to NYS. A description of sectors or industrial processes in the State that are a good fit to the technology and could therefore fit an industrial symbiotic production scheme based on CC and reuse.
- **Potential/feasibility in New York State:** A description of why the technology was shortlisted for NYS and what similar industrial processes may be present that could aid technology deployment; for instance, providing the opportunity to utilize existing infrastructure.
- **Natural constraints:** A qualitative description of constraints resulting from process needs such as freshwater use or land area requirements.
- **Traditional market description and potential partners:** For the shortlisted CC technologies, the names of selected relevant technology providers or developers are provided.
- **Strengths and weaknesses:** An overview of strengths and weaknesses for a technology (relevant to NYS), including the description of potential competing technologies.

4.2 Assessment of Shortlisted Carbon Capture Technologies

4.2.1 Capture Methods

There are four methods to capture carbon dioxide from industrial or power generation processes: post-combustion capture, pre-combustion capture, oxy-fuel combustion, and DAC (Table 7). Much of the current combustion processes use air as a source of oxygen. As a result, the flue gas typically contains low concentrations of CO_2 (<20%), which are more suitable for post-combustion capture technologies. Other capture technologies have been developed to allow for better retrofitting of existing power plants, for example, or independently from industrial emissions, capturing CO_2 from air. The concentration of CO_2 in different flue gas streams is a key parameter determining the cost of CO_2 captured: the cost of CO_2 capture is inversely proportional to the concentration of CO_2 in flue gas.[34]

4.2.1.1 Direct Air Capture

Carbon dioxide in air can be directly captured. Amines or potassium hydroxide can be used to absorb carbon dioxide present in air. The concentration of CO_2 in the atmosphere is low compared to industrial or power generation point sources. This means energy requirements associated with capture increases, and as a result so does the cost of capture.

4.2.1.2 Post-Combustion

Capturing CO_2 post-combustion involves capturing CO_2 present in industrial flue gases by adsorption following the combustion with air of a primary energy carrier (i.e., coal, gas). This can be done by an amine solvent for example. This capture mode can also be applied to process emissions, like from cement or hydrogen production. The concentration of CO_2 in a flue gas mixture is typically low and separating it from non-condensable gases (e.g., nitrogen), water, SO_x and NO_x contaminants embodies the challenges linked with this technology. Furthermore, the CO_2-containg flue gas is at a relatively low pressure, increasing the volume of gas that must be treated. The advantage of this method is that CO_2-emitting plants can relatively easily be retrofitted with post-combustion capture technology compared to other methods.[35]

4.2.1.3 Pre-Combustion

Pre-combustion capture refers to the conversion of a fuel (e.g., natural gas) into hydrogen and CO_2 via gasification under oxygen limited conditions.[53] A primary fuel is converted to syngas, yielding CO and hydrogen (H_2) and some CO_2. The CO is converted to CO_2 using the water gas shift reaction. The water gas shift is used to convert CO and steam to form CO_2 and H_2. CO_2 is then separated from the obtained CO_2/H_2 mix. The H_2 is used to generate heat or power on site or as a chemical feedstock. Pre-combustion capture involves two separations, but with lower overall energy requirements. The first is needed to enrich oxygen from air, and the second is required to separate CO_2 from H_2. In the case of the use of natural gas instead of coal as a fuel, a reformation step is used instead of the gasification of coal.

4.2.1.4 Oxy-Fuel Combustion

Oxy-fuel combustion is an emerging novel approach to near zero-emissions and cleaner fossil fuel combustion. Here, pure oxygen is used instead of air to combust a primary fuel. A nitrogen-free CO_2 off-gas stream is generated as a result. High-purity CO_2 can then be recovered more easily by condensation of water in the flue gas. This process results in a higher combustion flame temperature than in a normal air-blown combustion technology, which means that adapted combustors are required. There are also several methods which could be used to moderate the flame temperature, the most common being off-gas recycling. An air separation unit is required to generate the oxygen stream for the combustion step. The energy required for CO_2 capture via oxy-fuel combustion can be approximated to the energy required for air separation using an air separation unit.

Table 7. Description of CO_2 Capture Methods

Sources: Leung et al.,[35] Guidehouse analysis

Method	Description	CO_2 origin	CO_2 concentration in source
Direct air capture	CO_2 present in air is captured (biogenic or anthropogenic)	CO_2 is captured after emission	CO_2 is highly diluted and reaches low concentrations (approx. 0.04%)
Pre-combustion	Fuel is burnt under oxygen limitation in a gasification process to generate a secondary fuel	CO_2 is captured after gasification and before combustion of the generated secondary fuel (hydrogen)	> 20% in syngas[35]
Post-combustion	Fuel is completely burnt under air	CO_2 is captured from end-of-pipe	<15%[35]
Oxy-fuel combustion	Fuel is completely burnt in pure oxygen	CO_2 is captured after oxy-fuel combustion	> 80% depending on fuel used[35]

4.3 Selected Capture Technologies

4.3.1 Post-Combustion—Amine-Based Sorbent

4.3.1.1 Technology Description and Stage of Development

Amines (or alkanolamines) are part of a class of CC technologies based on chemical absorption of CO_2, which is based on a chemical reaction between CO_2 and an absorbent, such as an alkanolamine. Heating is required to release the CO_2 from the absorbent, yielding a CO_2-rich stream.[36]

Amines cover a large combination of solvents and additives, including hindered amines and advanced amines developed more recently. The technology making use of amines was derived from natural gas processing. It has been used for a number of decades to remove acid gases from natural gas

(H_2S and CO_2 for example). Commercially available solvents able to absorb CO_2 from dilute atmospheric pressure gas include monoethanolamine (MEA, standard amine technology), diglycolamine (DGA) and the KS-1 series of solvents.

Amine technology for CO_2-capture has been used for a number of years at commercial scale and is therefore classified as TRL 9. The CC projects of Petra Nova (formerly NRG Energy) and Boundary Dam in the U.S. and Canada, respectively, have shown the technology can be used at a scale above 1 $MtCO_2$/y in power generation for enhanced oil recovery (EOR).[37] Several types of amines have reached the market after MEA, notably the Fluor Econamine FG Plus or the KS-1 hindered amine offered by MIH.[38,39]

4.3.1.2 Physical, Environmental, and Co-location Requirements

Amine technology does not need to be used in conjunction with a particular source of carbon dioxide. This capture technology has been used commercially in the following industries: coal-fired power (Petra Nova and Boundary Dam projects, U.S. and Canada), natural gas processing (Sleipner and Snøhvit sites, Norway), ethanol production (ADM Decatur site, U.S.) and hydrogen production (Tomakomai plant, Japan).[40] As seen from this list, amine technology has been implemented for point sources of different CO_2 concentration. There are not any specific co-location requirements for this capture technology. Other capture technologies are aimed at specific sectors and will be discussed below.

Alternatives to the amine technology are being developed to lower the cost of CO_2 capture. This is mainly due to the heat required for the regeneration of the amine, its low CO_2 loading capacity, and the fact it can decompose (see strengths and weaknesses section below). It should be noted that within that context, current performance improvement potential for amine capture lies in making the technology more energy and cost-efficient through better plant process integration and facility heat integration, which would then be important to realize when implementing the technology in New York State.[41] Furthermore, the use of amines for the capture of CO_2 can lead to the emissions of nitrosamines or NO_x, which are regulated by State agencies and will need to be carefully managed.

4.3.1.3 Potential/Feasibility in New York State

Post-combustion amine capture can be applied to NYS's natural gas power plants, the main CO_2 emission point sources in the State, on top of other industrial manufacturing processes. Thus, the technology is flexible enough to be used on retrofitted power plants and new power plants alike.

4.3.1.4 Natural Constraints

No specific natural constraints have been identified when considering the implementation of amine post-combustion capture.

4.3.1.5 Traditional Market Description and Potential Partners

Several types of amines have reached the market after MEA. Multiple solvent suppliers offer amine-based solutions for amine capture. They include the likes of Fluor, MIH, General Electric, Shell Cansolv, and Dow Chemical among others. These technology developers would be the most relevant as far as participating in the development of this capture process for a given point source in New York State.

Some of the incumbent technology users would include Astoria Energy or Consolidated Edison (natural gas power plants), SUNOCO (ethanol producing plant), and Praxair (hydrogen production) for example. These would be the companies to partner with on the technology and user fronts, among others.

4.3.1.6 Strengths and Weaknesses

The flexibility of the amine capture technology and its applicability to a number of industrial sectors is a strength, along with its maturity and presence on the market. But there are several issues associated with amine-based capture technology, which are being dealt with by developing alternative capture technologies. First, they require a relatively large amount of energy (over 3 GJ/ton CO_2),[42] particularly in the amine regeneration step. Even though amines react readily with CO_2, amine have a low-CO_2 loading capacity which limits the efficiency of the capture step, on top of the high-energy consumption of the regeneration step. Secondly, other disadvantages are linked with the stability of amines under their condition of use. They cause equipment corrosion and the amines can be degraded by SO_2 and O_2 in flue gas. Finally, when heated, amines can also degrade and form either heat stable salts or toxic side products such as nitrosamines.[41] There are concerns linked with the handling of amine-based solvents and the generation of nitrosamines as a side-product. Lack of public acceptance for CCS has also been linked to the risks associated with the amine technology.

Regarding the use of amines for post-combustion capture, advantages include the possibility of retrofitting a power plant instead of building a new power plant. However, the problem here is the plot space requirement, since the backend of power plants might already be used for emission control equipment and other auxiliary systems.[43] Lastly, solvent storage in post-combustion capture, or the part-load regeneration of the amine solvent to allow for higher electricity production when market demand peaks, has the potential for improving the flexibility and the overall economics of power plants.[44]

4.3.2 Post-Combustion—Chilled Ammonia Process

4.3.2.1 Technology Description and Stage of Development

The chilled ammonia process (CAP) was developed by General Electric (Alstom previously) as an alternative to the amine absorption technology. It belongs to the absorption class of capture technologies, like the amine capture technology. Here, the flue gas is cooled before entering the absorber where it reacts with ammonium carbonate to form ammonium bicarbonate. Ammonia is released as a gas when the CO_2 is absorbed. Temperature has to be kept low (0-10 ºC) to minimize ammonia losses. Then, ammonium bicarbonate is heated in a regenerator, separating the CO_2, and the ammonium carbonate solvent is returned to the absorption step. Water and ammonia are removed from the CO_2 stream exiting the stripper column. CAP is known to adsorb three times more CO_2 than the amine technology. [45] This technology has reached TRL 8, some would argue of 9.

Several pilot and validation facilities using the CAP—with increasing capacity per evolution step—have been built and tested. However, no commercial capture plant making use of CAP are known. The CAP testing plants treated combustion flue gases from both power and industrial boilers and processes. Fuels used ranged from synthetic gas (SRI International) to coal (WE Energies Pilot plant, AEP Mountaineer Product), heavy oil (EONCAP Karlshamn Pilot Plant), catalytic cracker off-gas and refinery residue (Mongstad Test Center, Norway).[46]

4.3.2.2 Physical, Environmental, and Co-location Requirements

CAP does not require to be used in conjunction with a particular source of CO_2. This capture technology has been tested as part of capture processes at power plants using coal and natural gas, feedstocks, which all are relevant to New York State. Access to a cheap source of ammonia would be desirable for this technology, depending on the scale of capture required. However, this is a relatively cheap compound to start with, and it would not necessarily make a huge difference on the operating costs associated with the capture plant.

4.3.2.3 Potential/Feasibility in New York State

Post-combustion CAP can be applied to natural gas power plants, the main CO_2 emission point sources in the State. The application of CAP to high-CO_2 concentration point sources (>16 vol% CO_2) has been tested successfully on a cement plant as part of the European Union (EU)funded CEMCAP project at a 1 tonne per day pilot plant.[47,48]

4.3.2.4 Natural Constraints

Since ammonia needs to be kept under 10ºC, this technology typically would be best implemented in colder regions where a cold-water source is easily accessible for the heat exchanger. The potential implementation of CAP has been mentioned as dependent of the site's geography (e.g., access to a nearby cold-water source) by several capture technology developers and users. This will reduce the investments and energy required for cooling. Operations at such a low temperature not only reduces reaction kinetics with CO_2, but also would pose a severe challenge to the retrofit of existing power plants as additional cooling systems are required.[49]

Similar to the amine capture technology, better plant process and facility heat integration are sought after to drive down the energy requirement of the carbon dioxide capture.

4.3.2.5 Traditional Market Description and Potential Partners

General Electric is the sole supplier of CAP technology. As a result, GE would be the only partner available to develop this capture process for a given point source in the State. Technology users available in the State would include power generators such as Astoria Energy or Consolidated Edison among others.

4.3.2.6 Strengths and Weaknesses

One of the strengths of this technology is that CAP does not form toxic degradation products, such as nitrosamines, which is associated with the amine capture technology. However, it still does present corrosion issues. Furthermore, ammonia is considered a cheap bulk chemical, which is not subjected to IP restrictions like amines. CAP technology is solely owned by General Electric, which could still mean that the supply market is limiting customer bargaining power, which could limit cost reduction potentials when the technology is implemented commercially.

Together with reduced heat of reaction energy needs (60% lower than MEA), its greater CO_2 absorptive capacity, and low-energy requirement for absorbent regeneration mean CAP presents several improvements over the capture of CO_2 using amines. On the other hand, the low-temperature required to minimize ammonia loss, will lead to high-CAPEX and OPEX costs for refrigeration and water usage. In spite of the improvements over the amine capture technology, the CAP has not been implemented commercially. The slow commercial uptake is believed to be the effect of the low-incremental cost reduction offered by the technology, compared to the amine capture technology, negating the advantages of this process.[50]

4.3.3 Pre-Combustion—Physical Solvents

4.3.3.1 Technology Description and Stage of Development

Solvents are used to dissolve CO_2, but no chemical bond is either created or broken, as opposed to chemical absorption. The solvents used for this capture method are regenerated by either heating or pressure reduction and only limited heat consumption is required for the CO_2 release, as opposed to chemical absorption. The higher the pressure the more efficient the separation process.[51] The technology can be used on a concentrated stream of CO_2 at high pressures and a moderate temperature. Examples of solvents include cold methanol, dimethyl/polyethylene glycol, propylene carbonate, and sulpholane.[52]

Physical solvent technology pairs well with pre-combustion set-ups since these often involve relatively high-CO_2 concentrations and outlet pressure. This technology is suitable for recovering CO_2 from Integrated Gasification Combined Cycle (IGCC) pre-combustion capture plants, for example, where the exhaust CO_2 would leave a gasifier at elevated pressure. The CO_2 concentrations are usually on the order of 35–40%. The technology has not been commercialized yet and is estimated to have reached TRL 8.[53] Applications include natural gas processing, H_2 production via steam methane reforming, and syngas production.

Some known physical solvent processes include the Selexol process (dimethyl ether of polyethylene glycol, proprietary to UOP LLC), the Rectisol process (cold methanol, Linde AG, Air Liquide), the Fluor Solvent process (propylene carbonate), and the Purisol process (*N*-Methyl-2-Pyrrolidone). Some are licensed already. The Selexol process for example has been commercialized by UOP for natural gas processing, synthesis gas purification, and landfill gas treatment.[54]

4.3.3.2 Physical, Environmental, and Co-location Requirements

Natural gas processing, reforming, and gasification are conducted under pressure, and so typically over 40 bars. This means CO_2 will be present at a higher partial pressure rendering the use of pre-combustion capture with physical solvents possible. The regeneration of CO_2 is less energy consuming as it enables some of the CO_2 to be regenerated at pressure through a series of flash drums.[55] As a result, this capture technology is aimed at point sources producing CO_2 as part of their off-gas at high-partial pressure. Applications of pre-combustion capture are therefore mainly applied to natural gas processing, natural gas reforming, coal gasification plants (syngas production) and integrated gas combustion cycles.[55] Typically, pre-combustion capture using physical solvents would then be co-located with the above industries.

4.3.3.3 Potential/Feasibility in New York State

The use of physical solvents to carry out pre-combustion CO_2 capture is possible to implement in New York State. One particular match could be the Niagara Falls Praxair plant which produces liquid hydrogen via steam methane reforming.[56] In the future, IGCC power plants combining syngas production and electricity generation would be suitable candidates for this technology. In the U.S., such a plant was built in Mississippi, in Kemper County. The technology has yet to be implemented for a large number of power plants.

4.3.3.4 Natural Constraints

No specific natural constraints have been identified when considering the implementation of physical solvents pre-combustion capture.

4.3.3.5 Traditional Market Description and Potential Partners

Several technology providers exist. They include UOP for the Selexol process, Lurgi/Air Liquide and Linde for the Rectisol process, and Shell for the Sulfinol process. The air separation unit required can be provided by Air Products, Praxair, Air Liquide, and Linde. General Electric, Siemens, and MHI have developed gas turbine-based power blocks for the IGCC application with capture. Each of these companies are in a good position to supply the required technology to implement the use of physical solvents.[55]

4.3.3.6 Strengths and Weaknesses

Pre-combustion solvent-based capture should in theory present a lower energy penalty than post-combustion capture, “such that the overall GHG emissions and environmental impact is lower than for solvent-based, post-combustion capture, although only by about 5–13%.”[57] Another source quotes that “pre-combustion capture of the CO_2 under pressure incurs less of an energy penalty (~20%) than current post-combustion capture technology (~30%) at 90% CO_2 capture.”[51] The capture cost of the CO_2 should be lower compared to post-combustion capture as the concentration of CO_2 in the off-gas is higher. But the set-up of a hydrogen or syngas-fired power plant is rather costly per unit of power generated compared to an existing power plant. This makes the overall cost of pre-combustion capture in the power sector likely higher than that of post-combustion using “conventional” solvents. To illustrate this point, without CCS, the levelized cost of electricity without capture of an integrated gasification combined cycle (IGCC) power plant has been reported to be of 95 $/MWh compared to 46 $/MWh for a natural gas combined cycle (NGCC) plant.[58]

On the other hand, the use of fossil fuel gasification to obtain hydrogen can be troublesome. The technology takes a long time to operate at peak availability and reach the required system uptime. It has been reported that a gasifier in Puertollano (U.S.) took five years post-commission to reach peak availability at 62% during peak demand.[53]

Regarding the use of physical solvents over amines, the Selexol solvent, a physical solvent favored for pre-combustion capture, presents the advantages of high-solvent stability, low volatility, and low-vapor pressure, which minimizes losses during regeneration.[59]

4.3.4 Oxy-Fuel Combustion at Atmospheric Pressure

4.3.4.1 Technology Description and Stage of Development

Post-combustion capture processes are designed to separate the relatively dilute carbon dioxide from the bulk flue gas nitrogen. In oxy-combustion processes, the bulk nitrogen is removed from the air before combustion using an air separation unit, producing pure oxygen. The latter is injected alongside the fuel into a boiler where the combustion takes place.[60] Meanwhile, treated flue gases are recycled back to dilute the pure oxygen and control combustion conditions. This results in an off-gas with high concentrations of CO_2 and H_2O, requiring only physical separation (i.e., condensation of water) and particulate matter filtering prior to the use of carbon dioxide.[61] This technology is mainly aimed to be applied to power generation (coal and natural gas) and at cement production where partial oxy-fuel combustion capture has been trialed on the calciner.[62] The technology would allow for 98% capture of CO_2, as opposed to 90% for pre- and post-combustion.[43]

Oxy-fuel combustion technology has reached a TRL 8 (6 for cement partial oxy-fuel capture[63]). Examples can be seen at the Vattenfall's 30 MW pilot plant in Schwarze Pumpe in Germany, Total's Lacq pilot project in southwest France (natural gas power station) and the retrofitted 30 MWe scale Callide pilot project in Australia. Regarding the application of oxy-fuel combustion capture on a cement plant, a 30–50 tonnes per annum pilot plant has been built by a consortium including Air Liquide, FLSmidth, and Lafarge to evaluate the feasibility and cost linked to retrofitting a cement plant.[64]

4.3.4.2 Physical, Environmental, and Co-location Requirements

Atmospheric pressure oxy-fuel combustion is aimed at the capture of CO_2 emissions of power plants. Since natural gas power stations are responsible for the majority of emissions emitted in New York State, these power stations will be the main relevant application for oxy-fuel combustion capture technology. A natural gas turbine's working fluid is a CO_2 rich gas, requiring the gas turbine design to be reconfigured compared to a coal-fueled power plant as the properties of CO_2 are different from the properties of air. Furthermore, the heat of combustion is much higher in the presence of pure oxygen, requiring new boilers to be designed with higher heat resistance. An air separation unit is required to separate oxygen from air as well as a condenser to separate CO_2 and water in the off-gas. No other physical, environmental, or co-location requirements were identified.

4.3.4.3 Potential/Feasibility in New York State

In retrofitting State natural gas power and cement plants, it is possible to use oxy-fuel combustion capture at atmospheric pressure. In the case of a steam boiler for example, the retrofit requires adding an air separation unit (ASU) and a flue gas recycling unit to lower the flame temperature to the existing engineering work. In the case of NGCC plants, an advanced gas turbine is required to work with the new working fluid made of CO_2 and water vapor (no nitrogen).[65] In the case of partial oxy-fuel combustion capture applied to a cement plant, the pre-heater and pre-calciner would only have to be redesigned and made gas-tight, but retrofitting is expected to be made easier as the cement kiln and cooler used in the process would not change.[66] An air separation unit would also be required here.

4.3.4.4 Natural Constraints

Plot space requirements need to be considered when retrofitting a power plant, knowing that emission control equipment often takes up space at the backend of the power plant. An air separation unit can be important in size given the volumes of O_2 to separate. In 2016, Linde reported having completed six air separation units in Yinchuan City, China, each separating 3,600 tonnes of O_2 per day. Together, these six units constitute the size of a small industrial plant.[67] Other than that, no specific natural constraints have been reported when considering the implementation of atmospheric pressure oxy-fuel combustion capture.

4.3.4.5 Traditional Market Description and Potential Partners

Oxy-combustion capture power plant designs are based on the separate technologies which individually are mature and used in other sectors. However, it is their combination in an integrated system and the optimization of this system which require further development. Technology developers required include air separation unit developers and condensers developers. Potential partners for the implementation of this technology include leading vendors such as Air Products and Chemicals (U.S.), Air Liquide (France), Linde Engineering (Germany), Praxair (U.S.) for both cryogenic air separation units and partial condensation CO_2 purification units.[68]

4.3.4.6 Strengths and Weaknesses

The capture technology is not deemed fully mature yet and still needs to be implemented commercially. Furthermore, the LCOE of oxy-fuel combustion capture at atmospheric pressure for power plants is deemed relatively high, triggering the development of second and third generation oxy-fuel combustion capture processes. They include high-pressure, oxy-fuel combustion capture or solid looping oxy-fuel capture. These future generation technologies will be ready for demonstration scale by 2020–2025 and 2030–2035, respectively, which means that the momentum for oxy-fuel combustion capture technology might move away from atmospheric pressure technology.[61]

Oxy-fuel capture at atmospheric pressure has been reported to be aimed at the power plant sector specifically, as a means to retrofit existing plants, which could represent an opportunity for the New York State power fleet. Furthermore, power plants equipped with such capture technology should be able to deploy conventional, well-developed, high-efficiency steam cycles without the need to remove significant quantities of steam from the cycle for CO_2 capture, as in the case of post-combustion capture where steam is used to regenerate the amine. The use of an ASU and a particulate filter would allow the system to reach ultra-low emissions of conventional pollutants.[43] This is also applicable to cement production which has only reached a lower TRL and still needs development.

4.3.5 Direct Air Capture—Potassium Hydroxide Solvent

4.3.5.1 Technology Description and Stage of Development

Carbon dioxide emitted to air can be directly captured using a potassium hydroxide (KOH) solution to absorb CO_2. The KOH solution is put in contact with ambient air in an absorber, reacting with carbon dioxide to form a carbonate, specifically potassium carbonate ($K2CO_3$). The latter is then reacted with $Ca(OH)_2$ to regenerate the KOH capture solution and produce $CaCO_3$ in a pellet reactor. $CaCO_3$ is calcined at 900°C to produce CaO and CO_2. CaO is subsequently hydrated to obtain c alcium hydroxide ($Ca(OH)_2$) in a slacker. The calcium hydroxide produced is reacted with K_2CO_3, as mentioned above, repeating the cycle.[69] The technology has reached TRL 6.

The technology is characterized by its chemical shift reaction $2KOH + CaO \text{ -> } K_2CO_3 + Ca(OH)_2$, which is used to be able to regenerate KOH and produce free CO_2 following a calcination step. Here, it is used instead of a pressure or thermal shift in the case of solvent separation in other processes.

The main technology provider for this capture technology is Carbon Engineering based out of Canada. The company is targeting the production of fuels from CO_2.

4.3.5.2 Physical, Environmental, and Co-location Requirements

Low-temperature, solid-sorbent DAC requires mainly heat and electricity, which if supplied from renewable energy, would lead to a zero-emissions DAC system. The temperature required for the calciner cannot be supplied by waste heat. But some heat could be generated from heat pumps or sourced from residual heat from industries for the regeneration step. The regeneration in solid sorbent DAC happens at relatively lower temperatures (80–100°C), which is cheaper to produce or could be available as waste heat from some industrial plants, such as combined heat and power plants, power plants with cooling tower, pulp and paper mills, steel or glass making plants, or waste heat from exothermic synthetic fuel production processes.[70]

Therefore, in terms of co-location the utilization of waste heat is highly relevant, although this is sparsely available and not at the scales required for DAC. Potassium hydroxide is extremely corrosive and can be a hazardous irritant when exposure is at high levels and it should be managed accordingly as part of the capture plant.

4.3.5.3 Potential/Feasibility in New York State

A DAC plant needs to be connected to an electricity provider and a heat pump to allow for the regeneration of the potassium hydroxide solvent. A significant amount of space is therefore required. Several potassium hydroxide distributors are available in New York State to provide the main component of the capture solvent.

4.3.5.4 Natural Constraints

To have any significant effect on global CO_2 concentrations, it has been reported DAC would need to be rolled out on a large scale. This would have significant implications on land use. The pilot plant Carbon Engineering built in 2017 to demonstrate its technology to produce liquid fuels (1 barrel per day) occupies a land plot of 0.5 hectares (ha) where it captures one tonne CO_2/year,[71,72] suggesting that the land use for this technology would be high at the current scale of operations. The DAC systems can, however, be stacked to a certain extent and placed in areas where there is a low demand for land.

4.3.5.5 Traditional Market Description and Potential Partners

DAC using a potassium hydroxide solvent has only been championed by the Canadian company, Carbon Engineering. The company targets the production of liquid fuels for transportation and EOR—aiming to reach commercial scale by 2021. Carbon Engineering is a potential company to partner with if looking to implement DAC in New York State.

4.3.5.6 Strengths and Weaknesses

The main advantage of DAC is that it does not depend on the presence of a specific CO_2 source. It has been reported that if natural gas is used to power a DAC system aimed at offsetting the emissions of fossil fuel, the combined DAC-power system can deliver carbon-neutral energy at a flux of 90–100 W/m^2, a higher energy flux compared to wind or solar.[73] Another advantage is that DAC can be decoupled from electricity generation, if needed.

On the other hand, the technology using KOH as a solvent is only being developed by one company, eliminating the possibility of a price decrease due to commercial competition, at least in the immediate future. Other DAC technology developers exist but their technology is different in terms of the type of solvent and the regeneration temperature used.

Another benefit of DAC, from the perspective of policy making, is that a CCU technology using atmospheric CO_2 would not have issues over system boundaries to account for the CO_2 reductions. Namely, the DAC plant can receive a credit for capturing the CO_2 (as envisioned under the 45Q Tax Incentive, see section 6.3.3), and the CCU plant avoids emissions. When CO_2 is captured from an industrial installation that emits CO_2 this issue arises, since only one of the two (the emitter and the user of CO_2) can claim the emission reduction credit.

