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Carbon capture utilization and storage in review: Sociotechnical implications for a carbon reliant world

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ABSTRACT

The decarbonization of industry and industrial systems is a pressing challenge given the relative lack of low-carbon options available for "hard to decarbonize" sectors such as steelmaking, cement manufacturing, and chemical production. Carbon capture utilization and storage (CCUS) represents a promising and crosscutting solution to this formidable problem. This review takes a systematic and sociotechnical perspective to examine how CCUS can support industrial decarbonization and relevant associated technical, economic, and social factors. This includes a focus on the energy and climate impacts of carbon emitting activities, the role, and options for CCUS in global responses to climate change, technical aspects of capture, transport, storage, and utilization, as well as policy implications and areas requiring further research. In doing so, the Review examines hundreds of published studies on the topic over the previous twenty years to offer a state-of-the-art investigation on technical options for capture (including direct air capture), transportation (including pipelines, ships, and rail), storage (including biotic and abiotic), and utilization (including enhanced oil recovery and biochar). The Review also investigates the evidence base within the literature on enablers and barriers to CCUS, policy mechanisms, and international frameworks as well as themes such as geopolitics, trade, and future research gaps. We conclude with insights about future CCUS pathways and sociotechnical systems dynamics.

1. Introduction

Industry is an essential set of sectors and processes for meeting global climate and net-zero targets. While many global economies are already decarbonizing electricity, heat, transport and agriculture, heavy industry is often more difficult to address. Further, given how closely industrial production is connected to jobs and economic development, planners often acknowledge that industrial activity must continue even in a low-carbon society. As of 2022, more than 100 countries remain highly dependent on energy intensive industrial manufacturing and rely on fossil fuels in their industrial supply chains. Because of this expected growth in industrial production, coupled with the social and political urgency of decarbonization, Carbon Capture Utilization and Storage (CCUS) is imagined to become an instrumental part of facilitating economic development while also maintaining decarbonization pathways. As Fig. 1 indicates, CCUS reflects many different technical options that can store or utilize carbon. Because of this diversity of application, the International Energy Agency and Nordic Energy Research have even claimed that CCUS "represents the most important option among new technologies for reducing industrial CO_2 emissions after 2030. Currently, great uncertainties exist as to how to deploy CCS …" [1]. Indeed, scenarios in Europe even project that by 2050, at least 50% of all Nordic cement plants must be fully utilizing CCUS along with 30% of iron, steel, and chemical plants. This deployment of CCUS is presumed to underpin a necessary 60% reduction in carbon dioxide intensity across industry [2].

The major goal of emission mitigation is to help preserve the natural

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Acronyms and abbreviations

ASU	Air Separator Unit
BECCS	Bioenergy with Carbon Capture and Storage
CBA	Carbon Border Adjustments
CCUS	Carbon Capture and Utilization
CCU	Carbon Capture and Sequestration
CCS	Carbon Capture Utilization and Storage
CA	Carbonic Anhydrases
CEF	Connecting Europe Facility
CEQ	Council on Environmental Quality
DAC	Direct Air Capture
ETS	Emissions Trading System
EOR	Enhanced Oil Recovery
EPA	Environmental Protection Agency
IAC	Indirect Air Capture
JTF	Just Transition Fund
LIV	Leakage Impact Valuation
LCA	Life Cycle Assessment
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
LT	Low Temperature
MOF	Metal Organic Framework
MABC	Microalgal-Bacteria Consortia
MFC	Microbial Fuel Cells
MSA	Moisture Swing Adsorption
MCFC	Molten Carbonate Fuel Cells
NDRC	National Development and Reform Commission
NCGG	Natural Gas Combined Cycle
NET	Negative Emission Technology
P&D	Pilot and Demonstration
PE	Polyethylene
PP	Polypropylene
PS	Polystyrene
PU	Polyurethane
RCE	Recycle–CCS–EOR
R&D	Research and Development
SOFC	Solid Oxide Fuel Cells
TIS	Technological Innovation Systems
TSA	Temperature Swing Adsorption
VSA	Vacuum Swing Adsorption

environment and the long-term benefits of emission reduction must be shown to outweigh the effects on water resources, air quality, land, and climate [4–6]. Life Cycle Assessments (LCA's) are imperative to ensure the integrity of a CCUS project is not compromised, and these balances are being maintained. Further hurdles to widespread CCUS deployment include the high cost associated with the capture process, land area use challenges, limited geologic storage capacity, injection rate constraints, and infrastructure needs [7]. Continued R&D, government funding, and scale-up opportunities can bring costs down to a feasible level, but unsupportive policy and regulations in some countries has further limited CCUS deployment [8,9].

What is the current state of the art thinking on CCUS? How could these barriers be overcome? To provide answers, this review takes a systematic and sociotechnical perspective to examine how CCUS can support industrial decarbonization and the technical, economic, social, and political factors that will impact CCUS adoption. This includes a focus on the energy and climate impacts of carbon emitting activities, the role and options for CCUS on the global stage, technical aspects of capture, transport, storage, and utilization, as well as policy implications and areas for future research.

2. Research design

Our study uses a sociotechnical lens to provide a critical and systematic review of industrial decarbonization through Carbon Capture, Utilization, and Storage (CCUS). The framing of the sociotechnical system guides the review in addressing the stated research objectives with consideration for the complexities and interdependencies of industrial decarbonization via CCUS. The systematic review approach covers a vast cross-section of literature in this subject area, but falls short in several key ways. First, the review is limited to publications in English, which may exclude relevant and noteworthy publications in other languages. Additionally, systematic collection of new literature ceased in 2021, though authors performed targeted searches to draw from more recent publications. Finally, CCUS is a complex and multifaceted topic, and the intricacies are difficult to enumerate even in a comprehensive review. The authors hope that the high-level overview presented here, accompanied by the sources compiled for this review will lead any reader to satisfactory explanations on the elements of this emerging industry.

2.1. Analytical frame of sociotechnical system

The review is structured on the conceptual approach of sociotechnical systems, which considers both social and technical aspects of industrial decarbonization related to carbon capture, utilization, and storage. A sociotechnical lens means that this review focuses not only on the hardware and infrastructure shown in Fig. 2, but also policies and markets, public perceptions, and broad social drivers (and constraints).

2.2. Searching protocol and analytical parameters

To complete our critical and systematic review, three sets of search terms were combined to generate 312 distinct search permutations, which were queried across eleven databases for a total of 3432 distinct searches (see Fig. 3). The initial searches produced more than 2.4 million potentially relevant documents, of which 2964 were deemed relevant through screening of abstracts for relevance to industrial decarbonization. This sample was further screened for recency (papers published before January 1, 2000, were removed), relevance (sources must be related to industrial decarbonization with CCUS), and uniqueness (duplicates were removed), resulting in a final sample of 1896 publications, with additional consolidation occurring as the review developed. Granted, we don't cite all of these papers in the review, but they did form the evidence base from which we drew from the most insightful or relevant studies fully noted in our reference list. A total of 239 references were directly used.

Publication volume on industrial usage of CCUS has accelerated in recent years, with approximately half of the relevant sources reviewed having been published since 2018 (see Fig. 4). Journal articles comprise the majority of the references, accounting for 63.8% of the sample, followed by books and book excerpts at 25.7%, and technical reports at 10.3%. Technical reports largely fall into the category of "grey literature," usually published by governments, nonprofits, and industry associations..

2.3. Critical and systematic review approach

In identifying our review as critical and systematic, we describe both the reference collection methodology and the review process undertaken by the research team. As a critical review, this study demonstrates extensive coverage of the literature with an interpretive approach to evaluate evidentiary quality and identify potential research gaps. The systematic review approach provides a transparent methodology for identifying relevant sources while minimizing researcher bias [10–12].

3. Technical options for carbon capture utilization and storage

Understanding the chemical and physical properties of CO_2 is essential to ensure safe handling in capture, transport, and storage operations. Two oxygen atoms are covalently double bonded to one carbon atom in a linear shape with no electric dipole. It is fully oxidized, making the compound moderately reactive and non-flammable [13].

At standard pressure and temperature, CO_2 is in a gaseous state with a density of 1.98 kg/m3. Liquefaction occurs with increased pressure and decreased temperature. Conditions for liquefaction are generally 240 psia and −13.9° F. The liquid state is mostly used for shipping. Supercritical CO_2 viscosity and diffusivity change with density, affecting flow rates of CO_2 in pipelines (Table 1) [13,14]. The critical point on the phase diagram is often close to ambient air conditions (Fig. 5). Changing environmental conditions can prompt phase changes or even two-phase flow. This must be accounted for to ensure infrastructure is capable of handling density changes and no leakage will occur. CO_2 is an asphyxiant, so high concentrations can suffocate organisms reliant on oxygen. The relatively higher density of CO_2 than air allows it to accumulate in low lying areas, creating dangerous conditions if a sudden release of CO_2 occurs [15].

