Carbon Capture Technologies for Meeting Virginia Clean Economy Act Goals

Tara Illgner
Charlottesville, VA

Master of Arts, Rudolf Steiner College, 2014
Bachelor of Arts, University of Virginia, 2004

A Thesis presented to the Graduate Faculty
of the University of Virginia in Candidacy for the Degree of
Master of Arts

Department of Environmental Sciences
University of Virginia
May 2022

Table of Contents

List of Tables

List of Figures

List of Abbreviations

Allam-Fetvedt cycle	AFC
American Recovery and Reinvestment Act	ARRA
Appalachian Power Company	APC
Argonne National Laboratory	ANL
Carbon capture	CC
Carbon capture and storage	CCS
Carbon capture utilization and storage	CCUS
Carbon dioxide	CO_2
Clean Air Task Force (United States)	CATF
Department of Energy (United States)	DOE
Department of Homeland Security	DHA
Direct air capture	DAC
Energy Information Administration (United States)	EIA
Enhanced oil recovery	EOR
Environmental and Energy Study Institute	EESI
Environmental Protection Agency (United States)	EPA
Global Carbon Capture and Sequestration Institute	GCCSI
Greenhouse gas	GHG
Hydrogen	H_2
Infrastructure and Investment Jobs Act	IIJA
Intergovernmental Panel on Climate Change	IPCC
Integrated gasification combined cycle	IGCC
International College of Economics and Finance	ICEF
International Energy Agency	IEA
International Energy Agency Greenhouse Gas program	IEAGHG
International Energy Forum	IEF
IPCC 6th annual report	AR6
Life Cycle Analysis	LCA
Metric tonnes per annum	MTPA
Megawatts	MW
National Aeronautics and Space Administration (United States)	NASA
National Energy Technology Laboratory (United States)	NETL
Office of Fossil Energy and Carbon Management (United States)	FECM
Paris Climate Agreement	PCA
Post-combustion carbon capture	Post-CCC
Pre-combustion carbon capture	Pre-CCC
Regional Greenhouse Gas Initiative	RGGI
Senate Bill	SB
State Corporation Commission (Virginia)	SCC
United States Geologic Survey	USGS
Virginia Clean Economy Act	VCEA
Water-gas shift reaction	WGSR

Definitions

"Carbon dioxide," "carbon," or "CO_2" is the predominant greenhouse gas that is emitted into the air from the burning of carbon-rich substances such as wood, coal, oil, gasoline, or natural gas, causing a greenhouse effect that warms the Earth.

"Greenhouse effect" refers to the accumulation of greenhouse gases (GHGs) such as CO_2 and methane in the atmosphere, which trap heat from the sun in the same way that glass traps heat in a greenhouse and as a windshield traps heat in a car on a sunny day.

"Renewable energy" in the Virginia Clean Economy Act (VCEA) is referred to as energy derived from wind and solar. However, the *Oxford Languages* defines "renewable energy" as a source that can be renewed: "a source that is not depleted when used". This paper uses the *Oxford* definition of "renewable energy."

"Carbon capture" (CC) refers to the process of capturing CO_2 emissions to prevent release into the atmosphere. This paper focuses on "carbon capture" processes using technological and man-made carbon capture methods such as retrofitting industrial facilities to filter out carbon dioxide from smokestack emissions rather than natural methods such as reforestation.

Acknowledgements

I would like to thank my advisor, Dr. Deborah Lawrence, for her example, encouragement, and patient, dedicated guidance throughout.

I would also like to thank my other committee members, Drs. Marlit Hayslett, Bill Antholis, and Mike Pace, for sharing their support and enthusiasm.

The topic of this thesis is owed to the work with Virginia's Joint Commission on Technology and Science (JCOTS) during the 2021 COVES fellowship. I would especially like to thank Attorney David Barry at the Virginia legislature's Division of Legislative Services (DLS) for his mentorship and faith in helping this work move forward.

To the faculty, staff, and graduate students of the Department of Environmental Sciences, I am grateful for the community, friendship, and inspiration. Special thanks to Elise Heffernan for the 11th-hour moral and tech support.

Finally, I am thankful for my family's unending love and encouragement.

Preface

This topic began as a discussion with the attorneys at the Virginia legislature's Division of Legislative Services (DLS) in the summer of 2021. As a 2021 fellow with the Commonwealth of Virginia Engineering and Science (COVES), I had been assigned to serve as the science-policy analyst for the Virginia legislature's Joint Commission on Technology and Science (JCOTS). In this role, I expressed my concern to the DLS attorneys about the lack of carbon capture (CC) technology developments in Virginia. With the support of my mentor, Esq. David Barry, we conferred with Virginia's State Corporation Commission (SCC) and arranged meetings with Virginia's Department of Energy (formerly the Department of Mines Minerals and Energy). These meetings revealed that there had been sparse interest or discussion of CC technologies, and no known CC developments in the Commonwealth. Following these clarifications, I arranged meetings with key JCOTS legislators and the NET Power company. The NET Power company is based in North Carolina and operates a facility in La Porte, Texas that employs an emerging zero-emission CC technology to generate electricity. These meetings were intended to introduce CC technologies to the legislators and bring insights from the company's Chief Technology Officer to clarify the cost, benefits, and potential applicability of these technologies in Virginia. Discussions are ongoing.

Abstract

Rising carbon emissions, in the form of CO_2, are accelerating global warming, posing an existential threat to life on Earth. The Virginia Clean Economy Act (VCEA) calls for 100% carbon-emission-free electricity generation in the Commonwealth by 2045. The VCEA specifically calls for eliminating electricity emissions by replacing conventional power plants with renewable sources. However, Virginia's electricity sector only accounts for 35% of the state's carbon emissions, and the IPCC recommended 1.5^{o}C warming ceiling requires deployment of all available CO_2-abatement methods. Therefore, this thesis presents carbon capture technologies as one of the potential approaches to reducing or eliminating (1) interim electricity sector emissions until power facilities are replaced by renewables, and (2) the remaining 65% of Virginia's carbon emissions. This thesis reviews literature from scientific, economic, government, intergovernmental, and NGO sources. The review covers both established and emerging technologies that can harness Virginia's geographic, geologic, economic, and policy settings for significant and rapid reductions in the state's CO_2 emissions.

Here I present findings of Virginia's opportune suitability for implementing carbon capture through the following six approaches: Post-combustion carbon capture can be applied to Virginia's 98 existing power facilities. Pre-combustion carbon capture and the Allam Fetvedt are applicable for reducing or eliminating carbon emissions from new electricity-generating facilities. Enhanced oil recovery is already widely in use throughout the United States and can be expanded into Virginia for carbon sequestration at existing oil and gas wells, particularly in the western part of the state. Virginia's participation in the emerging carbon utilization market may accelerate carbon capture in Virginia while also supporting the overall market's growth. Finally, forming cooperative carbon sequestration hubs with regional carbon emitters can expand opportunities for reduced-cost sequestration in Virginia using shared pipeline infrastructure.

In summary, this thesis contributes to synthesizing the current state of development and deployment of carbon capture technology at the global, national, and Virginia state level. Additionally, I highlight potential paths to carbon neutrality in Virginia through layered applications of carbon capture technologies as well as regulatory and financial incentives. Lastly, I posit how layering carbon capture technology networks may further fuel a circular carbon economy toward energy independence.

Introduction

The latest Intergovernmental Panel on Climate Change (IPCC) 6th Assessment Report (AR6) presents the strongest statements to date about the ‘unequivocal’ role of human activities causing climate change, specifically due to carbon dioxide (CO_2) emissions, and the risks that climate change presents to life on Earth (IPCC, 2021). To halt warming at the 1.5°C ceiling as targeted by the 2015 Paris Climate Agreement (PCA) will require achieving net-zero global emissions by 2050 (PCA, 2015). Similarly, the Virginia Clean Economy Act (VCEA) specifically targets net-zero carbon emissions from energy generation by 2045 (VCEA, 2020). However, the world, U.S. and Virginia continue to rely in large part (80%, 61%, 68%) (EESI, 2020; EIA, 2021a; EIA, 2021b) on burning carbon-rich substances primarily for electricity generation and transportation (Rapier, 2020). Therefore, the latest IPCC report reiterates that reducing the costs of staying below the 1.5ºC warming limit will require the use of zero- and negative-emission technologies, “CCS (Carbon Capture and Storage) has the potential to reduce overall mitigation costs and increase flexibility in achieving greenhouse gas emission reductions” (IPCC, 2018a).

Carbon capture (CC) technologies (also known as Carbon Capture Utilization (CCU), and Carbon Capture and Storage (CCS)) including new and retrofitted facilities, are gaining interest in recent years to reduce or eliminate carbon emissions to the atmosphere (Jaruzel, 2021) and are projected to make substantial contributions on the pathway to decarbonization (Lane et al., 2021). CC technologies work by capturing CO_2 either from active industrial emissions or directly from the ambient air. This captured CO_2 can then be reused as a renewable resource for power generation, sold as a usable commodity to other industries, or permanently stored underground. Along with growth in renewable energies, CC technologies offer to reduce carbon emissions while potentially increasing energy independence through storage and reuse of the captured carbon (Feron, 2016). Applications for CO_2 reuse include product manufacturing, use as a renewable energy source (Illgner, 2021), or through conversion back into combustible fuel (NASA, 2013; ANL, 2020).

The motivations governing CCS research and deployment investments are varied. While some motivations prioritize maintaining a role for fossil fuels, others prioritize accelerating the drawdown of atmospheric CO_2 concentrations (negative emissions). This paper focuses on the latter. In line with the PCA, the VCEA goal of "100 percent carbon-free electric energy generation by 2045" (VCEA, 2020) can be accelerated with CC technologies. Beyond curbing energy sector emissions, CC can aid in reducing the carbon footprint of other carbon-emitting industries in Virginia until decarbonization is complete.

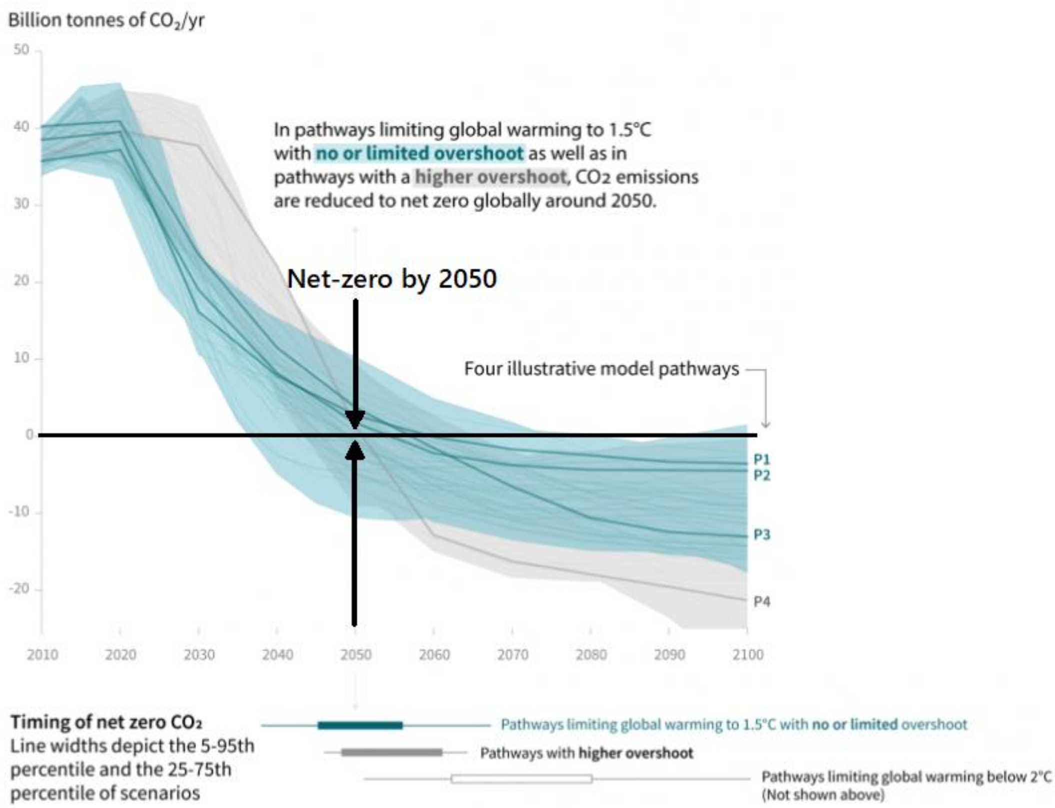

Figure 1: Reproduced from IPCC 1.5°C Special Report showing pathways to net-zero global emissions by 2050 to limit warming to 1.5°C, with deployment of CO_2 removal and net-negative emissions post 2050 (IPCC, 2018a). P1 represents lower energy demands and afforestation CCS. P2 represents sustainability focused scenario of global cooperation with limited CCS. P3 represents improvements in energy and product production efficiency. P4 represents business as usual with strong CCS use.