Furthermore, due to more stringent climate policy in the State, the expectation is that fossil CO_2 emissions will become scarcer. At some point, the easy-to-mitigate emissions will have been mitigated and the remaining potential for CO_2 capture may be expensive. At this point, DAC may be more cost-efficient on a large industrial scale compared to small-scale CO_2 capture from industrial sources.

Direct Air Capture—Supported Amines

More technologies for DAC are available than KOH. This explainer box describes the capture of atmospheric CO_2 using a supported amine to allow for a comparison with the Carbon Engineering DAC technology described earlier in this section. DAC using supported amines are being treated as a case-study, as the technology provider aims to produce CO_2 at lower specifications for the time being for traditional uses of CO_2, compared to other capture technologies in this study.[a]

Technology Description and Stage of Development

Carbon dioxide in air can also be captured using an amine solid sorbent. Here, the amine is supported on a polymer coated on a solid support. The supported amine can be regenerated to liberate the CO_2 in a second step upon exposition to steam producing a concentrated stream of CO_2. There are several technology providers for supported amine DAC. Climeworks is a commercial technology provider operating 14 projects globally. Global Thermostat has built two pilot plants (kilotonne scale, based in California), one commercial demonstration plant (kilotonne scale, based in Alabama), and another kilotonne scale demonstration commercial plant that is planned to be built in Oklahoma, which should come online by 2020. The company entered a large joint development project with ExxonMobil. Its technological development has been estimated at TRL 8-9. The technology relies on the use of skid mounted modular capture units. It uses waste heat (85–95°C) for the regeneration step over a short capture-regeneration cycle of 15 minutes to deliver low-cost CO_2 capture (below \$100/tCO_2) for traditional uses of CO_2. Compared to Carbon Engineering's technology mentioned earlier, Global Thermostat falls within the "low-temperature solid sorbent" category for direct capture, whereas Carbon Engineering falls into the "high-temperature aqueous solution" category.[b]

Low-temperature, solid-sorbent DAC also requires mainly heat and electricity, which if supplied from renewable energy, would lead to a zero-emission DAC system. Global Thermostat claims the overall electricity and heat demand are 150-260 kWh_{el}/tCO_2 and 1,170-1,410 kWh_{th}/tCO_2, respectively for CO_2 capture only by direct air capture.[b] Heat could be generated from heat pumps or sources from residual heat from industries. Compared to Carbon Engineering's energy requirements, with 366 kWh_{el}/tCO_2 and 1,458 kWh_{th}/tCO_2, both technologies are comparable in terms of thermal and electrical energy requirements. Carbon Engineering's electricity requirement is higher, as it includes the electricity required by the air separation unit to produce the oxygen used by the oxy-fuel calciner in the regeneration step. Global Thermostat's California pilot plant relies on steam produced by a neighboring co-generation plant powering the SRI International campus. But in terms of essential co-location requirements, access to waste heat is not required and colocation is not assumed in the energy data shared by Global Thermostat above.

In terms of land use, the modular kilotonne scale rigs can capture 30,000 tonnes of CO_2 per acre per year (or approximately 74,000 tonnes of CO_2 per ha per year), as a repeat unit and without any infrastructure and equipment sharing.[c] This is much higher compared to the two tonnes of CO_2 captured per hectare identified for Carbon Engineering's technology. Here the amine sorbent is custom made for this DAC technology, and is part of Global Thermostat's Intellectual Property. In the case of Carbon Engineering's technology, the KOH solvent used is a common chemical for which the process used is patent protected. Global Thermostat's amine polymer together with the solid support can be recycled. Their lifetimes are three and 20 years respectively and Global Thermostat is planning to lease these materials.

Global Thermostat aims to develop direct air capture for applications making use of 97% pure CO_2 such as beverage carbonation, glasshouse agriculture, dry ice production and fire suppression for which on-site CO_2 production is seen as an alternative to the loss of CO_2 supply. These are all relevant application in the State. Carbon dioxide use is a $6 billion market in the U.S.[d] The company is already generating a revenue from the installation and operation of its modular direct air capture plants and is reinvesting profits in the demonstration of its megatonne scale plants.

[a] Communication with Eric Ping, Director of Technology Development, Global Thermostat

[b] Fasihi, M., Efimova, O. and Breyer, C., Techno-economic assessment of CO_2 direct air capture plants. Journal of Cleaner Production, 2019, 224.

[c] Communication with Eric Ping, Director of Technology Development, Global Thermostat.

[d] Polaris Market Research, Carbon Dioxide (CO_2) Market Share, Size, Trends, & Industry Analysis Report, 2018-2026

4.4 Cost of Carbon Capture for New York State Energy and Industrial Point Sources

In previous parts of section 4, a basic understanding has been provided for the workings of CO_2 capture methods. Section 4.4 relates this to the cost of CC and how the cost differs depending on which the industry it is applied. Section 4.4.1 explores how the cost of post-combustion capture differs across industries in New York State, whereas section 4.4.3 dives into cost differences in capture technology in natural gas-fired power production.

4.4.1 Cost of Capture for New York State Point Sources

As outlined in section 3, the CO_2 emission profile of the State is led by emissions from power production, although there are also some noteworthy emissions from cement production, hydrogen production, and ethanol production. Since the characteristics of flue gas or process gas determine the size of the capture installation and the amount of energy needed to purify the CO_2 to a level suitable for storage or utilization, it is important to know the sources of CO_2 for the cost of post-capture. Costs for capture were taken from two comprehensive United States Department of Energy (NETL) publications: Cost and Performance Baseline for Fossil Energy Plants (2015) for natural gas and coal-fired power plants and Cost of Capturing CO_2 from Industrial Sources (2014) for industrial sources.

To arrive at a cost of capture, the studies make assumptions on the capture and auxiliary equipment needed and changes required to balance utilities. Power plants are assumed to source steam and power directly from the steam cycle and power output and use a Cansolv solvent,[74] capturing 90% of the CO_2. This assumption is made because it more closely reflects the reality of installing CCS equipment on a power station. Greenfield power stations with CCS would likely increase the nominal capacity of the power station compared to a design without CCS to maintain a similar net power output. The assumption that power and heat are sourced from the power station itself is also reflected in the modeling, as this lowers the sensitivity of the cost of avoided CO_2 to the grid emission factor and retail power prices. Sensitivity remains on the cost of fuel used by the plant, notably natural gas.

Industrial sources are categorized by pure sources of CO_2, like ethanol, and more diluted sources of CO_2 such as emissions from hydrogen and cement production. Pure sources only require the compression of CO_2 and therefore only demand a power supply. Diluted sources also require thermal energy in the form of steam; hence, the study assumed the installation of a steam boiler with import of power to compress the CO_2 and power auxiliary equipment like fans.

Factoring in these assumptions, the marginal cost of production can be calculated (e.g., of one tonne cement). Together with the emissions that are avoided by applying carbon capture compared to the initial situation without CCS (the "reference process"), costs for the avoidance of one tonne CO_2 were calculated and are shown in Table 8 below. Note that the avoidance cost listed excludes costs for transport and storage of CO_2, which suggests that at this cost, the CO_2 emission is technically not yet avoided but only captured and concentrated.

Table 8. Assumptions and CO_2 Avoidance Cost for Energy and Industrial Sources and DAC

Source: NETL, Guidehouse analysis

CO_2 source	Assumed annual production capacity	CO_2 avoided per installation	CO_2 avoidance cost
Coal power	581 MW (gross, before CCS)	3.02 $MtCO_2/y$	\$66
Natural gas power	641 MW (gross, before CCS)	1.51 $MtCO_2/y$	\$78
Wood power		*Assumed equal to coal power*	
Solid waste power		*Assumed equal to coal power*	
Cement	992,500 tonnes cement	1.12 $MtCO_2/y$	\$114
Ethanol	190 million liters	0.14 $MtCO_2/y$	\$26
Hydrogen	59,000 tonnes	0.27 $MtCO_2/y$	\$133

Note: Key financial assumptions used in these calculations include an economic lifetime of 25 years and a 10% discount rate.

Some of the industrial installations that were assessed have costs that differ substantially compared to what would be expected on the basis of their flue gas characteristics. Generally, the higher the concentration of CO_2 in the flue gas and the higher the outlet pressure, the lower the CO_2 capture cost. The pressure swing absorber tail gas in the steam methane reformer has a CO_2 concentration of about 45%, which would require less energy to purify the CO_2 compared to, for example, a natural gas-fired power plant with a CO_2 concentration below 5%. However, the refinery hydrogen production capacity of 59,000 tonnes that is assumed in the NETL study is a low- to medium-sized installation and production levels of 100,000 tonnes per year are not uncommon in the U.S.[75] Economies of scale significantly affect the capture cost, and a hydrogen capacity of over 100,000 tonnes would see an avoidance cost closer to \$60/tCO_2. For reference, the Praxair steam methane reformer in Niagara Falls has a capacity of about 20,000 tonnes per year.[75] The same goes for the cement plants. New York State's largest cement plant (Lafarge in Ravena) has a production capacity of 1.8 million tonnes clinker per year,[76] which equals over 2 million tonnes of cement. Avoidance costs of CO_2 could therefore be lower at that plant. The comparison, in other words, reveals that economies of scale are a key sensitivity to the capture cost and can vary the cost significantly from case to case.

Along these same lines, it is worth mentioning that wood and solid waste power have similar flue gas characteristics to coal-fired power but are typically smaller in size. Levelized capture costs are therefore estimated to be higher than that of coal-fired power. However, avoidance costs may fall within the same range since the energy used to drive the capture process is mostly biogenic (i.e., "emission-free"), from an accounting perspective. Capture costs and avoidance costs are therefore considered the same for these sources.

4.4.2 Cost of Direct Air Capture

Two different technologies to capture and purify CO_2 from the atmosphere were discussed in section 4.3.5:

- Carbon Engineering technology using KOH (high-temperature aqueous solution)
- Global Thermostat technology using a supported amine (low-temperature solid sorbent)

For both technologies, technology descriptions are provided. For the KOH technology from Carbon Engineering, more data is available from literature. Therefore, for this technology, CAPEX and OPEX can be estimated, whereas there remain many uncertainties in the avoidance cost estimate based on publicly available information from Global Thermostat on supported amine technology. The avoidance cost estimate for supported amine can be compared to the 199-357 $/tCO$_2$ avoided as estimated by the National Academy of Sciences for a liquid solvent DAC System powered by natural gas.[77] For KOH, the range 124-407 $/tCO2 avoided from the same publication can be used as a reference. Table 9 provides a comparison of carbon dioxide capture costs for both the KOH and supported amine technologies.

Table 9. Carbon Dioxide Capture Costs for DAC

*Sources: Keith et al.,[72] Eric Ping,**Error! Bookmark not defined.** Guidehouse analysis*

DAC technology	CAPEX ($/tCO$_2$)	OPEX ($/tCO$_2$)	CO_2 avoidance cost
KOH	133	112	$245
Supported Amine (higher uncertainty)	102	91	$193

4.4.3 Comparison of the Cost of Capture Modes

As illustrated in the previous section, the costs for CC are highly dependent on flue gas characteristics and hence, from the type of point source. This section looks at the change in capture cost for the single most important type of emissions in New York State: the emissions from gas-fired power. This section provides levelized cost of electricity data for the set-up of a new natural gas power plant equipped with post-combustion, pre-combustion, and oxy-fuel combustion capture. The levelized cost of electricity (LCOE) data was estimated as a part of a BEIS Department study (UK Department for Business, Energy & Industrial Strategy) done in the UK for the set-up of new natural gas plants over the next 30 years.[78] The LCOE is provided as a means to compare the overall costs of building and operating a plant for the duration of its anticipated lifetime on a consistent basis, knowing 90% of the CO_2 present in the flue gas is captured. CAPEX, OPEX, fuel costs, and the cost of emitting CO_2 are considered, but transport and storage of CO_2 are excluded from this analysis. The assumed CO_2 capture solvent is methyldiethanolamine (MDEA), which is also an amine-based solvent like Cansolv.

Table 10. LCOE Associated with the Capture of CO_2 for the Set-Up of a New Natural Gas Power Plant Using Different Modes of Capture

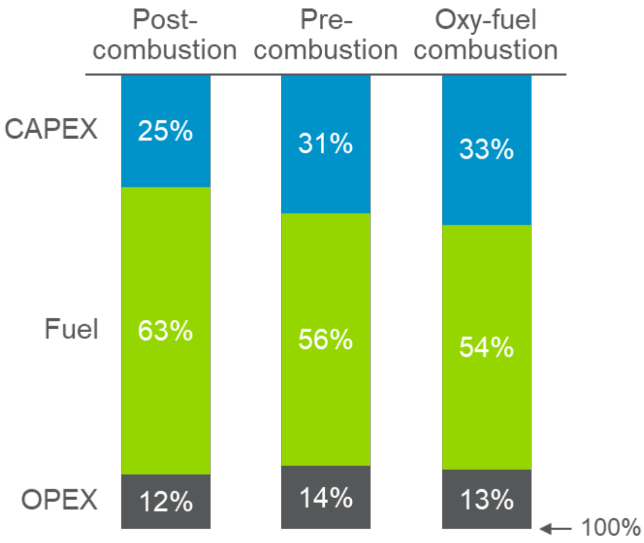
Source: UK Department for Business, Energy & Industrial Strategy

Characteristics	Post-Combustion	Pre-Combustion	Oxy-Fuel Combustion
	1,064 MWe and 52% Efficiency	818 MWe and 40.7% Efficiency	848 MWe and 52% Efficiency
LCOE ($/MWh)	80.4	117	93.9
CAPEX ($/MWh)	20.0	35.6	31.1
Fuel ($/MWh)	50.8	65.0	50.5
OPEX ($/MWh)	9.6	16.3	12.3

The LCOE for each capture technology mode varies greatly. As shown in Table 10, the lowest overall LCOE is provided by post-combustion capture at 80.4 $/MWh and the highest overall LCOE has been estimated for pre-combustion capture (117 $/MWh). Oxy-fuel combustion capture costs lie at 93.9 $/MWh. Pre-combustion capture presents higher capital and operating and fuel costs than any of the other capture modes. Besides different fuel costs, the difference in LCOE between the three capture modes can partly be attributed to the difference in the CAPEX contribution to each LCOE (Figure 20). The fact that pre-combustion capture presents the higher CAPEX and OPEX is expected, as a gasifier is required, which adds a piece of equipment that is not required for the two other capture modes. Gasifiers are known to be difficult to operate, explaining the high OPEX, as highlighted in section 4.3.3. Since pre-combustion also requires a natural gas reformation step to provide the syngas combusted by the power plant, fuel costs are higher for this technology.

Figure 20. Contribution of CAPEX, Fuel, and OPEX for the LCOE for Post-, Pre-, and Oxy-fuel Combustion Capture for a New Natural Gas Power Plant

Source: UK Department for Business, Energy & Industrial Strategy



5 Carbon Dioxide Transport and Storage

This section describes the options for CO_2 transport and storage using the assessment framework outlined in section 5.1. It concludes with an overview of the associated transport and storage costs and an overview of relevant storage locations in New York State.

5.1 Assessment Framework Introduction

The following is a list of aspects that are explored for CO_2 transport and storage:

- **Technology description and stage of development:** A description of CO_2 storage options and significant demonstration projects.
- **Potential/feasibility in NYS:** A description of potential for deployment in the State, depending on the presence of storage options.
- **Physical, environmental, and co-location requirements:** A description of criteria for deployment such as permitting and reservoir monitoring obligations.
- **Natural constraints:** A qualitative description of constraints to storage such as population centers or freshwater reservoirs.
- **Traditional market description and potential partners:** A description of relevant technology developers and typical CO_2 storage stakeholders.

5.2 Assessment of CO_2 Storage Potential in New York State and the Region

5.2.1 Technology Description and Stage of Development

Once CO_2 is captured at the point source through the methods described in section 4 it can be transported to a suitable location for permanent geological storage. Transport of CO_2 can take place via pipeline, vessel, or even by truck. The CO_2 can afterwards be stored in suitable storage formations, which can be either onshore or offshore formations.

Throughout CCS literature, the following types of geological storage options are most commonly considered, for which descriptions are provided in section 2.2:

- **Depleted oil and gas fields:** Previously, depleted oil and gas fields have not been used on a large scale for CCS. Precise coordination is required since oil and gas operators are usually required through regulations to decommission wells when the reservoirs are depleted. Redeveloping the well after decommissioning is significantly more costly than repurposing it for CCS after the end of operation. The first project set to utilize a depleted gas field is the Dutch Porthos project, which aims to store 2–3 $MtCO_2$/yr from the Port of Rotterdam industrial cluster, mainly focused on hydrogen producers.

- **Saline formations:** Since the 1990s, Norway has stored CO_2 from natural gas processing in offshore saline reservoirs and has demonstrated this to be a safe method of geological storage of CO_2. Subsequently there have been multiple large-scale demonstration projects aimed at storing CO_2 in saline formations, among them is the Decatur project in Illinois, which stored CO_2 from ethanol production and Shell's Quest project, a steam methane reformer used to upgrade oil from the Alberta oil sands.
- **EOR:** The U.S. has had a long history of enhancing oil production with CO_2. In the U.S. alone there are about 114 active commercial CO_2 injection projects that together produce over 280,000 barrels of oil per day. The most novel large-scale project is the Petra Nova project, which has successfully managed to capture CO_2 from 240 MW coal-fired flue gas and transport and store this 100 km away in the West Ranch Oil Field. With the injection of supercritical CO_2 into the field, the oil production of the field was increased by a factor of 50 to 15,000 barrels per day.[79] An important nuance is that most CO_2 for EOR has historically been sourced from natural CO_2 sources.
- **Shale formations (enhanced gas recovery):** Playing into the rapid increase of natural gas production in the U.S., enhanced gas recovery in rich organic shales has become a popular technology, especially for the Appalachian Basin. However, the status of research is less advanced compared to storing CO_2 in coal seams (explained below). Ongoing reservoir characterization and simulation studies illustrate that adsorption on organic material and in natural gas fractures is scientifically achievable, though there is a lack of sufficient testing of this concept with site-specific geologic and reservoir data and detailed reservoir simulation in a variety of gas shale settings.[80]
- **Un-mineable coal seams: enhanced coal bed methane recovery (ECBM):** Though significant progress has been made in understanding ECBM mechanisms in recent years, technical challenges persist such as the definition of un-mineable coal seams for CO_2 storage capacity evaluation and storage site characterization and methods for the enhancement of CO_2 injectivity. The low injectivity of coal seams and injectivity loss with CO_2 injection are the major technological challenges of ECBM. Since the 1990s, more than ten ECBM demonstration projects have been executed, seven of which are in the U.S. The largest was the Allison unit project, which injected 277 $ktCO_2$ in five years of operation. This increased the methane recovery ratio from 95% to 150%.[81]

5.2.2 Potential/Feasibility in New York State

The estimated average of the total amount of CO_2 that can be economically stored in the subsurface of NYS is about 14 $GtCO_2$, equivalent to about 70 years of the State's total emissions. However, it should be stressed that these estimates come with considerable uncertainty, as some estimates are less thorough, and some reservoirs have not yet been assessed for CO_2 storage potential. This storage potential is made up of depleted oil and gas reservoirs, saline formations, and shale formations (Table 11).

To support the development of regional infrastructure for CCS, the U.S. Department of Energy created a network of seven Regional Carbon Sequestration Partnerships. One of these partnerships is the MRCSP, in which the State is taking part. In this wider region, many more opportunities for geological CO_2 storage exist, such as EOR, ECBM in un-mineable coal seams, and abundant storage potential in saline formations.[82] A region-wide assessment of offshore reservoirs and shale formations is however not yet available.

Table 11. Overview of Geological CO_2 Storage Potential in New York State and the Midwest Regional Carbon Sequestration Partnership (MRCSP) Region

Source: Carbon Storage Atlas, NYSERDA, NYS Museum RCG, Geostock, Guidehouse analysis

Geography	Oil and Gas Reservoirs	Unmineable Coal Seams	Saline Formations		Shale Formations
			Onshore	Offshore	
NYS	80	0	4,370	9,350	400
MRCSP Region	14,000	<1,000	122,000	N/A	N/A

Note: Estimates presented are averages (in $MtCO_2$).

Different from the more well-known oil and gas reservoirs and saline reservoirs in NYS, less is known about unconventional organic-rich shales and offshore CO_2 storage. NETL is currently developing a methodology to assess the storage potential in shale reservoirs. A perceived benefit of this method is that natural gas can be extracted from the shales, after which the depleted shale becomes available for CO_2 storage. Recently, a study was sponsored by NYSERDA to study enhanced gas recovery (EGR) from shale formations in the Eastern U.S.[83] The researchers found that the Marcellus Shale in could store 0.2 to 0.6 billion tonnes (Gt) of CO_2.

EOR also offers the potential to sequester CO_2 while improving the extraction of oil from a partially depleted field. However, NYS does not have any oil fields that are suitable for EOR according to NETL. West Virginia and Ohio do have such fields.

Although inland NYS contains abundant CO_2 storage potential, most of the emission sources are relatively close to or part of New York City. This suggests that offshore CO_2 storage could be interesting too. In fact, offshore sedimentary basins in the State show better permeability and thickness compared to onshore formations.[84] Offshore storage could also face less regulatory and safety hurdles compared to onshore storage. NYSERDA recently sponsored a study to assess the geological storage potential of the Newark Basin and estimated that at least 1.9 $GtCO_2$ could be stored, with a maximum of 30.2 $GtCO_2$.[85] The COST-B-2 well in offshore New Jersey has also been demonstrated to have porosity and permeability in ranges that are adequate for CO_2 injection and storage, together with the Baltimore Canyon Area.[86]

Injection options with the highest potential for utilization of shale are likely in Steuben, Chemung, Tioga, Broome, Delaware, and Sullivan Counties.

5.2.3 Physical, Environmental, and Co-location Requirements

Co-location of CO_2 transport and storage is ideally done at locations where there is already a present CO_2 transport infrastructure and wells that can be repurposed for geological CO_2 storage. Since there is no EOR activity, co-location options are limited to existing hydrocarbon extraction activity in the far western parts of the State. An example is the current largest active gas well in Erie, NY operated by Weil Resources Inc.[87]

5.2.4 Natural Constraints

Scientific research over the past decades has pointed out that CCS is a safe mitigation option and is able to keep at least 98% of the stored CO_2 locked away for a period of 10,000 years.[88] However, each storage option presents different opportunities and challenges. The safe geological storage of CO_2 should be warranted by legislative frameworks, as is the case in the U.S. through some state-specific regulations,[89] and the EU,[90] Canada, and Australia, among others.[91]

Some regulations stress the importance of not conducting CO_2 storage activities in the proximity of populated areas and drinking water reservoirs, due to the extremely low but present risk of CO_2 leakage. The risk of CO_2 leakage is largest in depleted oil and gas reservoirs, since in a hydrocarbon reservoir, gaseous, or supercritical CO_2 will rise due to buoyancy effects. There is a risk that CO_2 can escape from the reservoir through or along wells or by means of a cap rock failure. CO_2 might also escape via spill points or dissolve in fluid flows in the reservoir rock beneath the CO_2 accumulation to surrounding formations, which may cause leakage. Another possibility is well failure, mainly from other less well-managed abandoned wells. Despite this, there is widespread confidence that oil and gas reservoirs can safely store CO_2 on the geological timescale that they have already stored the hydrocarbons. Carbon dioxide injected in deep saline aquifers can in some cases displace brine, salt groundwater. This can induce a rise of the groundwater table and enhance salinity in neighboring freshwater reservoirs. Therefore, this is best not done in the proximity of sweet water resources.

5.2.5 Market Description and Potential Partners

The driving stakeholders in the area of CO_2 transport and storage include existing gas Transmission System Operators (TSO), well operators, and energy companies involved in hydrocarbon production. Often, the company intending to capture CO_2 will also need to try to hook-up their facility to a more common transport grid. However, there are different ownership models for CO_2 pipelines and depending on the preferred option different stakeholders are involved. In EOR activities, the pipelines are typically managed by the oil producing entities—though in a set-up where multiple CO_2 emitters are involved, and CO_2 is intended solely for geological storage there may be different operators for every step in the storage process. State governments also need to be involved from an early phase onwards to facilitate the permitting process and possibly address market failures in case an oversized CO_2 transport pipeline is beneficial in the long term but cannot be realized by commercial entities alone.[92] Relevant actors in New York State are the National Grid, Cabot Oil & Gas, and Chesapeake Energy Corporation, among others.

5.3 Costs of CO_2 Transport and Storage

5.3.1 Costs of CO_2 Transport

Economics of different transport and storage options can vary considerably, and different combinations of different transport modes may be desired for cost-efficiency reasons. The storage location of choice is dictated by other reasons, such as geological favorability, existing infrastructure, storage size and regulatory options. The following transport options are generally distinguished:

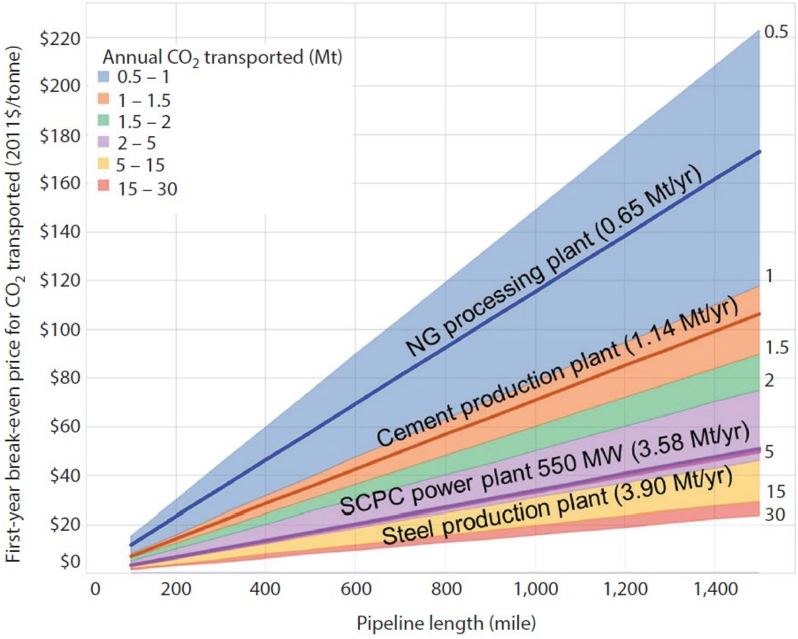
- **Pipeline:** Transport of CO_2 by pipeline is already done at scale in the U.S., and currently around 7,250 kilometers of dedicated CO_2 pipelines are in use. This is mainly for EOR in the Southern U.S. CO_2 is typically compressed prior to transportation into a supercritical state, making it dense like a liquid but with fluid properties like a gas.[93] Pipeline transport is generally considered to be the least costly mode of transport for CO_2 when multiple million tonnes of CO_2 are transported per year at distances under 1,000 kilometers. However, pipelines in densely populated areas can be prohibitively expensive and require specific attention to leakage. For offshore pipelines it may be less difficult to obtain right-of-way permits and there are less issues related to safety and regulatory approval due to the absence of population centers.[94] However, because of the operational difficulties in offshore conditions and increased complexity and project risk, offshore pipelines are usually more expensive than onshore pipelines for the same CO_2 volumes transported over equal distances. Due to the high share of capital costs in pipeline development, costs expressed in $/t$CO_2$ are proportional to pipeline length for the same length (Figure 21).
- **Ship:** CO_2 shipping is not yet done at a large scale but could be more economical for distances above 1,000 kilometers. Shipping of CO_2 does take place on a small scale in Europe, mainly for the food and beverage industry.[95] For ship transport, operating and maintenance costs are more substantial whereas capital costs contribute less than 40% to the overall costs. Shipping costs are therefore less sensitive to differences in capacity and distance compared to pipelines, rendering this a more flexible mode of transport. Vessels for CO_2 transport at large scale (10,000-40,000 m^3) have been proposed but do not yet exist. Combining CO_2 transport with multipurpose ships that are used for LNG/ethylene transport seems feasible and may prove to be a cost-efficient way of transporting CO_2.[96] However, since LNG and ethylene carriers have an atmospheric pressure of 4 to 7 bars, respectively, these will by definition not be suitable and will have to be redesigned. LNG importers Distrigas and Repsol could provide more perspective on the suitability of existing State infrastructure for CO_2 transport. In NYS, the Hudson River is the only potential waterway for CO_2 transporting vessels.