The variability of constituents often associated with CO_2 in industrial emissions is a formidable challenge. Small amounts of impurities can greatly change the phase diagram, usually increasing energy

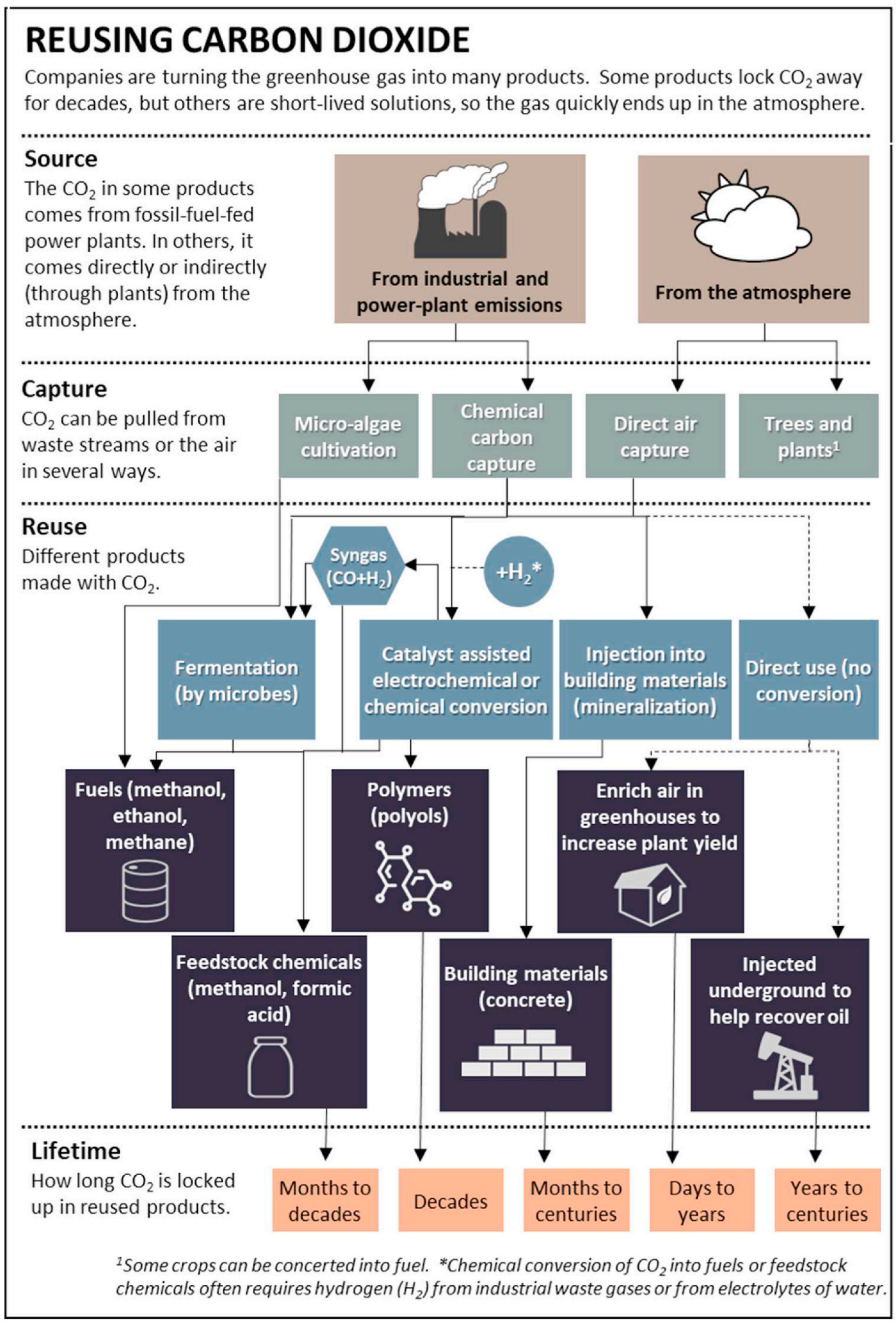

Fig. 1. Conceptualizing carbon capture utilization and storage [3].

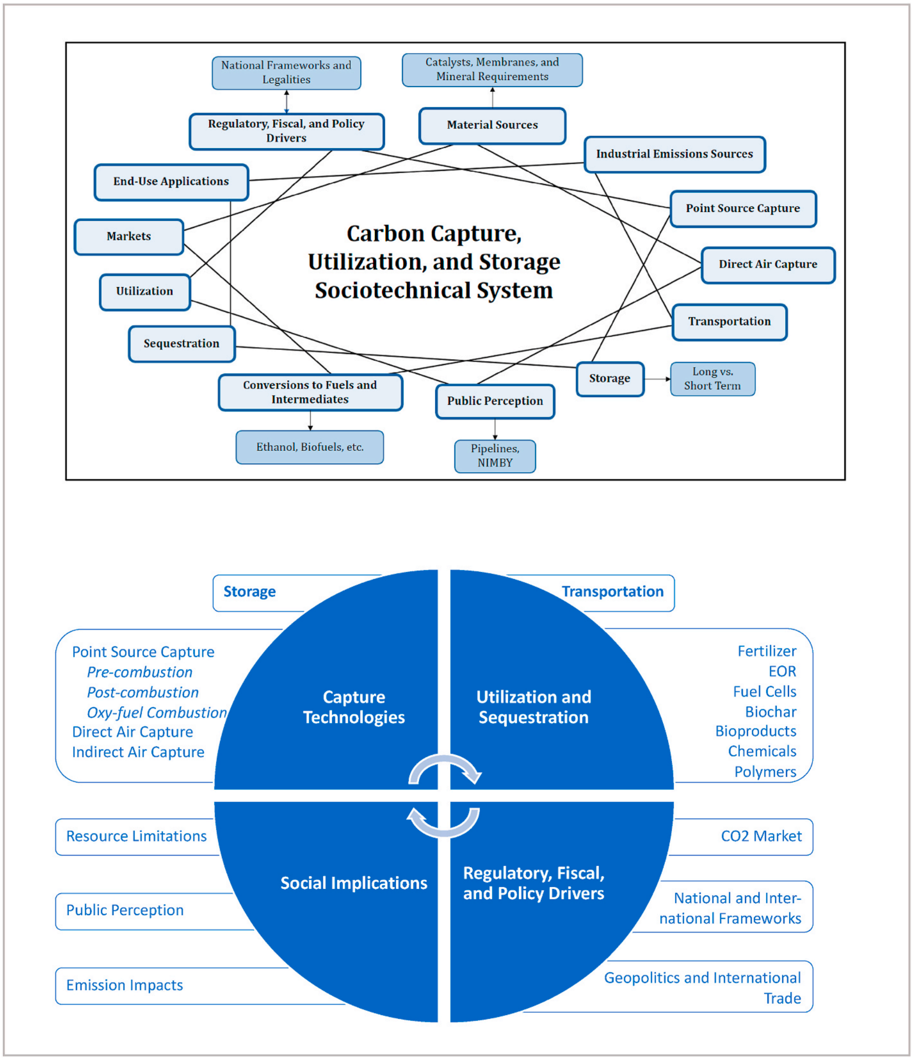

Fig. 2. Elements of the sociotechnical system for CCUS (connections are meant to illustrate the interconnected nature of these systems and are likely more complex than represented). EOR = Enhanced Oil Recovery.

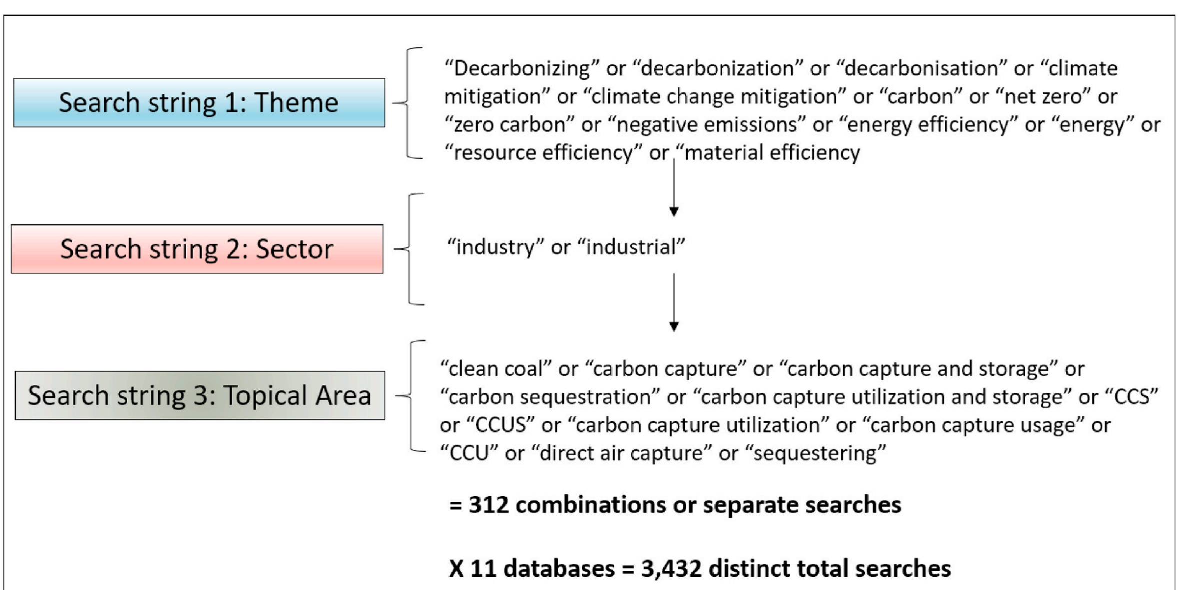

Fig. 3. Key words used for iterative literature search process for a total of 3432 distinct searches.