The VCEA prioritizes renewable energy sources to accomplish carbon-free energy, however, CC technologies can also contribute to advancing emission-free goals by being applied to other carbon-emitting industries beyond energy generation. CC technologies are not replacements for renewable energy sources (i.e., wind and solar) but are rather complementary tools supporting the transition from current fossil fuel use to negative emissions by mid-century (Figure 1). Even during Virginia's transition to all-renewable energy, as prescribed by the VCEA, CC can be applied immediately to mitigate interim carbon emissions until the switch to renewables is complete. A broad range of sectors, such as power, transportation, concrete, steel, continue to rely heavily on fossil fuel energy (EPA, 2021a) due in part to their higher thermal capacity needs which renewable energies cannot achieve at this time. For these hard-to-abate industries, CC offers reduced-carbon emission energy toward the decarbonization transition. Of the hard-to-abate industries in the U.S., Virginia is home to 17% of steel mills (DOE, 2010), 1.3% of power plants (EIA, 2021a; EIA 2019b), and 1.5% of cement production (USGS, 2020).

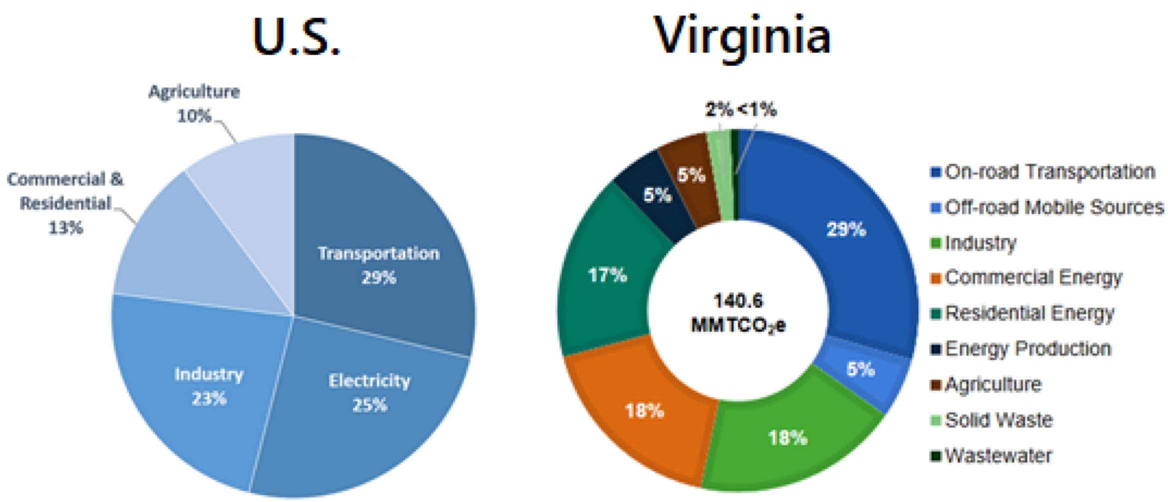

***Figure 2**:* Reproduced from EPA (2021a) and DEQ (2021) showing breakdown of greenhouse gas emissions sources in the US and Virginia, in Millions of Metric Tons of Carbon Dioxide Equivalent (MMTCO_2e).

Carbon capture involves capture, transport, and storage of carbon. This paper focuses primarily on the capturing portion of the process for deployment in Virginia and beyond. Later sections of the paper discuss destinations of captured carbon including storage and utilization options that complement CC deployment and can also support VCEA goals. This paper posits that the application of CC technologies should prioritize carbon drawdown efforts by working toward net-negative carbon emissions.

Background

Climate change is caused primarily by the emission of CO_2 and other greenhouse gases (GHGs) that come from burning fossil fuels for power generation, transportation, and industrial processes. Carbon is also emitted by deforestation, agriculture, and concrete production. In the United States, fossil fuels account for 61% of energy usage (EIA, 2021a). Energy, transportation, and industrial processes are the primary sources (77%) of U.S. carbon emissions (EPA, 2021a) (Figure 2). The primary sources of Virginia's 30 million tons of carbon-emissions are from heating and cooling (35%), transportation (34%), and industrial facilities (18%) (DEQ, 2021) (Figure 2), totaling 87% of Virginia's carbon emissions. Eliminating Virginia's power sector emissions (only 35% of the state's emissions), per the VCEA, does not address the rest of the Commonwealth's emissions. Limiting warming to the recommended 1.5°C will require preventing or intercepting CO_2 emissions from all sectors using a hierarchy of approaches beginning with prevention, followed by minimization, recovery, sequestration, or reuse (Figure 3) (Lehtonen et al., 2019). The remaining option depicted in Figure 3 is to continue venting emissions to the atmosphere, which would contribute to warming above 1.5°C.

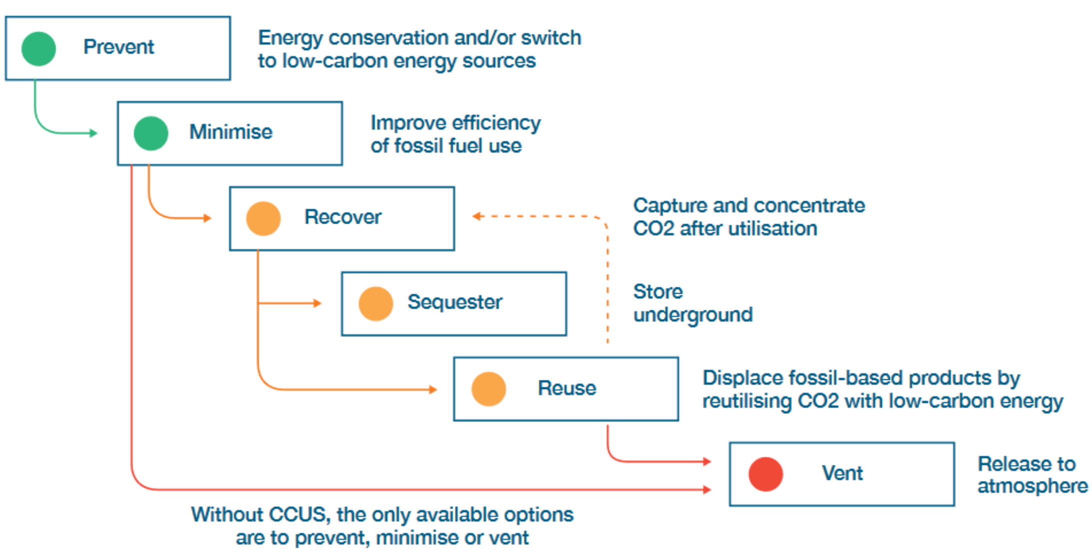

Figure 3: Decarbonization hierarchy of approaches reproduced from Lehtonen et al. (2019). Venting represents the final option that does not serve to limit warming.

Established Carbon-Reduction Approaches

To reduce CO_2 emissions into the atmosphere, the goals of the Virginia Clean Economy Act (VCEA) reflect those at the international and national level, emphasizing greater use of the following established emissions-reduction strategies:

1. Energy Efficiency, for *reduced* CO_2 emissions, including:
    - Light-emitting diode (LED) lightbulbs
    - Energy-Star certified appliances
2. Renewable Energy, for *zero* CO_2 emissions, including:
    - Wind
    - Solar
3. Carbon Capture, for *reduced*, zero, or *negative* CO_2 emissions
    - Natural (land-based adjustments), including:
        - Reforestation
        - Afforestation
        - Regenerative Agriculture
    - Technological, including:
        - Post-combustion carbon capture
        - Pre-combustion carbon capture
        - Allam-Fetvedt Cycle

As shown in Figure 4, the two main approaches for replacing and intercepting carbon emissions include (1) Renewables and (2) Carbon Capture. Each of these categories represents various methods and technologies. Renewables generally refer to methods of generating energy that produce *zero* emissions. Carbon capture methods can produce *reduced (low)*, *zero*, or *negative* emissions, and can either be (1) natural or (2) technological.

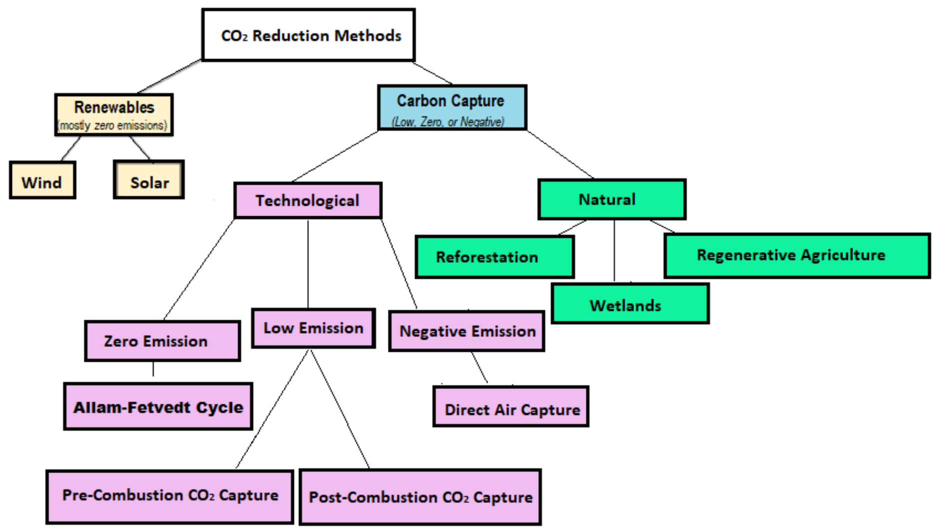

Figure 4: Chart displays two distinct categories of CO_2-reduction solutions: renewables and carbon capture. Each category is further broken down into various methods and technologies (Illgner, 2021).

Technological methods of carbon capture, the focus of this paper, encompass three established types: (1) pre-combustion carbon capture, (2) post-combustion carbon capture, (3) direct air capture (DAC), and (4) an emerging carbon capture technology called the Allam-Fetvedt cycle that can be categorized as a *zero*-emission technology, and potentially a *negative*-emission technology.

Carbon Capture

Carbon Capture technologies have been in use since 1920 (IEAGHG, 2019). While initially created to increase oil recovery efficiency, the modern purpose of CC is to prevent CO_2 emissions to the atmosphere by capturing CO_2 during combustion of fossil fuels, such as coal, oil, or natural gas. The captured CO_2 can then be compressed and transported to permanent underground storage in geological formations or for use in consumer products. The interrelated objectives of capture (CC), use (CCU), and storage (CCS) result in overlapping benefits. CC is required before CCU or CCS. In the near term, using captured carbon (CCU) in profitable applications can incentivize and accelerate CC deployment.

Types of Carbon Capture

As shown in Figure 4, *low* carbon-emission solutions are those that reduce the level of CO_2 emissions that are released into the atmosphere. *Zero* carbon-emission solutions are those that prevent all CO_2 emissions from reaching the atmosphere. *Negative* carbon-emission solutions are those that actively remove excess CO_2 from the atmosphere. Currently available CC technology used in industrial plants captures between 85-90% of CO_2 emissions and requires between 10-40% more energy than plants without CC (Figure 5) (IPCC, 2018b). Integrated Gasification Combined Cycle (IGCC) plants are on the low end of extra energy needs for CCS, and Pulverized Coal plants are on the high end. Captured CO_2 can then be reused, stored, or sold as a marketable commodity to offset costs of electricity production. In the interim to decarbonization, CCUS makes CO_2 useable before, during, and after energy generation, creating the potential for a circular carbon economy for energy independence (IEF, 2020).

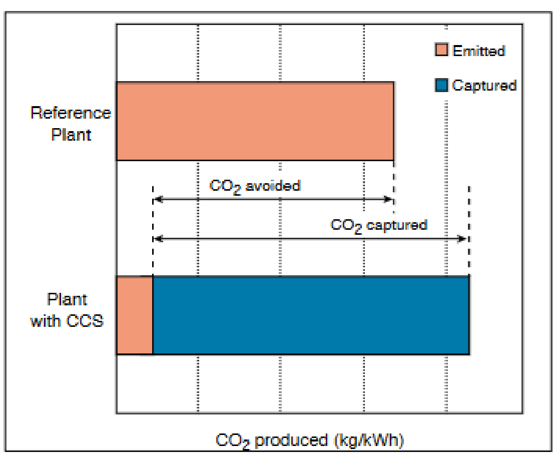

Figure 5: Reproduced from IPCC 2018 Special Report on Carbon Dioxide Capture and Storage depicting contrast between non-CCS plant emissions and conventional plant emissions (orange). CCS-related increases (blue) in CO_2 production due to CC efficiency and leakage (IPCC, 2018b).