- **Rail/Truck:** Trucking or transport by rail would likely only be considered if the point source of CO_2 does not have a ready and strategic access to pipeline facilities, shipping routes are not available or for small amounts of CO_2. This is generally the most expensive mode of transport given the small volumetric capacity of pressurized tank cars or truck tankers, which range in capacity from 2 to 30 tonnes CO_2.

In many cases, transport costs will be considerable if a pipeline is developed for one natural gas-fired power station, for example. As under development in various industrial clusters in Europe at the moment, it is more cost-efficient to collect and store CO_2 centrally in transport hubs, and then transport it further to a storage site to reduce infrastructure cost and utilize economies of scale. This also makes such a project more resilient to changes in players that wish to feed into such a grid. However, this requires a sizeable amount of CO_2.

Figure 21. Relationship between Pipeline Length, Transported Amount of CO_2, and Levelized Transport Cost

Source: NETL[97]



5.3.2 Costs of CO_2 Storage

The U.S. Department of Energy (NETL) recently developed a CO_2 Saline Storage Cost Model.[98] Based on the characterization of various saline storage options in the U.S., NETL developed a cost-supply curve. Around 70% of the total saline storage potential in the study could be realized at a cost of $7-16/t$CO_2$, (Figure 22).[99] Although no New York State reservoirs were included in this assessment, the team assumes costs for saline storage to fall within this range of $7-$16/tCO_2. Focus of research by NETL is mainly on saline reservoirs in the Midwest which have shown to have a significant and low-cost storage potential, such as the Mt. Simon Sandstone formation in Ohio, Indiana, and Illinois. If significant amounts of CO_2 can be captured, although far away, the Mt. Simon option may be the more cost-efficient one for NYS compared to in-state storage.

Detailed and recent U.S.-specific cost assessments for CO_2 storage in depleted hydrocarbon fields do not exist. Therefore, the study team assumes those costs to fall within the ranges mentioned in cost assessments made for the EU by Zero Emissions Platform (2011).[100] An overview of those estimates is shown in Table 12. A 2005 assessment for North America by IEAGHG mentions a mean storage cost for depleted gas and oil fields of \$16 and \$21/tCO_2, respectively.[101] This is higher than the EU based figures. Costs for EGR from shales are unknown, but due to the revenue from gas sales the business case is expected to be relatively similar to ECBM at a mean cost of around \$12/tCO_2.

Table 12. Overview of Cost Estimates for Depleted Oil and Gas Fields, Onshore and Offshore

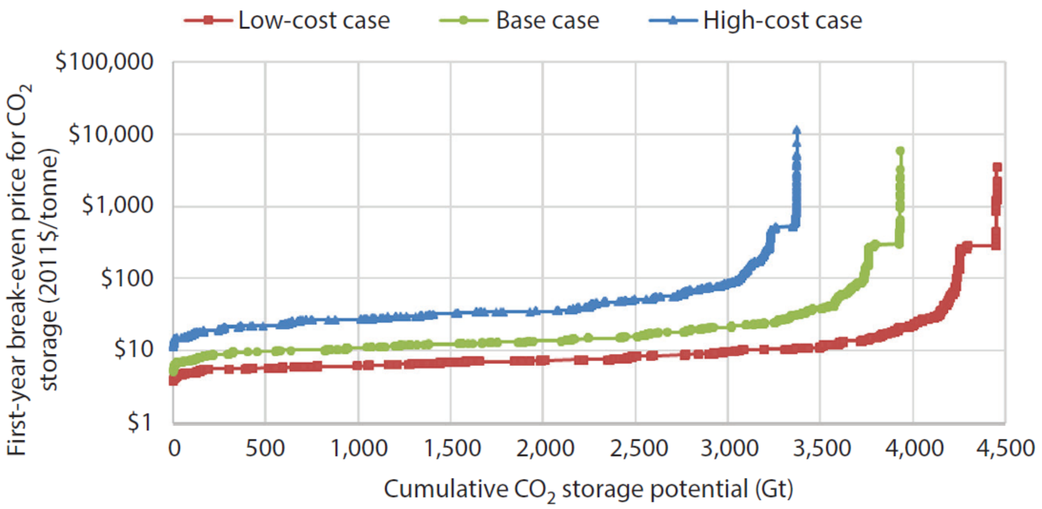
Source: Zero Emissions Platform

Reservoir type		Low	Medium	High
Depleted oil and gas fields—reusing wells	Onshore	1	4	8
	Offshore	2	7	11
Depleted oil and gas fields—new wells	Onshore	1	5	12
	Offshore	3	12	17

Note: Costs are in \$/tCO_2 and converted from 2009EUR to 2019USD.

Figure 22. National CO_2 Storage Cost-Supply Curve under Base, Low-, and High-Cost Scenarios for Saline Reservoirs

Source: NETL



6 Carbon Dioxide Utilization

This section describes the shortlisted CCU technologies following the assessment framework outlined in section 6.1. It concludes with an overview of the associated utilization costs and the abatement potential of the selected technologies. Throughout this section, different developers working on carbon utilization technology are mentioned. Appendix C provides an overview of these organizations.

6.1 Assessment Framework Introduction

The following is a list of aspects that are explored per technology as part of the shortlisted technology assessment.

- **Technology description and stage of development:** A description of the CCUS technology, as delivered as part of the longlist assessment; a description of maturity with a TRL indicator and information on research efforts to advance the technology.
- **Physical, environmental, and co-location requirements:** A description of criteria for deployment such as availability of feedstock and low carbon energy for CCU or presence of relevant geologic formation for CCS and how these criteria apply for NYS. A description of sectors or industrial processes that are a good fit to the technology and could therefore fit an industrial symbiotic production scheme based on CC and reuse.
- **Potential/feasibility in New York State:** A description of why the technology was shortlisted for NYS and what similar industrial processes may be present that could aid technology deployment; for instance, by providing the opportunity to utilize existing infrastructure. As part of this aspect the following is also addressed for CCU technologies (shortlisting criteria):
    - Global product demand for CO_2 based product through CCU route
    - Availability (yes/no) of local production demand of reference product for CCU route
- **Natural constraints:** A qualitative description of constraints resulting from process needs such as freshwater use or land area requirements.
- **Traditional market description and potential partners:** For the shortlisted CCU products, the most relevant final applications/markets will be qualitatively described as well as potential barriers to market entry (legislation, permits, testing/quality requirements, etc.). In addition, companies and other organizations in NYS that may be interested in developing or deploying CCUS technologies were identified.
- **Strengths and weaknesses:** An overview of strengths and weaknesses for a technology (relevant for NYS), including the description of potential competing technologies.

6.2 Assessment of Shortlisted Utilization Technologies

This section provides a detailed qualitative assessment for all shortlisted utilization technologies following the above assessment framework for each CCU application shortlisted.

6.2.1 Acetic Acid

6.2.1.1 Technology Description and Stage of Development

A route to produce acetic acid from CO_2 is being explored which involves anaerobic gas fermenting microorganisms that convert a CO_2 and H_2 mixture to acetic acid. LanzaTech, in collaboration with the Malaysian oil company Petronas, are developing this technology (TRL: 2-4).[102] The metabolic process uses acetogenic bacteria in an oxygen-free environment. The mixture of CO_2 and H_2 is compressed before the fermentation process. No additional energy is required in the fermentation process.[103] The reaction of CO_2 with hydrogen to produce acetic acid is highlighted below.

Equation 1: $\boldsymbol{2CO_2 + 3H_2 \rightleftharpoons CH_3COOH + 2OH}$

LanzaTech publicly stated plans to build a demo plant in Malaysia.[104] No recent updates were identified on the progress of this demonstration facility or the development of this technology.

6.2.1.2 Physical, Environmental, and Co-location Requirements

Due to the relatively low maturity of the technology, not much is known on the physical and environmental requirements for an industrial-scale plant.

Acetic acid serves as feedstock in the production of chemicals such as vinyl acetate monomer (VAM), purified terephthalic acid, acetic anhydride and acetate esters.[105] Guidehouse did not identify production of these chemicals in NYS.

The key inputs for this process are CO_2 and H_2 at ratios of 1.5 and 0.1 tonnes per tonne of acetic acid. To keep transport costs of these feedstock as low as practically possible, proximity to industrial sources of CO_2 and H_2 or infrastructure of these commodities is advisable.

6.2.1.3 Potential/Feasibility in New York State

The CCU pathway to produce acetic acid was shortlisted because out of the relatively less mature CCU technologies it produces a global commodity to a market that consumes over 10 megatonnes/yr. There are acetic acid producers identified in NYS at present who could benefit entering this market, and as a result, existing infrastructure and established value chains could be used.

Potential deployment of this technology in the State lies further in the future. Assuming an average maturation rate of two TRLs per decade, this pathway might reach commercialization before 2050.

6.2.1.4 Traditional Market Description and Potential Partners

Conventional acetic acid is part of a long and relatively complex supply chain. In comparing the major chemicals that require acetic acid as feedstock, VAM has the highest consumption of acetic acid in 2017, accounting for nearly 31% of the market.[106] VAM is used to produce resins, adhesives, paints, and coatings. These products are mainly applied in construction, packaging, and furniture.

To date, LanzaTech and Petronas have developed this technology and are likely partners for further development.

Potential partners in establishing a green value chain to deploy CO_2-derived acetic acid should be sought in the markets described above. Due to the low-technology maturity, it is more likely that large multinational players with a sizeable R&D budget can play a role in advancing this technology. Momentive Performance Materials is a privately-owned specialty chemicals company with headquarters in NYS.[107] It is worth investigating if this company could indeed play a role in developing this technology further.

6.2.1.5 Natural and Other Constraints

This technology is reported to only need CO_2 and H_2 to produce acetic acid. Hence, further constrains in terms of required resources is expected to be limited. Due to the relatively low maturity of the technology, not much is known on the land area requirements of an industrial-scale plant.

An important requirement is the availability of a source of freshwater to be able to carry out the water splitting to produce the required hydrogen.

6.2.1.6 Strengths and Weaknesses

The major weakness for this pathway is its relatively low maturity. Not much is public on recent development to progress the technology. If it were to materialize however, it could serve a sizeable domestic and global market that is expected to grow.

A competing sustainable alternative is acetic acid production from biomass pyrolysis. Its current development is not known. A U.S. patent dating from 2012 discloses the technology.[108] It is recommended to compare competitive advantages of both technologies.

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, synthesizing acetic acid from CO_2 is estimated to cost $234 per tonne of avoided CO_2. This is assuming a baseline of conventional fossil acetic acid production.

6.2.2 Aggregates from Natural Mineral Carbonation

6.2.2.1 Technology Description and Stage of Development

Carbon dioxide can be captured and stored in various ways, such as storage in geological formations or utilization in chemical products as discussed extensively in this report. Mineral carbonation is another method to lock away CO_2. Mineral carbonation tries to imitate the natural process of rock weathering, which is the reaction of a metal oxide mineral with atmospheric CO_2. In this process, a thermodynamically stable carbonate mineral is formed. This process can be replicated and accelerated and, therefore, used to permanently sequester CO_2 in minerals and/or treat alkaline waste streams from the construction or waste incineration industries. The most suitable natural minerals for the process of carbonation are magnesium or calcium silicate minerals such as olivine, wollastonite, or serpentinite. Highly suitable waste streams include fly ash from coal combustion, air pollution control residue, blast furnace slag, paper mill waste, cement kiln dust, and demolition and construction waste. Kirchofer et al. estimate the combined potential of utilizing all such industrial alkaline waste streams in the U.S. has the potential to mitigate approximately 7.6 $MtCO_2$/yr.[109]

Since the utilization of industrial alkaline waste has the benefit of not having to quarry and transport the minerals and has the co-benefit of being a waste treatment option, most research has focused on this route and various demonstration plants have been developed to date—most notably in the UK by Carbon8 Aggregates.[110] Carbonation based on industrial waste can therefore be argued to have reached TRL 8. Nevertheless, carbonation of natural minerals continues to receive attention mainly in geographies with an abundance of suitable silicate minerals. The focus of research here is on reducing the significant energy penalty induced by having to quarry, transport, and grind the rock. Front runners in the demonstration of carbonation based on natural minerals include Mineral Carbonation International, which has a carbonation technology in research phase (TRL 3-4). They currently aim to develop a demonstration plant with a capacity of 5–10 kilotonne CO_2/yr. with the goal of ultimately sequestering 1 $MtCO_2$ per facility. The process binds CO_2 with crushed serpentinite rock to create magnesium carbonate, which can subsequently be turned into construction materials.[111]

Various process routes are explored in the field of mineral carbonation, most notably gas-solid carbonation and aqueous carbonation. Aqueous carbonation is considered the most promising route, mainly due to improved CO_2 solubility, where various reactions take place in the same reactor in the presence of water: CO_2 dissolution, silicate dissolution, and carbonate precipitation.

6.2.2.2 Physical, Environmental, and Co-location Requirements

The main inputs needed to produce carbonated minerals are the silicates themselves, CO_2, power, thermal energy and a freshwater supply if the more promising aqueous carbonation process is pursued. A logical option for NYS to pursue would be wollastonite ore, since of all the minerals with a high potential for carbonation wollastonite is the only mineral that has existing quarries in the State, namely in Lewis and Essex Counties.[112] A tonne of carbonated mineral contains around a third of CO_2 in terms of weight, which means that around 2.6 tonnes of mineral are needed per tonne of CO_2.

Per tonne of carbonated mineral, an estimated 168 kWh is required to run the carbonation reactor and crush the rock into a size that is optimal for silicate dissolution. If a company wishes to engage in carbonate mineralization but is not in charge of managing the quarry supply, it will have to purchase the silicate ore. Costs for wollastonite ore are on the order of $19/tonne.[113]

Co-location can be useful to avoid transport costs and reduce transport-related emissions, which would also improve the life-cycle environmental performance of the carbonation process. A sensible location could be near a quarry and a CO_2 point source. Since the mineral carbonation process does not require 100% pure CO_2 it could be economically attractive to develop the plant close to a flue gas stream with an approximately 15% CO_2 concentration, such as the Lafarge Holcim and Lehigh cement plants in Warren and Albany County, respectively. This has the added benefit of utilizing existing transport infrastructure for minerals.

6.2.2.3 Potential/Feasibility in New York State

The CCU application of producing aggregates from carbonated natural minerals was selected in the shortlisting process due to the significant demand for construction aggregate in the State. At the same time, there is an established traditional market (as mentioned in the next paragraph) that can be used in an effort to make the construction industry more sustainable.

6.2.2.4 Traditional Market Description and Potential Partners

The traditional aggregate market in NYS is mostly based on crushed stone production from limestone and dolostone and sand and gravel mining. In 2012, crushed stone production was 36 million tonnes, whereas sand and gravel production was slightly lower at 28.8 million tonnes. Most of this is used in the construction industry. Leading producers of aggregate include Hanson Aggregates New York, Callanan Industries, Tilcon, Dolomite Products Co. and Lafarge Holcim.[114] Since one tonne of CO_2 produces about 2.6 tonnes of aggregates, at the megatonne scale, this would influence the existing aggregate market.

If wollastonite were chosen as the mineral of choice for carbonation, potentially other markets could be tapped into. The automotive industry is a main consumer of wollastonite. Plastics for interior, exterior, and under-hood components utilize wollastonite as a strengthening agent and for its heat-resistant properties. Wollastonite production in New York State in 2009 was around 65,000 tonnes of which most was produced by NYCO Minerals Inc.[114] It requires further consideration whether carbonated wollastonite can be used in similar applications.

6.2.2.5 Natural and Other Constraints

If mineral carbonation were deployed on a megatonne sequestration scale, vast amounts of minerals would be required that would require opening quarries or displacing the demand in existing quarries. Mining minerals significantly increases the emissions of particulate matter and scores higher on life-cycle categories of human toxicity and terrestrial acidification compared to not storing the CO_2 at all.[115] The life-cycle GHG emissions impact of carbonating natural minerals is very sensitive to energy requirements during mining and processing, hence proper safeguards would need to be in place to ensure that this process is leading to a net sequestration of CO_2. Depending on the specific configuration of the carbonation process (e.g., whether pre-heating of the rock is considered), transport distances, and the grid emission factor of the power that is used, the process may or may not lead to avoided emissions per tonne of CO_2 captured.

6.2.2.6 Strengths and Weaknesses

The advantage of utilizing CO_2 to carbonate natural minerals is that it permanently locks away CO_2, so in that sense it is a technology on the interface between CO_2 storage and CO_2 utilization. In addition, the cost of CO_2 capture in combination with this technology is less complicated since flue gas concentration can be used to carbonate the minerals. However, the life-cycle GHG impact is strongly influenced by the amount of energy needed for mining and transport, and together with its particulate matter emissions is therefore environmentally less attractive than mineralization based on industrial waste streams. Due to these reasons, no significant demonstration has taken place, whereas industrial waste stream mineralization has seen larger demonstration projects in recent years.

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing aggregates from naturally occurring minerals using CO_2 is estimated to cost \$182 per tonne of avoided CO_2. This is assuming a baseline of conventional aggregate production.

6.2.3 Concrete Curing

6.2.3.1 Technology Description and Stage of Development

Carbon dioxide can be utilized in the curing, or hardening, of concrete. Conventional concrete is made from cement, aggregates, and water in which the water and cement paste binds with the sand and rock to harden, known as hydration. Alternatively, part of this cement can be substituted with CO_2. Although the CO_2 utilization is relatively small at only 0.6 kilograms (kg) CO_2 per tonne of concrete, the CO_2 savings by substituting and avoiding cement production is much larger, at 6–8 kg CO_2 per tonne of concrete.[116]

The two main companies in this space with patent protected processes are Solidia and CarbonCure. In the Solidia process, referred to as hydrothermal liquid-phase densification, Solidia cement powder and sand are packed together and CO_2 (at temperatures of 40–70°C) and water are added. The components react to produce calcium carbonate and silica concrete. [117] The CarbonCure process is a similar form of carbonation-curing where CO_2 is first captured and then injected into wet concrete while being mixed. The CO_2 reacts with the minerals in the cement mixture to form nanoparticles of calcium carbonate in between the larger cement grains, which is known to enhance the material properties of concrete.[118] Due to this phenomenon, manufacturing efficiencies on the order of 15–20 kg cement savings per m^3 of concrete can be achieved.[119] The Solidia process is mainly applicable to precast concrete while the CarbonCure process can be applied to precast, ready-mix, and masonry concrete. The CarbonCure process does not directly lead to a reduced energy demand but does indirectly lead to embedded energy savings since less concrete is needed. For the Solidia process, additional energy savings can be achieved higher up in the value chain with Solidia cement. This process uses a cement kiln that is fired nearly 250°C lower than conventional cement plants, leading to an additional energy savings for cement on the order of 30%, and these savings trickle down to reduce the embedded energy demand for concrete.

Solidia technology has at TRL of 7. It is in a post-demonstration phase and has been tested on a lab scale and in pilot plants, such as through its partnership with LafargeHolcim in a U.S. plant. The strength and durability of Solidia Concrete products has been tested and verified according to all market standards like ASTM, AASHTO, EN, and CSA.[120] CarbonCure is currently deployed at a larger scale and is implemented in around 130 concrete plants throughout North America and Singapore, thus has a higher TRL of 9.[121]

6.2.3.2 Physical, Environmental, and Co-location Requirements

This technology requires concrete producers with batching plants or precast concrete production. Since it is an add-on technology, it only requires a small batching module to dose the CO_2 and some CO_2 injection equipment. The concrete plant may also need to reserve some storage space for CO_2 tanks. Due to high transport costs, concrete is typically produced locally, thus limits plant locations relatively close to demand.

As material inputs, concrete plants require cement, aggregates, water, and CO_2. This CO_2 does not have to be 100% pure and requires less purification than some other applications. However, there have not yet been studies to determine the minimum CO_2 purity since food-grade CO_2 transported in tanks has been used to date. Since impurities may affect concrete properties, concentrations of >90% should probably be expected.

For conventional precast concrete, there is an energy demand of 0.32 GJ/tonne, of which one-sixth in the form of electricity (15 kWh or 0.054 GJ).[122] The additional energy demand for the CCU add-on unit is negligible.

6.2.3.3 Potential/Feasibility in New York State

With global production of 4.4 billion tons of concrete, the potential CO_2 utilization for this application is only 2.4 megatonnes CO_2 due to the low-utilization rate of this technology (although the avoided CO_2 from reduced cement production would be much larger at around 28 megatonnes).[123] Concrete curing was initially deselected from the longlist of technologies for this reason. It was reselected due to its technological maturity. This CCU application is already being used commercially and CarbonCure technology is even currently used at an Oneonta Block masonry concrete plant in New York. This can be very feasibly scaled to other concrete plants and implemented immediately across the State.

6.2.3.4 Traditional Market Description and Potential Partners

According to the New York Portland Cement Association, New York State consumed nearly 3 megatonnes of cement in 2016, part of which is used for concrete production.[124] There are three main cement plants in the State, two of which are operated by Lehigh Hanson (part of the Heidelberg Cement Group) and one operated by LafargeHolcim. Part of Lehigh Hanson's product portfolio is ready-mix concrete and LafargeHolcim produces both ready-mix and Ultra-High Performance Concrete. However, concrete is typically produced at many small decentralized batch plants, and NYS has several hundreds of concrete plants owned by nearly a hundred different regional companies.[125]

CarbonCure is a suitable company to partner with as their technology is most mature and as a Canadian based start-up, they are very active in North America. Their technology can also be used in a wider array of concrete applications, whereas Solidia is exclusively for precast concrete.

6.2.3.5 Natural and Other Constraints

There are limited constraints for concrete curing other than the raw materials needed for concrete, which typically are abundant and easily transported. This technology also does not require large areas of land or pure water sources.

6.2.3.6 Strengths and Weaknesses

The greatest strength of this technology is the maturity and commercial viability. CarbonCure technology has been used by over one hundred producers across North America and recently expanded to Singapore by partnering with concrete manufacturer Pan-United in 2018. They claim to have a cost-neutral business case, as the cost of the licensing fee for the add-on unit is offset by the cost savings from using less cement. This technology can also improve the function of the concrete; both Solidia's and CarbonCure's processes improve the compressive strength of the concrete while lowering the carbon footprint. The Solidia process also has the advantage of reducing the time for concrete curing from 28 days to 1 day.

The weakness of this technology is the relatively direct low-CO_2 utilization in comparison to other technologies. The abatement potential arises mostly from the embedded CO_2 of the cement avoided in the concrete. Since concrete is produced in relatively small and decentralized plants, this means that CO_2 is transported in tanks rather than at a large scale via pipeline. The technology is also limited in that it cannot yet be used for steel-reinforced concrete, which limits its scalability. Pan-United Corporation noted possible issues with the use of CO_2 cured concrete for steel-reinforced concrete. Carbonation occurs during concrete curing and lowers the pH, ultimately leading to rusting of the steel. This can compromise the strength of the concrete but can potentially be mitigated with countermeasures such as electrochemical chloride extraction, which applies a negative charge to the rebar to reduce corrosion products on the reinforcing steel surface.[126]

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, curing concrete using CO_2 is estimated to cost $7 per tonne of avoided CO_2. This is assuming a baseline of conventional concrete production.

6.2.4 Carbon Monoxide

6.2.4.1 Technology Description and Stage of Development

Carbon monoxide (CO) is a valuable compound which is used abundantly as a chemical building block. It is one of the key components of synthesis gas (syngas), which is used to make methanol or to produce hydrogen and combine it with nitrogen in the integrated ammonia production process (Haber-Bosch). Furthermore, carbon monoxide is used to produce formic acid and oxalic acid.

Carbon monoxide can be produced from CO_2 and water through the reversed water gas shift (RWGS) process, see the equation below. The technology is still under development and has not been commercialized yet. The RWGS reaction is a desired route for industrial applications, most commonly in conjunction with the Fischer-Tropsch (FT) reaction to synthesize hydrocarbon fuels from syngas. It was first demonstrated on a pilot scale in South Korea in the CAMERE project, which used the reverse shifted CO_2 for methanol production. Sunfire and Soletair have more recently used the RWGS process in the production of blue crude—i.e., synthetic crude oil. There are also no companies known to develop RWGS technology for commercialization. The technology is therefore expected to be in TRL 7. The reaction of CO_2 with hydrogen to produce carbon monoxide (CO) is highlighted below.

Equation 2: $$\boldsymbol{CO_2 + H_2 \rightleftharpoons CO + H_2O}$$

RWGS is also gaining importance as it allows for the reversibility of the “normal” water gas shift reaction and therefore allows for configuring the H_2 to CO ratio of the reformed fossil fuel. Although CO can be synthesized with hydrogen to produce syngas, energetically it might not be too attractive since hydrogen was used to produce CO in the first step of the process. RWGS with the purpose to produce CO could therefore be more attractive for direct use in chemicals production.

6.2.4.2 Physical, Environmental, and Co-location Requirements

The production of carbon monoxide using RWGS is mainly dependent on the inputs of CO_2, water, power, and thermal energy. Due to the chemical stability of CO_2, it is a relatively unreactive molecule and so the reaction to convert it to the more reactive CO is energy intensive. Reaction temperatures of up to 1,000°C are required to optimally convert the CO_2 to CO.[127] RWGS is cited to have an energy demand of 3.5 GJ per tonne FT fuel. As around 2 units of CO are needed per unit of FT fuel, the energy demand per tonne of CO is around 7 GJ.[128] Of this energy demand, around 82% is thermal energy and the rest is power.[129]

The key inputs for this process are CO_2 and H_2 at ratios of 1.6 and 0.1 tonnes per tonne of carbon monoxide. Due to the large demand of hydrogen it is useful to co-locate a RWGS unit with a hydrogen supply or electrolyzer, for example. More importantly is that carbon monoxide is a chemical building block and is dangerous to transport due to its toxicity. Hence, depending on in which chemical process it is used for, it is sensible to co-locate it with that production.

6.2.4.3 Potential/Feasibility in New York State

Due to the prohibitive nature of transporting carbon monoxide, production is often integrated into the chemicals production process. NYS-based PVS Chemicals produces sulfuric acid and for which no carbon monoxide is needed. Another is Van De Mark chemicals, which is a leading producer of phosgene in State. Industrial production of phosgene requires passing purified carbon monoxide and chlorine gas through a bed of porous activated carbon, which serves as a catalyst.[130] It is expected that Van De Mark already has significant experience in handling carbon monoxide, so this may be a sensible location to explore the use of CCU-derived carbon monoxide.

6.2.4.4 Traditional Market Description and Potential Partners

The dominant conventional technology underlying the production of syngas is steam methane reforming, although gasification is also used to produce syngas from coal, such as in the Eastman Integrated Coal Gasification facility in Tennessee. New York State has one steam methane reformer located in Niagara Falls by Praxair, soon to be Linde Gas. This may be a sensible point of contact to further develop the idea of producing CO from hydrogen and CO_2 to reduce their plant emissions.