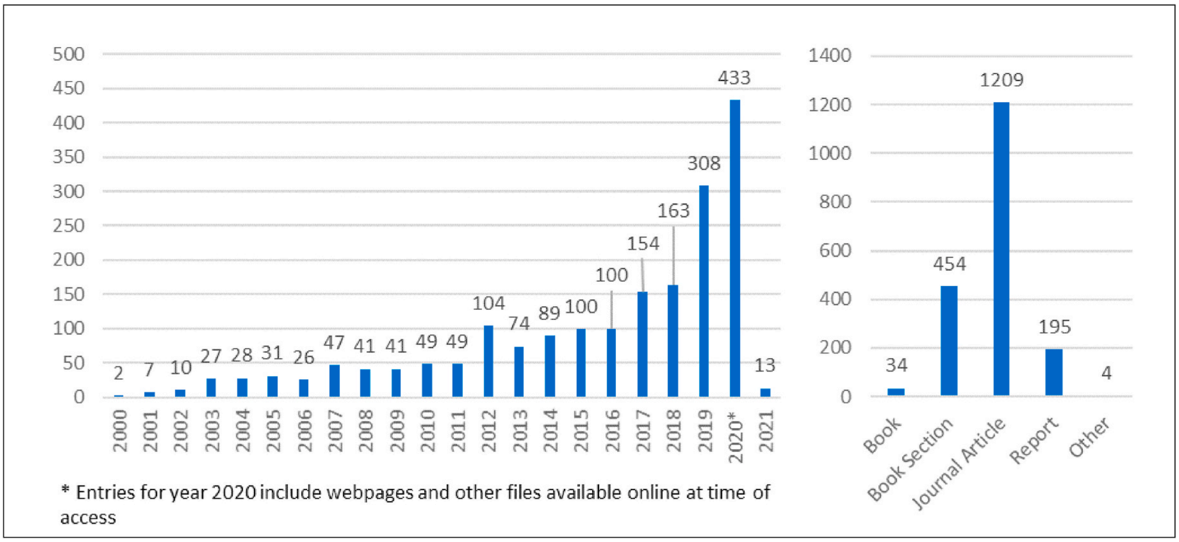

Fig. 4. Distribution of publication dates from resulting literature search and relative amount of book, article, report, or other publications.

Table 1
Physical properties of gaseous, supercritical, and liquid CO_2, recreated from Ref. [13].

State	Density (g mL $^{-1}$)	Viscosity (Pa s)	Diffusivity (cm^2 s^{-1})
Gaseous	10^{-3}	10^{-5}	0.1
Supercritical	0.1–0.9	10^{-4}	10^{-3}
Liquid	1	10^{-3}	10^{-5} – 10^{-6}

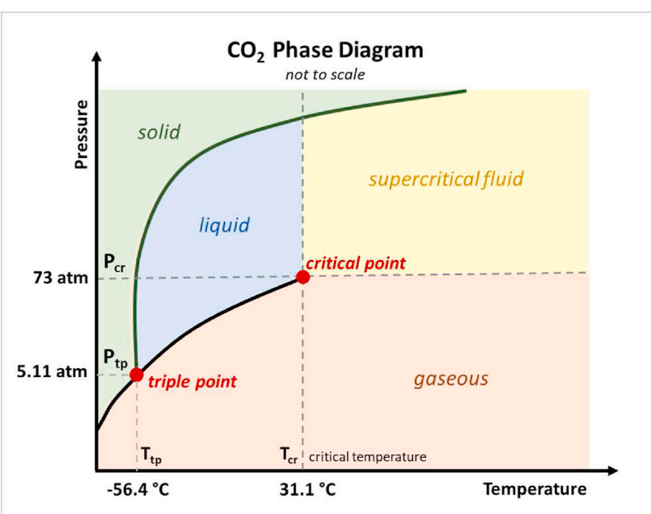

Fig. 5. Temperature-pressure phase diagram, showing CO_2 supercritical fluid region (subject to change with impurities) [16].

requirements for phase change (Fig. 5) [16]. CO_2 is soluble in water, forming carbonic acid, although high amounts of impurities are known to reduce water solubility. The variability of CO_2 streams from various industrial processes and capture processes means that for geologic sequestration projects, this stream must be carefully characterized for its specific unique chemical properties. Interactions between injected CO_2, the formation brine, and the reservoir rock makes each geologic sequestration site unique, and geochemical interactions must be modeled to anticipate any reactions that could be detrimental to injection efforts and permanent storage capabilities [17].

CCUS technologies can help relieve CO_2 emissions that cannot be avoided and help remove existing emissions in the atmosphere, but to date, implementation has been slow. CO_2 capture technologies could allow continued fossil fuel combustion without the associated CO_2 emissions, addressing the “difficult to decarbonize” sectors [18]. Though even this implementation is challenged, as most capture technologies can also be energy, water, and material intensive [19].

Carbon capture is the process of capturing CO_2 from either an emitting source or from the atmosphere so it can be terrestrially stored or utilized in other industries. Point source emissions can be directly captured before entering the atmosphere through pre-combustion, post-combustion, and oxy-fuel combustion capture technologies [16]. Emissions generated from varying sources in space and time can be captured with Direct Air Capture (DAC) and Indirect Air Capture (IAC) technologies, pulling CO_2 directly from the atmosphere.

3.1. *Current and emerging technologies for CO2 capture*

The entire process of CCUS involves the capture of CO_2, transport, utilization, and/or final storage of CO_2. Since 2007, 30 new integrated CCUS projects have been announced. Currently, there are 18 large scale CCUS facilities in operation, 5 under construction and 20 in other development stages with most facilities in the United States and Europe (Fig. 6) [9].

3.1.1. *Point source capture*

CO_2 capture technologies are most efficient at stationary point sources of emissions where CO_2 is highly concentrated. Large quantities of CO_2 can be directly captured from industrial sources such as fossil fuel power plants, fuel processing plants, and other industrial operations [15]. Carbon capture technologies have existed and been utilized for decades, but consistent research did not become prevalent until 2008, following climate change legislation and increased public awareness [20]. Primary capture system technologies are categorized based on when the capture process happens relative to combustion, labeled as pre-combustion capture, post-combustion capture, and oxy-fuel combustion capture (Table 2) [8,15,16,20].

Post-combustion carbon capture refers to technologies that are applied to point source emitters to capture CO_2 from flue gas generated through fossil fuel combustion and other industrial processes [21]. The world is still heavily reliant on fossil fuels, with more than 80% of commercial energy coming from fossil fuel combustion [22]. This reality makes the application of post-combustion capture an important tool for mitigating CO_2 emissions during a transition to renewable energy