Low Carbon Emission Options

Pre-combustion carbon capture (pre-CCC) reduces the amount of CO_2 emissions that reach the atmosphere by separating CO_2 from fuels *before* they are burned to generate electricity (Figure 6). During the process of pre-CCC in an IGCC power plant, the carbon-based fuel (typically methane or gasified coal) undergoes a pressurized reaction with steam and oxygen to create synthesis gas (syngas). Syngas is primarily composed of hydrogen (H_2), carbon monoxide (CO), and CO_2 (NETL, 2022b). Using a water-gas shift reaction, the remaining CO is converted to CO_2 while increasing the H_2/CO_2 ratio, making more H_2 available for later combustion. The resulting high partial pressure of the CO_2 in the syngas increases its separation efficiency and subsequent capture. The syngas is passed through liquid solvents, solid sorbents, or membranes that separate the CO_2 from the H_2. The H_2 is then cleanly combusted, resulting in energy production and water as the waste-product (Di Lorenzo et al., 2013). The remaining CO_2 can then be compressed into a liquid for transport to storage or resale. Through pre-combustion carbon capture, the final burned gases that are emitted to the atmosphere contain 90-95% less CO_2 than they otherwise would have (Basile et al., 2011). The higher concentration of CO_2 in the syngas makes the pre-CCC more efficient than post-combustion carbon capture (NETL, 2021). However, despite the higher efficiency, a deterrent for pre-CCC deployment is that it is not a retrofit option, therefore the initial costs of building a pre-CCC facility can be cost-prohibitive for smaller entities.

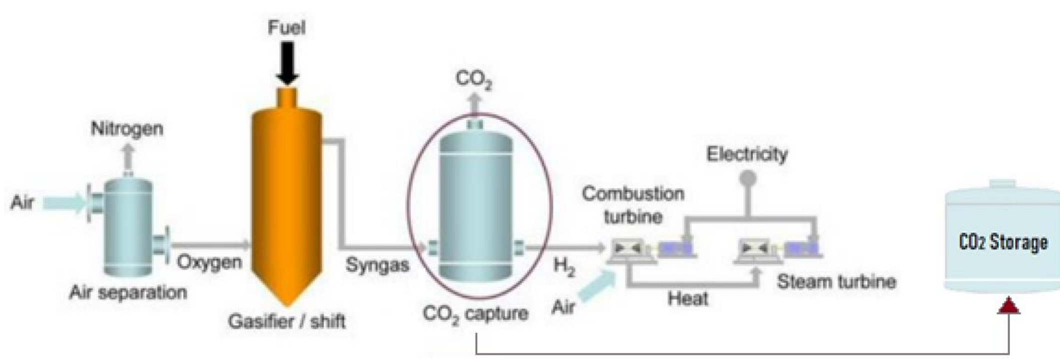

Figure 6: National Energy Technology Laboratory illustration of Pre-combustion carbon capture process stages. Reproduced from NETL carbon capture information site (NETL, 2021).

Post-combustion carbon capture (post-CCC) also reduces the amount of CO_2 emissions that reach the atmosphere but does so by separating the CO_2 from the exhaust *after* fossil fuels are burned (Figure 7). Having been in use for nearly a century, post-CCC is an older technology than pre-CCC (Institute for Environmental Analytics Green House Gas, 2019). While post-combustion carbon capture is less efficient, more energy-intensive, and more costly than pre-CCC, it is more often employed because it allows for retrofitting, which can make it a more attractive option for existing facilities.

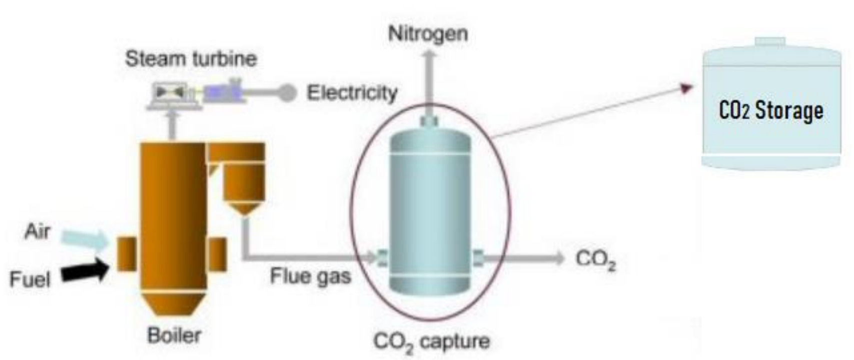

Figure 7: National Energy Technology Laboratory illustration of post-combustion carbon capture process. Reproduced from NETL carbon capture information site (NETL, 2021).

Zero Carbon Emission Options

The Allam-Fetvedt cycle (AFC) produces zero carbon emissions by functioning both as a renewable and as a CC technology (Figure 8). While most carbon capture methods reduce CO_2 emissions by either absorbing CO_2 from the atmosphere (like direct air capture) or filtering out some of the CO_2 before it reaches the atmosphere (like pre- and post-CCC), the AFC claims to do both. While pre- and post-CCC generate electricity by burning fossil fuels and emitting some CO_2, the AFC traps all of the CO_2 that is created from burning minimal amounts of natural gas. This trapped CO_2 is then compressed and used as a renewable resource by circulating through closed pipes to generate electricity, similar to how the flow of water or steam through turbines generates electricity. Therefore, rather than emitting CO_2 as an environmentally harmful waste product, the Allam-Fetvedt cycle makes use of the CO_2 in a closed-loop to recycle within its pipes (NET Power, 2021). Any excess CO_2 is then transported for geologic storage or for sale to other industries for reuse. Furthermore, by switching to sourcing the CO_2 from a Direct Air Capture (DAC) facility rather than natural gas and by using solar energy to operate the CO_2 compressor, the AFC has the potential to operate as a negative-carbon energy-generation system.

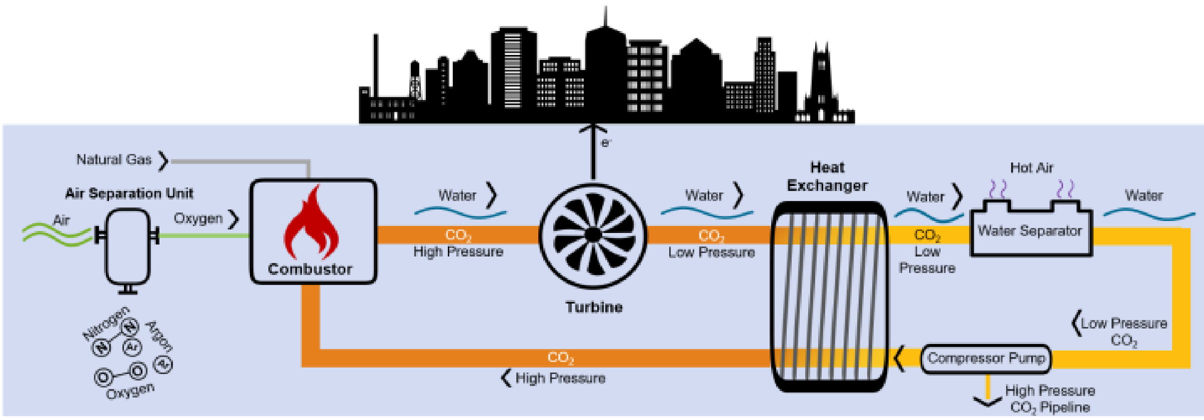

Figure 8: Allam Fetvedt cycle oxy-combustion process, reproduced from NET Power company public information (NET Power, 2021).

Negative Carbon Emission Options

Direct air capture (DAC) facilities are a negative carbon-emission technology. They are designed exclusively to pull CO_2 from the atmosphere using fans to draw air in to react with chemicals that selectively bind with CO_2. The chemicals are generally either liquid solvents or solid sorbents. Once chemically captured, heat is used to separate the CO_2 from the solvent or sorbent, after which the CO_2 is compressed for transport destined for sale or storage (Lebling, 2021). DACs are the only established carbon-*negative* CC technology currently in use, however they do not currently support energy needs like the other CC technologies listed.

Currently, there are 19 operational DAC facilities worldwide (IEA, 2021a). Together these plants are capturing more than 11,000 tons of CO_2 annually. Additionally, an upcoming U.S. DAC plant in Texas is due to capture over 1 million tons (Mt) of CO_2 per year (Reuters, 2020). The resulting captured CO_2 can be sold for industrial purposes or stored in geologic storage sites underground. The 2021 DAC plant by Climeworks, called Orca, is storing over 4 thousand tons of CO_2 into Iceland's underground basalt formations. Figure 9 displays Climework's 2015 technology operating in Switzerland.

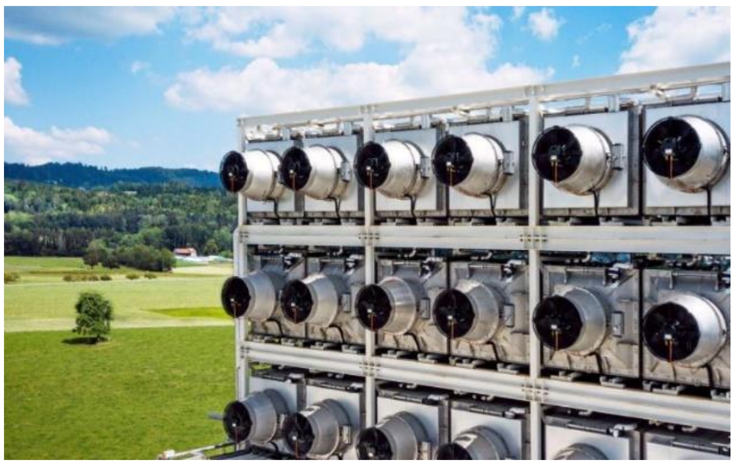

Figure 9: The first DAC plant by Climeworks in Hinwil, Switzerland. Reproduced from Climeworks (2015).

Growth in DAC is currently limited due to relatively low atmospheric concentrations of CO_2 which results in lower-efficiency (averaging \$500 per ton) operations compared with CC applied at industrial point sources (averaging \$50 per ton). While proponents argue that increasing the scale of DAC can reduce unit costs, the pathway to cost competitiveness with industrial CC remains unclear (Biniek et al., 2020). However, the accelerating growth in renewables (IEA, 2021b) may lead to declining need for smokestack CC (like pre- and post-CCC) and leave a larger role for DAC. Adhering to the 1.5^{o}C prescribed pace of carbon reduction entails a mid-century shift in the balance of CCS from fossil fuel-based positive emissions toward negative emissions such as DAC. Supporting costly DAC operations require more profitable destinations of carbon, including marketable products made from CO_2.

Destinations for Captured Carbon

The forecast for CCUS is mixed. The McKinsey and Company 2020 report titled “Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage” projects a 10-fold increase in the annual carbon captured by 2030 (50Mt to 500Mt) (Biniek, 2020). Based on current annual emissions of CO_2 (42Gt), 500Mt would represent 1% of annual emissions. Even to achieve this increase in annual carbon captured, McKinsey and Company specify that continuing progress in the following requirements is needed: “(1) capture costs fall, (2) regulatory frameworks provide incentives to account for CCUS costs, and (3) technology and innovation make CO_2 a valuable feedstock for existing or new products.” However, a more optimistic estimate along the same timeline by Kätelhön et al. (2019) estimates CCS to capture 8% (3.5Gt) of current annual emission amounts by 2030. Furthermore, the 45% growth in renewable energies from 2019 to 2020 (IEA, 2021b), resulting in lower carbon emissions, would increase the proportional contributions of future CC. Such a proportional shift would position CC, particularly DAC, with a more substantial role in reducing atmospheric CO_2 concentrations.

According to the IPCC 1.5^{o}C Special Report (2018), in addition to reducing carbon emissions through zero-carbon (renewables, AFC) and reduced-carbon (energy efficiency) technologies, a further total of 350Gt to 1200Gt of CO_2 must be captured and sequestered through CCS in order to limit warming to the 1.5°C target. A growing CC capacity would also require a commensurate expansion of destinations (products and geologic storage) for the captured carbon. In addition to geologic sequestration, the Global CCS Institute’s 2021 report projects that by 2030, policy and market forces will drive the CO_2-reuse industry to utilize 15% of global carbon emissions. Profitable destinations and uses for the captured carbon are particularly important for supporting the higher-cost DAC operations that will likely displace fossil-fuels-based CC, such as pre-CCC and post-CCC, along the path to decarbonization. However, while emerging technologies offer marketable products from the captured carbon (Figure 10), geologic storage currently remains the primary destination for captured CO_2.