6.2.4.5 Natural and Other Constraints

Producing hydrogen from CO_2 and hydrogen requires about 70 kg of hydrogen per tonne of carbon monoxide produced. A constant low-carbon hydrogen supply is therefore important to ensure the continuity of the production process. Furthermore, the significant demand for power and thermal energy requires availability of low-carbon power and steam.

6.2.4.6 Strengths and Weaknesses

The RWGS process is energy intensive and makes up the dominant part of the production cost for carbon monoxide using this method. If this constraint can be met, RWGS can be an attractive low-carbon way to upgrade CO_2 to a higher energy state molecule, as currently carbon monoxide is almost exclusively produced from fossil fuels. However, due to the health risks involved, it is important that the chemical be integrated into the production of following chemicals and that cross-state transport is limited. A strength is that RWGS is gaining importance because it allows for the reversibility of the "normal" water gas shift reaction and therefore allows for configuring the H_2 to CO ratio of the reformed fossil fuel. There are other sustainable methods available to produce CO which are today more economically attractive than RWGS, such as biomass gasification or steam reforming of biogas.[131]

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing carbon monoxide using CO_2 is estimated to cost \$119 per tonne of avoided CO_2. This is assuming a baseline of conventional carbon monoxide production.

6.2.5 Methanol to Olefins

6.2.5.1 Technology Description and Stage of Development

The methanol to olefins (MTO) production pathway is based on the methanol production from hydrogen and CO_2 followed by the conversion of methanol to olefins. This final step is currently commercially deployed, with commercial operations mostly located in China. No MTO plants are currently present in the U.S.[132] This multistep process involves the partial reduction of CO_2 to methanol, followed by the dehydration of two methanol molecules to form one molecule of dimethyl ether, prior to its conversion to olefins (ethylene or propylene). The MTO technology has reached a TRL 9. The low-carbon methanol production from CO_2 and green hydrogen has reached a TRL 7, based on the maturity of the electrolysis process producing hydrogen from water.[133] The reactions involved in the MTO pathway are highlighted below. CO_2 first reacts with hydrogen to produce methanol (CH_3OH), which is then used to produce dimethyl ether (CH_3OCH_3), the intermediary to ethylene (C_2H_4) and propylene (C_3H_6):

Equation 3: $CO_2 + 3H_2 \rightarrow CH_3OH + H_2O$

Equation 4: $2\,CH_3OH \rightarrow CH_3OCH_3 + H_2O$

Equation 5: $CH_3OCH_3 \rightarrow C_2H_4 + H_2O$

Equation 6: $3\,CH_3OCH_3 \rightarrow 2\,C_3H_6 + 3H_2O$

Different processes are licensed: UOP's Hydro MTO technology based on the MTO-100 silicoaluminophosphate synthetic molecular sieve catalyst and Lurgi's MTP (methanol-to-propylene) process based on a proprietary ZSM-5 (zeolithe) type of catalyst supplied from Clariant (former Süd-Chemie). Other technology developers include ExxonMobil, Lurgi & Statoil, and SYN Energy Technology Co. together with Lummus Technology.[134] The fine-tuning of the catalyst allows to efficiently adjust the ratio of propylene and ethylene produced so operators can most effectively meet demand for those products.[135]

6.2.5.2 Physical, Environmental, and Co-location Requirements

The main benefit of the low-carbon process sequence for the MTO process in terms of CO_2 emissions originates from the low-carbon methanol production from captured CO_2 and H_2 issued from an electrolysis process, as this route has been shown to be a net CO_2 consuming process.[133] The key inputs for this process are CO_2 and H_2 at ratios of 3.1 and 0.4 tonnes per tonne of ethylene.

The MTO process's energy demand is composed of the energy demand for hydrogen-based methanol production as well as the energy demand for the MTO process, resulting in a total energy demand of 95.5 GJ per tonne of olefin produced (26.6 MWh/t). But 90.5 GJ per tonne of olefin produced is the energy requirement attributed to the hydrogen production via water electrolysis.[133] In comparison, the production of the olefins from naphtha requires 16.5 GJ per tonne of olefin but this does not include the energy required to obtain naphtha.

The MTO process will benefit from being co-located next to a power plant, which would provide energy as well as a source of CO_2 to be captured. The production scale of those CO_2-emitting plants would have to be verified in order to ascertain whether the required amount of CO_2 could ultimately be matched with the required scale of operation of the MTO process for the bulk production of olefins. Finally, water electrolysis is not a fully commercialized technology. At TRL 7, links with technology developers will have to be forged to determine the best set-up close to a suitable freshwater source.

6.2.5.3 Potential/Feasibility in New York State

This pathway has been selected based on the high-product demand for olefins in the U.S. and the fact it would render an accessible key intermediary such as alkenes from a non-fossil feedstock within the petrochemical industry. However, the majority of the olefin supply chain is located on the coast of the Gulf of Mexico, with no capacity in NYS. Here a novel supply chain based on the use of CO_2 and H_2 as feedstocks would have to be established.

6.2.5.4 Traditional Market Description and Potential Partners

The global ethylene propylene diene monomer market size was valued at USD 3.90 billion in 2017 and is projected to witness a CAGR of 6.5% from 2018 to 2025.[136] Many consumer products are produced from ethylene and propylene. Propylene is used to produce acrylonitrile, which is used to make clothing and fabrics, and high-performance polymers used in automotive parts, hard hats, and other hard plastic products. Ethylene is used to produce ethylene vinyl acetate copolymers, which are used to make adhesives, foams, medical devices, photovoltaic cells, and other products, as well as C4 olefins for the production of butadiene, an ingredient in synthetic rubber.

Within the ethylene value chain, manufacturers of ethylene vinyl acetate are located in the State (e.g., MSI, Inc.). This indicates the presence of a value chain relevant to several high-value applications in the medical sectors and in solar photovoltaics. For these applications, the sheets of plastic will be required to be of the highest purity grade possible. It is worth noting that DuPont has a facility producing ethylene vinyl acetate in New Jersey. Butylene-based rubber manufacturers are also present in NYS. Examples include Web Seal Inc. (ethylene acrylic, ethylene propylene), Advanced Rubber Products (polybutadiene rubber materials), and U.S. Rubber Supply Co. or Howard J. Moore Company Inc. (styrene-butadiene rubber compounds). Linking the ethylene and propylene value chains, manufacturers of acrylonitrile butadiene styrene can be found in the State (e.g., Emco Industrial Plastics and E&T Plastics Mfg. Co., both in Upstate New York. However, no acrylonitrile producers could be found.

Regarding the production of the two major plastics derived from olefins, polyethylene (PET) and polypropylene, Caplugs in Buffalo manufactures polyethylene and propylene plastic materials. A Saint Gobin site has also been identified in NYS where they produce performance plastics, attachment tapes, and sealants in Granville, using propylene.[137]

Other main chemicals based on ethylene or ethylene oxide will be discussed in the following sections.

6.2.5.5 Natural and Other Constraints

Carbon dioxide and H_2 are required to produce olefins. In terms of land demand, 2.2 m^2 per tonne of olefin produced are required based on the engineering design used for the MTO Jiangsu Sailboat plant built in China.[138] An important requirement to produce methanol from green hydrogen is the proximity to a source of freshwater to be able to carry out the water splitting to produce this required hydrogen. Salt water can also be used, after purification.

6.2.5.6 Strengths and Weaknesses

The opportunity to produce olefins from CO_2 is a particularly important potential outcome of CCU, as olefins are a key building block within the petrochemical industry. Short chain olefins are prominent base materials for the petrochemical industry, from which a number of downstream chemicals are produced and used in a wide variety of application sectors (i.e., adhesives, resins, plastics, fibers and textiles, additives). With the technology having been implemented at commercial scale,[139] this seems like a promising CCU pathway.

The U.S. olefin market is anticipated to grow in the future, exceeding 1,541 kilotons by 2025, due to the abundant availability of cheap, raw material (i.e., shale gas),[140] An additional total capacity of 10.7 million tonnes is planned to come online in the U.S. by 2022.[141] In order to reach commercialization, the MTO process will have to compete cost-effectively with the current production process using natural gas liquids—primarily ethane and propane.

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing olefins through MTO and methanol production using CO_2 is estimated to cost $343 per tonne of avoided CO_2. This is assuming a baseline of conventional olefins production. The realization of this pathway will be challenging as new investments in both hydrogen-based methanol plants and MTO plants would be necessary in New York State.

The MTO process has first been implemented in China, where coal is mostly used as a source of energy, making coal-based methanol production interesting and allowing China to reach resource independence. The adoption of the MTO process is seen there as an outlet for methanol production and the use of methanol as a chemical feedstock.[142] In the U.S., coal is being increasingly phased out to the benefit of lower cost natural gas, renewable energy, and regulations designed to reduce greenhouse gas emissions and protect public health.[143] The fit of this technology with the current policy and technological landscape in the U.S. will only make sense if methanol is obtained from capture CO_2 and H_2.

But a new supply chain based on these feedstocks could represent an opportunity for the State. As cheap propane, ethane, and methane are made available following growing shale gas exploitation in the U.S., this has caused the production of ethylene from ethane over propylene, as steam crackers shift from naphtha feed to lighter shale condensates.[144] This has caused a supply issue for propylene due to the strong growth in propylene demand compared with that of ethylene. Steam cracker units cannot fill this gap due to their low-propylene/ethylene ratio. Therefore, new production routes presenting higher propylene/ethylene ratios are sought after.[145] The MTO process catalyst being tunable for this specific purpose, presents again a strength with regards to the use of this pathway in the State.

6.2.6 Ethylene Oxide

6.2.6.1 Technology Description and Stage of Development

Ethylene oxide can be produced from CO_2 though the carboxylation of olefins such as ethylene using a metal catalyst.[146] This route has reached TRL 3 and is pursued by RTI International, who have developed a mixed metal oxide with tin, iron, and alumina catalyst.[147] Ethylene oxide is mainly used as an intermediate to produce ethylene glycol. The reaction of ethylene (C_2H_4) with CO_2 to produce ethylene oxide ($(CH_2)_2O$) is highlighted below.

Equation 7: $$C_2H_4 + CO_2 \rightleftharpoons (CH_2)_2O + CO$$

6.2.6.2 Physical, Environmental, and Co-location Requirements

Due to the relatively low maturity of the technology, not much is known on the physical and environmental requirements for an industrial-scale plant. The current catalyst in development by RTI International, does not make use of scarce metals such as rhodium, palladium, platinum, or iridium for catalysis applications. As an example, palladium catalysts are used in the oxidation of alcohols and carbon-carbon bond forming reactions, which is the backbone of chemical processing.[148]

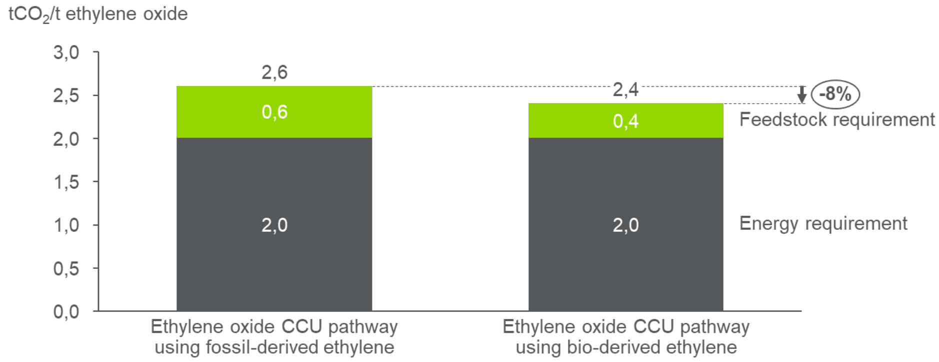
Epoxides, the class of cyclic ethers ethylene oxide belongs to, have a large market as monomers for polymers such as polycarbonates. Another main use is in the production of ethylene glycol, especially in the U.S. Other chemicals accessible from ethylene oxide include polyethylene glycols, ethylene glycol ethers, ethanol amines and ethoxylates.[149]

The global distribution of ethylene oxide production plants closely follows that of ethylene, as part of an integrated continuous process. Generally, ethylene plants are co-located with ethylene oxide plants as ethylene oxide is a chemical intermediate that cannot be directly used and is further reacted to produce a wide spectrum of products.[150] Ethylene oxide is reacted with carbon dioxide to form ethylene carbonate, which is then hydrolyzed to form (mono)ethylene glycol and carbon dioxide.[151] The U.S. is one of the major producers of ethylene together with China. Major U.S. ethylene producers include Chevron Phillips Chemical, DowDuPont, ExxonMobil, INEOS Olefins & Polymers, LyondellBasell, and Shell Chemicals.[152] These operations are all located near the Gulf of Mexico (i.e., in Texas and Louisiana) except for the new Shell site in Pennsylvania.[153,154]

The key inputs for this process are CO_2 and ethylene at ratios of 1.0 and 0.6 tonnes per tonne of ethylene oxide. This CCU pathway only makes sense if bio-derived ethylene issued from the production of bioethanol is used as a feedstock to produce ethylene oxide. Figure 23 illustrates how the emissions associated with this pathway decrease by 8% when using bio-derived ethylene instead of fossil-derived ethylene.

Figure 23. Difference in CO_2 Emissions for Producing Ethylene Oxide Using Fossil- or Bio-Derived Ethylene as Feedstock

Source: Inter-American Development Bank (IDB),[155]*ETSAP & IRENA,*[156] *Climate Policy Watchers,*[157] *Guidehouse analysis*



To keep transport costs of these feedstock as low as practically possible, proximity to industrial sources of CO_2 or C_2H_4 infrastructure for these commodities is advisable. This pathway could be implementable in NYS because bio-derived ethylene is accessible from ethanol production and the State possesses an ethanol industry. However, the scale of operation to allow the cost-effective production of ethylene oxide would have to be matched against the one of ethanol and ethylene.

6.2.6.3 Potential/Feasibility in New York State

Ethylene oxide is an important chemical intermediary within the petrochemical industry and the fact it could be accessed from CO_2 in the future is important knowing the volumes of ethylene oxide produced in the U.S. One producer of ethylene oxide was identified in NYS: Mil-Spec Industries Corp.

Furthermore, the potential deployment of this technology lies in the future since it has currently reached only TRL 3, compared to other CCU pathways such as MTO. Assuming an average maturation rate of two TRLs per decade, this pathway might reach commercialization before 2050.

6.2.6.4 Traditional Market Description and Potential Partners

Currently, ethylene oxide is commercially produced by the direct oxidation of ethylene. Ethylene oxide is used directly to produce fibers for both carpets and clothing and polyester resins used in plastic bottles and films. Ethylene oxide is the precursor to ethylene glycol, a chemical used in automotive antifreeze. A direct CCU pathway to produce ethylene glycol also exists, which is discussed in section 6.2.7. It was estimated that the direct route to ethylene glycol from CO_2 requires 1,904 kWh/tonne of ethylene glycol of both electricity and heat. In comparison, the production of ethylene oxide alone from CO_2 would require 10,873 kWh/tonne of ethylene glycol in heat and 300 kWh/tonne of ethylene glycol, making the direct pathway to ethylene glycol more energy efficient.

Ethylene glycols represent the single-largest outlet for ethylene oxide though, accounting for about 65% of the ethylene oxide market in 2018. But other dominant end uses include higher value derivatives such as carbonates, ethoxylates, ethanolamines, glycol ethers, polyethylene glycol, and polyether polyols (urethanes materials).[158,159]

To date, RTI International is reported to have developed this technology and is a likely partner for further development. Potential partners in establishing a green value chain to deploy CO_2-derived ethylene oxide should be sought in the markets described above, bar ethylene glycol. Due to the low-technology maturity, it is more likely that large multinational players with a sizeable R&D budget can play a role in advancing this technology. Manufacturers and end-users of ethylene oxide include Alfa Chemical Corp. (Kings Point), which distributes standard and custom chemicals including ethylene diamine (e.g., ethanolamine, ethylene dichloride, ethylene glycol, and ethylene oxide); and Abtex Corporation and Elastomers Inc. who manufacture urethanes in the State, making use of polyether polyols. It is worth noting GJ Chemical produces polyethylene glycol in New Jersey.

6.2.6.5 Natural and Other Constraints

The technology is reported to only need CO_2 and ethylene to produce ethylene oxide. Hence, further constrains in terms of required resources is expected to be limited. Due to the relatively low-maturity of the technology, not much is known on the land area requirements of an industrial-scale plant. The production of bio-ethylene is commercial however, and the land use is known. It has been reported the land usage for bio-ethylene produced from corn (as it is the case in the U.S.) would be 4,700 m^2 per tonne of bio-ethylene produced.[160]

6.2.6.6 Strengths and Weaknesses

The major weakness for this pathway is that ethylene oxide is mainly used to produce ethylene glycol and its production is usually captive. It is not widely traded as a commodity. Furthermore, the technology has yet to mature. Apart from RTI International's catalyst development for the production of ethylene oxide from CO_2, no major technology developer was identified. If it were to materialize however, it could serve a sizeable domestic and global market that is expected to grow. The ethylene oxide market was valued at \$45 billion in 2018 and is projected to reach \$65 billion by 2024 (6.3% CAGR over the forecast period).[161]

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing ethylene oxide using CO_2 is estimated to cost \$323 per tonne of avoided CO_2. This is assuming a baseline of conventional ethylene oxide production.

6.2.7 Ethylene Glycol

6.2.7.1 Technology Description and Stage of Development

An electrochemical reduction of CO_2 to polyols ($(CH_2OH)_2$) is possible according to the reaction below with hydrogen:[102]

Equation 8: $$2CO_2 + 3H_2 \rightleftharpoons (CH_2OH)_2 + 2OH$$

Literature on the electrochemical reduction of CO_2 to ethylene glycol production[162,163] shows Toshiba has developed a technology using photo-electrochemical processing. A molecular catalyst which is an imidazolium salt is absorbed onto a metal surface, suppressing hydrogen production, and enabling direct conversion of CO_2 to ethylene glycol in an aqueous solution.

The range of TRL reported is TRL 3-7.[102] A patent to the technology is pending and Toshiba is reported to aim for commercialization in the next decade.

Covestro has developed the Cardyon process to produce polyols from traditional feedstock and CO_2. Since June 2016, Covestro has been operating its own production plant at its site in Dormagen, Germany. It has an annual capacity of 5,000 tonnes.[164] This process is different from the above direct reduction as it uses propylene oxide as a feedstock to synthesize polyols using a double metal cyanide catalyst.[165] This pathway is not further discussed here.

6.2.7.2 Physical, Environmental, and Co-location Requirements

Due to the relatively low maturity of the technology, not much is known on the physical and environmental requirements for an industrial-scale plant.

Typically, conventional ethylene glycol production is located near ethylene or propylene crackers that produce chemical derivatives such as polyols. This will not be needed for this electrochemical process for it only requires CO_2, hydrogen, and sunlight as inputs.

Ethylene glycol is used as an anti-freezing agent and to manufacture polyester fibers (PET) and resins. Production of these goods exists in the State by companies such as Terphane, DuPont, and Momentive Performance Materials. If these production processes indeed use ethylene glycol as feedstock, a future ethylene glycol production plant could be located close to polyester fiber or resins production sites operated by such companies and potentially even use part of their conventional production flue gases.

The key inputs for this process are CO_2 and H_2 at ratios of 1.4 and 0.1 tonnes per tonne of ethylene glycol. To keep transport costs of these feedstock as low as practically possible, proximity to industrial sources of CO_2 or infrastructure of these commodities is advisable.

6.2.7.3 Potential/Feasibility in New York State

The CCU pathway to produce ethylene glycol was shortlisted because out of the relatively less mature CCU technologies it produces a global commodity to a market that consumes over 27 megatonnes of ethylene glycol annually. There are ethylene glycol producers identified in NYS at present who could benefit entering this market, and as a result, existing infrastructure and established value chains could be used.

Potential deployment of this technology in the State may happen before 2030, as Toshiba was reported to plan for commercialization in the next decade as described above. A more conservative approach would be to start with the current average TRL 5 and assume an average maturation rate of two TRLs per decade. When viewed this way, this pathway might reach commercialization in the mid-2040s.

6.2.7.4 Traditional Market Description and Potential Partners

Conventional ethylene glycol serves as feedstock to produce polyester film and fibers, PET, antifreeze and coolant and other niche markets. Polyester fiber is the largest application[166] and sees an increased adoption in the furniture market as cushioning material.[167] Key industrial sectors that use ethylene glycol are automotive, textiles, furniture, and food and drink.

To date, Toshiba is reported to have developed this technology and is a likely partner for further development.

Potential partners in establishing a green value chain to deploy CO_2-derived ethylene glycol should be sought in the markets described above. Due to the low-technology maturity, it is more likely that large multinational players with a sizeable R&D budget can play a role in advancing this technology. Dupont, a Down Chemical subsidiary, owns and operates plants in NYS that produce films and fibers.[168] Momentive Performance Materials is a privately-owned specialty chemicals company with headquarters in the State.[169] It is worth investigating if these companies could indeed play a role in developing the technology further.

Further downstream, consumer-facing companies that look to offer green products might be interested in partaking in such a green value chain—and might be able to raise a premium for the resulting product. Some companies with retail activities in NYS that could potentially be interested in such a scheme are IKEA, Coca-Cola, and Starbucks.

6.2.7.5 Natural and Other Constraints

This technology is reported to only need CO_2 and H_2 to produce ethylene glycol. Hence, further constrains in terms of required resources is expected to be limited. Due to the relatively low maturity of the technology, not much is known on the land area requirements of an industrial-scale plant.

A process that requires catalysts can be sensitive to catalyst deactivating mechanisms such as poisoning or sintering due to unwanted impurities in the feedstock gas stream. Hence, it is likely the technology used to synthesize propylene glycol from CO_2 will need high-purity CO_2.

6.2.7.6 Strengths and Weaknesses

A weakness for this pathway is its relatively low maturity. Besides the scientific materials cited above, not much is public on recent development to progress this technology. Once commercial, it could serve a sizeable domestic and global market that is expected to grow.

A threat to commercial viability of CO_2-based ethylene glycol is the competition of bio-based ethylene glycol derived from the bio-based ethanol value chain. Both can arguably be labeled a green product, where bio-based ethylene glycol is already commercially deployed. Coca-Cola uses bio-based ethylene glycol in a bottle called the PlantBottle, making the overall PET about 30% renewable.[170] The process to produce bio-based ethylene glycol continues to receive attention from technology developers such as Avantium and Braskem that are looking to improve efficiency and reduce cost.[171]

Another threat to commercial viability is the connection of polyester fibers to microfibers and their significant contribution to plastic pollution such as the so-called “plastic soup;” the growing pollution of the sea by plastics.[172] Carbon dioxide-based ethylene glycol by itself does not solve the large environmental problem that occurs in the use phase of one of its major applications; the washing of clothes made from ethylene glycol releases large amounts of microplastics that largely end up in rivers and oceans.

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing ethylene glycol using CO_2 is estimated to yield revenue that exceeds projected production costs. This is assuming a baseline of conventional ethylene glycol production.

6.2.8 Formaldehyde

6.2.8.1 Technology Description and Stage of Development

Formaldehyde (CH_2O) can be produced from CO_2 in different ways. The synthesis route analyzed here was reported in 2014 by a group of French scientists[173] and can be described as follows:

Equation 9: $\boldsymbol{2CO_2 + 2H_2 \rightleftharpoons 2CH_2O + O_2}$

The reduction is done using a polyhydride ruthenium complex that reportedly enables up to 74% selectivity. Using hydrolysis, amine, and formalin solutions are produced.

As this synthesis was proven in laboratory conditions, the route is classified as TRL1-3.[102]

6.2.8.2 Physical, Environmental, and Co-location Requirements

Due to the relatively low maturity of the technology, not much is known on the physical and environmental requirements for an industrial-scale plant.

Conventional formaldehyde is produced from methanol. In fact, 35% of methanol today is used to produce formaldehyde.[174] Co-location with methanol production will not be required for the CO_2-derived production route as methanol is not a required feedstock.

Formaldehyde is used as a chemical building block. Typical applications are its use in synthesizing resins, disinfectants, plastics, alcohols, and solvents. A physical location close to existing production plants for these products may reduce transport cost.

The key inputs for this process are CO_2 and H_2 at ratios of 1.5 and 0.1 tonnes per tonne of ethylene glycol. To keep transport costs of these feedstock as low as practically possible, proximity to industrial sources of CO_2 or infrastructure of these commodities is advisable.

6.2.8.3 Potential/Feasibility in New York State

This CCU pathway to produce formaldehyde was shortlisted because out of the relatively less mature CCU technologies it produces a global commodity to market that consumes over 37 Mtonnes of formaldehyde annually. There are formaldehyde producers identified in NYS at present who could benefit entering this market, and as a result, existing infrastructure and established value chains could be used.

Potential deployment of this technology in NYS lies further in the future. Assuming an average maturation rate of two TRLs per decade, this pathway might reach commercialization before 2050.

6.2.8.4 Traditional Market Description and Potential Partners

Formaldehyde is used as a chemical building block. Typical applications are its use in synthesizing resins, disinfectants, plastics, alcohols, and solvents. An estimated 26–30 mil tonne of formaldehyde currently is produced globally as formaldehyde is a key precursor to a number of materials used in automobiles, electrical equipment, household textile, and wood furniture (e.g., resins and adhesives).[175,176] Of these applications, resins account for more than half of the total market.[177]

Companies active in manufacturing resins, plastics, and other high-value chemicals have a presence in the State. Examples are DuPont, Eastman Kodak Company (headquarters in Rochester), and Momentive Performance Materials (headquarters in Waterford).

Potential partners in establishing a green value chain to deploy CO_2-derived formaldehyde should be sought in the markets described above. Due to the low-technology maturity, it is more likely that large multinational players with a sizeable R&D budget can play a role in advancing this technology.

Using formaldehyde as a liquid hydrogen carrier and therefore as an energy transport and storage medium is a potential application, but this application is in its infancy.[178]

6.2.8.5 Natural and Other Constraints

This technology is reported to only need CO_2 and H_2 to produce formaldehyde. Hence, further constrains in terms of required resources is expected to be limited. Due to the relatively low maturity of the technology, not much is known on the land area requirements of an industrial-scale plant.

A process that requires catalysts can be sensitive to catalyst deactivating mechanisms such as poisoning or sintering due to unwanted impurities in the feedstock gas stream. Hence, it is likely the technology used to synthesize propylene glycol from CO_2 will need high-purity CO_2.

6.2.8.6 Strengths and Weaknesses

A weakness for this pathway is its relatively low maturity. Besides the scientific materials cited above, not much is public on recent development to progress this technology. Once commercial, it could serve a sizeable domestic and global market that is expected to grow.

Used as an energy storage medium, the production of formaldehyde could support electricity grid stability. This application will however face competition from numerous other chemical storage technologies, such as hydrogen, methane, or methanol. It remains to be seen which of these applications will be best suited for different storage requirements needed to balance the grid on hourly, daily, or even seasonal timeframes.

Section 6.3 shows the potential cost and abatement for this technology once it is deployed at scale, compared to other shortlisted technologies. By 2050, producing formaldehyde using CO_2 is estimated to cost $1,239 per tonne of avoided CO_2. This is assuming a baseline of conventional formaldehyde production.

6.2.9 Formic Acid

6.2.9.1 Technology Description and Stage of Development

Formic acid can be derived from CO_2 hydrogenation (TRL 6). A ruthenium- and phosphino-based catalyst can be used. Det NorskeVeritas (DNV) and Mantra Venture Group have both reported results on the production of formic acid by electroreduction and have scaled-up their process in recent years. The reaction scheme below describes the reaction of CO_2 with hydrogen to produce formic acid (HCOOH).