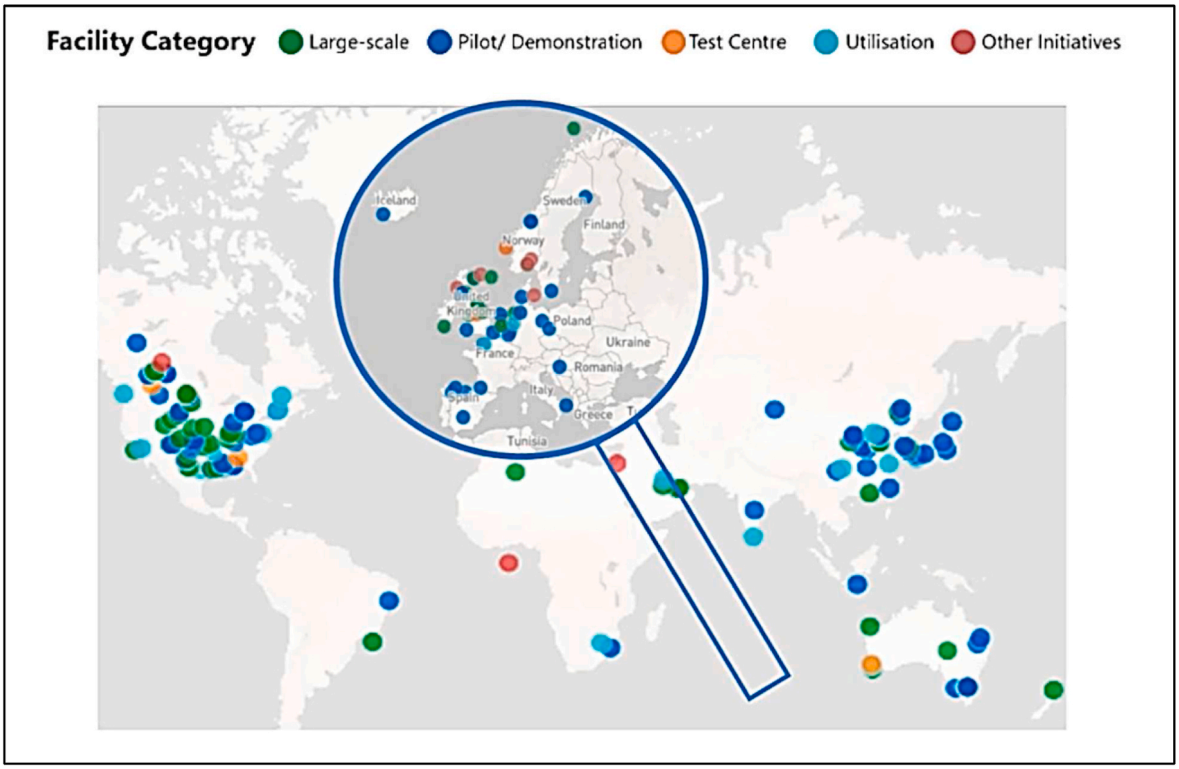

Fig. 6. Global distribution of current CCUS facilities [9].

Table 2
Summary of differences in point source capture processes. Recreated from Ref. [16].

Capture Technology	Equipment/Application	Method	Advantages	Disadvantages
Post combustion	Mostly applicable to coal fired power generators	Separation of CO2 from flue gas using air	-Highly developed -Can easily be retrofitted to existing units	-CO_2 level quite low -less than 15% -High energy consumption
Pre-Combustion	Power plants IGCC	Separation of CO2 from flue gas using air, steam, or oxygen	CO_2 range 15–60%; H2-rich gas used as fuel	Requires additional investment cost of capture equipment
Oxyfuel Combustion	Power plant with oxygen fired boiler	Fuel is burnt with pure oxygen for CO_2separation	CO_2 concentration over 80%; CO2 flow purified to eliminate non-condensable gases	-Large oxygen required make the process expensive -Technology less developed

generation.

For existing industrial emitters, post-combustion capture represents the most practical approach for CO_2 abatement due to the infrastructure needs, corrosion risks, and high maintenance expenses associated with both pre-combustion and oxy-fuel combustion [22]. Despite the utility of post-combustion capture, two primary challenges exist for widespread deployment: the scale of current CO_2 emissions and the energy required in the separation process [23,24]. Post-combustion technology capture methods can be categorized as adsorption, absorption, and membrane separation [22]. Within each of these methods are many variations as shown in Fig. 7 [22] each presenting unique challenges and benefits.

Membrane technology relies on a permeable material and the differential rates of permeation for each flue gas constituent [23]. Chemical agents are sometimes added to membranes to facilitate the preferential transport of CO_2 [23]. Strengths of membrane technology include the relatively low spatial footprint compared to other technologies and the low energy required for operation [23]. Challenges exist, especially for application to coal-fired plants as the particulate material associated with flue gas can accumulate on the membrane surface and decrease its permeability or damage it physically over time [23]. A review of various membrane materials and technologies suggested further development to improve material and process efficiency are necessary before this technology becomes competitive [25].

Advancing membrane technologies does involve notable tradeoffs [241]. Even though many membrane designs have been commercialized and deemed competitive for gas separation processes, air separation processes, or the sweetening of natural gas, challenges remain. These include the stability of the membrane versus its lifetime, the ability for membranes to work under high temperatures and/or exposure to steam and/or acid gases. Cutting-edge examples of novel membrane options include highly permeable ultrathin Polaris™ membranes for carbon capture, high-performance fixed-site-carrier (FSC) membranes, and hollow fiber membranes.

Adsorption refers to the process of preferential partitioning of substances from the gaseous or liquid phase onto the surface of a solid substrate. For carbon capture, various porous materials have been tested for their capacity to adsorb CO_2 molecules [22]. CO_2 is adsorbed onto these surfaces through physical and chemical adsorption processes. The efficacy of adsorbents are evaluated by their capacity, selectivity, rate of adsorption and desorption, temperatures required for adsorption and desorption, thermal and mechanical stability, the ability and expense of regeneration, ability to handle impurities in flue gas, and overall environmental impact of the application [22]. Vacuum Swing Adsorption

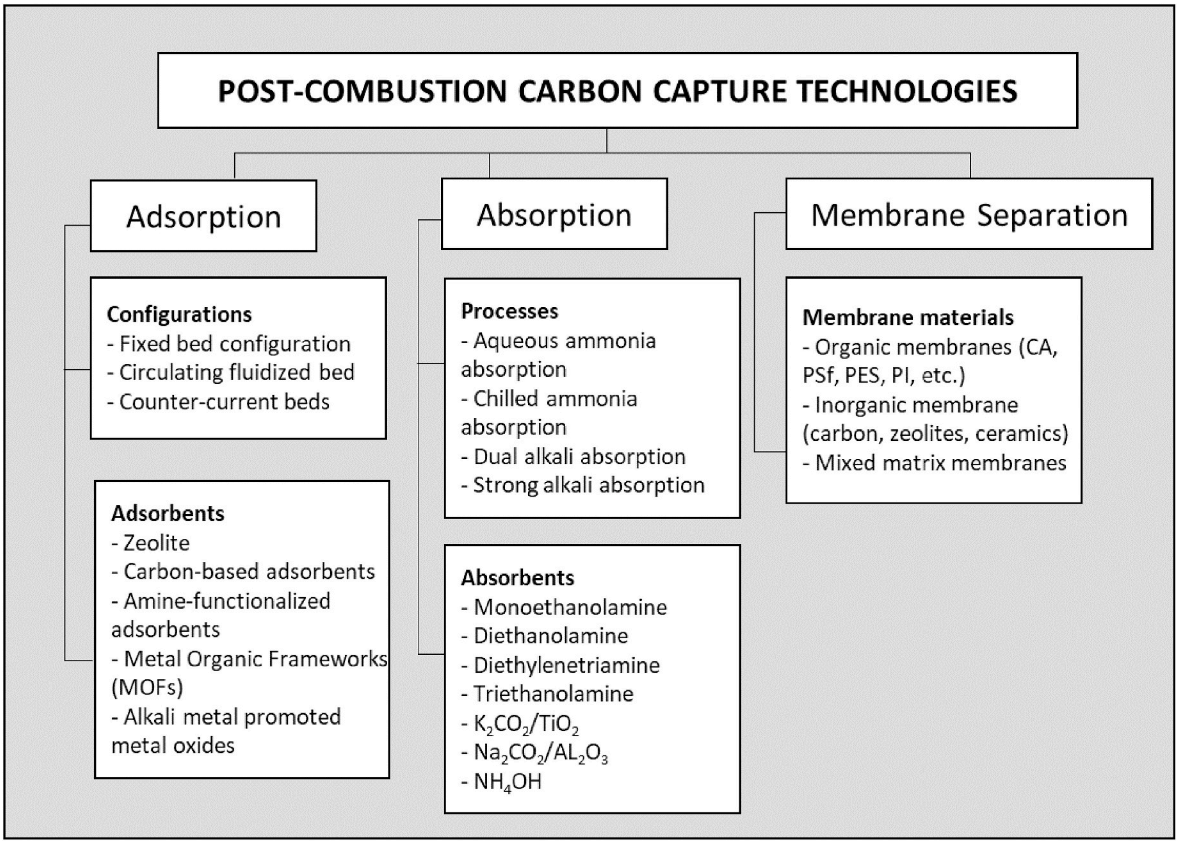

Fig. 7. Brief description of post-combustion capture technologies and the materials utilized. Modified from Chao et al., 2021 [22].

(VSA) with Metal-Organic Framework (MOF) is considered a developing post-combustion adsorption technology with lower energy demands and high efficiency [26].