Geologic Storage

Historically, tremendous reservoirs of fossil fuels have been transferred from terrestrial beds into the atmosphere through combustion, however new work in geochemistry is offering to reverse this process by transferring carbon from the atmosphere back into terrestrial deposits (DePaolo, 2018). As with the Orca DAC plant, the bulk of captured carbon in the near-term is fated to be permanently stored in underground geologic formations where the vast storage potential is estimated between 3000Gt of CO_2 (USGS, 2022) to over 6000Gt (Nagabhushan, 2019). To maintain warming below 2^{o}C, Kelemen et al. (2019) note that "it will be essential to permanently sequester about 10Gt tons of CO_2 per year by mid-century, and roughly twice that amount each year by 2100" by maximizing the potential of CO_2 capture, removal, and storage technologies.

The primary approaches to geologic sequestration are Enhanced Oil Recovery (next section) and enhanced weathering. Enhanced weathering involves sequestering CO_2 in geologic formations by injecting CO_2-rich water into subsurface basalt formations to induce carbonate mineralization (Bach et al., 2019). Geologic formations of ultramafic rocks, rich in magnesium and iron, such as basalts, comprise more than 10% of the continental surface area and most of the ocean floor. These are the places sought for their carbon sequestration potential (Marieni et al., 2013). Basalts and peridotite are ultramafic, igneous rocks containing silicate-rich minerals such as olivine, pyroxene, and serpentine, which are derived from the upper part of the Earth's mantle in the form of magma. Olivine is composed of magnesium and iron silicates (Mg_2SiO_4, Fe_2SiO_4) that are far from equilibrium with the atmosphere, such that they react readily with CO_2 to form carbonates. The rate of mineralization is accelerated by injecting the porous basaltic rocks, rich in divalent cations (Ca2+, Mg2+, and Fe2+), with an acidic fluid of water containing dissolved inorganic carbon. Upon exposure to the CO_2-charged acidic fluid, the rocks release these metals through basalt dissolution to form carbonate minerals such as calcite ($CaCO_3$), magnesite

($MgCO_3$), and siderite ($FeCO_3$), resulting in permanent mineral storage of 95% of injected CO_2 (Matter et al., 2016).

A study of Virginia's geologic CO_2 sequestration potential (Roth et al., 2012) conducted in partnership between the Virginia Department of Energy (formerly the Virginia Department of Mines, Minerals and Energy) and the Virginia Center for Coal and Energy Research (VCCER) at Virginia Tech, found that the Piedmont and coastal plain provide suitable reservoirs for large-scale, permanent CO_2 storage. The study investigated the region's geologic suitability, including characteristics of mineralogical properties, porosity, permeability, ease of injection, storage capacity, and proximity to power plants for lowest-cost CO_2-transport scenarios. The promising results of this study suggest a significant potential for deployment of CO_2 geologic storage operations in the Commonwealth.

While the subsurface CO_2 storage potential is vast and promising, three primary challenges of geologic storage of CO_2 are (1) cost, (2) public acceptance, (3) property laws, (4) establishing a durable injection rate and scale to cap warming at 1.5^{o}C, and (5) ensuring the integrity and chemistry of the injection site to prevent CO_2 from returning to the surface. Further expansion of CO_2 subterranean storage can be encouraged and financially supported through regulatory action, such as a price on carbon. A price on carbon can incentivize the research and investments meet the complex challenges of geologic CO_2 storage (Lane et al., 2021).

The National Academies of Sciences Engineering and Medicine 2019 research agenda recommends an investment of $1 billion spread over 10-20 years to expand development and deployment of CO_2 geologic sequestration. The investments can also be applied toward resolving property law complications and ameliorating risks of leaks. Eminent domain, the government's right to seize private land for public use, has historically been a valuable tool for the fossil-fuel industry while being targeted by environmental groups to halt the construction of natural gas pipelines. However, eminent domain may now be a critical tool for climate objectives such as transporting electricity from rural wind and solar farms to high-energy-demand areas and for building CO_2-transport infrastructure (Krawczyk, 2021). The 2018 IPCC Special Report on Carbon Dioxide Capture and Storage states that "The importance of future capture and storage of CO_2 for mitigating climate change will depend on several factors, including financial incentives provided for deployment, and whether the risks of storage can be successfully managed." Preventing leaks would require risk-reduction measures such as avoiding (or properly plugging) abandoned wells along with monitoring for potential leakage to help maintain the permanence of storage sites (McGlade and IEA, 2019a).

Carbon Utilization

Beyond subsurface storage, Figure 10 illustrates additional destinations for the captured carbon, and Figure 11 shows the International Energy Agency (IEA) projected applications for CO_2 reuse by 2070 (GCCSI, 2021). Carbon capture utilization (CCU) presents a potentially profitable near-term catalyst for expanding CO_2 transport and storage infrastructure to the scale needed for decarbonization. However, not all carbon utilized equals new carbon captured or stored. Carbon utilization pathways can vary from "' cycling', 'closed', and 'open'" (Hepburn et al., 2019). According to Hepburn et al. (2019), 'cycling' represents the reuse of industrially captured CO_2 but does not remove CO_2 from the atmosphere, 'closed' represents CO_2 utilization resulting in near-permanent storage, and 'open' pathways generally represent less permanent biological CO_2 removal and storage (biomass and soil). In the IEA illustration below (Figure 10), "Algae & Bioproducts" and "Fuels & Chemicals" represent "cycle" pathways that do not result in permanent CO_2 sequestration (or net carbon removal from the atmosphere), while the "Inorganic Materials" and "Working Fluids" are forms of utilization that represent "closed" pathways of CO_2-utilization resulting in long-term to permanent CO_2 storage. Algae and Bioproducts, such as biofuels, have the potential of offering negative emissions by first drawing down CO_2 through photosynthesis to produce biofuels that can be burned using post-CCC to capture all emissions for geologic storage. This process would result in drawing down, burning, and burying atmospheric carbon to result in negative emissions.

While the amount of CO_2 utilized does not inherently equate to atmospheric CO_2 removed or stored, scalable applications of CO_2 utilization that use low-carbon energy can advance climate goals where the novel application displaces higher-emission processes. The U.S. Department of Energy (DOE) describes CO_2 utilization as an emerging field that "encompasses many possible products and applications: fuels, organic and inorganic chemicals, food and feeds, construction materials, enhanced resource recovery (e.g., oil, gas, water, and geothermal energy), energy storage, wastewater treatment, and others" (Figure 10) (NETL, 2022a). Expanding profitable "closed" pathway uses for captured CO_2, like enhanced oil recovery (EOR) (Hepburn et al., 2019), is critical to buffering the cost of developing and scaling new carbon capture technologies to meet climate goals (Cho, 2019). While the IEA 2019 report "Putting CO_2 to Use" projected the near-term CO_2-utilization market to increase to 10Mt per year (IEA, 2019a), the GCCSI 2021 report projects more significant increases in CO_2 reuse of up to 15% of current emissions (6.3Gt) primarily through EOR.

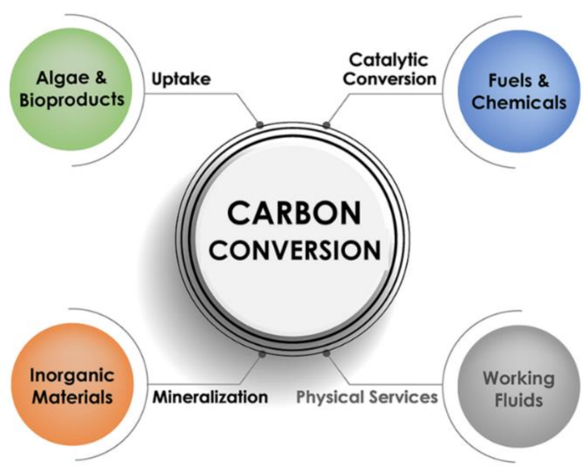

Figure 10: Reproduced from National Energy Technology Laboratory, depicting current primary pathways for carbon utilization (NETL, 2022a).

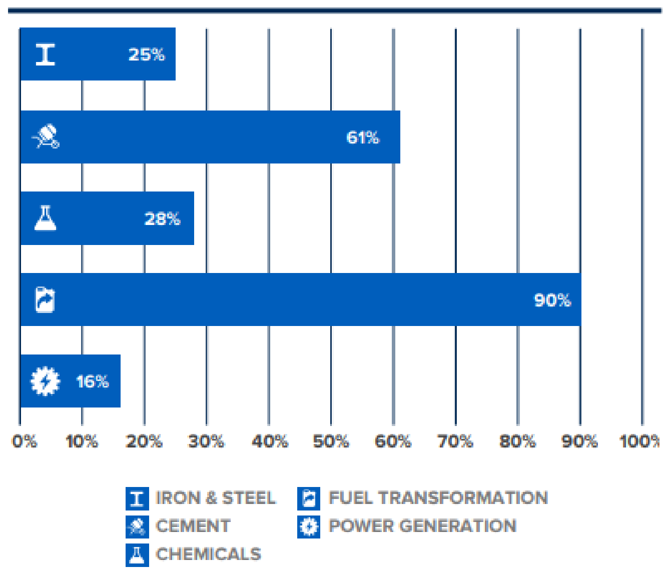

Figure 11: Reproduced from Global CCS Institute illustrating IEA CO_2-reuse projections (GCCSI, 2021).

Enhanced Oil Recovery

Under the "Working Fluids" category in Figure 10, EOR currently leads the CO_2-utilization market, accounting for 90% of all CO_2 reuse and contributing to 20% of all U.S. oil production (Biniek et al., 2020). Enhanced oil recovery uses captured CO_2 by injecting the gas into oil reservoirs, thereby raising the pressure of the reservoirs forcing oil toward production wells, resulting in permanent below-ground storage of 90-95% of the injected CO_2. The remaining CO_2 is returned to the EOR process, creating a closed loop. EOR is distinct from hydraulic fracking in that the former moves into existing cavities while the latter uses higher pressure fluids to force new subterranean fissures to form. While EOR can be performed using a variety of substances, including water, nitrogen, and natural gas, CO_2 is the most commonly used substance. Since this form of CO_2 reuse results in geologic storage as the final destination of captured CO_2, Hepburn et al. (2019) characterize EOR as a 'closed' pathway for captured CO_2. Since the birth of EOR in 1972, the U.S. has emitted approximately 217Gt of CO_2 (Pretel and Linares 2021; EPA 2021c; IEA 2022) and injected 1Gt of CO_2 via EOR (Godec et al., 2011). The carbon-reduction potential of EOR could be significantly higher if more anthropogenic CO_2 (captured from industrial emissions) is used versus natural existing underground CO_2 reservoirs. Given that most CO_2 (70%) is captured at oil and gas operations, these industrial sites are well-positioned to apply their own captured CO_2 emissions to their EOR operations. Policy incentives, such as a price on carbon, can increase industries' preference for using captured CO_2 over terrestrial sources. Additionally, EOR infrastructure can be repurposed into "Stacked Storage Operations" (Figure 12), enabling CCS to achieve substantial climate-change mitigation levels of CO_2 storage (Nagabhushan, 2019). Stacked Storage Operations allow the existing EOR pipelines to be used for saline injection geologic CO_2 sequestration methods, as described in Matter et al. (2016), into formations that have already established their long-term hydrocarbon storage capabilities. The smaller CO_2 molecule further allows for a 40-fold increase of carbon storage into vacated oil or methane formations (Powell et al., 2022). Nagabhushan (2019) estimates the CO_2 sequestration capacity of EOR at 5Gt in the southern United States, with an estimated 6000Gt of additional CO_2 storage capacity further down beneath EOR sites (Figures 12 and 13), which would result in a substantial combined CO_2 storage capacity of approximately 6500 Gt. Given estimates that U.S. pipeline capacity for moving captured CO_2 needs to grow by 3-5-fold by 2050 to meet climate-mitigation goals (Beck, 2019), the expanding EOR infrastructure and profitability can help meet this need by catalyzing expansion of saline injection operations (Figure 12).