Equation 10: $$CO_2 + H_2 \rightleftharpoons HCOOH$$

DNV has a small-scale demonstration electroreduction plant producing 350 kg of formic acid every year, while the Mantra Venture Group designed a 35 tonnes a year formic acid pilot plant. Further research is focusing on the development of a continuous process for the electroreduction, solvent use and material enhancement for the electrode.[179]

The electrochemical reduction of CO_2 is still behind in terms of TRLs compared to catalytic pathways but has the advantage that it can be fully developed at atmospheric temperature and pressure. This is important to enable the energy transition with an increasing share of intermittent renewables. The efficiency of electrochemical reduction of CO_2 needs to improve. This will require the further development of more efficient and durable materials for the cathode (CO_2 reduction reaction) and the anode (O_2 evolution reaction). Electrolytes presenting better conductivity are needed as well to allow for sufficient ion mass transport in solution. All would contribute to improving the overall performance of the technology.[180] Formic acid fuel cells are aimed at powering small electronic devices such as phones on top of its use as a transport fuel.

6.2.9.2 Physical, Environmental, and Co-location Requirements

Formic acid is used in product formulation or article treatment rather than as a chemical building block, which indicates the chemical can possess a market of its own, as opposed to ethylene oxide. The exception here is that it can be used as a simple acid in the pharmaceutical sector.

The key inputs for this process are CO_2 and H_2 at ratios of 1.0 and 0.04 tonnes per tonne of formic acid, respectively. To keep transport costs of these feedstock as low as practically possible, proximity to industrial sources of CO_2 or infrastructure of these commodities is necessary. Again, the production of green hydrogen (using renewable resources) through water splitting will require access to a freshwater source.

6.2.9.3 Potential/Feasibility in New York State

Formic acid has been selected as part of this assessment for its potential future application as a fuel and hydrogen carrier within the context of the development of a hydrogen and methanol economy. NYSERDA is interested in linking the present study on CCUS to the electrification of transport and formic acid, as a CCU application offers a link to fuel cell technology that could potentially be used in automobiles, hence its selection in this CCUS study. In their original form, fuel cells are electrochemical cells where hydrogen and oxygen are combined to produce water and electricity. The technology involves the chemical energy of a fuel (hydrogen or formic acid) combined with an oxidizing agent (often oxygen) through a redox reaction involving the transfer of electrons and hence, the production of electricity. Formic acid has been considered as a fuel over hydrogen as the storage of formic acid is easier and safer than that of hydrogen as it does not require low temperatures or pressures. Furthermore, formic acid is non-flammable.

Plug Power is an American company headquartered in NYS engaged in the design and manufacturing of hydrogen fuel cell systems (PEM fuel cells). This is a commercial stage company as opposed to a demonstration company. It also targets applications in vehicles, as opposed to Fuel Cell Energy, another American fuel cell company commercializing molten carbonate fuel cells aimed at the stationary power market.[181] Toyota has commercialized its Mirai hydrogen vehicle in the U.S. All the above companies could play an instrumental role in developing the formic acid CCU pathway in the State. Partnering with them would be the first step toward enabling the CO_2-derived formic acid value chain.

6.2.9.4 Traditional Market Description and Potential Partners

More conventionally, formic acid finds its applications in textiles, pharmaceuticals, and food chemicals, due to its activity as a fungicide, acid, and biocide.[182] Traditionally, the leather and tanning industry has been the largest consumer of this compound. Tanning, food production, and textile treatment applications are all present in New York State.

No formic acid plant can be found in the State. The only known production plant in the U.S. is operated by BASF at its Geismar site in Louisiana since 2015 (50,000 tonnes per annum capacity).[183] NYS users of formic acid exist, at least in the food formulation and pharmaceutical sectors, which could be used to establish a value chain for this CCU pathway. Examples include Barilla America, Kraft Heinz, Seneca Foods, and Mott's as food manufacturers and Bristol-Meyer Squibb, Medeva Pharmaceuticals, and Showa America among other pharmaceutical companies.

6.2.9.5 Natural and Other Constraints

As highlighted above, the technology is reported to only need CO_2 and H_2 to produce formic acid. However, an important requirement of this technology is the proximity to a source of freshwater to be able to carry out the water splitting to produce this required hydrogen. Salt water can also be used, after purification. Further constrains in terms of required resources is expected to be limited.

This technology, based on electrochemistry reaction, falls in the modular technology class where economy of scale plays a lesser role compared to the production of bulk chemicals such as ethylene. Scale-up of an electrochemical process is achieved through the multiplications of the electrochemical cells linked in parallel where formic acid is produced as opposed to the increase of the equipment sizing. The challenge for electrochemical processes is to design a multi-cell ‘‘industrial’’ reactor using an economically viable continuous process.

6.2.9.6 Strengths and Weaknesses

A major weakness for this pathway is its low maturity, especially when considering the use of formic acid as a hydrogen carrier. The first integrated power supply unit that can convert formic acid to hydrogen fuel electricity production has been reported last year by a team of scientists in Switzerland at École Polytechnique Fédérale de Lausanne (EPFL). The technology circumvents the problem of storing hydrogen without compression or cooling. The HYFORM-PEMFC is reported to produce 7,000 kWh per year, and its nominal power is 800 W, with an electrical efficiency (from formic acid to electricity) of 45%.[184] Additionally, the use of formic acid as a hydrogen carrier requires the development of the hydrogen infrastructure in the U.S., which is still in its early market phase.[185]

Should the process reach commercialization, which is unlikely before 2030, the use of formic acid in both consumer-facing products and as an energy carrier (batteries and hydrogen storage) is a strength compared to chemicals such as ethylene oxide, which do not find applications as such and are part of a longer and more complex value chain. Furthermore, formic acid is not the only available product from the electrochemical reduction of CO_2. The electrochemical conversion of CO_2 is also capable of synthesizing methanol, carbon monoxide, methane, dimethyl carbonate via the use of different catalysts.[186]

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing formic acid using CO_2 is estimated to cost $3,219 per tonne of avoided CO_2. This is assuming a baseline of conventional formic acid production.

6.2.10 Refrigerant Gas

6.2.10.1 Technology Description and Stage of Development

Refrigerants are used in heat pumps and refrigeration cycles and undergo phase transitions from liquid to gas phase and vice versa. The market for refrigerants is changing rapidly, mainly due to the ozone-depleting effects of conventional refrigerants such as chlorofluorocarbons (CFCs). This has since the 2000s led to the replacement of ozone-depleting substances with hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs), which were not ozone depleting but still had a high-global warming potential.[187] In 2016, world leaders decided to phase out these kinds of refrigerants in the Kigali Amendment to the Montreal Protocol.[188] This has led to substantial interest into the use of "natural" refrigerants such as ammonia, carbon dioxide, and hydrocarbons.[189]

The use of carbon dioxide as a refrigerant (with refrigerant designation R744) has become popular due to its safety, as it is non-flammable and as non-toxic as most fluorocarbon refrigerants. When used as a refrigerant, CO_2 generally needs to be operated at a higher pressure than other refrigerants. This makes the design and installation more challenging and costlier, whereas the use phase is more economical. In terms of compatibility with existing system lubricants, it cannot be used with polyol ester and polyvinyl ether lubricants.[189]

The CO_2 as a refrigerant market in the U.S. has experienced considerable growth over the past years, with 52 stores now operating transcritical systems with CO_2. New technologies are becoming available that would also allow these developments in the warmer southern states and in cascade systems U.S.-wide. In fact, United Natural Foods in Montgomery, NY opened a new distribution center in 2014 operating with CO_2 as a refrigerant.[189]

A standard CO_2 refrigeration system would use a load of about 150 kg CO_2 per year, of which 5% leaks away. Considering the scale of use, the environmental benefit of this CCU application does not lie in the storage of CO_2 in the system, but rather the displacement of global warming inducing HFCs and PFCs. Additionally, energy savings during the use phase compared to conventional refrigerants can be observed.[190] Avoided emissions fully depend on the type of refrigeration system the CO_2 system is compared to. However, to get a sense of scale, a system in France reported a savings of 960 tCO_2e per year compared to a standard HFC-404A DX system. System size was 800 kW medium temperature and 105 kW low temperature for an 8,000 m^2 mall.[191] U.S.-based Sobeys reported that some of their supermarket systems carry approximately 1,250 kg of HFC refrigerant and that a significant portion (up to 30%) of their direct climate footprint is attributable to refrigerant leakage. Average rates of leakage are between 10% to 30% and a 1 kg leak of standard R-507 refrigerant is equivalent to 3,985 kg of CO_2 emissions.[191] This illustrates the significant climate benefits of switching to CO_2 based systems.

6.2.10.2 Physical, Environmental, and Co-location Requirements

Due to its long atmospheric lifetime, CO_2 as a refrigerant does not lead to the byproduct formation or decay that was observed in CFCs and HFCs.

6.2.10.3 Potential/Feasibility in New York State

United Natural Foods has demonstrated that deployment in the State is feasible, together with seven stores. Lower ambient temperatures generally favor the use of CO_2 transcritical systems, whereas cascade and secondary systems are favored in the southern U.S. states and makes the implementation of CO_2 as a refrigerant slightly more challenging. Technological breakthroughs are also allowing more transcritical systems in warmer climates.

6.2.10.4 Traditional Market Description and Potential Partners

Transcritical CO_2 systems can almost be called a traditional market already due to its fast development. Abroad, these systems are developing even faster, with Europe seeing a growth of 117% from 2011 to 2013 to almost 3,000 systems and 5,200 in 2015. This compares to around 50 in the U.S. (in 2015). Leading companies globally in CO_2 based refrigeration systems include Lawson and AEON, whereas in the U.S. Sobeys and Aldi are the main companies. Some leading technology developers include Carnot, Carel, Danfoss, Carrier, and Enex.[192] All but Enex are located in New York State.

6.2.10.5 Natural and Other Constraints

Infrastructural constraints should be considered, due to the different infrastructural requirements of CO_2 transcritical systems compared to standard HFC systems.

6.2.10.6 Strengths and Weaknesses

Users perceive the higher upfront installation cost compared to HFC-based systems as a downside (~1.5 times higher),[191] as well as concerns about poorer efficiency of CO_2 transcritical systems in warmer ambient temperatures.

6.2.11 Synthetic Kerosene

6.2.11.1 Technology Description and Stage of Development

Synthetic kerosene can be produced from CO_2 and hydrogen using Fischer-Tropsch (FT) synthesis after RWGS. RWGS is the same process used to produce carbon monoxide as detailed in section 6.2.4. A simplified reaction scheme is as follows:[128]

Equation 11: **RWGS:** $$CO_2 + 3H_2 \rightleftharpoons CO + 2H_2 + H_2O$$

Equation 12: **FT:** $$CO + 2H_2 \rightleftharpoons \text{-}CH_2\text{-} + H_2O$$

The technology is still under development and has not yet been commercialized. The combination of the RWGS reaction and the (FT) reaction to synthesize hydrocarbon fuels from syngas was first demonstrated on a pilot scale in South Korea in the CAMERE project, which used the reverse shifted CO_2 for methanol production. Sunfire and Soletair have more recently used the RWGS process in the production of blue crude—that is, synthetic crude oil. The technology is in TRL 7.

In principle, the FT process is flexible in producing a broad range of hydrocarbons by changing process conditions such as temperature, pressure, and feedstock ratio. A lower temperature regime creates linear hydrocarbon waxes ($-CH_2-$), which can be hydrotreated and processed further into synthetic kerosene. Depending on the selectivity of hydrocracking, hydrocarbons outside of the kerosene range may be produced, such as diesel or methane. These products may serve different markets with different competing fuels and could prove to be a disadvantage. This will be further discussed under Strengths and Weaknesses.

6.2.11.2 Physical, Environmental, and Co-location Requirements

The energy required to produce synthetic kerosene using RWGS is 3.5 GJ per tonne of kerosene, excluding hydrogen feedstock where it assumed the excess heat from the exothermic FT process is recuperated to supply heat for subsequent water evaporation.[128]

The hydrogen demand per tonne of kerosene in this process is 0.33 tH_2, and the process utilizes 3.11 tCO_2 per tonne of kerosene. Due to the large demand of hydrogen, it is useful to co-locate such an industrial plant with a hydrogen supply (e.g., large electrolyzer modules). Hydrogen from electrolysis requires freshwater available in sufficient volumes.

Local transport of kerosene is usually done via trucking or pipeline. Larger NYS airports have extensive pipeline infrastructure to source jet fuel. Locating a synthetic kerosene production facility in proximity of such existing infrastructure may help reduce transport cost and limit environmental impact compared to constructing new pipeline infrastructure. The fuel considered here is drop-in and as such is compatible with existing infrastructure. As analogue, most successful biofuel operations blend biofuel in central fuel farms and use existing hydrant systems at airports.

6.2.11.3 Potential/Feasibility in New York State

If today's global demand for jet fuel were to be fully met through CO_2-derived synthetic kerosene, this would consume close to 800 megatonnes of CO_2 per year.[193] The State's consumption of jet fuel would equate close to 14 million tonnes of CO_2 per year following the same hypothetical line of reasoning.[194] There is no kerosene production taking place in NYS, however, leading to an initial deselection of this technology. For reasons outlined below, this technology was added despite the absence of local production.

The State is home to 162 public airports and consumed close to 35 million barrels of jet fuel in 2017.[194] Aviation is often considered a transport subsector that is hard to decarbonize. With stringent requirements on gravimetric energy density and safety, deployment of non-kerosene fuel types is not expected soon. This in contrast to other forms of transport such as passenger cars, where many sustainable alternatives exist (e.g., electrification or hydrogen). Moreover, aviation requires one fuel that is available at all airports. Facilitating multiple fuel infrastructure at all airports is considered cost-prohibitive.[195] The synthetic kerosene considered here is “drop-in,” which means it is chemically near identical to conventional Jet-A fuel, the globally accepted standard kerosene blend for aviation. Other technologies do exist to produce sustainable aviation fuel. These are considered under Strengths and Weaknesses.

6.2.11.4 Traditional Market Description and Potential Partners

Traditional kerosene is produced through distilling oil. This is done at oil refineries operated by traditional oil companies such as Phillips 66, ExxonMobil, or Shell. As mentioned above, these operations do not take place in NYS. Many larger, international oil companies are vertically integrated and therefore have operations from producing crude oil all the way down to final sale. Such companies typically have considerable R&D budget and increasingly focus on low(er) carbon fuels, thus could be a partner in developing local production and market for synthetic kerosene.

Sustainable aviation fuels (SAF) are being developed to reduce the footprint of flights. SAFs roughly come in two different types: fuels produced from biological feedstock (biomass) or produced from hydrogen and industrially (or atmospherically) sourced carbon. The main hurdle for both types to overcome is cost competitiveness. Conventional kerosene is relatively cheap and is therefore difficult to compete with on cost alone. However, bio-based SAF pathways are less expensive than the synthetic, hydrogen-based routes. Some operators have overcome these costs through corporate programs in which customers pay a premium for SAF to lower their travel footprint, and there have been thousands of commercial passenger flights to date fueled with blended SAF.[196] Some airlines have also entered long-term, bio-based jet fuel offtake agreements to reduce their footprint. For example, jetBlue signed a ten-year agreement with bioenergy producer SG Preston to purchase more than 33 million gallons of blended jet fuel per year to supply flights in New York-metropolitan area airports.[197] Partnerships should be explored with airlines such as these that have ambitious CO_2 targets and motived to invest in synthetic kerosene plants. Another partnership to explore is with SkyNRG who has the most extensive track record in SAF supply chain development and is involved in several innovation projects.

Synthetic kerosene can be produced from industrial effluent CO_2 in several ways. LanzaTech developed a process that uses anaerobic bacteria to produce ethanol from syngas (a mixture of CO and H_2). Today, rather than sourcing CO_2 and converting this to syngas, this process is applied directly to effluent CO. LanzaTech partnered with Virgin Atlantic and produced 1,500 gallons of jet fuel in 2017.[198]

The process focused on in this study to produce synthetic kerosene from CO_2 is different to the LanzaTech process. It combines hydrogen and CO_2 to produce syngas through RWGS and takes this syngas to produce kerosene using FT. One of the companies developing this pathway is, for example, Sunfire. This German company offers a co-electrolysis system that produces syngas from CO_2 and water in a single step using waste heat and renewable power.[199] They are working with Nordic Blue Crude, an FT technology provider and Climeworks, a DAC technology provider to design a two-step process to go from electricity, water, and CO_2 to what they refer to as e-Crude, or liquid hydrocarbons.[134] The explainer box later in this section provides more information on Sunfire and its technology outlook.

6.2.11.5 Natural and Other Constraints

Producing synthetic kerosene requires hydrogen; an estimated 0.33 tonnes of H_2 for every tonne of kerosene produced. An important requirement is a source of freshwater to carry out the water splitting to produce the required hydrogen. Salt water can also be used if first purified. An industrial scale FT plant can be sizeable. Using the world-scale Quest GtL plant in Qatar as a reference, a FT plant excluding carbon capture can take up 230 ha.

6.2.11.6 Strengths and Weaknesses

A key strength for synthetic kerosene is that it will serve a market with a lack of sustainable alternatives, as described above. Full electrification for long-haul flights is not expected to materialize before 2050.[200] Fuels besides kerosene often do not meet gravimetric density requirements. With an intrinsic international market like jet fuel, a global standard is key for uptake. However, there is one competing sustainable alternative: biofuels. Deployment of biofuels is ongoing today, but availability of sustainable feedstock is a concern.

The key hurdle to overcome for SAF, be it biofuels or synthetic, hydrogen-based fuels, is cost competitiveness. Bio-based jet fuel prices are higher than fossil kerosene.[201] Synthetic kerosene costs are higher still. In a recent European aviation roadmap, synthetic kerosene is projected to be six times more expensive compared to conventional jet fuel by 2020.[202] At the same time, biofuels are produced at costs closer to a factor of two or three times the conventional jet fuel, which will play a bigger role in the near term to reduce the footprint of flying.[203] Such cost differences are difficult to mitigate. To level the playing field, production costs of synthetic kerosene must come down, and local adoption could be incentivized through legislation. A carbon tax, for example, could help to lower the difference between conventional and sustainable aviation fuels.

The process described here results in production of a range of hydrocarbons, also outside of kerosene, like diesel or methane. As these products do not serve aviation, other markets with more competing sustainable alternatives will come into play. To avoid such increased competition, increased selectivity towards kerosene will need to be a key R&D topic. In general, for CCU technologies using hydrogen this a relevant barrier, as CO_2 hydrogenation may produce a range of hydrocarbon by-products. Research into a catalysis that boosts selectivity is ongoing for many such CCU technologies.

As previously explained in section 1.2.1, CCU technologies that deliver fuels face one fundamental problem: using the product re-releases CO_2. In a setup where local industrial effluent CO_2 is sourced, this released CO_2 still contributes to increasing global warming. The industrial entity and the airline operator only have one carbon credit to share, and they are likely inclined to both claim this credit fully for themselves. This double counting of carbon reduction is to be avoided. Regulation is required to prevent double counting but also ensures there is sufficient incentive for both parties to partake in such a CO_2 re-use scheme. When biogenic or atmospheric CO_2 is sourced, this is no longer an issue.

Section 6.3 shows the potential cost and abatement for this technology once deployed at scale, compared to other shortlisted technologies. By 2050, producing synthetic kerosene using CO_2 is estimated to cost $1576 per tonne of avoided CO_2. This is assuming a baseline of conventional kerosene production.

Synthetic Fuel Technology Case Study: Sunfire

The production of synthetic fuels such as kerosene from CO_2 is a quickly developing technology space. Kerosene specifically has the promise of a large-volume market because a lack of alternative fuel sources, as explained elsewhere in this section. This box is a deep dive into one specific technology provider, Sunfire, and is largely based on an interview with one of Sunfire's representatives.[a]

Cost Developments of Producing Synthetic Fuel

In section 6.3.2, a summary of cost estimates for CCU technologies is provided. It shows that for the technologies to produce synthetic kerosene to become economically viable, they need to dramatically lower in costs. Sunfire develops a high-temperature co-electrolysis system producing synthesis gas in a single step using water, CO_2, and green electricity. With this route, they claim significant reduction in investment and operating costs for Power-to-X projects such as e-Crude.[b] Combined with a Fischer-Tropsch (FT) reactor, this syngas can indeed be converted into synthetic waxes, that in turn can be refined to fuels such as kerosene. The two major cost drivers are both related to scale: the scaling of electrolyser production will lower cost and the scaling of fuel plants will allow synthetic fuels to compete with incumbent fuels. Sunfire claims that a pilot plant scheduled to start operating in Norway in 2023 can already reach a level of a little over $2 per litre of product, in part because of the low-cost green electricity in constant supply from hydropower sources in Norway and because it includes efficient heat integration and other technology improvements. On the longer term and at much larger scale, $1.50 per litre should be reachable according to Sunfire. Note these projected cost levels are a factor of three lower than the projected levels in this study (section 6.3.2, Figure 27). Their assumptions such as cost of capital, renewable power source, and uptime differ in this study; Sunfire assumes hydropower, whereas this study assumes solar power. Nevertheless, this shows that monitoring current technology developments is paramount. Step-change breakthroughs in technology are notoriously difficult to predict.

Policy Required to Support Synthetic Fuels

Blending quotas for SAFs will provide tremendous support. There are discussions about SAF blending in European countries, but this is mostly related to biofuels. Technically, such quotas could equally be applied to e-fuels. At the same time, regulation can be a barrier. Regulatory uncertainty can be a hurdle towards further technological development. Regulation, such as those under discussion in the EU that will prescribe allocation rules of CO_2, may mean only kerosene synthesized from CO_2 from DAC and green electricity from dedicated renewables would be recognized as “lower carbon.” Sunfire believes the intermittency of (dedicated) renewables such as solar and wind may pose an economic hurdle for Power-to-X technology such as co-electrolysis. Regulation allowing Power Purchase Agreements or siting close to constant renewable energy, such as geothermal or hydropower could be a solution to overcome intermittency.

Promising Markets for Power-to-X

Today's principle is the following: the longer the hydrocarbon molecule, the higher the value. This means that in today's markets, the synthetic waxes produced from co-electrolysis and FT are more valuable than the refined fuels from it. As a result, Sunfire is looking for high-value markets to directly sell their product, such as cosmetics and pharmaceuticals. Volumes in these markets are small compared to fuels, but very large compared to current production of Power-to-X products such as e-Crude.

Longer term, with larger scale and lower cost, fuels could be next. FT-waxes could be fed directly into existing refineries. This is a capital-efficient way of producing e-fuels, provided certificate systems will be in place to account for these molecules. At present, ESTM-norms prohibit this upfront blending of crude and only allow blending of synthetic kerosene with conventional kerosene after their respective production. There is work ongoing to change this. Sunfire believes there is no technical reason to prevent upfront blending.

Sunfire sees interest in their technology globally. They are active in Europe but see interest from Japan and the U.S. as well. Major corporations with a strong sustainability agenda are key partners in scaling further.

Scaling Bottlenecks

There is no principle limitation to the scale of Sunfire's technology in combination with FT. The latter is a commercial technology deployed at scale globally in gas-to-liquid plants and coal-to-liquid plants. Sunfire announced a pilot project of 20MW in Norway. The first commercial plant will likely be a ten-fold increase of this capacity. Co-electrolysis is a modular setup and is therefore not directly limited. The entire production pathway from electricity to wax is most capital-efficient at high uptime. Therefore, Sunfire believes that using their technology as a congestion tool is not a feasible business case. At present, the first bottleneck is the availability of renewable energy. Since the technology is autonomous, especially when DAC is the source of CO_2, it can be located next to wherever cheap and abundant renewable electricity is available.

Key Lessons for NYSERDA

- **Monitor technology developments closely.** The cost levels predicted by technology developer Sunfire are up to a factor of three lower than the 2050 projection in this study. Even though the cost levels predicted by Sunfire are based on different assumptions and have yet to materialize, the difference in projection does show the importance of continued monitoring of developments.
- **Lower cost synthetic fuel technology requires high uptime**, limiting the technology's capability to function as a congestion management tool. Because the technology is capital intensive, high-operational uptime is needed to reduce the marginal production cost. This is at odds with a congestion managing technology that by design needs to ramp up and down according to the availability of renewable power.

[a] Communication with Jens Baumgartner, Ph.D., Business Development Manager Electrolysis, Sunfire GmbH.

[b] Sunfire, Breakthrough for Power-to-X: Sunfire puts first co-electrolysis into operation and starts scaling, January 2019. https://www.sunfire.de/en/company/news/detail/breakthrough-for-power-to-x-sunfire-puts-first-co-electrolysis-into-operation-and-starts-scaling

6.2.12 Synthetic Methane

6.2.12.1 Technology Description and Stage of Development

The rationale to produce synthetic or substitute natural gas (SNG) is that it contributes to the resilience of the energy system. Curtailed renewable power can be used to produce hydrogen and together with CO or CO_2 from biomass or industrial sources can be converted to methane using a methanation reactor. Such a system is generally referred to as Power-to-Gas (PtG). The benefit here is that the produced methane can directly be fed to the gas grid or used as a transport fuel using existing infrastructure. The production of methane from CO_2 and H_2 can be done in either biological or catalytic reactors. For this study, the focus was on the catalytic conversion to methane, since biological methanation is sourcing most of the CO_2 from the biomass feedstock.

Catalytic methanation is a known concept since the early 1900s and interest spiked during the 1970s oil crisis to produce natural gas from syngas. Since then several large proposals for coal-to-gas plants have been proposed.[204] Catalytic methanation is typically done at temperatures of 200°C to 550°C in the presence of Ni, Ru, Rh, or Co catalysts for the methanation reaction. Nickel is often considered the more suitable catalyst due to its high activity, low cost as raw material and is almost 100% selective to methane.[205] A drawback is that nickel catalysts are sensitive to impurities in the feed gas.

The largest PtG facility in the world is the Audi e-gas plant in Germany. The hydrogen supply is produced by three alkaline electrolyzers with a combined capacity of 6 MW and the CO_2 is supplied by a nearby biogas plant which produces a 100% pure CO_2 stream. The plant uses cooled, fixed-bed methanation reactors.[206] Annual SNG output of the plant is on the order of 850 tonnes per year.

6.2.12.2 Physical, Environmental, and Co-location Requirements

The production of SNG through methanation requires CO_2 (or CO), hydrogen, thermal energy, and a catalyst. Half a tonne of hydrogen per tonne of SNG and 2.7 tonne of CO_2 per tonne of SNG are required. The costs will be dominated by the half tonne of hydrogen needed per tonne of SNG produced, therefore a low-cost supply of hydrogen is needed from, for example, curtailed wind power. When the reaction is carried out using a nickel catalyst, the feed gas may not include impurities. A useful CO_2 source would in this case be the pure CO_2 from the bioethanol process of which the State has a few plants. In any other case, CO_2 purification would be required as a first step.

6.2.12.3 Potential/Feasibility in New York State

NYS is intending to develop 2.3 GW of offshore wind by 2030.[207] This might deliver some curtailed power that could be used for PtG applications, although there will likely be a high demand for low-cost power. Furthermore, NYS has various incentives in place for the stimulation of natural gas-based vehicles such as the Alternative Fueling Infrastructure Tax Credit and the Idle Reduction and Natural Gas Vehicle Weight Exemption. No technical or legislative barriers were identified to the deployment of SNG facilities in the State.