Unlike adsorption, where molecules are captured on the surface of a material, in absorption, CO_2 molecules dissolve into the bulk phase of another material [23]. Both processes are widely utilized in industrial processes including refining, and chemicals production [23]. Absorption of CO_2 is achieved through acid-base reactions, where acidic CO_2 reacts with a basic solution at flue gas temperatures [23]. Because these techniques are widely applied in existing industrial processes, absorption is the most mature technology for capturing CO_2 today. The same challenges face the application of absorption to CCUS projects as do other technologies, with a large energy requirement for solvent regeneration [23]. Of all the reactive solvents being applied to PCC (amines, hot potassium carbonate, chilled ammonia, ionic liquids etc.) the most developed and widely deployed are amine based systems [27].

Relying exclusively on chemical reactions to separate CO_2 from emissions sources is impractical due to the sheer scale of existing emissions. Bhown et al. demonstrate that with equimolar ratios, the demand for chemicals such as ammonia will far outpace current availability, and make only a small dent in CO_2 emissions [23]. This of course, assumes that all industrial retrofits for post-combustion capture would be using chemical processes, which is unlikely to be the case. This study does demonstrate, yet again, the importance of applying not one, but all practical technology for achieving mitigation targets rapidly. Other capture technologies will be critical to incorporate, though post-combustion capture is currently the most impactful and efficient method for preventing CO_2 from entering Earth's atmosphere. It is also the only technology that has been demonstrated at full commercial scale (Table 3) [23].

Calcium looping is a post-combustion technology that captures CO_2 with a solid sorbent in a calcium – carbonation cycle, represented by the main reaction in Equation 1 below [18]. Flue gas is directed to the first carbonation reactor where CO_2 reacts with calcium oxide, forming calcium carbonate. The reaction is then reversed in the calcination reactor to regenerate the sorbent and release the CO_2. Added heat is required to overcome the exothermic reaction. High temperature heat recovery is utilized to improve overall energy efficiency. Utilization of smaller nano sized particles of CaO (the solid sorbent) have shown improved efficiency for multicyclic performance [28]. Alternatively, the spent sorbent can be used for processes in cement production, flue gas desulfurization, steel plants, and pulp/paper plants, providing economic and environmental advantages [18,29]. A conceptual design of a calcium looping is shown in Fig. 8 below [18].

Table 3
State of post combustion CO_2 capture development. Recreated from Ref. [23].

	Absorbent	Adsorbent	Membrane
Commercial usage in chemical process industries	high	moderate	low/niche
Operational Confidence	high	high, but complex	low to moderate
Primary source of energy penalty	solvent regeneration (thermal)	sorbent regeneration (thermal/ vacuum)	compression on feed and/or vacuum on permeate
Development Trend	new chemistry, thermal integration	new chemistry, process configuration	new membrane, process configuration

$$CaO + CO_2 \leftrightarrow CaCO_3 \ \Delta H_r^0 = -178 \text{ kJ/mol}$$

Equation 1 [18]

The main advantage of calcium looping capture technology is the

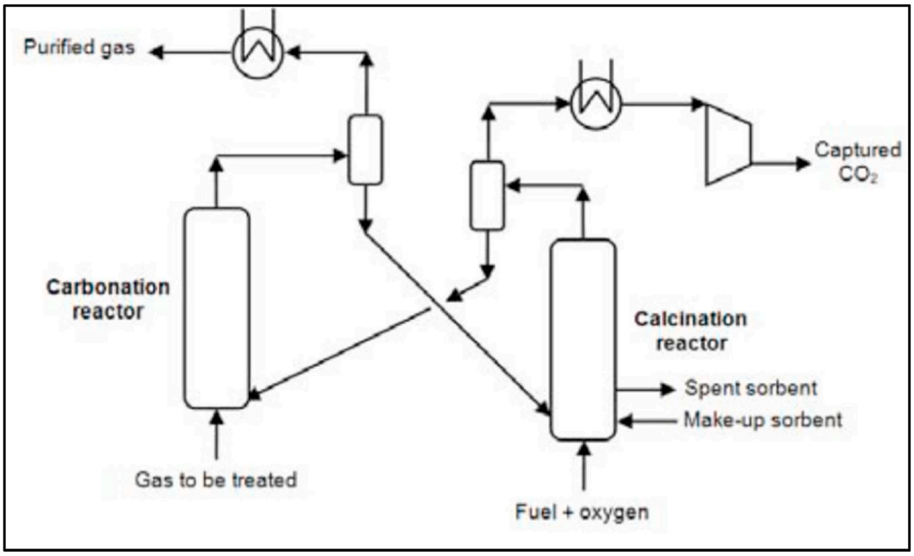

Fig. 8. Conceptual design of calcium looping process [18].

lower energy requirements and reduced costs resulting from the potential high heat recovery as well as possible retrofitting applications [18,29]. Calcium looping is still in the pilot stage so continued development is needed to reach the large industrial scale [18]. Application of calcium looping is considered a critical technology for industrial decarbonization, particularly in the cement industry [29,30]. A technoeconomic analysis on the decarbonization of the pulp and paper industry found calcium looping to be an effective technology if carbon credits are valued above 41.8 Euros/tCO_2 [29]. Steel mills also could reach 2050 decarbonization goals by 2030 with calcium looping, maintaining economic feasibility [31]. The main advantage of calcium looping capture technology is the lower energy requirements and reduced costs resulting from the potential high heat recovery as well as possible retrofitting applications [18,29]. Calcium looping is still in the pilot stage so continued development is needed to reach the large industrial scale [18]. Application of calcium looping is considered a critical technology for industrial decarbonization, particularly in the cement industry [30]. Steel mills also could reach 2050 decarbonization goals by 2030 with calcium looping, maintaining economic feasibility [31].

3.1.2. Pre-combustion

Pre-combustion capture technologies separate CO_2 from the commodity before the combustion process begins, allowing the product to meet downstream specifications and CO_2 emission requirements [8,9]. This capture method can be applied to any CO_2 producing power plant, but it is mainly used in the context of power plants based in gasification with Methyl diethanolamine (MDEA) as the capture solvent [9,32]. The process is placed in front of the combustor and works by converting the fuel to a stream of carbon monoxide, carbon dioxide and hydrogen, and then removing CO_2 [33].

The fuel, typically coal or biomass, is reacted with oxygen or air to produce a 'synthesis gas' (syngas) composed of carbon monoxide, carbon dioxide and hydrogen. The CO_2 is separated from the syngas with physical or chemical absorption processes (discussed in more detail in the following section) and a hydrogen-rich fuel is produced in the Water Gas Shift Reaction (WGS) [9]. The power generated from this process is generally referred to as Integrated Gasification Combined Cycle (IGCC) [8,20].

Pre-combustion technologies can also be used in natural gas reformation, but it is much more expensive than the alternative of post-combustion with natural gas as a fuel [8]. However, mixed matrix membrane technologies can help mitigate high costs and energy requirements needed to separate CO_2 from raw natural gas [34]. The application of this process to natural gas also could have major clean energy benefits given that the Gas Turbine Combined Cycle (GTCC) is considered one of the most energy efficient sources of power and can be used in hybrid systems with fuel cells. Pilot studies on the integrated systems of gas turbines (GT), solid oxide fuel cell production (SOFC), molten carbonate fuel cell (MCFC), and the Organic Rankine Cycle (ORC) indicate possible next generation low carbon power systems utilizing capture technology and natural gas [33].

The gas stream CO_2 concentration in pre-combustion is generally higher than post combustion (>20% in pre-combustion and 5–15% in post-combustion), creating relatively lower energy requirements and capture costs for applicable power plants [9]. While post-combustion technology generally used an amine-based capture process, many studies have indicated that Pressure Swing Adsorption (PSA) technology is much more energy efficient in pre-combustion capture [33]. Analysis on the different capture technologies estimates the water footprint of pre-combustion IGCC to be approximately 0.74 m3/ton CO_2 captured [5]. Pre-combustion capture systems can also be retrofitted to existing power plants, allowing for timely deployment of CO_2 capture [35].

3.1.3. Oxyfuel Combustion

Oxyfuel combustion uses pure oxygen, rather than air, as the oxidant for combustion. This concept is has been employed in the metallurgic industry where extremely high furnace temperatures are required, but has gained attention in CCUS because it produces a waste stream consisting of just water and CO2 which simplifies downstream CO2 separation processes [36]. Oxy-fuel combustion processes and machinery can be easily integrated with existing powerplant infrastructure because the process is not restricted to a specific fuel type. Infrastructure retrofits using oxy-fuel combustion result in the least efficiency drop for emission reductions as compared to other combustion capture processes; however, there is concern that the risk management of certain fuels has been understudied [37,38]. Oxy-fuel combustion applies primarily to turbomachinery emissions within the power sector [39]. Power cycles can capture greater than 99% of produced carbon dioxide. A diagram of the oxy-fuel combustion carbon capture cycle for power generation can be seen in Fig. 9 [39].