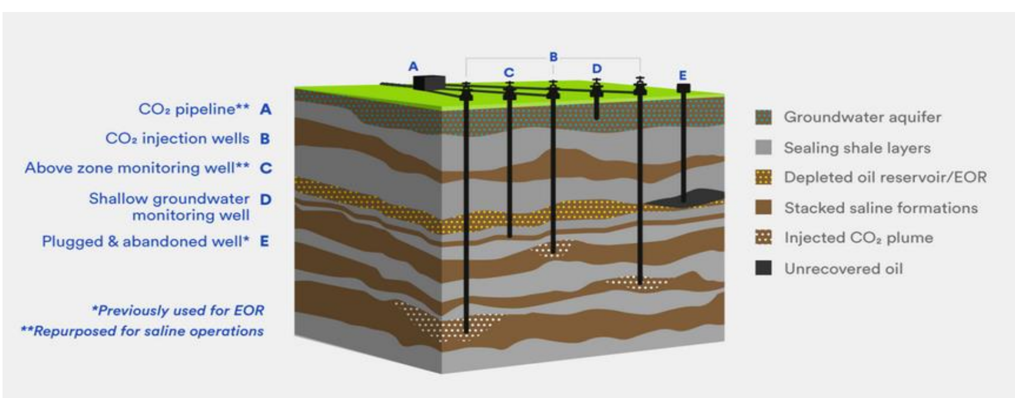

Figure 12: Reproduced from Nagabhushan (2019), illustrating Stacked Storage Operations repurposing EOR infrastructure for saline injected CO_2 storage underground.

Enhanced oil recovery can present conflicting interests of supporting oil and gas production versus decarbonization goals. However, life cycle analyses (LCAs) by Núñez-López et al. (2019) and the Clean Air Task Force (CATF) (2019) suggest an overall net-negative carbon contribution of EOR. Núñez-López et al. (2019) estimate that EOR projects are net negative for the first 6-18 years of operation while there remains oil to recover. However, EOR carbon contributions depend on whether EOR operations displace conventional oil recovery methods or just add to global fossil fuel usage. Accordingly, analyses by the Clean Air Task Force (2019) using IEA LCA, accounting for the added supply of oil through EOR, determined that EOR results in a 37% overall decrease in CO_2 emissions compared with relying on conventional oil recovery methods alone.

Expansion of EOR depends on profitability and convenience. Until the passage of the Infrastructure Investment and Jobs Act (IIJA), the only financial incentive for sequestering CO_2 via EOR came from the Internal Revenue Service (IRS) Code section 45Q offering \$12-\$50 per metric ton of carbon sequestered, to be claimed 12 years after storage begins (CRS, 2021). However, the new 2021 IIJA extends 45Q tax credits till 2031 and additionally offers a \$130/ton tax credit for EOR (Grubbs, 2022). To further enhance financial incentives for expanding EOR operations, a price on carbon

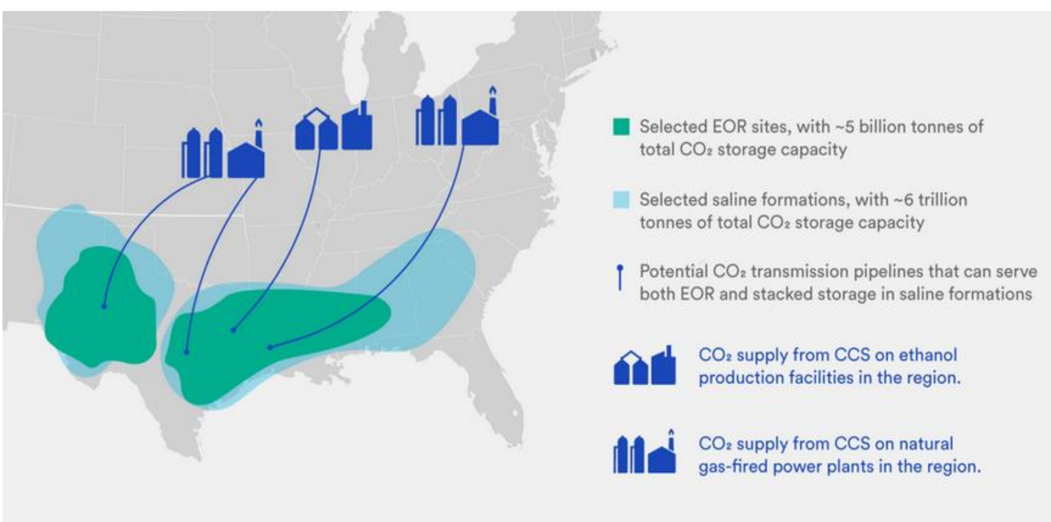

Figure 13: Reproduced from Nagabhushan (2019), illustrating EOR sites in southern U.S. overlying saline formations for additional CO_2 storage.

emissions would be needed, either through a carbon tax or cap-and-trade program. The combined incentives of rising tax credits in addition to baseline EOR profits (oil sales), along with the convenience of Stacked Storage above vast available subterranean CO_2 storage capacity (Figure 13), could serve to drive significant increases in oil operations that opt to use EOR over conventional oil recovery methods. There are currently no known EOR operations in Virginia.

In addition to EOR, the U.S. Department of Energy's office of Fossil Energy and Carbon Management (FECM) list of "Innovative Concepts for Beneficial Reuse of Carbon Dioxide" will receive $1.4 billion in funding from the American Recovery and Reinvestment Act (ARRA). The list of carbon-reuse projects include mineralizing captured CO_2 into carbonates (to use in concrete), applying captured CO_2 to grow algae/biomass combined with CCS, as well as converting CO_2 into other chemicals and fuels toward a circular carbon economy (NETL, 2021). The 2021 Infrastructure Investment and Jobs Act further allocates $310 million in grants toward products that reuse CO_2 in a manner that results in significant emissions reductions compared with conventional alternatives (FECM, 2021).

Fuels

Separate from employing captured CO_2 in the fossil fuel industry, as in EOR, the ARRA and IIJA support CO_2 reuse into new fuels, to reduce interim net emissions on the path to decarbonization. While EOR currently dominates the CO_2-reuse economy, IEA projects CO_2-conversions to new fuels will dominate the carbon-utilization market by 2070 (Figure 11) (GCCSI, 2021). Research from the Argonne National Laboratory (ANL) in 2020 announced the discovery of a new high-efficiency and low-cost method of employing an electrocatalyst to combine CO_2 and water to form ethanol. Ethanol is a highly desirable fuel with broad applicability, used in nearly all U.S. gasoline as well as in chemical and pharmaceutical industries. Being able to produce efficient and affordable alternative fuel using captured CO_2 serves the purpose of reducing or eliminating the need for extracting fossil fuels while also creating a profitable incentive for capturing CO_2, resulting in a circular carbon economy (ANL, 2020).

Materials

In addition to using captured CO_2 toward energy needs, the ARRA and IIJA support applications for CO_2 reuse in high-demand materials, such as concrete. Carbon reuse in concrete is particularly highlighted as a promising application to contribute to global atmospheric CO_2 emission reduction (ICEF, 2017). Growing global demand for over 30Gt of concrete each year amounts to a 3-fold increase in concrete demand since 1980. Traditional concrete production is responsible for over 8% of global carbon emissions and rising (Chatham House, 2020). However, technologies such as the Montreal-based CarbiCrete, may offer significant global carbon-reduction potential. Research by Ravikumar et al. (2021) comparing 75 studies on concrete production methods identifies CO_2-utilization and mineralization in cement as resulting in the most significant climate benefit compared with conventional methods, in terms of carbon sequestered. Carbicrete's describes their process as "flipping the carbon footprint from a release of 2 kg to an absorption of 1 kg" from every 2kg of concrete made, resulting in a material that is 50% stronger and 20% less expensive to produce than conventional concrete (Bourzac, 2017). Permanent sequestration of CO_2 in concrete can simultaneously reduce atmospheric carbon emissions while serving the growing need for concrete as a vital building material (Cho, 2019; Nature Editorial, 2021). McKinsey and Company estimate that by 2030 CO_2-utlization in concrete manufacture can sequester up to 150 million tons per year (Biniek et al., 2020).

In addition to concrete, uses for captured CO_2 are currently being developed in the steel, paper, plastic, food, vodka, textile, detergents, fertilizer, and jewelry industries (Cho, 2019; Corbyn, 2021). As of 2021, investments from venture capital organizations into carbon-utilization startups had risen over 5-fold compared to 2020 (Cleantech, 2022). Growing markets for captured CO_2 may incentivize more investment in CC technologies at the federal level and in the Commonwealth of Virginia.

Policy

In Virginia, the VCEA represents the Commonwealth's primary policy effort to reduce emissions of CO_2 to the atmosphere, with a goal of net-zero emissions from energy generation by 2045. The VCEA (*SB 851* (McClellan, 2020) and *HB 1526* (Sullivan, 2020)) directs the State Air Pollution Control Board to adopt regulations to reduce CO_2 emissions from electric-generating units beginning in 2031, with a goal of 100% carbon-free electricity by 2045. Additionally, the 2021 Clean Energy and Community Flood Preparedness Act (*SB 1027*) directed Virginia to join ten other states in adhering to the Regional Greenhouse Gas Initiative (RGGI) cap-and-trade program emission limits and prices per ton of CO_2 emitted. Under RGGI, the current average auction price for emitting a ton of CO_2 has been $5.08, generating a net economic benefit of $4.7 billion across all RGGI states. The RGGI cooperative claims credit for 48% emission reductions between 2009-2017, which also coincides with a significant decline in regional coal-plant operations and emissions. Together, these regulatory incentives can accelerate the application of CC technologies to help meet VCEA and RGGI goals. However, as mentioned in the Background section, emissions from energy generation only represent 35% of the Commonwealth's total carbon emissions. Therefore, additional mechanisms, such as CCUS, must be considered to address the remaining 65% of the Commonwealth's carbon emissions.

In February of 2021, the Virginia General Assembly passed *SB 1374* (Lewis, 2021 Special Session), establishing a carbon sequestration task force to only evaluate natural carbon capture methods. Natural carbon capture methods include regenerative agriculture, improved forestry, wetland management, and protecting coastal vegetation. The Task Force was scheduled to issue its preliminary report to the Virginia general assembly by the first day (January 12th) of the 2022 Session. However, there is currently no legislation in Virginia that specifically directs evaluation of CC technology options.

Experts repeatedly note the need for more supportive regulatory environments for CC (Biniek et al., 2020; Jaruzel, 2021). This is particularly vital for fossil-fuel-producing states like Virginia, which produces 28,050 megawatts (MW) per year (Smolinski, 2018), and relies on fossil fuels for 68% of its energy needs (EIA, 2021b). Virginia's fossil-fuel production sites and combustion facilities make it amenable to EOR and regional infrastructure cooperatives for CO_2 transport and Stacked Storage operations below active and depleted wells. In addition to state and regional policy incentives to expand the carbon capture landscape in the Commonwealth of Virginia, like VCEA and RGGI, federal policy and funding support for CC technologies are also rapidly growing. Specifically, the Department of Energy's 2022 fiscal year budget requested a 19% increase in CC research and development compared with the 2021 fiscal year appropriations, from $446 million to $531 million (DOE, 2021). Additionally, the ARRA allocates $3.4 billion for CCS projects through the DOE (CRS, 2016), and the recent IIJA (*H.R. 3684*) further allocates $10 billion in support of CCS technologies (FECM, 2021). In the 117th congress alone, there have been 109 CCUS-supporting legislative proposals, of which two have become law (*H.R. 3684*, *S. 1605*), while seven more have passed one chamber (Legislative Search Results, 2022). The National Defence Authorization Act (*S. 1605*) directs the Pentagon, the DOE, and the Department of Homeland Security (DHS) to research CO_2-reuse in creating new fuels. The substantial federal support aimed at expanding the CC industry can benefit states, including Virginia, to reap economic rewards in increasing engagement in the reusable-carbon market, employment, and technological advancements.

Status of CCUS

The Global CCS Institute and IEA 2021 report indicates that there has been strong growth in development of commercial carbon capture facilities around the globe over the past three years and their corresponding CCS capacity (Figure 14). As of 2021, there were 65 carbon capture facilities worldwide at various stages of development, of which 26 are operational. The United States claims 38 of the world's carbon capture facilities (Figure 15) (GCCSI, 2021). Operational carbon capture facilities across the globe have resulted in 340Mt of CO_2 captured to date, while the Americas currently average an annual CO_2 capture capacity of 33Mt (Figure 16) (GCCSI, 2021).