6.2.12.4 Traditional Market Description and Potential Partners

Naturally, the current natural gas market is dominated by the existing gas TSOs. Demonstration projects on SNG production often involve these TSOs. In Europe, notable examples include the Falkenhagen PtG project in Germany (Uniper/ONTRAS),[208] the BioCat project in Denmark (HMN) and the Audi e-gas project (Audi/TenneT).[209] It would therefore be sensible to explore opportunities in NYS together with the gas TSO National Grid and technology providers such as Haldor Topsoe, Siemens, and General Electric.

6.2.12.5 Natural and Other Constraints

Methanation plants and the associated hydrogen production take up land. Audi's e-gas methanation plant with 6 MW of electrolyzer capacity takes up about 3.5 ha. However, it is expected that land area requirements do not scale linearly with the plant production.

6.2.12.6 Strengths and Weaknesses

Section 6.3 shows the potential cost and abatement for this technology once it deployed at scale, compared to other shortlisted technologies. By 2050, producing synthetic methane using CO_2 is estimated to cost $454 per tonne of avoided CO_2. This is assuming a baseline of conventional natural gas production.

Costs for SNG are significantly more expensive than conventional natural gas today, at around 20 eurocents/kWh ($0.26/kWh) for a 5 MW plant operating at 3,000 full load hours.[210] Natural gas in NYS is currently priced around $0.02/kWh. Biomethane, methane produced from biomass feedstock, is also more competitive than SNG today at around $0.07/kWh.[210] With the utilization of heat and byproduct oxygen from the water electrolysis process, costs could decrease toward 2050 to 7.2–10.6 eurocents/kWh ($0.08-0.12/kWh) according to a study commissioned by GRT Gaz.[211] Despite this discrepancy in cost, SNG also represents a value in its potential to provide flexibility to the energy system. Finally, scaling a methanation plant will be challenging in the coming decade due to the dependency on a low-carbon hydrogen supply and a pure CO_2 stream. Because of this, the largest plant today has a capacity of 6 MW.

6.3 Cost and Abatement Potential of Utilization Technologies

The previous section described all shortlisted CCU technologies in detail. This section will compare them on technoeconomic terms; what do they cost and what can they deliver in terms of avoiding CO_2 emissions in NYS?

To calculate both cost and potential of these technologies, assumptions and estimates were made on key model inputs such as costs and emissions factors. Appendix A provides an overview of these reference case assumptions.

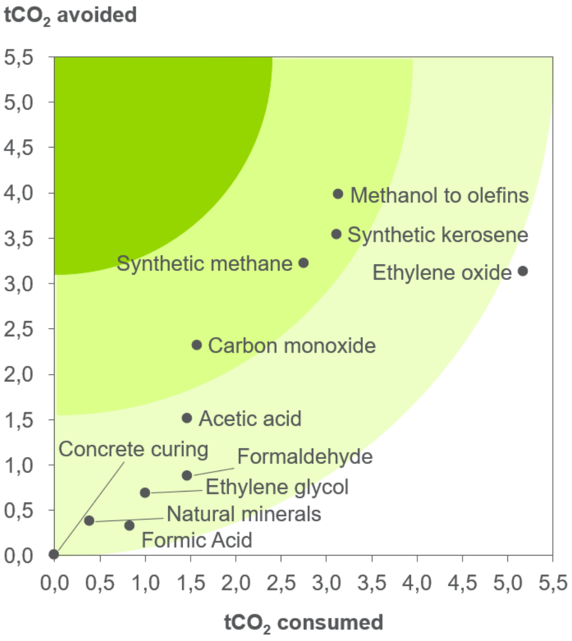
6.3.1 Abatement Potential of Utilization Technologies

Key in establishing whether any utilization technology will be sensible to deploy in NYS is to establish if the technology avoids more CO_2 than is emitted in its production process. This is shown in Figure 24 for the selected CCU technologies. The green shaded areas indicate how much CO_2 is avoided per tonne of CO_2 consumed—the darker the shade the more effective the technology appears to be.

It can be immediately recognized that by 2050 all considered technologies avoid more CO_2 than they emit under the listed assumptions in Appendix A, as all technologies show positive CO_2 avoidance per tonne of product. This is not to say that aiming to deploy these technologies immediately follows from this assessment. As described in section 1.2.3, an emphasis on making a comparison against other decarbonization levers is required to determine if a CCU technology will be an effective decarbonization lever for the State. In the previous sections describing individual technologies shown in Figure 24, key competing technologies are mentioned under strengths and weaknesses.

Figure 24. Carbon Dioxide Consumption versus CO_2 Avoidance per Tonne of Product for Selected CCU Technologies in New York State in 2050

Source: Guidehouse



Establishing the scale of potential abatement per technology is different compared to CCS, where storage is primarily confined by available geological storage space. For CCU, the capacity of one future reference plant to develop a sense of scale of abatement was identified. This is not always straightforward. For some CCU technologies demonstration or pilot plants exist today and for most the size of an industrial-scale plant is not known. The following procedure was used to establish a reference capacity.

For each of the selected CCU technologies, one reference industrial plant was modeled at commercial scale of a technology similar to a selected CCU technology sourced from one of the following:

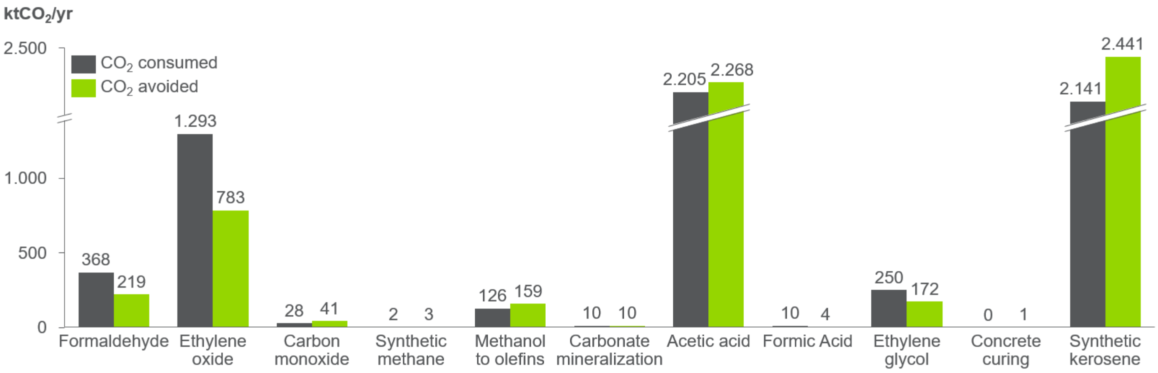
- Existing industrial processes required in the CCU technology (preferred)
- Literature projections thereof (next best option)
- Incumbent production of the same product (last resort)

When applying this merit order to the selected CCU technologies, a comparison on the potential scale of abatement in NYS was allowed (Figure 25). This remains somewhat arbitrary as many technologies are still in their infancy, and one could vary actual plant capacity and number of plants.

What can be identified from Figure 25 is that the potential scale of abatement associated with a single plant varies wildly across CCU technologies, from avoiding a single kilotonne to over 1.5 megatonnes of CO_2 per year. Note that selected technologies indicate a larger avoided CO_2 potential compared to the CO_2 consumed. This is because the displaced production emissions associated with the incumbent fossil production route are larger than the projected emissions associated with the energy and feedstock requirements of the CCU route. Section 6.3.3 expands on the abatement potential associated with CCU when potential drivers and limiting factors of plant capacities, such as feedstock availability, are identified.

Figure 25. Annual Abatement Potential by 2050 of Selected CCU Technologies in New York State Based on a Single Plant Reference Capacity

Source: Guidehouse



6.3.2 Cost of Utilization Technologies

The cost of CCU technologies were estimated based on key inputs defined in Table 13. Transport of CO_2 is not factored into this estimate as it is highly variable: CCU plants can be co-located with CO_2 sources, integrated in a larger CO_2 grid, or transported over long distance using various modes (pipeline, trucking, shipping). In general, CO_2 transport costs are expected to be small compared to CCU process costs.

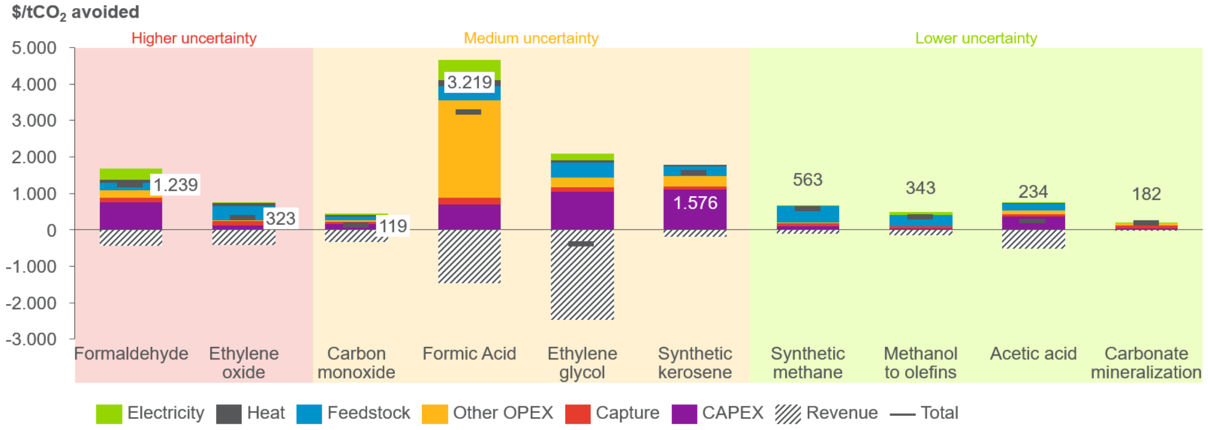
Table 13. Inputs Required to Estimate Cost of Utilization Technologies

Source: Guidehouse

Cost item	Estimating approach	Typical sources used
Energy input	Identify energy requirements per tonne of product in literature sources describing CCU process. When not available, a theoretical estimate is made from stoichiometry.	Industry literature, scientific literature
Feedstock input	Estimated from stoichiometry.	Reaction equations
Other OPEX	Identify other OPEX components, such as non-energy-related feedstock, catalysts and O&M. When not available, a standard O&M surcharge is applied from CAPEX estimates.	Industry literature, scientific literature
Capture costs	Natural gas-fired power is assumed to be the source for all CCU pathways selected.	See section 4.4.1
CAPEX	Identify capital expenditure in literature sources describing CCU process and apply consistent annuitization factor to discount per tonne of product. When not available, CAPEX is derived from OPEX estimate based on a standard ratio from reference plant.	Industry literature
Revenue	Identify potential revenue from selling CCU-derived product from present U.S. market prices of incumbent product.	Market research

Figure 26. Cost of Utilization Technologies per Tonne of CO_2 Avoided by 2050

Source: Guidehouse



Note: Data labels indicate total cost when resulting product revenue is accounted for. Technologies projected to have revenue exceed production cost are not indicated with data labels as the $/tCO₂ avoided metric fails once it turns negative. Concrete curing is not depicted here as the production costs are equal to current production costs and the costs of CO_2 per tonne of product are negligible due to the low-utilization factor of this technology. Uncertainty categories indicate uncertainties around catalyst development. See main text for further information. Table 14 indicates costs and revenues as displayed here.

Table 14. Production Costs and Revenue of CCU Products

Source: Guidehouse

Product	Production costs	CO_2 revenue	Product revenue	Total cost	Source product revenue
Unit	$/tCO₂	$/tCO₂	$/t Product	$/tCO₂	
Formaldehyde	1,673	435	391	1,239	Dynea
Ethylene oxide	737	414	1,330	323	Market Watch
Carbon monoxide	455	336	787	119	openPR
Synthetic methane as fuel	671	109	355	563	US EIA
Methanol to olefins	493	150	604	343	Argus
Carbonate mineralization	206	24	9	182	Statista
Acetic acid	756	521	800	234	ICIS
Formic Acid	4,670	1,451	482	3,219	KTVN
Ethylene glycol	2,085	2,474	1,744		Plastics Insight
Synthetic kerosene	1,757	181	650	1,576	IATA

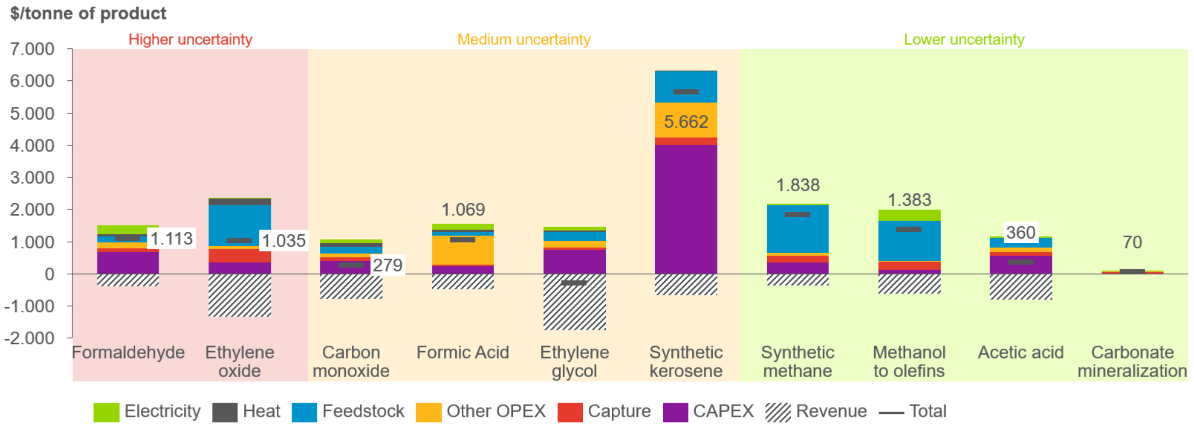
Figure 26 and Figure 27 show the cost of utilization technologies expressed in US$ per tonne of product and per tonne of avoided CO_2. Most important to realize is that these cost projections to 2050 of often relatively immature technologies come with considerable uncertainty. Key uncertainties are the capital requirements of these technologies, the cost and emission factors of energy and feedstock, and the cost of catalysts.

This last aspect, cost of catalysts, is indicated as the key uncertainty aspect in both figures. As many of these technologies need to overcome considerable thermodynamic hurdles,[212] development of efficient catalysts is key in scaling up and bringing down the cost of the technologies. The magnitude of these costs is illustrated by formic acid, for which reliable literature was available to enable quantification of catalyst costs. These costs are categorized as Other OPEX in Figure 26 and Figure 27. Indeed, this is the largest cost impact for formic acid.

Table 15 lists the stage of development and uncertainties associated with catalysts for all CCU technologies. This shows that the estimates provided in this study could underestimate the impact of production cost regarding catalysts for formaldehyde and ethylene oxide and, to a lesser extent, carbon monoxide, ethylene glycol, and synthetic kerosene.

Figure 27. Cost of Utilization Technologies per Tonne of Product by 2050

Source: Guidehouse



Note: Data labels indicate total cost when resulting product revenue is accounted for. Concrete curing is not depicted here as the production costs are equal to current production costs and the costs of CO_2 per tonne of product are negligible due to the low-utilization factor of this technology.

Table 15. Uncertainties Associated with CCU Pathways

Source: Guidehouse

CCU Pathway	Catalyst Investigated	Development Maturity	Estimated Cost	Uncertainty Linked to Catalyst Choice
Formaldehyde	Polyhydride ruthenium catalyst complex	Low—Catalyst development work still ongoing	Low—Ruthenium complexes are known redox Lewis acid and base catalysts	High—Catalyst development to be followed by catalyst optimization
Ethylene oxide	Mixed metal oxide with tin, iron, and alumina catalyst	Low—Catalyst development work still ongoing	High—Due to the low maturity of the catalyst development	High—Catalyst development to be followed by catalyst optimization
Carbon monoxide	Mixed metal catalysts of the following composition: Fe/Al_2O_3, Fe-Cu/Al_2O_3 and Fe-Cs/Al_2O_3	Medium—Several catalysts have been identified, optimization and scale-up work will determine which one can be used commercially	High—Due to the low maturity of the catalyst development	Medium—Catalyst is being optimized (i.e., increasing catalyst life and improving activity)
Synthetic methane	Nickel-based catalyst	High--Commercialized by Johnson Matthey among other (CRG technology)	Low—Known catalyst used for hydrogenation reactions in the petrochemical industry	Low

Table 15 continued

CCU Pathway	Catalyst Investigated	Development Maturity	Estimated Cost	Uncertainty Linked to Catalyst Choice
Synthetic kerosene	Mixed-metal catalyst (RWGS reaction), iron and cobalt-based catalyst (FT reaction) and platinum-loaded sulphated or tungstated zirconia supported catalysts on zeolites (wax hydrocracking).	High—For the iron and cobalt-based catalyst typically used for FT (e.g. process used commercially by Sasol) and the hydrocracking of waxes (e.g. crude oil refining); the catalysts are implemented in known processes. Medium—For the catalyst used for the RWGS reaction to produce CO as it is in development (see above).	Low—Known catalyst used for FT and the hydrocracking of waxes. High—The RWGS catalyst's cost is estimated to still be high given its low maturity.	Medium—The application of the mixed metal catalyst in the RWGS reaction (refer to CO production).
Methanol to olefins	MTO-100 silicoaluminophosphate synthetic molecular sieve catalyst (UOP's Hydro MTO), ZSM-5 molecular sieve (Lurgi's methanol-to-propylene process).	High—Catalysts have been licensed and commercialized.	Low—Used for the catalytic cracking of gas oil.	Low
Carbonate mineralization	No catalyst used as part of the mineralization process.	N/A	N/A	N/A
Acetic acid	No catalyst used as part of the fermentation reaction.	N/A	N/A	N/A
Concrete curing	No catalyst used as part of curing process.	N/A	N/A	N/A
Formic acid	Ruthenium-based catalyst with phosphine ligands.	Low—Catalyst development work still ongoing.	Low—Ruthenium complexes are known redox Lewis acid and base catalysts.	Medium—Catalyst development to be followed by catalyst optimization. Literature available on potential cost and volumes of current catalyst.
Ethylene glycol	Molecular catalyst of imidazolium salt.	Medium—Toshiba has patented the technology.	Low—But the catalyst will have to be coated on a metal surface as part of a high-density layer which might raise the cost of the catalyst.[213]	Medium—Catalyst is being optimized (i.e., increasing catalyst life and improving activity).

With these caveats concerning uncertainty addressed, the modeling outcomes reveal that except for ethylene glycol and concrete curing, abatement costs are above 150 \$/tCO_2 avoided and over half of the CCU technologies are at or above 300 \$/tCO_2 avoided. Key drivers in these costs are the capital expenditure and the cost of feedstock, mostly hydrogen. The cost of hydrogen is projected to be around 2.90 \$/kg by 2050, based on a reference LCOE of 0.04 \$/kWh.[214] These are relatively moderate cost projections. LCOE projections for the U.S. can be as low as 0.02 \$/kWh,[215] leading to a reduction of hydrogen cost to under 2.00 \$/kg. Such low prices of hydrogen will bring down the cost of CCU technologies considerably. Figure 28 and Figure 29 also show that just reducing the cost of feedstock is not enough to render the technologies competitive with incumbent production. Even without feedstock costs, the remaining production costs keep exceeding existing market prices in most cases. Further cost reduction and a more expensive incumbent product are required.

Policy, then, is another factor that may support CCU technologies in becoming economically attractive. A carbon price could help bridge the financial gap indicated in the previous figures. If the 45Q Tax Incentive considered by Congress was implemented, tax breaks could be awarded to CCU and CCS projects worth \$35 and \$50/tCO_2 respectively. A minimum project threshold for CCU is 25,000 tCO_2.[216] However, these levels of tax support will not be sufficient to render competitive the CCU technologies considered here. A combination of tax credit, carbon tax, and technological innovation are likely required.

6.3.3 Carbon Dioxide Purification and Intermediate Storage

To avoid the damaging of catalysts used in CO_2 utilization, pure CO_2 with a low-oxygen content is needed.[217] Even for purposes of enhanced oil recovery, the oxygen content should be reduced to below 100 ppm to avoid oxidation of hydrocarbons and limit aerobic bacterial growth.[218]

When CO_2 is captured using post-combustion capture, CO_2 is often already at a purity of >99%. The dominant impurities in this stream are nitrogen (N_2), oxygen (O_2) and water (Table 16), although the CO_2 purity and the level of impurities can be affected by process conditions. To further increase this purity level for the purpose of CO_2 utilization the dominant technology in the industry is liquefaction,[219] following the below steps:

1. **Pre-cooling and compression**. This unit cools down the water-containing gas and the pressure is adjusted for operating conditions.
2. **Scrubbing**. The CO_2 gas is scrubbed and washed to remove water-soluble components such as alcohols.
3. **Drying and adsorption**. Remaining traces of water and other chemical components are removed in interchangeable dryers.

4. **Liquefaction**. Dry CO_2 gas passes through a reboiler followed by a CO_2 distillation column. Inert components leave the column at the top, and liquid CO_2 is drawn off the bottom and sent to storage.
5. **Storage and loading**. Liquefied CO_2 is stored in pressurized tanks for later shipping or pressurized for pipeline transport.

Table 16. Overview of CO_2 Concentration and Impurities from Post-combustion Capture Technology

Range is Explained by Different Point Sources of CO_2.

Source: Porter et al.

	Unit	Concentration in captured gas
CO2	v%	99.6–99.8
O2	ppmv	35–150
N2	ppmv	450–2,900
Ar	ppmv	11–21
NOx	ppmv	20–39
SO2	ppmv	0–67
H2O	ppmv	100–640
CO	ppmv	1.2–10

To estimate the costs of CO_2 liquefaction, known cost figures from an existing CO_2 liquefaction plant with onsite carbon storage at an ethanol plant, operating since 2013, in Lüdinghausen in North Rhine-Westphalia in Germany were used. The liquid CO_2 leaves the process at around -25°C and is pressurized with a purity specification of 99.999 v%. The oxygen content after liquefaction is less than 5 ppm, which is generally sufficient for the catalysts used in CO_2 utilization processes.[217] Costs are scaled to a scale relevant for large-scale CO_2 utilization. For this scale, the size of the current largest CO_2 liquefaction plant in the world is assumed, at a capacity of 1,500 tonnes/day or over 0.5 Mt/year and a scaling factor of 0.7 is used.[220,217] Smaller capacities are possible, but will slightly increase levelized capital expenditures:

- **Capital expenditures**: with an investment of $3.8 million for the 17,000 tonnes/year plant and a scaling factor of 0.7, the annuitized costs of CO_2 purification under the assumptions in this study will be $7.2/t$CO_2$. These costs include the liquefaction plant and about five days of storage capacity at full production.[217]
- **Energy costs**: at an energy consumption of 206 kWh/tCO_2,[217] electricity costs will be in the order of $10–14/t$CO_2$ when varying the electricity price between $0.04–0.07/kWh.

These parameters together provide a cost estimate of $17–21/t$CO_2$ for the large-scale purification of CO_2 for utilization processes.

7 Integrated Assessment of CCUS in New York State

The previous three sections provide an overview of shortlisted CC, CCS, and CCU technologies and how they may play a role in NYS to reduce CO_2 emissions. This section provides an integrated assessment of these three groups of technologies. In section 7.1, the findings across the entire technological spectrum were synthesized by looking at common traits identified across technologies and by comparing technologies on the same technoeconomic merits. Section 7.2 looks at four integrated pathways selected to span the total CCUS solution space in the State.

7.1 Synthesis of All CCUS Technologies

7.1.1 Power Generation is the Most Relevant Source of CO_2 for CCUS.

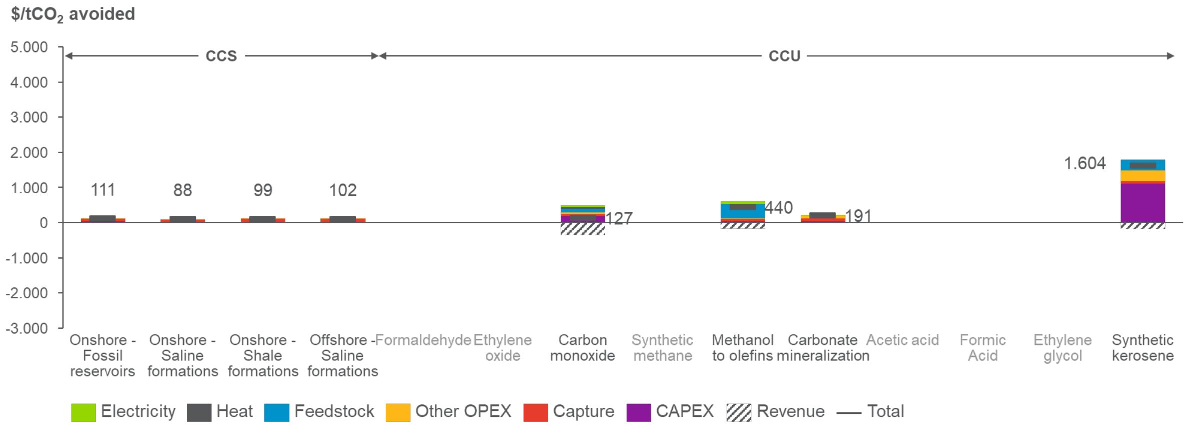
Typically, CCUS technologies require scale to be cost-competitive. In the analysis, Guidehouse set a threshold of 220,000 tonnes of CO_2 emitted annually, above which the point sources are considered eligible for CCUS. Over 88% of emissions of these larger point sources are from power generation.

7.1.2 CCS, and to a Smaller Extent CCU, Can Act as Key Levers to Decarbonize Power Generation in the State, but They Will Face Competition from Increasingly Lower Cost Renewables

Figure 28 shows that by 2030, four of the shortlisted CCU technologies have a reasonable chance of being mature, but CCS is a cheaper decarbonization technology. Figure 29 shows that by 2050, CCU options generally remain more expensive compared to CCS technologies, except for ethylene glycol.[221] Section 6.3.1 explains that the CCU technologies can have abatement potential on the order of 1–2,500 $ktCO_2$/yr, whereas CCS is technically confined by storage potential only, which creates a much larger abatement potential. It is advisable to closely monitor how the combination of dispatch power and CCS will compete against the lowering cost in renewable power generation, potentially in combination with storage options. The development and pace of deployment of these key competing technologies will determine the potential of CCS over the next few decades. If planning to retire gas-fired power generation, refurbish plants with capture technology, or add new capacity to the gas-fired power generating fleet with pre-installed capture technology, this development of renewables in NYS needs to be considered.

Figure 28. Projected Abatement Cost of CCUS Technologies by 2030

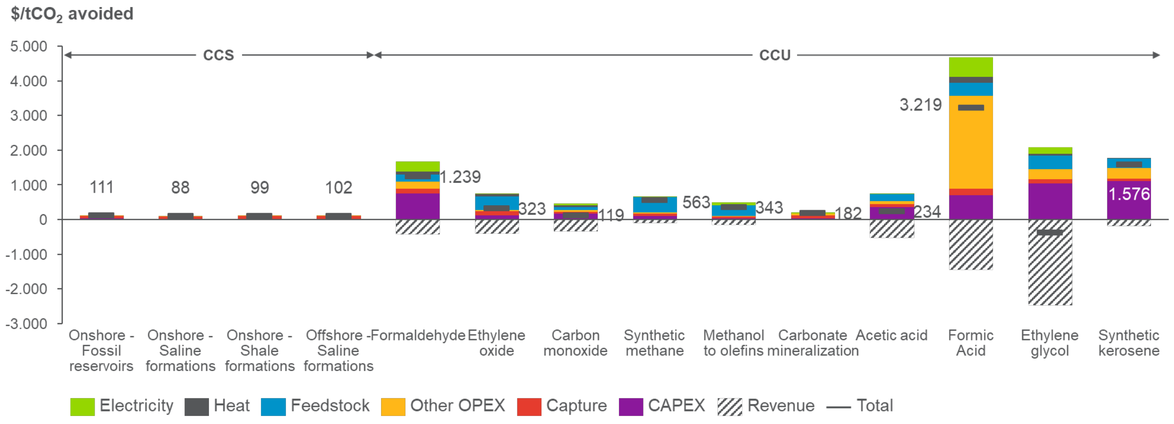
Source: Guidehouse



Note: Capture of CO_2 from gas-fired power is assumed. Data labels indicate total cost when resulting product revenue is accounted for. Technologies projected to have revenue exceed production cost are not indicated with data labels as the \$/tCO_2 avoided metric fails once it turns negative. Technologies with TRL<7 are not expected to have fully matured by 2030 and are therefore not shown.