The primary challenge for deployment of oxy-fuel combustion is its expense. Production of pure oxygen with greater than 95% purity is expensive in terms of both capital and operational costs [36]. The cost of CO2 capture per ton is estimated to be $63–74 in 2022 USD using cryogenic oxygen production [18]. Other methods to produce pure

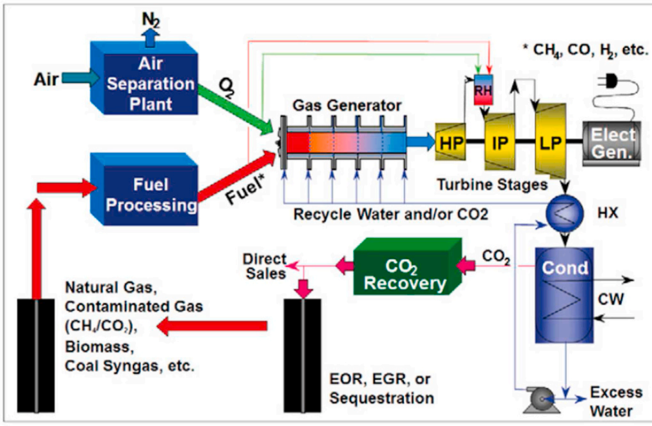

Fig. 9. Oxy-Fuel Cyclic Power Cycle [39].

oxygen include using membranes or using chemical looping technology as outlined in the previous sections [18]. One other issue is that pure oxygen burns hotter than air. Given the temperature rise it is necessary to expend significant capital cost to retrofit process equipment like heaters, boilers, furnaces, and turbines to handle higher temperatures [18].

3.1.4. *Direct air capture (DAC)*

Direct Air Capture (DAC) is a unique technology that can remove CO_2 from ambient air, regardless of when and where it was released. This technology provides a potential synthetic carbon sink to balance industrial emissions that were not captured with point source technologies (Table 4) [40]. This emerging carbon removal technology has scaling potential to capture ~980 Mt CO_2 per year by 2050 from ambient air to produce a pure CO_2 stream that can be geologically stored or utilized in other industries such as food processing or synthetic fuels. DAC plant location can be selected independently of the emission source location, increasing flexibility for CO_2 transportation, and ideally limiting infrastructure expenses [41]. Alternatively, DAC plants located near power plants can capitalize on waste heat to meet high energy requirements [40,42]. The ability to capture atmospheric CO_2, regardless of when and where it was released, can help offset emissions from sectors that are more difficult to decarbonize, such as aviation and remote or decentralized industrial processes [40,43].

Table 4
Global annual CO_2 DAC capacity demand by sector. Recreated from Ref. [40].

Sector		Unit	2020	2030	2040	2050
Power	power-to-gas	Mt_{CO2}/a	3	7	142	363
	waste-to-energy	Mt_{CO2}/a	0	−17	−99	−165
	sewage plant	Mt_{CO2}/a	0	n/a	n/a	n/a
Transport	road (cars/ bus/trucks)	Mt_{CO2}/a	0	218	1309	1101
	rail	Mt_{CO2}/a	0	7	66	82
	marine	Mt_{CO2}/a	0	56	962	1667
	aviation	Mt_{CO2}/a	0	54	964	1543
Industry	chemical industry	Mt_{CO2}/a	0	224	1157	3255
	pulp and paper	Mt_{CO2}/a	0	−8	−52	−95
	cement mills (limestone)	Mt_{CO2}/a	0	−69	−425	−607
	others	Mt_{CO2}/a	0	n/a	n/a	n/a
Co_2 DAC Energy System		Mt_{CO2}/a	**3**	**473**	**4025**	**7144**
Co_2 Removal		$Mt_{co2\ captured}/a$	0	0	1000	10,000
Thereof other net's		$Mt_{co2\ captured}/a$	0	0	300	2500
Thereof CO_2 DAC, CO_2 removal		Mt_{CO2}/a	**0**	**0**	**767**	**8213**
CO_2 DAC Total		Mt_{CO2}/a	**3**	**473**	**4792**	**15,356**

Deployment of large-scale DAC is considered critical to meet climate action goals set forth in the Paris Climate Accord by many analyses, including the IPCC and IEA [41,44]. As of November 2021, there are 19 DAC plants operating in Europe, the United States, and Canada with a cumulative capture rate of more than 0.01 Mt CO_2/year [41]. The IEA's Net Zero Emissions by 2050 Scenario predicts DAC will capture more than ~980 Mt CO_2/year, although it has an estimated potential of 0.5–5 Gt CO_2/yr [41]. DAC plants in operation today are relatively small, but large-scale development is within reach. Climeworks and CarbFix currently operate the largest DAC plant in Iceland, sequestering 4000 t CO_2/year in basalt rock formations. Construction of the first 1 Mt CO_2/year DAC plant is now underway in the United States, expected to come online in 2024 [40–42].

Most operating DAC plants utilize either a liquid or solid sorbent to capture dilute CO_2 from ambient air. In both approaches, ambient air containing ~400 ppm CO_2 is brought into the system via large fans, CO_2 is captured with the respective sorbent in an air contactor, methodically released, and transported or sequestered for varying uses. The sorbent is then regenerated, and the process repeats (Fig. 10) [40]. Many different sorbent technologies have been explored in attempt to improve capture efficiency. Liquid hydroxide sorbents such as calcium hydroxide (lime) are among the most commonly utilized, but there has been increasing research on solid sorbents, such as amines [45]. Seven large-scale companies with active DAC plants are shown in Fig. 11 below with their associated technologies [40].

The main barriers to DAC are the high energy requirements for capture and sorbent regeneration, water burden, and high costs of initial investment, facility operation, and sorbent maintenance [44]. Material requirements, environmental risks, and aerosol emissions are other considerations, but pose little impediment to large-scale DAC deployment [47]. While DAC can help alleviate the effects of climate change by removing CO_2 emissions, it should also be noted that significant CO_2 removal could also limit photosynthetic in regions within facility area or downstream of the facility, negatively impacting natural carbon capture mechanisms.

Improvements to sorbent technologies are focused on reducing energy and water requirements. The high energy demand is attributed to the high temperature and pressure required for the regeneration of the sorbent and subsequent release of the CO_2. Thus, it is imperative that the added heat and electricity are supplied from low carbon emitting energy sources, otherwise the goal of DAC is countered [46]. The sorbent-air contact process of DAC also requires freshwater, with an estimated water footprint of 4.01 m^3/ton CO_2 removed, although this number is subject to change dependent on environmental conditions (temperature, humidity, etc.) and specific operations utilized [5,47]. The footprint of DAC systems, at 7000 km^2 to capture 1 Gt CO_2/year, represents a potential hurdle; although, DAC does not require arable land [47]. The water footprint and land requirement of DAC is relatively lower compared to other NET's, such as BECCS. In a NET comparison study, DAC was estimated to be the most efficient use of water and land for indirect CO_2 removal methods [5].

All of these hurdles and challenges in efficiency manifest in a high cost of removal per ton of CO_2, $100 to $600/ton of CO_2 removed. This, coupled with an underdeveloped CO_2 market, makes the economics of DAC challenging [47,48] As with many technologies, the cheapest way to meet the heat and electricity demands is often the most emission and water intensive. Using renewables or waste heat increases the overall net CO_2 removal but can also greatly increase costs. Improvements to sorbent technology and heat recovery could help reduce operating costs and increase net removal by lowering the energy demand [40]. Currently, DAC relies on the carbon market more than other NET's because it produces pure CO_2 [47]. The most profitable use of CO_2 is

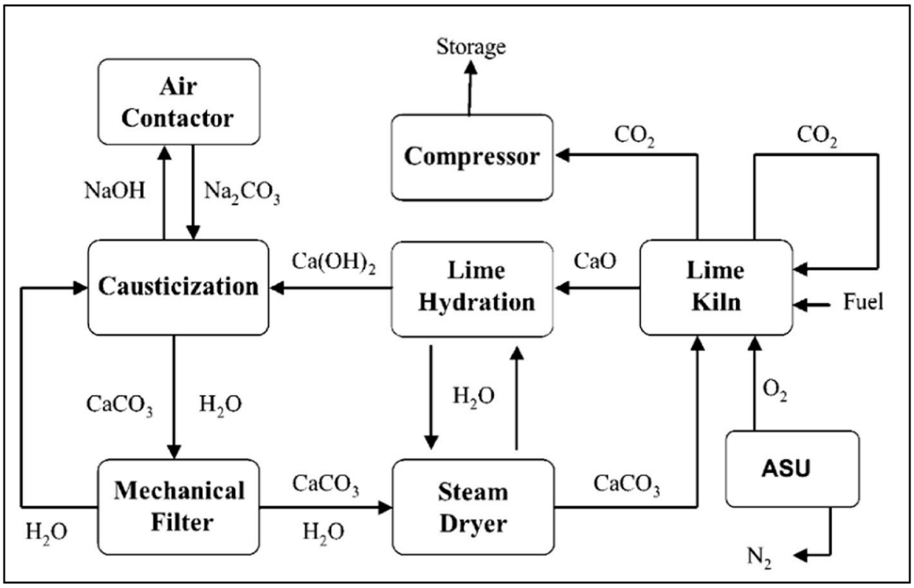

Fig. 10. Overview of the general process of DAC using a lime-based sorbent and an Air Separator Unit (ASU) [46].