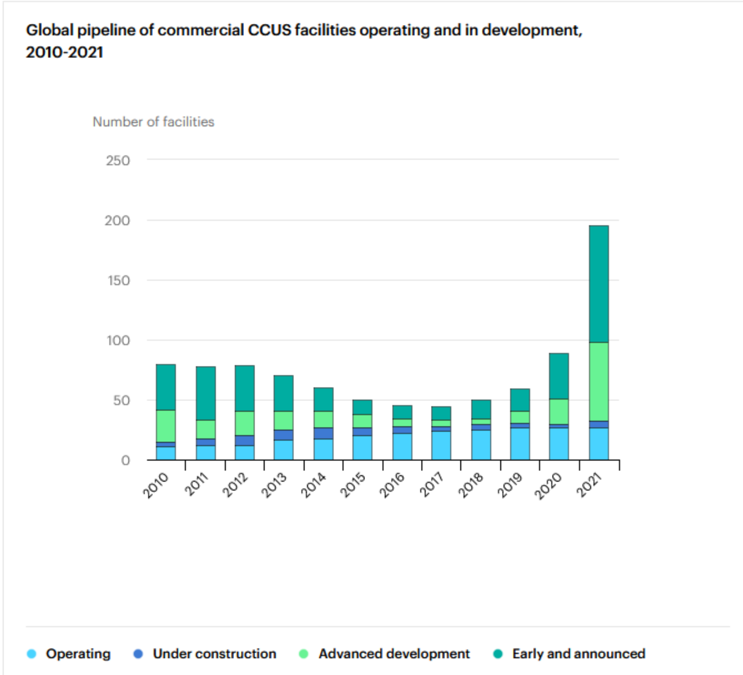

Figure 14: Chart reproduced from International Energy Agency depicting expansion of carbon capture facilities (IEA, 2021a).

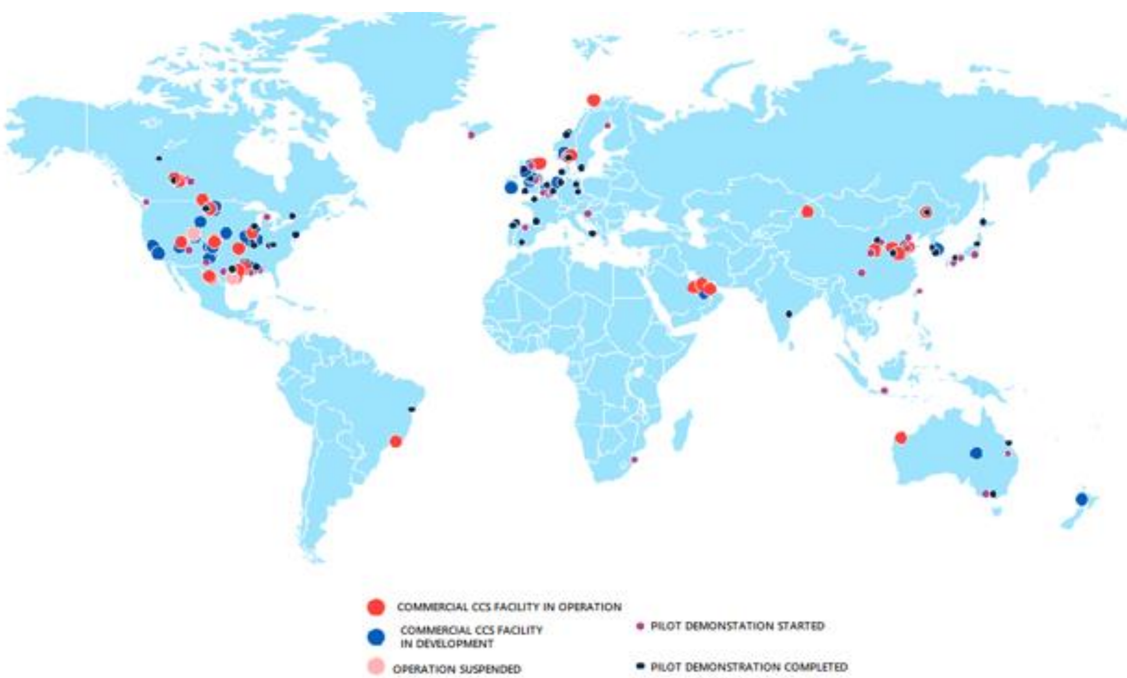

Figure 15: Reproduced from Global CCS Institute report documenting CC locations and status of CC (GCCSI, 2021).

Geographic clustering of facilities into hubs allows for CO_2 transport and storage pipelines that significantly reduce the unit cost of transporting and storing the captured CO_2. Most U.S. carbon capture facilities employ Pre-CCC and Post-CCC in the natural gas processing and coal power generation industries, respectively, along with participating in EOR and the resulting CO_2 sequestration (Figures 15 and 16) (GCCSI, 2021). However, current global carbon emission rates average nearly 42Gt per year. Therefore, to close the gap with *current* emissions rates, the rates of carbon capture (using natural and technological methods) would need to increase by over 1000-fold.

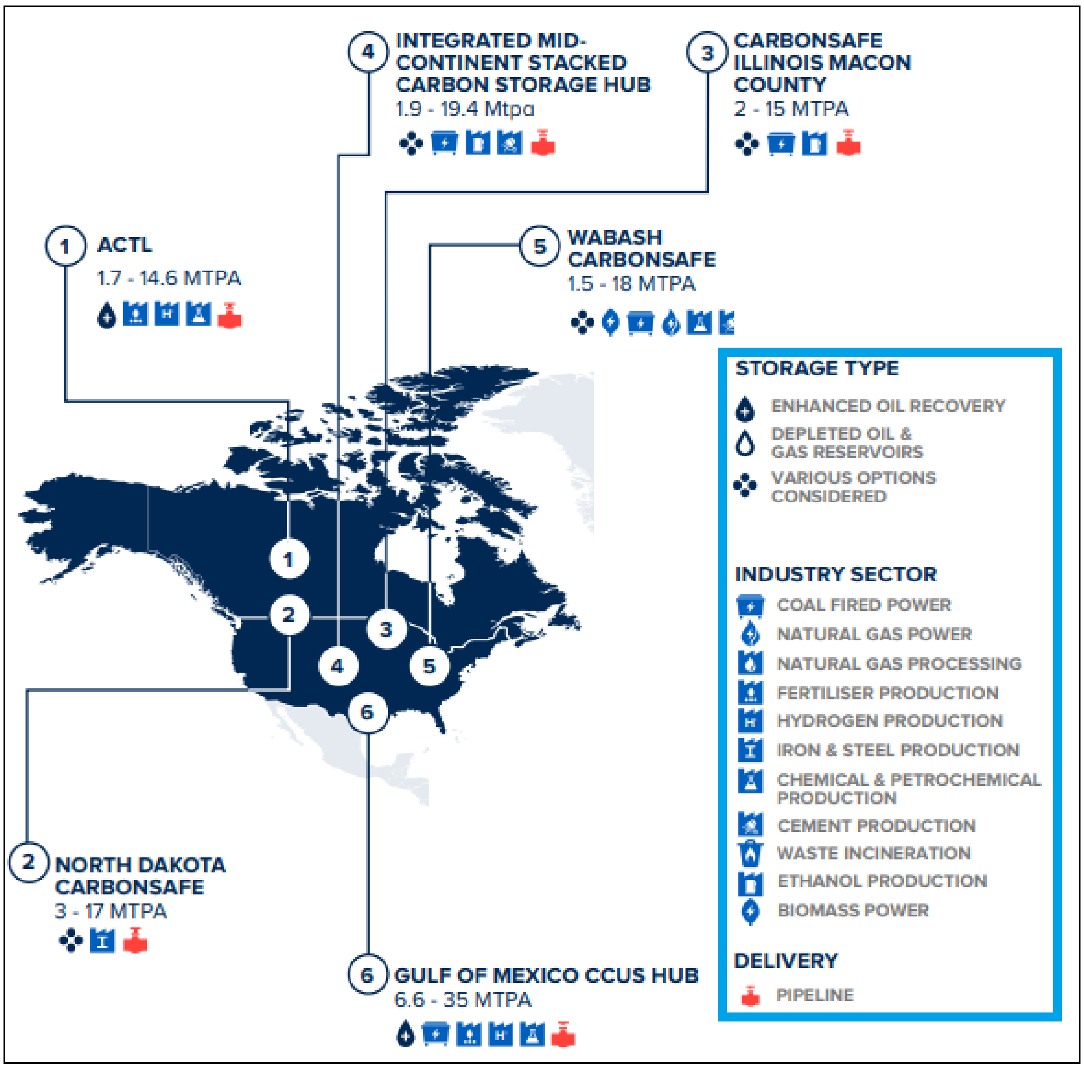

Figure 16: Reproduced from the Global CCS Institute report showing locations and functions of CCUS hubs in the U.S. and Canada, capturing capacity shown in millions of tonnes per annum (MTPA) (GCCSI, 2021).

Among current carbon capture options, the AFC and CO_2-conversion to ethanol (ANL, 2020) stand out for being capable of establishing a circular carbon economy, by first capturing carbon and then using it as a renewable resource. While the AFC is currently a *zero*-carbon emission technology by burning natural gas and capturing all the resulting CO_2, it is also capable of being modified to be a *negative* carbon emission technology by using CO_2 from a DAC facility (that absorbs CO_2 directly from the atmosphere) and using solar power to run the compressor. Therefore, if future natural gas sources were limited, the AFC could continue producing electricity as a *negative* carbon emission method. The company, NET Power, is building and operating AFC facilities in neighboring North Carolina. In August of 2021, I initiated talks between NET Power and legislators about growing zero-carbon energy partnerships for potential expansion of AFC into Virginia.

While it may be cost-prohibitive for individual facilities to independently establish a complete CCS chain of CO_2 capture, compression, transport, and permanent storage, clusters of facilities can instead benefit from forming a shared CCS infrastructure. Known as CCS hubs, the Global CCS Institute and the Clean Air Task Force advocate for networks of geographically clustered facilities to cooperate in building a single, shared, centralized infrastructure connecting facilities to a large strategically located CO_2 storage site (GCCSI, 2016; Jaruzel, 2021). Clusters of power plants are often co-located with other industrial emitters that together form a large source of localized emissions and present a mutual opportunity for large-scale carbon capture and storage. Sharing the costs of building pipelines, compression facilities, obtaining government approvals, etc., can significantly improve the feasibility and efficiency of CCS efforts for individual facilities. There are currently five CCS hubs in the U.S (Figure 16) (GCCSI, 2021).

Carbon Capture and Storage in Virginia

The only identified activity related to carbon capture in Virginia is a case brought by Appalachian Power Company to the State Corporation Commission (SCC) on July 7, 2007 (VA SCC, 2007). In this case, Appalachian Power sought a rate adjustment to its customers' energy bills to accommodate the added cost of building a pre-CCC facility. While the planned building site was in West Virginia, the costs would have resulted in rate adjustments to Appalachian Power customers in Virginia, West Virginia, and Tennessee (APC, 2022). The timing of this case was in response to a 2006 Virginia law (Va. Code § 56-585.1 (A)(6)) requiring the SCC to review proposed adjustments to electricity rates based on changes in operations. However, with legal pressure from large companies, the final order, issued on May 29, 2008, denied Appalachian Power Company's request for a rate adjustment, halting the building plans of the pre-CCC plant.

Given that Virginia is home to 98 operational fossil fuel power plants (Figure 17), the Commonwealth is well-positioned to form or join a CCS hub to accelerate CC expansion. As an incentive to capture more carbon, Virginian facilities are now paying to emit at an average auction price of $5.08 per ton of CO_2 under RGGI cap-and-trade program (RGGI, 2022). If CCS net costs can be made lower than $5/ton then industries will choose to capture and store CO_2 rather than buy emissions permits. Additionally, Virginia's proximity to the southeastern hub, Wabash Carbonsafe, may facilitate rapid connections to this established network for more efficient transport and storage of captured carbon. For participating facilities in the network, a hub's shared carbon transportation infrastructure offers the advantage of reduced risks and costs while facilitating CO_2 capture from smaller facilities (GCCSI, 2016).

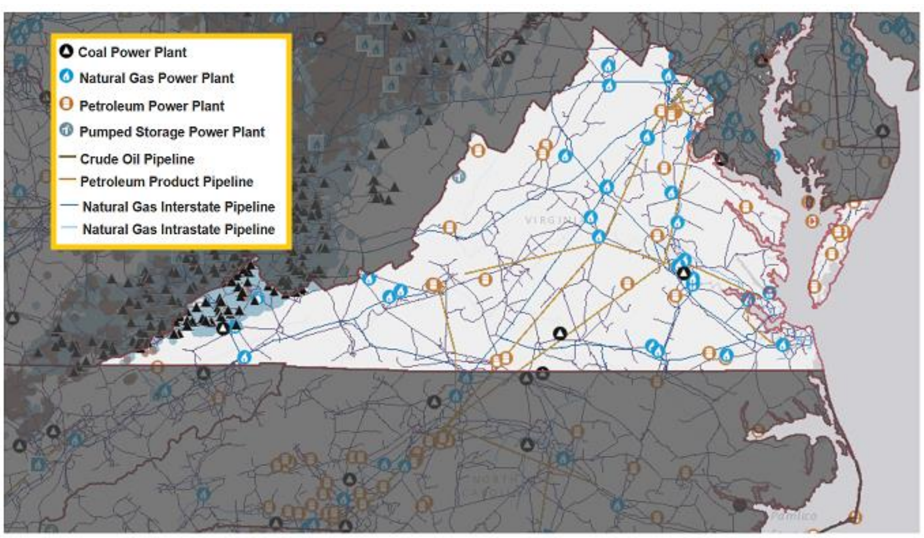

Figure 17: Reproduced from International Energy Agency data on Virginia power plants (IEA, 2019b).