Figure 29. Projected Abatement Cost of CCUS Technologies by 2050

Source: Guidehouse



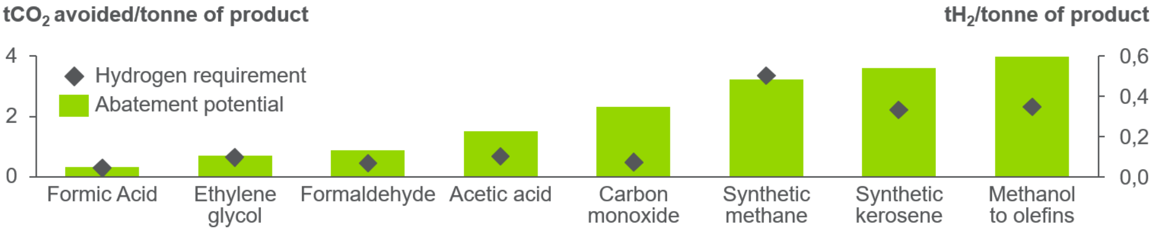
Note: Capture of CO_2 from gas-fired power is assumed. Data labels indicate total cost when resulting product revenue is accounted for. Technologies projected to have revenue exceed production cost are not indicated with data labels as the \$/tCO_2 avoided metric fails once it turns negative.

7.1.3 CCU Technologies are Expensive to a Large Extent due to the Required Hydrogen

Figure 30 shows the relation between abatement potential and hydrogen consumption. Typically, CCU technologies with a larger potential to avoid CO_2 emissions require a larger volume of hydrogen to do so. At the same time, hydrogen is a leading driver of production cost of CCU-derived products, as shown for synthetic methane in Figure 31. Reducing the cost of hydrogen is key in CCU cost reduction. This is even more important because several technologies may face tough competition from sustainable alternatives. Products such as olefins, kerosene, methane, or ethylene glycol can also be synthesized from bio-based feedstocks, usually at lower cost. Figure 31 also shows that more cost reduction is required to make synthetic methane competitive—this is true for most CCU technologies in this study.

Figure 30. Abatement Potential and Hydrogen Requirements for Selected CCU Technologies

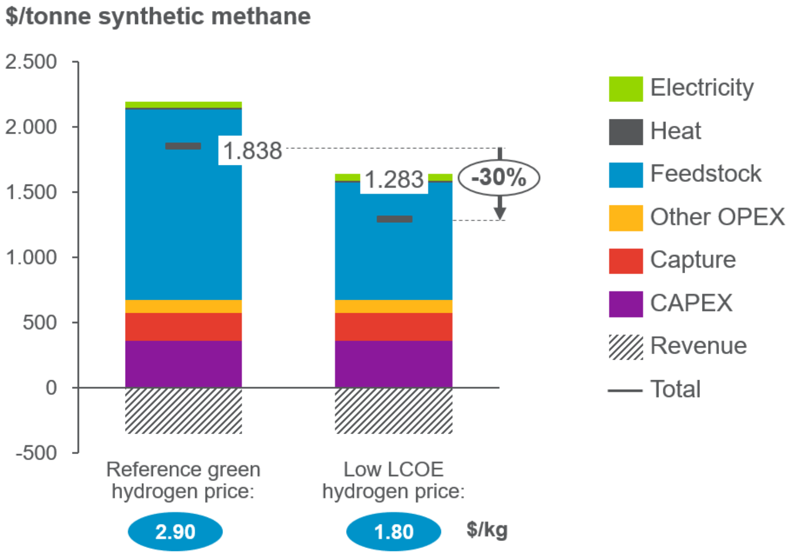
Source: Guidehouse



Note: Only hydrogen-sourcing CCU technologies are shown at increasing rates of tCO_2 avoided per tonne of product. This shows a trend of higher abatement per tonne of product for technologies that require more H_2.

Figure 31. Price Impact of Hydrogen Cost Reduction in Overall Costs of Producing Synthetic Methane from CO_2

Sources: LCOE prices used to derive hydrogen costs are from U.S. EIA AEO 2019 (reference) and Fraunhofer[222]*; Guidehouse*



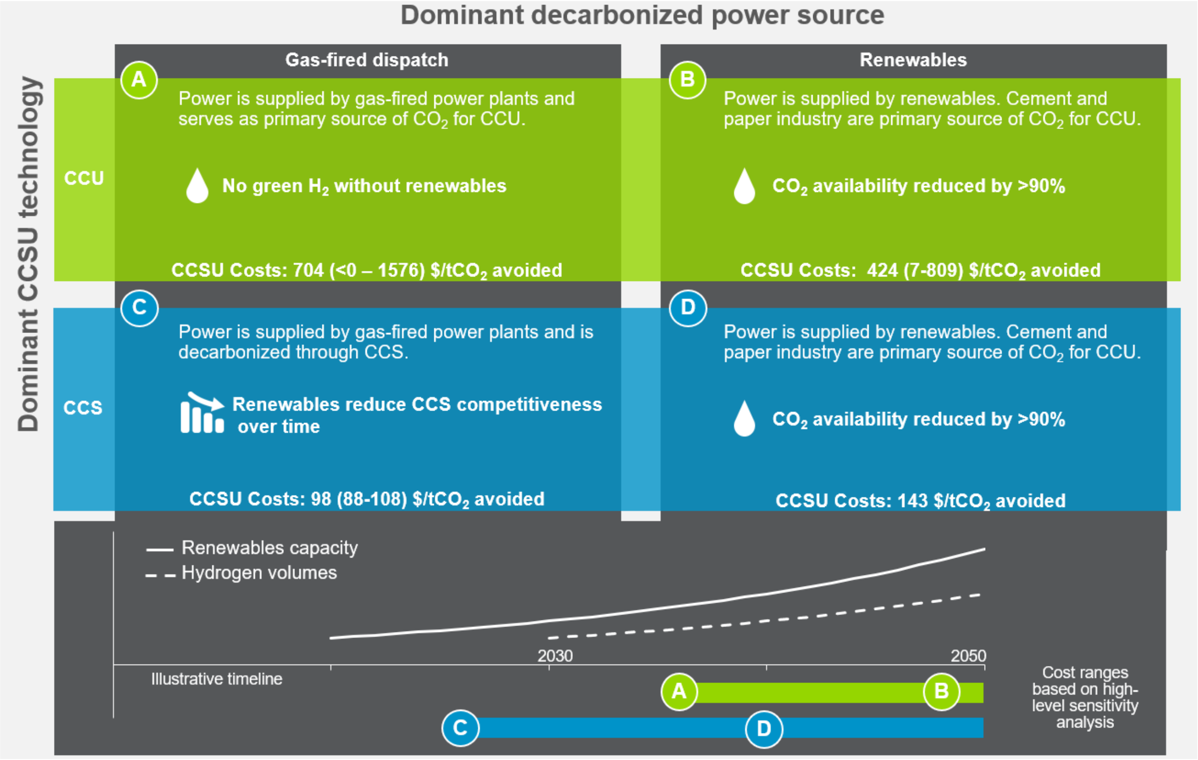
7.1.4 Renewables Required for Low-Carbon Hydrogen will Decarbonize Power Generation First

Abundant renewable energy, including the energy required to produce feedstock like hydrogen, is a prerequisite for CCU technologies to materially contribute to mitigating climate change.[223,224] This study, therefore, assumes hydrogen to be low carbon—it can be produced using renewable power (green hydrogen). However, these renewables are set to replace conventional power production first, eliminating the largest sources of CO_2 in NYS. Significant CO_2-emitting industries remaining are cement producers and paper mills. Where CO_2 emissions from paper production can be reduced through a variety of technologies,[225] emissions from cement are among the most challenging to abate and CCUS could play an important role.[226] Atmospheric CO_2 could be harvested using DAC, which fits a long-term circular State economy, but bringing down the cost of such routes is crucial. Figure 35 shows the interdependency of CCUS and power generation and how availability of renewables dictates CCU's role in the economy of NYS. In the next section (section 7.2), each of the extremes of this 2X2 matrix were explored to illustrate how they may fit the State.

Figure 32 also shows an illustrative timeline that depicts where in time these extremes could potentially materialize. This is highly dependent on the share or renewables in the grid as this will determine the availability of green hydrogen to a large degree. In section 1.1 the State's targets for the share of renewables in the grid are mentioned, these serve as the basis for this timeline.

Figure 32. CCUS Choices versus Decarbonized Power Generation Sources

Source: Guidehouse



Note: CCUS costs are total avoidance-weighted average costs, the spread per pathway indicates spread over selection of technologies within that pathway.

7.1.5 Selected CCU Technologies May Open Up Opportunities for New York State to Help Decarbonize the Manufacturing Industry and Create Jobs

Despite a smaller role in climate change mitigation compared to CCS, CCU may have a role to play in making NYS carbon neutral. Sectors present in the State with limited sustainable alternatives, such as cement, could look to CCU to reduce their CO_2 emissions. NYS's Innovation Agenda should focus on technologies and sectors that are, or have the potential to be, a key strength.

Where these strengths lie is highly dependent on national and international market developments. Will the Gulf of Mexico basin remain an industrial powerhouse, sourcing relatively cheap fossil fuels? If so, it will be harder to find markets for any of the relatively expensive CCU-derived chemical commodities from NYS, such as olefins or acetic acid. Conversely, will a new battery or fuel cell manufacturing industry emerge in the State in need of renewably sourced formic acid?

It has been demonstrated that the low-carbon transition, and in particular the deployment of renewable energy and energy efficiency, will bring important new employment opportunities.[227,228] But the development of these sectors will also have an impact on many carbon-intensive sectors and will require the adaptation of skills and working methods. CCUS can play a critical role in making the low-carbon transition much more socially inclusive by creating and securing large numbers of jobs in NYS.[229] Based on required large annual investments, CCS and CCU technologies deployment can help preserve highly qualified jobs in local power generation and other industries. Such deployment will also boost local manufacturing and construction industries by helping NYS remain competitive and by bringing new economic opportunities around the development of low-carbon energy technologies.

7.1.6 Key Uncertainties Remain in Both Potential and Cost for CCU Technologies

The challenge with most of the CCU technologies lies in finding suitable catalysts to enable a continuous and efficient synthesis of the product. Many CCU technologies are relatively immature and, therefore, it is difficult to accurately estimate capital requirements for a future industrial-scale plant. These uncertainties have a large influence on the cost of the selected CCU technologies for this study. In addition, the technology shortlisting process followed for this study excluded technologies that could still have a potential to support NYS's climate and innovation objectives. Even though the design of this process was to select the most relevant technologies, this is not a guarantee. A lot can change in climate technology and innovation. Guidehouse recommends taking stock of all CCU technologies in several years to keep abreast of such developments.

7.2 Selected Integrated CC to Utilization or Storage Pathways

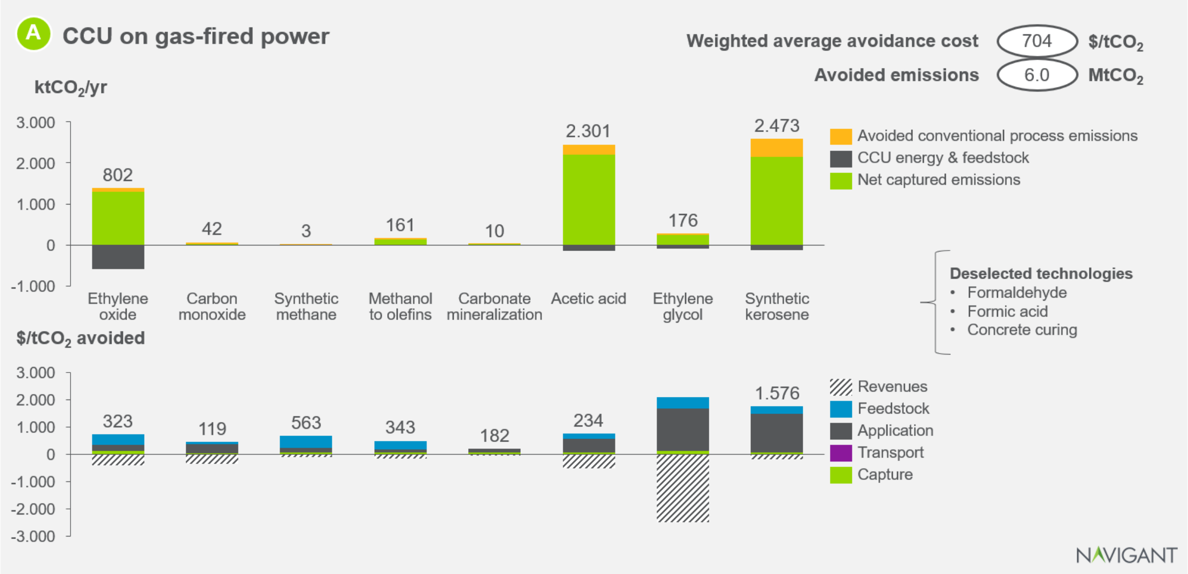
In Figure 32, four rather extreme pathways are depicted. Together, those four pathways span the solution space of CCUS in NYS. It is likely that CCUS deployment will develop along a pathway that combines aspects from all four. In this section, the extremes were explored as they provide insight into what CCUS in NYS may look like.

7.2.1 Pathway A: CCU on Gas-Fired Power

When gas-fired power is still the dominant source of power generation, CCU technologies could be part of the abatement solution and source all CO_2 from these power plants. However, these technologies will need to source hydrogen from outside NYS. Without CCS, blue hydrogen will not be produced in NYS, and without sufficient renewables, there will be no green hydrogen either. This is likely to increase the cost of hydrogen, but this has not been modeled in this pathway. Formaldehyde, formic acid, and concrete curing were deselected for this pathway. This pathway captures 6.1 and avoids 6.0 megatonnes of CO_2 per year (Figure 33). For reference, 6.1 megatonnes of CO_2 per year equals some 34% of present-day emissions from gas-fired power where a capture rate of 90% is assumed.

Figure 33. Costs and Abatement in Pathway A

Source: Guidehouse



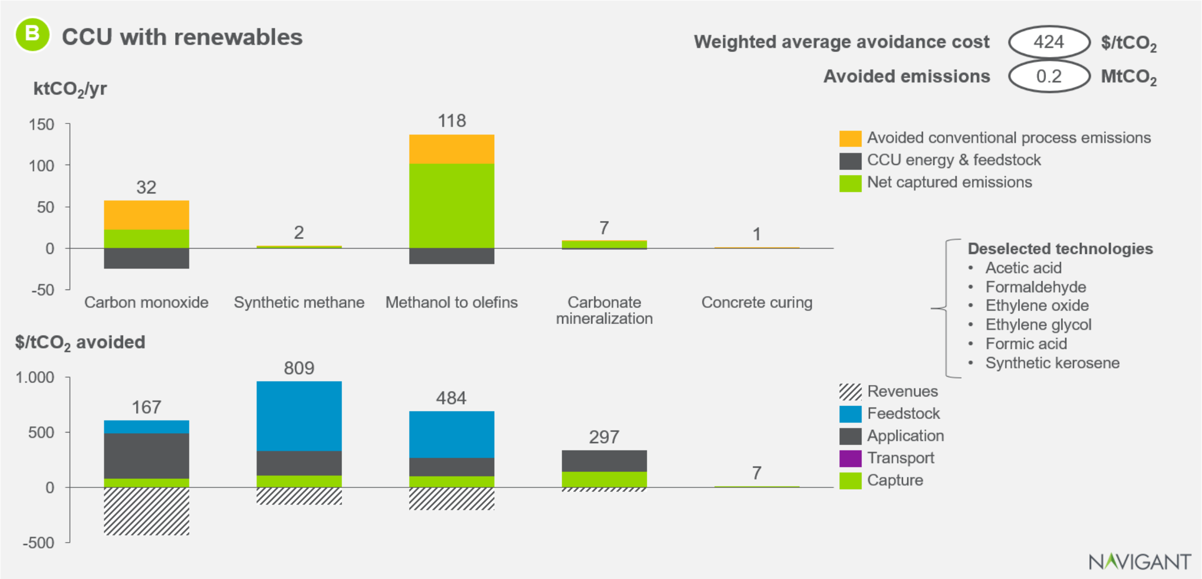
Note: Technologies projected to have revenue exceed production cost are not indicated with data labels as the $/tCO$_2$ avoided metric fails once it turns negative.

7.2.2 Pathway B: CCU with Renewables

In a power system that is dominated by renewables, CCU technologies will need to be deployed in other industries than power to source CO_2. Hydrogen will be delivered through renewables and electrolysis. With the dominant source of CO_2 no longer active in NYS, less CCU is required to capture the remaining emissions. In this pathway, it was assumed all CO_2 comes from cement production. A single reference plant was deployed to produce carbon monoxide, synthetic methane, olefins, aggregates from carbonate mineralization, and concrete. This pathway captures 166 and avoids 159 kilotonnes of CO_2 per year (Figure 34). For reference, 166 kilotonnes of CO_2 per year equals some 35% of present-day emissions from cement in the State.

Figure 34. Cost and Abatement in Pathway B

Source: Guidehouse

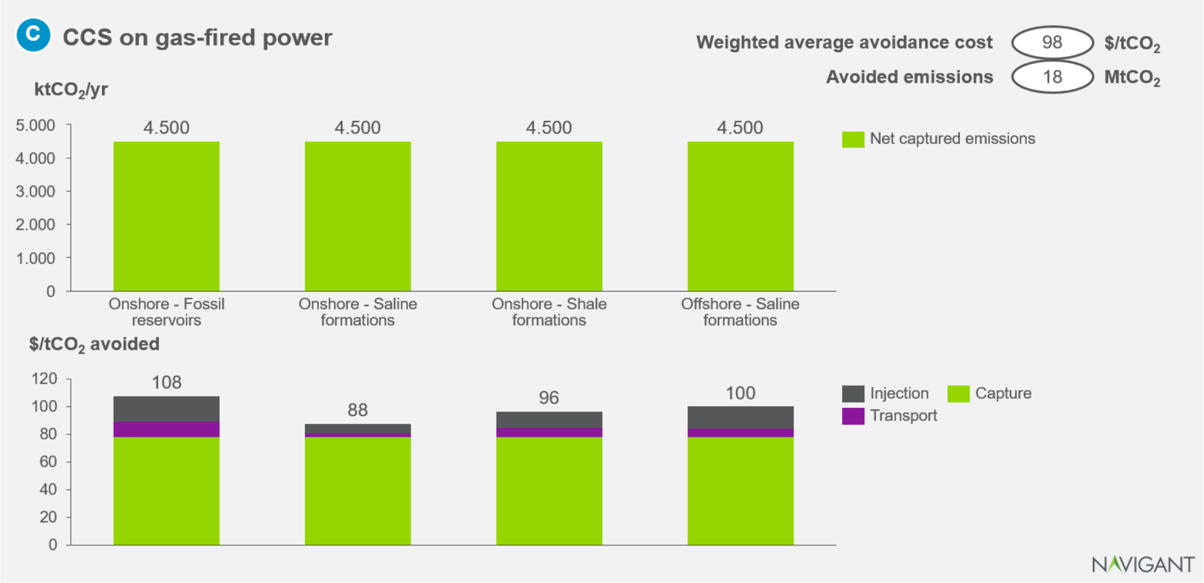


7.2.3 Pathway C: CCS on Gas-Fired Power

When gas-fired power is still the dominant source of power generation, CCS technologies could be the abatement solution and source all CO_2 from these power plants. In this pathway, streams of CO_2 coming from the entire natural gas fleet was divided equally among depleted oil and gas reservoirs and saline aquifers onshore as well as offshore, resulting in 18 megatonnes of CO_2 captured and avoided per year by 2050 (Figure 35).

Figure 35. Cost and Abatement in Pathway C

Source: Guidehouse

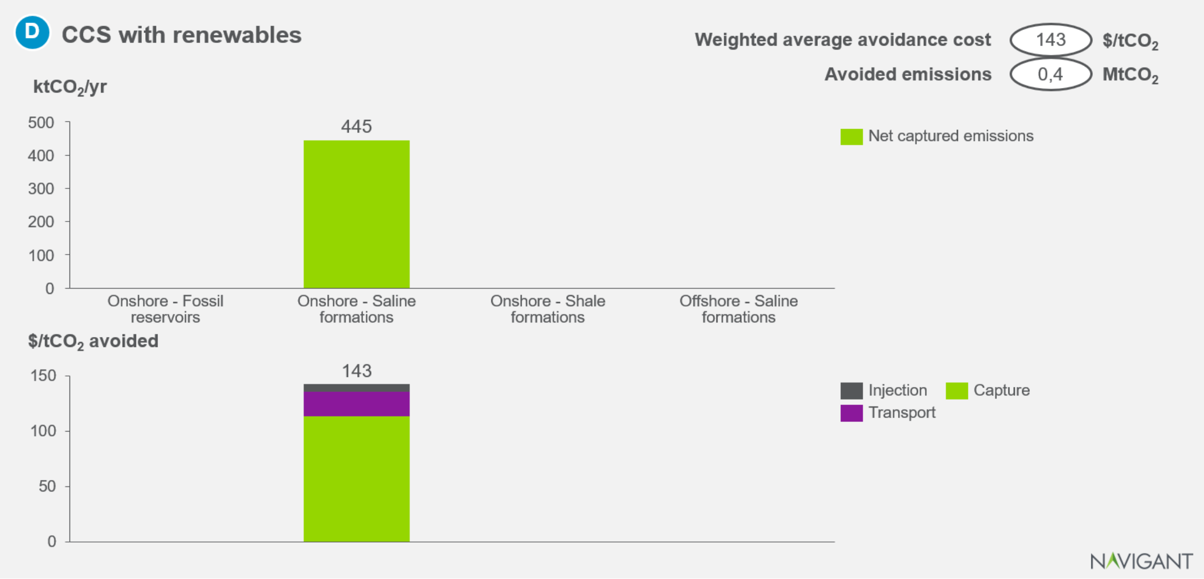


7.2.4 Pathway D: CCS with Renewables

When renewables become the dominant source of power generation, CCS technologies could help mitigate emissions in other industries. In this pathway, the streams of CO_2 coming from all cement plants were injected in onshore saline aquifers, resulting in 0.4 megatonnes of CO_2 captured and avoided per year (Figure 36). What is important to note in this pathway is the relatively high-transport cost. Because the annual emissions are relatively low, the CAPEX for pipeline infrastructure needs to be discounted over lower amounts of CO_2; thus, the price per tonne increases. Compared to pathway C, capture costs are higher because capturing CO_2 from a cement plant is more expensive compared to gas-fired power.

Figure 36. Cost and Abatement in Pathway D

Source: Guidehouse



7.2.5 Pathway X: A Middle-of-the-Road Scenario

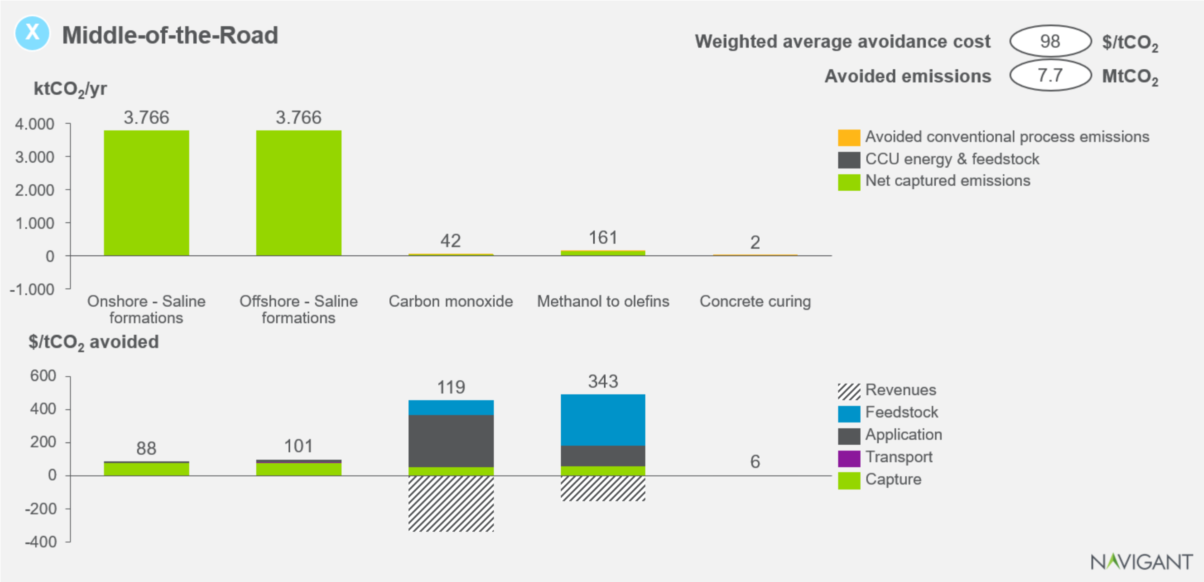
The previous pathways A-D explored the four corners of the “solution space” that Figure 32 illustrated by a 2X2 matrix. This final, fifth pathway “X” is meant to provide a view on what a more balanced CCUS deployment-at-scale scenario may look like for NYS.

This pathway starts from the premise that by 2050, natural gas-fired power still has an important role to play in delivering decarbonized power to NYS and CCUS is the tool to decarbonize this power. The projected annual power generation by 2050 is less than half of present-day generation, but, with other emission sources assumed unchanged, this still renders gas-fired power the dominant source of CO_2. With renewables replacing at least half of present-day power generation, it may reasonably be assumed some green hydrogen is available for CCU technologies. This pathway sees three CCU technologies deployed, two of which require hydrogen; one carbon monoxide production plant and one methanol-to-olefins plant where methanol is CO_2 based. The third is concrete curing, scaled to the combined production of the two cement producing sites in NYS. With onshore and offshore saline aquifers being the two largest available subsurface CO_2 sinks in NYS, the remaining emissions are assumed to be divided equally over these two sinks.

Figure 37 shows costs and abatement of the technologies modelled in this pathway. With 98% of all emissions from the remaining gas-fired power fleet captured and stored, the CCS routes dominate the weighted average avoidance cost at 98 $/tCO_2$ avoided. This pathway also illustrates that concrete due to its low-CO_2 utilization factor has only a small contribution to overall CO_2 avoidance compared to other technologies. Overall, this pathway would avoid 7.7 megatonnes CO_2 per year.

Figure 37. Cost and Abatement in Pathway X

Source: Guidehouse



7.2.6 Notes on Interpreting the Pathways

The preceding four sections provide an overview of the extremes of the CCUS solution space. Key in interpreting the abatement potential and associated cost is that considerable uncertainties remain. This section provides relevant considerations when interpreting these outcomes.