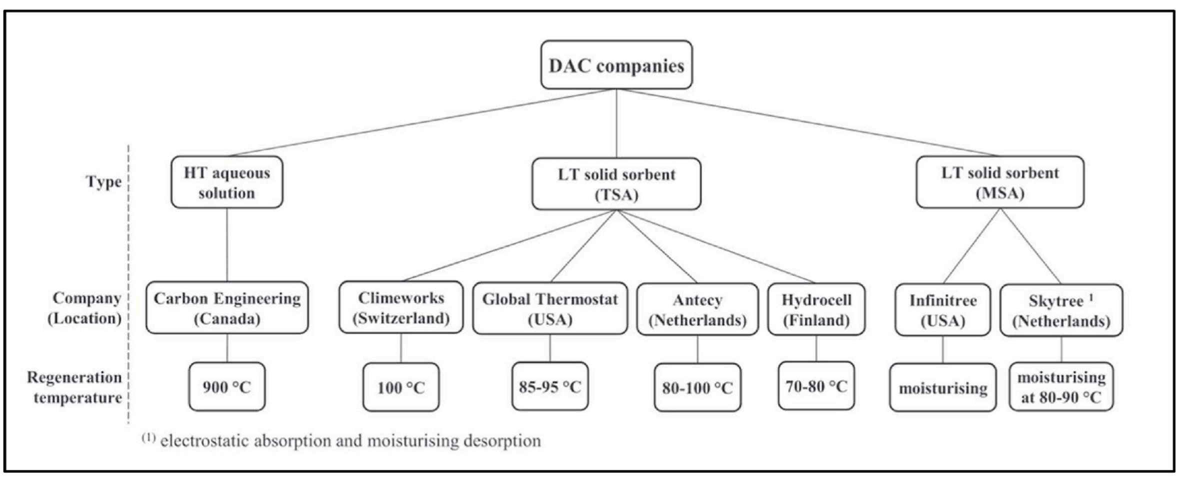

Fig. 11. Major active DAC companies as of 2019 with the respective technology used and the regeneration temperature required for the most energy intensive step in the process. *Abbreviations: high temperature,* HT, *low temperature,* LT, *moisture swing adsorption,* MSA, *temperature swing adsorption,* TSA [40].

currently EOR, but existing markets in EOR will not be sufficient to drive commercial DAC deployment [48]. Government support will be essential to the future large-scale deployment and market development of DAC (Fig. 12) [49].

Combining novel technologies has already shown efficiency improvements for DAC [51]. A case study of a DAC plant in Morocco supplied by hybrid PV-Wind-battery and heat pumps indicated major cost reductions that could be used as a model for future implementation [40]. Techniques such as DAC, in the early stages of development, are worth consideration because there is still room for cost reduction through future technological advancements. The resource and cost barriers will have to be overcome if DAC is to be deployed as part of our future energy system. DAC has significant advantages over BECSS, an alternative NET capture method, including relatively lower land, water, and energy requirements. DAC has also shown cost advantages to post-combustion capture. A study indicated DAC was the cheaper

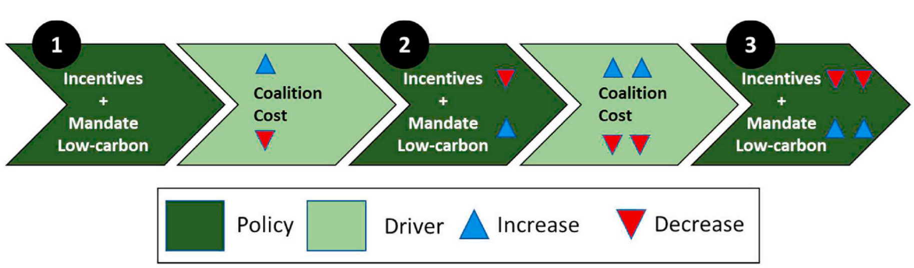

Fig. 12. Proposed policy sequence to develop DAC with an incentive + mandate mix. Recreated from Ref. [50].

capture option for at least 1/3 of natural gas-related emissions [52].

3.1.5. Indirect air capture (IAC)

Indirect Air Capture (IAC) is another non-point source carbon removal strategy that can capture CO_2 from ambient air. IAC technologies capture CO_2 emissions by enhancing natural carbon capture processes such as photosynthesis and carbon mineralization. Photosynthetic processes utilize CO_2 and H_2O from the atmosphere and soil to create glucose (releasing oxygen by-product) from solar energy that can be used for plant growth in plants, trees, and algae [53]. This process acts as a natural carbon capture mechanism, storing atmospheric CO_2 in the form of biomass [54]. Many microorganisms including algae, cyanobacteria, yeast, anaerobic gas-fermenting bacteria, have been found to have extremely efficient CO_2 capture rates [55–57]. As such, biomass growth is considered the most efficient method of carbon capture, although subsequent microbial degradation can rerelease captured carbon [58]. Methods such as biomineralization or pyrolysis can prevent degradation and allow for various utilization options, as mentioned in the utilization section below [13,55,58]. The enhancement of natural processes, rather the production of synthetic chemical sorbents used by DAC, can increase capture rates with lower energy requirements [53, 59]. Main IAC processes can be categorized as geoengineering, algae culturing, and Bioenergy with Carbon Capture and Storage (BCESS) [53].

3.1.6. Afforestation and forestry

Considering plant growth and other associated ecological processes are known to absorb around 30% of anthropogenic emissions, ecosystem management is critical to balance atmospheric CO_2 [60]. Forests are natural carbon sinks, storing CO_2 both above and below ground. Tropical deforestation is estimated to account for 8–15% of global annual anthropogenic carbon emissions [61]. Land conversion for agricultural practices releases 20–50% of soil carbon [53]. Illegal logging is currently the leading cause of deforestation. Regenerating forests with afforestation can help alleviate these lost emissions by increasing terrestrial carbon sinks [62]. Just a 50% reduction of deforestation between 2005 and 2030 can avoid 1.5 Gt of CO_2 annual emissions. A land-use scenario study in the Latin American tropics indicated an additional 31.09 Pg of CO_2 could be sequestered with the application of low-cost regeneration to lowland second-growth forests [61]. Large-scale afforestation will require major land-use adjustments and nutrient supplementation to enhance growth (nitrogen and phosphorus). Removal of 1.1–3.3 Gt CO_2/year is estimated to require 320–970 million hectares. Proper management of the carbon sequestered in the biomass is necessary to prevent rerelease; carbon sink potential in forests can be enhanced with the use of native species [63]. Threats to afforestation include forest fires, sulfur dioxide and heavy metal pollution, policy changes that allow for resource development, and an increase in GHG emitting microbes in the soil [64,65].

3.1.7. Blue carbon and ocean storage

In addition to afforestation on land, productivity in the ocean should also be considered to increase natural CO_2 capture mechanisms. The ocean is responsible for capturing around 40% of global atmospheric CO_2. Historical studies indicate rates of ocean CO_2 uptake has followed anthropogenic emission patterns, with a sharp increase since the 1950s and a slow decline in the past decade [66]. The rapid degradation of the planet's single largest CO2 capture source could allow industrial emissions to further contribute to rising global atmospheric CO2 concentrations. Thus, options to increase ocean productivity are critical to balance rising industrial emissions.

Phytoplankton are the main organisms responsible for transferring atmospheric carbon to the ocean. CO_2 is consumed in photosynthetic processes and eventually transferred to the deep ocean for burial or passed to other predatory organisms [67]. Ocean and coastal-based negative emission approaches have been minimally utilized but may have significant potential for carbon capture [68]. One option being explored is ocean fertilization. Photosynthetic activity is often limited by nitrogen and phosphorus availability, so fertilizing the ocean with these macronutrients can support biomass productivity, increasing the amount of CO_2 captured from the atmosphere. This process must be monitored and properly implemented to avoid possible harmful side effects such as eutrophication which can create anoxic conditions and further reduce ocean pH [53].