Electricity Cost Comparison

The ever-changing cost of electricity depends on many factors, including the region, energy source, age of facilities, capacity factors, carbon-allowance auction prices in regional cap-and-trade programs, discount rate, supply, and demand. Of the 50 states, Virginia's 2021 energy consumption demand showed the highest increase over the previous year's (EIA, 2022b), highlighting the need for cost-effective low- or zero-carbon energy sources. The energy cost estimates listed in Table 1 may not reflect changing costs across time or location. If these estimates are accurate, the AFC provides substantially more cost-effective energy, in addition to the high-efficiency carbon-capture potential.

Electricity Source	Cost (cents/KWh)
Baseline Electricity Cost in the United States	11.21 (EIA, 2022)
Baseline Electricity Cost in Virginia	9.3 (EIA, 2022)
Coal	5.0 (NETL, 2021)
Natural Gas	6.5 (Looney, 2016)
Concentrating Solar	10.8 (Jaganmohan, 2021)
Solar Photovoltaics	5.7 (Jaganmohan, 2021)
Offshore Wind	8.4 (Jaganmohan, 2021)
Onshore Wind	3.9 (Jaganmohan, 2021)
Hydro	4.4 (Jaganmohan, 2021)
Pre-combustion carbon capture (Gas)	10.2 (NETL, 2021)
Post-combustion carbon capture (Coal)	6.3 – 8.25 (IEAGHG, 2004; NETL, 2021)
Allam-Fetvedt cycle	1.9 (Conca, 2019)

Table 1: Energy cost comparison in cents per kilowatt hour (kWh).

Conclusion

The climate crisis is catalyzing innovative emission-abatement solutions. For industries in which decarbonization seemed elusive, such as steel, cement, and energy, CC technologies that capture 85-90% of CO_2 emissions are placing carbon-neutrality within reach. Carbon capture technologies capture the CO_2 that is emitted during industrial processes rather than releasing it into the atmosphere. Such CO_2 can then be reused for power generation as a renewable resource or sold as a commodity to other industries. To reduce CO_2 emissions to the atmosphere for serving the goals of the (1) VCEA of 100% carbon-free electric generation by 2045, (2) the U.S. goal of 100% carbon pollution-free electricity in the U.S. by 2035, and (3) the IPCC 1.5^{o}C warming ceiling, requires the deployment of all available carbon abatement methods. The expansion of carbon-reduction technologies like CC (CCS &CCUS) along with cooperative hubs can accelerate achieving these state, national, and international carbon-reduction goals. Furthermore, Virginia's advantageous position as a home to 98 fossil fuel facilities enables VA to reap the benefits of CCS hubs. The pairing of effective policies, such as RGGI, and CC technology momentum can facilitate significant carbon-reduction rates in Virginia and beyond.

While the CC developments are promising, the IEA (2017) warned that CCS deployment was not on track to meet net-zero by 2050. In addition to building new facilities at large scale, achieving net-zero carbon emissions by mid-century will require retiring older emission-intensive facilities and upgrading others with CC retrofits. Of the CC technology options presented here, the AFC appears to offer the most efficient and cost-effective energy-generation option. Fortunately, current federal policies incentivize development and implementation of CC technologies, which can also benefit state economies through increased engagement in the reusable-carbon market with corresponding growth in employment and technological advancement. Regulatory incentives, such as the RGGI cap-and-trade program, can aid investments in and expansion of CC facilities and network hubs.

References

APC. (2022). *Appalachian Power Company - About Us*. Appalachian Power. https://www.appalachianpower.com/company/about/

Argonne National Laboratory. (2020). *Turning carbon dioxide into liquid fuel | Argonne National Laboratory*. ANL. https://www.anl.gov/article/turning-carbon-dioxide-into-liquid-fuel

Bach, L. T., Gill, S. J., Rickaby, R. E. M., Gore, S., & Renforth, P. (2019). *CO_2 Removal with Enhanced Weathering and Ocean Alkalinity Enhancement: Potential Risks and Co-benefits for Marine Pelagic Ecosystems*. Frontiers in Climate, *1*. https://doi.org/10.3389/fclim.2019.00007

Basile, A., Gugliuzza, A., Iulianelli, A., & Morrone, P. (2011). *Membrane technology for carbon dioxide (CO_2) capture in power plants.* Advanced Membrane Science and Technology for Sustainable Energy and Environmental Applications, 113–159. https://doi.org/10.1533/9780857093790.2.113

Beck, L. (2019). *Carbon capture and storage in the USA: the role of US innovation leadership in climate-technology commercialization*. Clean Energy, 4(1), 2–11. https://doi.org/10.1093/ce/zkz031

Biniek, K., Henderson, K., Rogers, M., & Santoni, G. (2020). *Driving CO_2 emissions to zero (and beyond) with carbon capture, use, and storage*. McKinsey & Company. https://www.mckinsey.com/business-functions/sustainability/our-insights/driving-co2-emissions-to-zero-and-beyond-with-carbon-capture-use-and-storage

Bourzac, K., Savage, N., Owens, B., & Scott, A. R. (2017). *Materials and engineering: Rebuilding the world*. Nature, 545(7654), S15–S20. https://doi.org/10.1038/545s15a

Carbo, M., Boon, J., Jansen, D., van Dijk, H., Dijkstra, J., van den Brink, R., & Verkooijen, A. (2009). *Steam demand reduction of water–gas shift reaction in IGCC power plants with pre-combustion CO_2 capture.* International Journal of Greenhouse Gas Control, *3*(6), 712–719. https://doi.org/10.1016/j.ijggc.2009.08.003

Carbicrete. (2021). *Carbon Negative Concrete.* CarbiCrete. https://carbicrete.com/

Chatham House. (2020). *Making Concrete Change: Innovation in Low-carbon Cement and Concrete*. Chatham House – International Affairs Think Tank. https://www.chathamhouse.org/2018/06/making-concrete-change-innovation-low-carbon-cement-and-concrete

Cho, R. (2019). *Capturing Carbon's Potential: These Companies Are Turning CO_2 into Profits.* Columbia Climate School: State of the Planet. https://news.climate.columbia.edu/2019/05/29/co2-utilization-profits/

Clean Air Task Force (CATF). (2019). *CO_2 EOR Yields a 37% Reduction in CO_2 Emitted Per Barrel of Oil Produced*. CATF. https://www.catf.us/wp-content/uploads/2019/06/CATF_EOR_LCA_Factsheet_2019.pdf

Clean Tech Group (Cleantech). (2022). *Championing Sustainable Innovation, Catalyzing Business Opportunities*. Clean Tech Group. https://www.cleantech.com/

Climeworks. (2015). *Climeworks builds first commercial-scale direct air capture plant*. https://climeworks.com/news/climeworks-ag-builds-first-commercial-scale-co2-capture

Conca, J. (2019). *Net Zero Natural Gas Plant -- The Game Changer*. Forbes. https://www.forbes.com/sites/jamesconca/2019/07/31/net-zero-natural-gas-plant-the-game-changer/?sh=9e2478b1de22

Congressional Research Service (CRS). (2021). *The Tax Credit for Carbon Sequestration (Section 45Q)* (No. IF11455). https://sgp.fas.org/crs/misc/IF11455.pdf

Congressional Research Service (CRS). (2016). *Recovery Act Funding for DOE Carbon Capture and Sequestration (CCS) Projects*. https://sgp.fas.org/crs/misc/R44387.pdf

Corbyn, Z. (2021). *From pollutant to product: the companies making stuff from* CO_2. The Guardian. https://www.theguardian.com/environment/2021/dec/05/carbon-dioxide-co2-capture-utilisation-products-vodka-jet-fuel-protein

DePaolo, D. J. (2018). *Geochemistry of Geologic* CO_2 *Sequestration (Reviews in Mineralogy & Geochemistry)*. De Gruyter. https://doi.org/10.1515/9781501508073

di Lorenzo, G., Barbera, P., Ruggieri, G., Witton, J., Pilidis, P., & Probert, D. (2013). *Pre-combustion carbon-capture technologies for power generation: an engineering-economic assessment. International Journal of Energy Research*, *37*(5), 389–402. https://doi.org/10.1002/er.3029

Department of Energy (DOE). (2010). *Steel Industry Profile*. Energy.Gov. https://www.energy.gov/eere/amo/steel-industry-profile

Department of Energy (DOE). (2021). *Department of Energy FY 2022 Congressional Budget Request*. Energy.Gov. https://www.energy.gov/sites/default/files/2021-06/doe-fy2022-budget-in-brief-v4.pdf

Energy Information Administration (EIA). (2020). *Fossil fuels account for the largest share of U.S. energy production and consumption*. US EIA. Today in Energy. https://www.eia.gov/todayinenergy/detail.php?id=45096

Energy Information Administration (EIA). (2021a). *Frequently Asked Questions (FAQs) - What is U.S. electricity generation by energy source?* US EIA. https://www.eia.gov/tools/faqs/faq.php?id=427

Energy Information Administration (EIA). (2021b). *Virginia - State Energy Profile*. US EIA. https://www.eia.gov/state/?sid=VA

Energy Information Administration (EIA). (2022a). *Electric Power Monthly*. US EIA. https://www.eia.gov/electricity/monthly/epm_table_grapher.php?t=epmt_5_6_a

Energy Information Administration (EIA). (2022b). *Electricity Monthly Update*. US EIA. https://www.eia.gov/electricity/monthly/update/print-version.php

Environmental and Energy Study Institute (EESI). (2020). *Fossil Fuels.* EESI. https://www.eesi.org/topics/fossil-fuels/description

Environmental Protection Agency (2021a) *Sources of Greenhouse Gas Emissions*. US EPA. https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

Environmental Protection Agency (EPA). (2021b). *Power Plants and Neighboring Communities*. US EPA. https://www.epa.gov/airmarkets/power-plants-and-neighboring-communities

Environmental Protection Agency (EPA). (2021b). *Climate Change Indicators: U.S. Greenhouse Gas Emissions*. US EPA. https://www.epa.gov/climate-indicators/climate-change-indicators-us-greenhouse-gas-emissions

Feron, P. (2016). *Absorption-Based Post-Combustion Capture of Carbon Dioxide*. Elsevier Gezondheidszorg. ISBN: 9780081005156. https://www.sciencedirect.com/book/9780081005149/absorption-based-post-combustion-capture-of-carbon-dioxide

Global CCS Institute (GCCSI). (2016). *Understanding CCS Clusters and Hubs: Global Status of CCS - Special Report*. https://www.globalccsinstitute.com/wp-content/uploads/2019/08/Understanding-Industrial-CCS-hubs-and-clusters.pdf

Global CCS Institute (GCCSI). (2021). *Global Status of CCS Report 2021*. https://www.globalccsinstitute.com/resources/global-status-report

Godec, M., Kuuskraa, V., van Leeuwen, T., Stephen Melzer, L., & Wildgust, N. (2011). *CO_2 storage in depleted oil fields: The worldwide potential for carbon dioxide enhanced oil recovery*. Energy Procedia, *4*, 2162–2169. https://doi.org/10.1016/j.egypro.2011.02.102

Grubbs, E. (2022). *The Infrastructure Investment And Jobs Act—Carbon Capture Utilization And Storage*. Energy and Natural Resources - United States. https://www.mondaq.com/unitedstates/oil-gas-electricity/1153220/the-infrastructure-investment-and-jobs-actcarbon-capture-utilization-and-storage

Hannula, I., & Reiner, D. (2017). *The race to solve the sustainable transport problem via carbon-neutral synthetic fuels and battery electric vehicles.* Energy Policy Research Group EPRG, University of Cambridge. EPRG Working Paper 1721. Cambridge Working Paper in Economics 1758. https://www.eprg.group.cam.ac.uk/ eprg-working-paper-172

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019). *The technological and economic prospects for CO_2 utilization and removal*. Nature, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6

Idriss, H., Scott, M., & Subramani, V. (2015). *Introduction to hydrogen and its properties.* Compendium of Hydrogen Energy, 3–19. https://doi.org/10.1016/b978-1-78242-361-4.00001-7

Illgner, T. (2021). *Meeting the Goals of the Virginia Clean Economy Act Using Carbon Capture* (Brief 71). Virginia Department of Legislative Service. http://dls.virginia.gov/pubs/briefs/brief71.pdf