- The choices to decarbonize the power sector using renewable energy determine, to a large extent, the potential for CCUS options. Therefore, CCUS solutions should not be assessed by itself but in the broader context of decarbonization options in the power sector.
- Furthermore, the manufacturing industry has other options to reduce CO_2 emissions. CCUS technologies should also be assessed and weighted against alternative decarbonization options.
- The technology for most CCU processes is not mature; therefore, the market dynamics cannot be accurately assessed. On top of this, the deployment of CCUS technologies is highly dependent on the existence (or absence) of sustainable alternatives or the development of current supply chains.

- The development timeline of CCU technologies and their projected costs and abatement potential remain uncertain. For example, ethylene glycol seems to be the single CCU technology where production costs are lower than product revenue. This could make producing ethylene glycol using CO_2 an economically attractive decarbonization option. However, this technology is somewhere between TRL 3 and TRL 7. It remains uncertain whether this technology can actually be deployed at scale in NYS and if scale-up can be done economically. This is why ethylene glycol was not selected in the above CCU pathways—banking on the single most attractive option may distort the view of costs of CCU technologies.
- Most technologies require considerable volumes of hydrogen. This study assumes no restrictions on the availability of low-carbon hydrogen for CCUS technologies. It is recommended NYSERDA explore actual availability of low-carbon hydrogen and where in the NYS economy its deployment is most attractive from both an economic and a climate abatement point of view.

8 Recommendations

This study looked at the current annual CO_2 emissions across sectors and explored the role CCUS technologies could play in reducing these emissions. It did so by estimating abatement potential and cost, the feasibility of their deployment in NYS, their strengths and weaknesses and providing an overview of the markets that they may serve. The study allows distilling the following recommendations:

- Examine and closely monitor how the combination of dispatch power and CCUS will compete against renewables for CO_2 abatement.
    - Data delivered in this study can be used to inform complementary modeling and analytics efforts.
    - Define technology development metrics and their tipping points, which will enable monitoring of these developments and will support recognizing timely CCUS deployment opportunities in NYS.
- Focus NYS's innovation agenda on technologies and sectors where renewable options are limited.
    - Investigate CCU deployment to decarbonize selected manufacturing industries such as cement and paper mills where fewer alternatives exist (compared to power generation).
    - Seek technologies that fit these sectors to allow a more resilient and circular manufacturing industry—for example, concrete curing or aggregates production using CO_2 from cement production. Support the cost reduction of DAC.
- Support reducing the cost of DAC. DAC is a prerequisite to renewable, CO_2-based fuels if biogenic CO_2 are not available and it can be part of a CDR scheme when combined with permanent CCU technologies or CCS.
    - Investigate supporting R&D or deploying a pilot or demonstration-scale DAC plant in NYS to accelerate DAC technology maturation. This study lists several technology developers that could be sought out to deliver this technology.[230]
- Support the economics of CCUS.
    - Support the cost reduction of renewable power and low-carbon hydrogen using subsidies or development grants.
    - Support research and development (R&D) efforts on promising CCU technologies, specifically around catalyst development.
    - Create equal opportunity in CCUS-relevant markets by incorporating externalities from incumbent production processes in such markets.
- Develop and support job training as necessary to anticipate new skill needs.

- Explore the following areas for further study:
    - More study is required on comparing the cost and grid value of natural gas-fired power with carbon capture and renewable power with balancing solutions such as integrated storage.
    - More study on the potential role for selected CCU technology in fuel-based energy storage.
    - Revisit CCUS technology readiness and economics periodically over time. Monitoring these developments is important as technology development and associated cost reductions are difficult to predict.

Glossary

Source: Synthesis report of the Fifth Assessment Report (AR5) of the IPCC, Guidehouse

Term	Description
Avoided emissions/CO_2 avoided	The reduction of GHG emissions following from a process or technology compared to a baseline.
Baseline/reference	The baseline (or reference) is the state against which change is measured.
BECCS	Bioenergy and Carbon Capture and Storage. The application of CCS on bioenergy conversion processes. See: CCS, CDR.
CAPEX	Capital expenditure. In the context of this study these are funds required to build or upgrade a plant.
Carbon cycle	The term used to describe the flow of carbon (in various forms, e.g., as CO_2) through the atmosphere, ocean, terrestrial and marine biosphere, and lithosphere.
Captured emissions/ CO_2 captured	GHG emissions that are prevented from directly entering the atmosphere.
CCS	Carbon Capture and Storage. A process in which a stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed, and transported to a storage location for long-term isolation from the atmosphere.
CCU	Carbon Capture and Utilization. A process in which a stream of CO_2 from industrial and energy-related sources is separated (captured), conditioned, compressed, and used to create products or otherwise add value.
CCUS	Carbon Capture, Utilization and/or Storage. The umbrella term for CCS and CCU processes.
CDR	Carbon Dioxide Removal. CDR methods refer to a set of techniques that aim to remove CO_2 directly from the atmosphere by either increasing natural sinks for carbon or using chemical engineering to remove the CO_2, with the intent of reducing the atmospheric CO_2 concentration.
Consumed emissions/CO_2 consumed	GHG emissions required as feedstock for a CCU technology to produce a certain number of products.
DAC	Direct Air Capture. A process separating CO_2 from air.
End of pipe methods	Methods used to remove already formed pollutants from a waste stream such as removing CO_2 from industrial flue gas.
GHG	Greenhouse gas.
LCOE	Levelized cost of electricity. The average total cost to build and operate a power-generating asset over its lifetime divided over the total electricity output of the asset over that lifetime.
Negative emissions	A situation of net negative emissions is achieved when, as result of human activities, more GHGs are sequestered or stored than are released into the atmosphere. Can be achieved through CDR methods.
Net captured emissions/CO_2 net captured	GHG emissions that are prevented from directly entering the atmosphere minus the GHG emissions associated to energy required for this capture process.
OPEX	Operating expenditure. In the context of this study, these are ongoing costs to run a system or process.
Power-to-X	Umbrella term for various electricity conversion, storage and reconversion technologies such as power-to-gas, power-to-heat or power-to-ammonia.

Appendix A: Technoeconomic Assessment Parameters

Table A-1. List of Parameters Used to Estimate CCUS Abatement

Parameter	Unit	2030	2050	Reference
Grid electricity cost	$/kWh	0.07	0.07	U.S. EIA AEO 2019 Electricity: End-Use Prices: Industrial: Reference case.
Natural gas cost	$/kWh	0.02	0.02	U.S. EIA AEO 2019 Electricity: Energy Prices: Industrial: Reference case.
LCOE renewable electricity (Solar PV)	$/kWh	0.05	0.04	U.S. EIA AEO 2019 Estimated levelized cost of electricity (capacity-weighted average) for new generation resources entering service in 2023/2040.
Green hydrogen	$/kg	3.22	2.90	Based on LCOE renewable electricity, assumptions on electrolyzer efficiency cost and FLH.
Ethylene	$/kg	0.30	0.30	Fossil spot price 2018, fixed, Polyestertime.com
Bio-based ethylene	$/kg	2.00	2.00	US-based bio-ethylene production, IEA 2013.
Grid electricity emissions factor	kg CO_2 / kWh	0.12	0.00	Linear interpolation between 2017 (439 lbs. CO_2/MWh) and 2050 (set to 0), validated using literature projection.[231]

The impact of embedded emissions associated with energy storage in a net-zero electricity grid has not been taken into account in the numbers presented in this study. The projected emission factor for grid electricity by 2050 is set to follow the statewide targets as noted in section 1.1. Many CCU and DAC technology cost estimates in this study are impacted by this emission factor: a nonzero emission factor will increase cost of avoiding CO_2 emissions and reduce the abatement potential of said technologies. It should be noted that such technologies typically have high uptime, that is, over 90%, whereas renewable power generation has a capacity factor of 40–50%. A net-zero grid will likely make use of energy storage such as batteries, hydrogen production during peak production, or other storage mechanisms. Such systems will have embedded emissions that are not reflected in an emissions factor equal to zero.

Appendix B: CCU Cost Sensitivity Analysis

The cost estimates for CCU modelled as part of this project are sensitive to several key variables. To assess the impact of these variables, a sensitivity analysis was performed. The sensitivity analysis was performed on all gas-fired power plants in the State with 2050 as the target year, where a single reference plant of each of the shortlisted CCU technologies is applied. The key variables selected are CAPEX, CRF, energy and feedstock prices together with emission factors as these are central to the model:

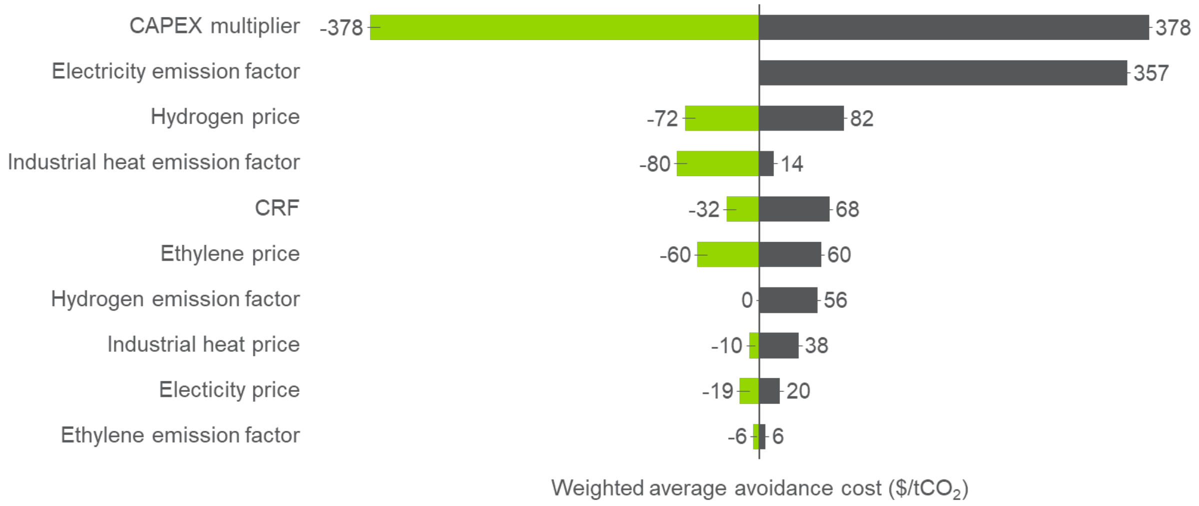
- **CAPEX.** Here we determine the impact on total project cost if the CAPEX of the project is 50% lower or higher than the initial base case.
- **CRF.** The financial results are very sensitive to the selected discount rate and assume lifetime of the project, affecting the CRF of the project. A high-internal rate of return is often required for investments with a high-risk profile that need to be covered by larger returns on investment. Projects often become less risky through technology maturation, but also through optimal risk allocation, insurances, or state guarantees.
- **Gas, electricity, and feedstock prices.** Here, the impact on total project cost if from a change in electricity price, industrial heat price, hydrogen price or ethylene price is determined. A change in these price levels impacts the OPEX of a project.
- **Emission factors.** Here, the impact on costs of the variation of the emission factors associated with the production of electricity, industrial heat, hydrogen and ethylene as the technology evolves is determined. By 2050, green hydrogen and bio-ethylene are assumed to be used, for which the emission factors will be null. Whereas in the low case the associated emission factors are nonzero. Emission factors affect the weighted average avoidance costs, as higher emission factors of key inputs will reduce overall avoidance and therefore increase cost.

A sensitivity analysis was only carried out on CCU technologies. The underlying assumption in the CCS costing model is that for a power plant, the energy required for the capture and storage of CO_2 in this case will originate from the energy produced by the power plant itself. No external energy would be used, which means no external factors would affect the key variables chosen for the sensitivity analysis. This does mean that an energy penalty occurs with applying CCS; a power plant retrofitted with CCS will produce less electricity for the grid compared to the case without CCS.

The results of the sensitivity analysis are presented in Figure B-1. The tornado plot shows the difference between the weighted average avoidance cost for CCU (\$/t CO_2 avoided) between a minimum and a maximum case compared to the baseline case. The uncertainty was quantified on the CCU costs obtained by varying CAPEX, CRF, energy costs, and emission factors, using a one-factor-at-a-time approach between the minimum, baseline, and maximum cases. As part of the baseline case, the selection of CCU technologies applied here costs \$727 per tonne of CO_2 avoided.

The strongest impact on the weighted average avoidance cost for CCU is related to the variation of the CAPEX by +/- 50%, leading to a difference in the weighted average avoidance cost of \$378 per tonne of CO_2 avoided for both minimum and maximum cases. Knowing the baseline weighted average avoidance cost of CCU is \$727 per tonne of CO_2 avoided, this means that by decreasing or increasing the CAPEX by 50%, you respectively reach a weighted average avoidance cost of \$349 and \$1,105 per tonne of CO_2 avoided. The second most important key variable is the emission factor of electricity followed by the price of hydrogen. The variation of the electricity emission factor between 0 and 0.2 kg CO_2/kWh_e causes the weighted average avoidance cost of CCU to increase by \$357, reaching \$1,084 per tonne of CO_2 avoided. Finally, by increasing the price of hydrogen from 1.8 to 4.150 \$/kg between the minimum and maximum cases in comparison to the baseline case, the avoided cost of CCU varies from \$655 to \$809 per tonne of CO_2 avoided, respectively. The sensitivity to the electricity and gas price are much smaller than the sensitivity to the hydrogen price.

Figure B-1. Sensitivity Analysis of Weighted Average Avoidance Costs for CCU (Baseline Weighted Average Avoidance Cost of \$727 per Tonne of CO_2 Avoided)



A list of the sensitivity input values used in all three cases to carry out this sensitivity analysis are given in Tables B-1, B-2 and B-3. The reference for the values used in the baseline case is given in the footnotes. In each case, sensitivity values had to be determined for the minimum and maximum scenarios for the cost data and the emission factors. Regarding the cost data, for the grid electricity and the industrial heat, the EIA Annual Energy Outlook 2050 prices for high- and low-oil and gas resource technology were used and \$0.03/kWh was subtracted and added based on expert judgement to determine the minimum and maximum case sensitivity input. The hydrogen price variance was based on the U.S. renewable electricity LCOE (\$0.02-0.063/kWh) published by Fraunhofer Institute.[232] The cost variance of bio-ethylene for the minimum and maximum cases employed a decrease or increase of 75% compared to the baseline case.

The values for emission factor for electricity and industrial heat was set to zero, assuming that by 2050, renewable electricity is carbon-free, and the heat supply has been decarbonized. This is the same assumption as the base case. The maximum grid electricity emission factor is based on the maximum value of the current emission factor (439 lbs CO_2/MWh or 0.2 kg CO_2/kWh), same for the natural gas emission factor (0.2 kg CO_2/kWh). It should be noted that for the maximum scenario, a 2017 electricity grid factor has been used as an approximation for the highest emission factor. This is considered the absolute upper bound of this parameter. This emission factor is projected to drop soon, however, and in a state with many CCU applications it is rather unlikely such a large CO_2 intensity will still be associated with electricity production. The electricity emission factor has a relatively large influence on the CCU costs because for the lower TRL technologies, where the energy carrier is not yet known, a 50/50 split across heat and electricity is assumed. For hydrogen, the maximum emission factor was based on the conventional production of hydrogen from natural gas (8.1 kg CO_2/kg and 33.33 kWh/kg hydrogen with carbon capture applied). Since 90% of the CO_2 emitted is captured during the production of such blue hydrogen, the emission factor of blue hydrogen for the maximum case is set to 10% of the emission factor for conventional hydrogen. For bio-ethylene, an emission factor of 1 kg CO_2/kWh) was taken based on conventional (fossil) ethylene production.

Finally, note that not all uncertainties have been explicitly modelled in this study. For example, a large uncertainty remains around the cost (and development) of appropriate catalysts for many CCU applications. This is discussed qualitatively at greater detail in section 6.3.2.

Table B-1. Sensitivity Input on the CAPEX

CAPEX	Unit	Minimum case	Baseline case	Maximum case
CRF[233]	-	0.08	0.11	0.14
CCU CAPEX multiplier	%	-50	0	50

Table B-2. Sensitivity Input on Energy Prices

Energy prices	Unit	Minimum case	Baseline case	Maximum case
Electricity price	$/kWhe	0.032	0.069[234]	0.108
Industrial heat price	$/kWht	0.012	0.020[234]	0.050
Hydrogen price	$/kg	1.800	2.903[235]	4.150
Ethylene price	$/kg	0.500	2.000[236]	3.500

Table B-3. Sensitivity Input in Emission Factors

Emission factors	Unit	Minimum case	Baseline case	Maximum case
Electricity emission factor	$kgCO_2$/ kWhe	0.000	0.000[237]	0.200
Industrial heat emission factor	$kgCO_2$/ kWht	0.000	0.181[238]	0.200
Hydrogen emission factor	$kgCO_2$/kg hydrogen	0.000	0.000[239]	0.81
Ethylene emission factor	$kgCO_2$/kg ethylene	0.000	0.570[240]	1.000

Appendix C: Carbon Capture and Carbon Utilization Technology Developers

Throughout sections 4 and 6, several companies are mentioned that are developing relevant technologies to capture and purify or utilize CO_2. This appendix provides an overview of all those mentioned companies, per shortlisted technology (Table C-1 and C-2). As such, this appendix provides an overview of the technology providers mentioned in this study but is not an exhaustive inventory of all technology developers that are active in CCUS. Most of these companies were identified from literature review and desktop research. With selected companies, interviews were conducted to gain a more detailed understanding of their technologies.

Table C-1. Carbon Capture Technology Developers (Not Exhaustive)

Carbon Capture	Technology developer
Post-Combustion—Amine-Based Sorbent	• Dow Chemicals—monoethanolamine (MEA, standard amine technology) • Schlumberger—diglycolamine (DGA) • MIH—KS-1 series of solvents • Fluor—Econamine FG Plus
Post-Combustion—Chilled Ammonia Process	• General Electric (previously Alstom)
Pre-Combustion—Physical Solvents	• UOP LLC—Selexol process (dimethyl ether of polyethylene glycol) • Linde AG, Air Liquide—The Rectisol process (cold methanol) • Fluor Solvent process (propylene carbonate) Lurgi AG—Purisol process (N-Methyl-2-Pyrrolidone)
Oxy-Fuel Combustion at Atmospheric Pressure	• Vattenfall • Total • Callide
Direct Air Capture—Potassium Hydroxide Solvent	• Carbon Engineering
Direct Air Capture—Supported Amines	• Global Thermostat • Climeworks

Table C-2. Carbon Utilization Technology Developers (Not Exhaustive)

Carbon Utilization	Technology developer
Acetic acid	• LanzaTech • Petronas
Aggregates from natural mineral carbonation	• Carbon8 Aggregates • Mineral Carbonation International
Concrete curing	• CarbonCure • Solidia
Carbon monoxide	• Sunfire and Soletair
Methanol to olefins	• UOP - Hydro MTO technology based on the MTO-100 silicoaluminophosphate synthetic molecular sieve catalyst • Lurgi AG - MTP (methanol-to-propylene) process based on a proprietary ZSM-5 (zeolithe) type of catalyst supplied from Clariant (former Süd-Chemie) • ExxonMobil • Lurgi & Statoil • SYN Energy Technology Co. • Lummus Technology
Ethylene oxide	• RTI International
Ethylene glycol	• Covestro • Toshiba
Formaldehyde	• N/A
Formic acid	• NorskeVeritas (DNV) together with Mantra Venture Group
Refrigerant gas	• Carnot • Carel • Danfoss • Carrier • Enex
Synthetic kerosene	• Sunfire • Soletair • Nordic Blue Crude • Climeworks (DAC)
Synthetic methane	• Audi/TenneT

Appendix D: Conversion Factors

Reported units	Alternative units	Conversion
kWh (natural gas)	1000 cubic feet	0.0034
	Btu	3,412
kg	lbs	2.22
short ton	metric tonne	0.91
liters	gallon	4.55
cubic meters	cubic yards	0.76
Celsius	Fahrenheit	C = F*1.8 + 32
meter	feet	3.28
hectare	acre	2.47

Endnotes

[1] On October 11, 2019, Guidehouse LLP completed its previously announced acquisition of Navigant Consulting Inc. As a result, Navigant Consulting Inc. was recently renamed as Guidehouse Inc.

[2] See Section 2 for an explanation of how these technologies were selected.

[3] Top-33 emitters are all emitters exceeding 220,000 tCO_2 annually or emitters that have a high concentration of CO_2 in their flue gas.

[4] Assumed discount rate of 10%, depreciation period of 25 years.

[5] For an overview of key input assumptions, see Table A-1. Projections come with considerable uncertainty. Section 6.3.2 discusses CCU cost and revenue estimates. This Section also provides an overview of the current development status of catalysts and how these developments add uncertainty to the cost estimates provided here.

[6] This 90% rule-of-thumb differs per technology (see Section 4.3.4 for the example of oxy-fuel combustion) and may be subject to change. Research on increasing carbon capture efficiency suggests that capture rates can be increased from 90% to close to 99% at only 1% increase of total capture cost, see Frailie, Modeling of carbon dioxide absorption/stripping by aqueous methyldiethanolamine/piperazine, Doctoral dissertation, 2014.

[7] Section 4.3.5 discusses two different DAC technologies and their developers.

[8] The elements of CCUS may also be implemented separately: carbon capture (CC), carbon capture and storage (CCS), and carbon capture and utilization (CCU).

[9] NYSERDA, New York State Greenhouse Gas Inventory: 1990–2015, September 2018.

[10] Governor Andrew M. Cuomo, 2019 Justice Agenda, January 2019.

[11] This 90% rule-of-thumb differs per technology (see Section 4.3.4 for the example of oxy-fuel combustion) and may be subject to change. Research on increasing carbon capture efficiency suggests that capture rates can be increased from 90% to close to 99% at only 1% increase of total capture cost, see Frailie, Modeling of carbon dioxide absorption/stripping by aqueous methyldiethanolamine/piperazine, Doctoral dissertation, 2014.

[12] CDR refers to technologies that enable CO_2 removal from the atmosphere. Examples are biochar or bioenergy with CCS (BECCS). Some CCUS technologies can be part of CDR, such as enhanced weathering of minerals or DAC. See the Glossary for an overview of these terms.

[13] This is not always the case—it is entirely possible for reactions to be exothermic, such as the reaction between CO_2 and ethylene oxide to produce ethylene carbonate. See Styring et al., Carbon Dioxide Utilisation, Closing the Carbon Cycle, Elsevier 2015 for a thorough review of these thermodynamic concepts.

[14] This displacement effect should ideally be quantified through a lifecycle analysis (LCA) comparison of both synthetic and conventional products. This was not done in this study.

[15] Agora Verkehrswende and Agora Energiewende (2018): The Future Cost of Electricity-Based Synthetic Fuels: Conclusions Drawn by Agora Verkehrswende and Agora Energiewende.

[16] A circular industry is an industry where waste and pollution are designed out, making the most of resources.

[17] Qiu, Yang, "An Assessment of Technological Innovation Capabilities of Carbon Capture and Storage Technology Based on Patent Analysis: A Comparative Study between China and the United States," Sustainability 10, 877 (2018).

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[22] CarbonNext, DECHEMA The University of Sheffield, Trinomics, http://carbonnext.eu/

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[26] A carboxylation is a chemical reaction in which a carboxylic acid group (-COOH function) is produced by treating a substrate such as an olefin (e.g., ethylene) with CO_2.

[27] NYSERDA, New York State Greenhouse Gas Inventory: 1990–2015, final report, September 2018.

[28] Department of Environmental Conservation, "Summary 2017 Emission Inventory", New York State, https://www.dec.ny.gov/chemical/116072.html

[29] This means that most data is obtained from this source, but in case of data gaps, this source is supplemented by the supporting data source.

[30] Facility Level Information on Greenhouse Gasses Tool, "2017 Greenhouse Gas Emissions from Large Facilities," Environmental Protection Agency, https://ghgdata.epa.gov/ghgp/main.do

[31] Guidehouse selected this cut-off based on expert judgement that sites with more than a quarter million tons of CO_2 emissions are most suitable to select for CCUS applications. To include one of the cement production locations that was slightly smaller, the cut-off was set to 240,000 U.S. tonnes or about 220,000 (metric) tonnes.

[32] In comparison, power plants have CO_2 concentrations in the flue gasses of 4%-12%.

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[214] Table A-1 indicates the underlying cost assumptions, including hydrogen and LCOE of solar PV.

[215] Fraunhofer, Agora EnergieWende, Current and Future Cost of PV, February 2015, p. 65, table 5, US.

[216] Waltzer, The Role of 45Q Carbon Capture Incentives in Reducing Carbon Dioxide Emissions, Clean Air Task Force.

[217] LBST & dena, The potential of electricity-based fuels for low-emission transport in the EU: An expertise by LBST and dena, p. 69.

[218] Porter et al., The range and level of impurities in CO_2 streams from different carbon capture sources, International Journal of Greenhouse Gas Control, 36. 161 – 174.

[219] Linde, CO_2 purification and liquefaction

[220] Linde, Linde to build world's largest CO_2 purification and liquefaction plant, https://www.linde.nl/en/news_and_media/press_releases/news_20130822.html

[221] Note that cost estimates for CCS do not change from target year 2030 to 2050 in Figure 30 and Figure 31. Avoidance costs are shown for CCS on gas-fired power. The energy required for carbon capture comes from the power plant, and not from external sources. Therefore, emission factors and power cost do not vary from 2030 to 2050 as they do for other technologies in the analytical model used to generate these figures.

[222] Fraunhofer, Agora EnergieWende, Current and Future Cost of PV, February 2015, p. 65 table 5, US.

[223] SAM, Novel carbon capture and utilisation technologies, Scientific Opinion 4/2018.

[224] Bains et al., CO_2 Capture from the industry sector, Progress in Energy and Combustion Science 63 (2017) 146-172.

[225] Ultradeep geothermal energy, electrification, biogas, novel drying technologies and alternative solvents replacing water such as alcohol can all contribute towards reducing emissions. See Pöyry, "Paper and board welcome CO_2.Ø", VNP, 2017 for a sketch of what these technologies might achieve for the sector.

[226] IEA, "Transforming Industry through CCUS", 2019, www.iea.org/publications/reports/TransformingIndustrythroughCCUS/

[227] Marcacci, "Renewable Energy Job Boom Creates Economic Opportunity As Coal Industry Slumps," Forbes, April 2019.

[228] IRENA, Renewable Energy and Jobs, Annual Review 2018.

[229] TUC, CCSA, The economic benefits of carbon capture and storage in the UK, 2014.

[230] Section 4.3.5 discusses two different DAC technologies and their developers..

[231] Approximately 200 kg/MWh by 2025 according to Howard et al., Current and near-term GHG emissions factors from electricity production for New York State and New York City, Applied Energy 187 (2017) 255–271.

[232] Fraunhofer Agora EnergieWende, Current and Future Cost of PV, Feb 2015.

[233] Typical CRF values used as part of techno-economic analysis. See: https://cen.acs.org/environment/greenhouse-gases/Capturing-carbon-save-us/97/i8

[234] EIA Annual Energy Outlook 2019, https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf

[235] Guidehouse analysis.

[236] Production of Bio-ethylene, IEA-ETSAP and IRENA Technology-Policy Brief I13, January 201, https://iea-etsap.org/E-TechDS/PDF/I13IR_Bioethy_MB_Jan2013_final_GSOK.pdf

[237] Set to zero, in accordance with net-zero policy target. See: https://www.eia.gov/electricity/state/newyork/

[238] NYSERDA Greenhouse Gas inventory, fixed. See: https://www.nyserda.ny.gov/-/media/Files/EDPPP/Energy-Prices/Energy-Statistics/greenhouse-gas-inventory.pdf

[239] Guidehouse analysis.

[240] 40% GHG reduction versus fossil production. See: https://iea-etsap.org/E-TechDS/PDF/I13IR_Bioethy_MB_Jan2013_final_GSOK.pdf

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