Institute for Environment Analytics Green House Gases (IEAGHG). (2004). *Improvement in Power Generation with Post-Combustion Capture of CO_2*. IEAGHG. https://ieaghg.org/docs/General_Docs/Reports/PH4-33%20post%20combustion.pdf

Institute for Environmental Analytics Green House Gas (IEAGHG). (2019). *A Brief History of CCS and Current Status*. www.ieaghg.org. https://ieaghg.org/docs/General_Docs/Publications/Information_Sheets_for_CCS_2.pdf

Intergovernmental Panel on Climate Change (IPCC). (2005). *CARBON DIOXIDE CAPTURE AND STORAGE* (ISBN-13 978–0-521-86643-9). Cambridge University Press. https://repository.ubn.ru.nl/bitstream/handle/2066/230961/230961.pdf?sequence=1

Intergovernmental Panel on Climate Change (IPCC). (2018a). *Global Warming of 1.5°C, Summary for Policymakers*. IPCC. https://www.ipcc.ch/sr15/chapter/spm/

Intergovernmental Panel on Climate Change (IPCC). (2018b). *IPCC Special Report on Carbon dioxide Capture and Storage: Capture of CO_2*. IPCC. https://www.ipcc.ch/site/assets/uploads/2018/03/srccs_chapter3-1.pdf

Intergovernmental Panel on Climate Change (IPCC). (2021). *Climate Change 2021: The Physical Science Basis.* Summary for Policymakers. https://www.ipcc.ch/report/ar6/wg1/#SPM

International College of Economics and Finance (ICEF). (2017). *Carbon Dioxide Utilization (CO2U): ICEF Roadmap*. Innovation for Cool Earth Forum. https://www.icef.go.jp/pdf/summary/roadmap/icef2017_roadmap1.pdf

International Energy Agency (IEA). (2017) *Tracking Clean Energy Progress 2017 – Analysis*. IEA. https://www.iea.org/reports/tracking-clean-energy-progress-2017

International Energy Agency (IEA). (2019a). *Putting CO_2 to Use – Analysis*. IEA. https://www.iea.org/reports/putting-co2-to-use

International Energy Agency (IEA). (2019b). *Virginia - State Energy Profile Overview - U.S. Energy Information Administration (EIA)*. IEA. https://www.eia.gov/state/?sid=VA

International Energy Agency (IEA). (2021a). *Carbon capture, utilization and storage - Fuels & Technologies*. IEA. https://www.iea.org/fuels-and-technologies/carbon-capture-utilisation-and-storage

International Energy Agency (IEA). (2021b). *In 2020, U.S. coal production fell to its lowest level since 1965 - Today in Energy - U.S. Energy Information Administration (EIA)*. IEA. https://www.eia.gov/todayinenergy/detail.php?id=48696

International Energy Agency (IEA). (2021c). *Renewable electricity – Renewable Energy Market Update 2021 – Analysis*. IEA. https://www.iea.org/reports/renewable-energy-market-update-2021/renewable-electricity

International Energy Agency (IEA). (2022). *EIA expects U.S. energy-related CO_2 emissions to decrease annually through 2021 - Today in Energy - U.S. Energy Information Administration (EIA)*. IEA. https://www.eia.gov/todayinenergy/detail.php?id=42515

International Energy Forum (IEF) (2020). *The Circular Carbon Economy.* https://www.ief.org/programmes/circular-carbon-economy

Jaganmohan, M. (2021). *Global renewable electricity generation price 2020, by resource*. Statista. https://www.statista.com/statistics/478049/global-utility-scale-electricity-generation-cost-by-resource/

Jaruzel, M. (2021). *Carbon capture in the U.S. is growing like never before, but further policy support is crucial*. Clean Air Task Force. https://www.catf.us/2021/07/us-carbon-capture-growth/

Kätelhön, A., Meys, R., Deutz, S., Suh, S., & Bardow, A. (2019). *Climate change mitigation potential of carbon capture and utilization in the chemical industry*. Proceedings of the National Academy of Sciences, *116*(23), 11187–11194. https://doi.org/10.1073/pnas.1821029116

Kelemen, P., Benson, S. M., Pilorgé, H., Psarras, P., & Wilcox, J. (2019). *An Overview of the Status and Challenges of CO_2 Storage in Minerals and Geological Formations.* Frontiers in Climate, 1. https://doi.org/10.3389/fclim.2019.00009

Krawczyk, K. (2021). *Eminent domain: Renewables' new best friend?* U.S. Energy News. https://energynews.us/digests/eminent-domain-renewables-new-best-friend/

Lane, J., Greig, C., & Garnett, A. (2021). *Uncertain storage prospects create a conundrum for carbon capture and storage ambitions.* Nature Climate Change, *11*(11), 925–936. https://doi.org/10.1038/s41558-021-01175-7

Lebling, K. (2021). *Direct Air Capture: Resource Considerations and Costs for Carbon Removal*. World Resources Institute. https://www.wri.org/insights/direct-air-capture-resource-considerations-and-costs-carbon-removal

Legislative Search Results. (2022). Congress.Gov | Library of Congress. Retrieved January 25, 2022, from https://www.congress.gov/search?

Lehtonen, J., Alakurtti, S., Arasto, A., Hannula, I., Harlin, A., Koljonen, T., Lantto, R., Lienemann, M., Oharheim, K., Penttila, M., Pitkanen, J., & Tahtinen, M. (2019). *The Carbon Reuse Economy, Transforming CO_2 from a pollutant into a resource* (ISBN 978–951-38-8709-4). VTT Technical Research Centre of Finland. https://doi.org/10.32040/2019.978-951-38-8709-4

Looney, M. G. A. A. (2016). *The Real Costs of U.S. Energy*. Brookings. https://www.brookings.edu/opinions/the-real-costs-of-u-s-energy/

Marieni, C., Henstock, T. J., & Teagle, D. A. H. (2013). *Geological storage of CO_2 within the oceanic crust by gravitational trapping.* Geophysical Research Letters, 40(23), 6219–6224. https://doi.org/10.1002/2013gl058220

Matter, J. M., Stute, M., Snæbjörnsdottir, S., Oelkers, E. H., Gleason, S. R., Aradottir, E. S., Sigfusson, B., Gunnarsson, I., Sigurdardottir, H., Gunnlaugsson, E., Axelsson, G., Alfredsson, H. A., Wolff-Boenisch, D., Mesfin, K., Taya, D. F. D. L. R., Hall, J., Dideriksen, K., & Broecker, W. S. (2016). *Rapid carbon mineralization for permanent disposal of anthropogenic carbon dioxide emissions*. Science, 352(6291), 1312–1314. https://doi.org/10.1126/science.aad8132

McGlade, C. & IEA. (2019). *Can CO_2-EOR really provide carbon-negative oil? – Analysis*. International Energy Agency. https://www.iea.org/commentaries/can-co2-eor-really-provide-carbon-negative-oil

Nagabhushan, D. (2019). *Leveraging Enhanced Oil Recovery for Large-Scale Saline Storage of CO_2*. Clean Air Task Force. https://www.catf.us/2019/06/leveraging-enhanced-oil-recovery-for-large-scale-saline-storage-of-co2/

National Academies of Sciences, Engineering, and Medicine (NASEM). (2018). *Negative Emissions Technologies and Reliable Sequestration: A Research Agenda*. The National Academies Press. https://www.nap.edu/catalog/25259/negative-emissions-technologies-and-reliable-sequestration-a-research-agenda

National Aeronautics and Space Agency (NASA). *Solar Powered Carbon Dioxide (CO_2) Conversion | T2 Portal*. (2013). NASA Technology Transfer Program. https://technology.nasa.gov/patent/TOP2-160

National Energy Technology Laboratory (NETL). (2021). *9.1.1. Carbon Dioxide Capture Approaches*. Netl.Doe.Gov. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/capture-approaches

National Energy Technology Laboratory (NETL). (2022a). *Carbon Utilization Program*. Netl.Doe.Gov. https://netl.doe.gov/coal/carbon-utilization

National Energy Technology Laboratory (NETL). (2022b). *Syngas Composition*. netl.doe.gov. https://netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/syngas-composition

Nature Editorial. (2021). Concrete needs to lose its colossal carbon footprint. *Nature*. https://www.nature.com/articles/d41586-021-02612-5?error=cookies_not_supported&code=1926a022-f485-45db-89a7-b65193c3c030

NET Power. (2021). NET Power - *Making Clean Cheaper Than Dirty*. https://netpower.com/technology/

Núñez-López, V., Gil-Egui, R., & Hosseini, S. (2019). *Environmental and Operational Performance of CO_2-EOR as a CCUS Technology: A Cranfield Example with Dynamic LCA Considerations.* Energies, 12(3), 448. https://doi.org/10.3390/en12030448

Office of Fossil Energy and Carbon Management (FECM). (2021). *Innovative Concepts for Beneficial Reuse of Carbon Dioxide*. Energy.Gov. https://www.energy.gov/fecm/innovative-concepts-beneficial-reuse-carbon-dioxide-0

Office of Fossil Energy and Carbon Management (FECM). (2021). *THE INFRASTRUCTURE INVESTMENT AND JOBS ACT: Opportunities to Accelerate Deployment in Fossil Energy and Carbon Management Activities*. DOE FECM. https://www.energy.gov/sites/default/files/2021-12/FECM%20Infrastructure%20Factsheet.pdf

Paris Climate Accord (PCA). (2015). *United Nations Framework Convention on Climate Change (UNFCCC): What is the Paris Agreement. United Nations Climate Change*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

Patel, S. (2021). *Breakthrough: NET Power's Allam Cycle Test Facility Delivers First Power to ERCOT Grid*. POWER Magazine. https://www.powermag.com/breakthrough-net-powers-allam-cycle-test-facility-delivers-first-power-to-ercot-grid/

Rao, A. (2010). *Gas-fired combined-cycle power plant design and technology*. Advanced Power Plant Materials, Design and Technology, 32–53. https://doi.org/10.1533/9781845699468.1.32

Rapier, R. (2020). *Fossil Fuels Still Supply 84 Percent Of World Energy — And Other Eye Openers From BP's Annual Review*. Forbes. https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/?sh=6053766e66a1

Ravikumar, D., Keoleian, G. A., Miller, S. A., & Sick, V. (2021). *Assessing the Relative Climate Impact of Carbon Utilization for Concrete, Chemical, and Mineral Production*. Environmental Science & Technology, *55*(17), 12019–12031. https://doi.org/10.1021/acs.est.1c01109

Reuters. (2020). *Occidental-backed company will build new U.S. CO_2 removal plant*. Reuters. https://www.reuters.com/article/us-usa-carboncapture-dac/occidental-backed-company-will-build-new-u-s-co2-removal-plant-idUSKCN25F1VN

Regional Greenhouse Gas Initiative (RGGI). (2022). RGGI. *https://www.rggi.org/*

Roth, B., Hernon, K., Lassetter, W., & Ripepi, N. (2012). *Evaluation of Large-Scale Geologic Carbon Sequestration Potential in the Virginia Piedmont and Coastal Plain*. Carbon Management Technology Conference. https://doi.org/10.7122/151252-ms

Smolinski, J. (2018). *Power Plants in the U.S.* https://storymaps.arcgis.com/stories/61347cdb55414eeea69c0bf2e70d5c4d

Stangeland, A. (2007). *A model for the CO_2 capture potential. International Journal of Greenhouse Gas Control*, *1*(4), 418–429. https://doi.org/10.1016/s1750-5836(07)00087-4

United Nations Framework Convention on Climate Change (UNFCCC). (2015). *The Paris Agreement*. https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

United States Geologic Survey (USGS). (2020). *Cement: U.S. Geological Survey, Mineral Commodity Summaries, January 2020.* USGS. https://pubs.usgs.gov/periodicals/mcs2020/mcs2020-cement.pdf

US Geologic Survey (USGS). (2022). *How much carbon dioxide can the United States store via geologic sequestration? | U.S. Geological Survey*. United States Geological Survey. https://www.usgs.gov/faqs/how-much-carbon-dioxide-can-united-states-store-geologic-sequestration

Virginia Clean Economy Act (VCEA), HB 1526 (2020*).* https://lis.virginia.gov/cgi-bin/legp604.exe?201+sum+HB1526

Virginia Department of Environmental Quality (DEQ). (2021). *Virginia Greenhouse Gas Inventory*. DEQ. https://www.deq.virginia.gov/home/showpublisheddocument/12633/637725680592630000

Virginia State Corporation Commission (VA SCC). (2007). *Virginia State Corporation Commission* (PUE-2007-00068). https://scc.virginia.gov/docketsearch/DOCS/4c%24z01!.PDF