Feasibility of four of ocean NETs was assessed by Guttuso et al. based on effectiveness, duration of effect, cost, governability, co-benefits, and potential disbenefits (Fig. 13) [69]. These technologies include marine BECCS, restoring and increasing coastal vegetation, enhancing open ocean activity, and enhancing weathering and alkalinization [70]. Based on the trade-off's examined, none of these methods proved to be conclusively superior, though the method with the highest GHG removal effectiveness was enhancing weathering and alkalization. The addition of pulverized carbonate or silicate rocks to increase alkalinity of ocean ecosystems can sequester CO_2 with high duration and essentially permanent effects. The feasibility of this process is uncertain, with limitations in the mining of these materials and distribution infrastructure. Cost estimates are largely speculative, estimated between 72 and 159 US $ per ton CO_2 captured for full life cycle and 30–50 US$ per ton CO_2 for direct addition [69].

Other issues limiting the productivity of the ocean as a natural CO_2 sink include over-fishing, pollution, and direct habitat destruction. While these concerns are out of the scope of this paper, it should be noted that the improvement of overall ocean conditions could have drastic effects on managing industrial emissions on the global level.

3.1.8. Algae culturing

Algae is considered the primary bioproduct feedstock pertaining to CCUS because it can capture CO_2 from ambient air, flue gas, power plants, and soluble carbonate, while simultaneously producing large volumes of biomass with high market potential [71]. In addition, algae can thrive in habitats that many crops cannot such as arable land, wastewater, and high salinity water [72]. In some cases, algae and cyanobacteria can tolerate CO2 concentrations of up to 50% [55]. Algal capture rates are known to be 10–50x faster than terrestrial plants, capturing 1.83 kg of CO_2 per 1 kg of algal biomass produced, by mass [73]. Manmade pools of algae with large CO_2 concentrations are a popular form of large-scale algae synthesis, but photobioreactors (PBR) show the greatest efficiency for utilization [13]. Flue gas containing a fixed CO_2 concentration can be fed to PBR's to increase algal growth rates, doubling time, and carbon fixation rate which be utilized to produce fuels or other valuable co-products [74,75]. Scale up of this technology, however, is limited.

Continued research in biotechnology and processes integration has shown potential means to increase efficiency and minimize limitations [76–78,243]. Algae cultivation often requires added fertilizer containing limiting nutrients such as nitrogen and phosphorus. Production of synthetic fertilizer is associated with heavy GHG emissions. Substituting synthetic fertilizers with recycled nitrogen and phosphorus leeched from fishermen "trash" fish can provide microalgae cultures with suitable nutrients without the added emissions from synthetic fertilizer [79]. Studies to improve growth rates and capture efficiency have also helped improve industrial scalability potential. Application of CRISPR/Cas9-based genome editing can help mutate genomes to improve scaling potential for both oil production and carbon sequestration, as studied with the industrial oleaginous microalga, *Nannochloropsis oceanica* [78]. Additionally, Microalgal-bacteria consortia (MABC), the concept of combining microalgae and bacteria mechanisms to increase and control productivity, has been shown to increase carbon capture rates and simultaneously produce biofuel in wastewater bioremediation processes [73]. The specific strains of algae and bacteria that can be used for biofuel production via MABC technologies can be further explored in the cited reference [73]. Economic feasibility is largely

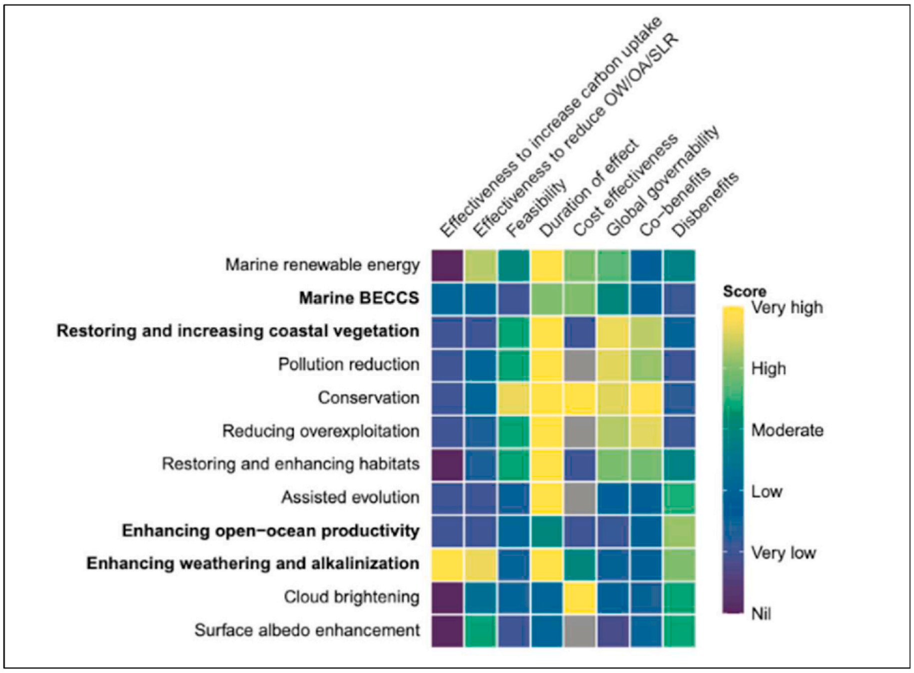

Fig. 13. Assessment of four ocean-based negative emissions approaches (bold) compared to other ocean-based measures [69].

determined by utilization method applied. Integrating many of these culturing technologies can help this technology reach industrial scalability for both capture and utilization.

3.1.9. Bioenergy with Carbon Capture and Storage (BECCS)

BECCS is an emerging integrated technology that combines bioenergy operations with solutions to capture the CO_2 emitted during biogenic energy production. Negative emissions can be achieved in the industrial sector if the CO_2 captured and permanently stored is greater than emissions associated with the entire bioenergy operation [9, 80–82]. Operation consists of 4 main components: biomass feedstock production, energy conversion processes, end-use product creation, and final CO_2 capture and storage [80,83]. Proper implementation of BECCS can remove CO_2 from the atmosphere and simultaneously produce useable energy [84]. Annual mitigation potential of industry sectors including steel, paper, cement, chemical, and H_2 sub sectors, could reach a combined 13.7 Gt CO_2 per year by 2050 with BECCS [85,86]. A schematic of the BECCS process is shown below in Fig. 14 [87].

An overview of bacteria capable of capturing CO_2 is show in Fig. 15 [88]. Technologies used to derive the energy for the final use can generally be categorized under combustion or conversion methods [87]. Combustion methods are used to produce heat for electricity generation or industrial application (cement, pulp, paper, waste incineration, steel, iron, and petrochemicals); conversion methods are used to produce gaseous fuel via biomass digestion or liquid fuels via biomass fermentation [83,87]. Currently, corn and soy are the most common biomass feedstocks, ethanol is the primary fuel generated, and EOR is the most common utilization option.

There are other recent studies that assessed the role of BECCS to achieve net-zero emissions considering CCS and CCUS of sustainable biomass feedstocks and point sources emitting biogenic CO2 (incinerators, pulp and paper mills, biopower plants) [251]. Biomass feedstocks can also be used to decarbonize hard to abate industries (cement, steel, ammonia, glass) by producing biohydrogen [252]. Moreover, traditional BECCS supply chains involve permanent CO2 sequestration in appropriate geological formations, which require long distance transport [253]. The alternative option is to permanently store CO2 in materials such as concrete, creating BECCUS supply chains [253].

Most climate mitigation studies indicate BECCS will play a critical

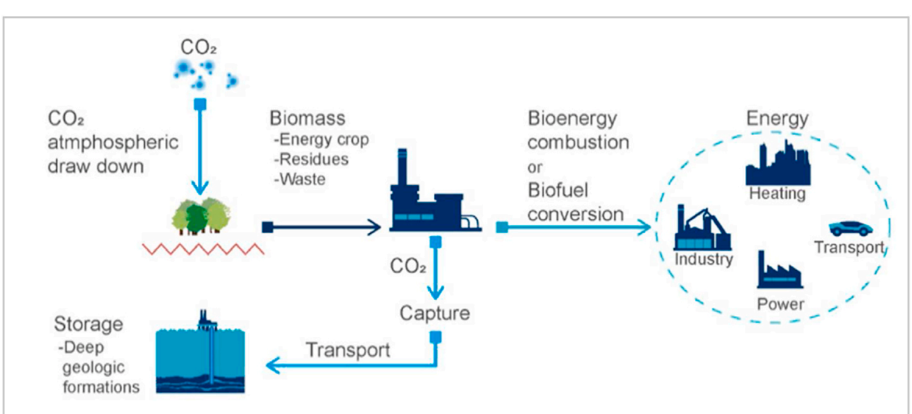

Fig. 14. Schematic showing the general BECCS process [87].

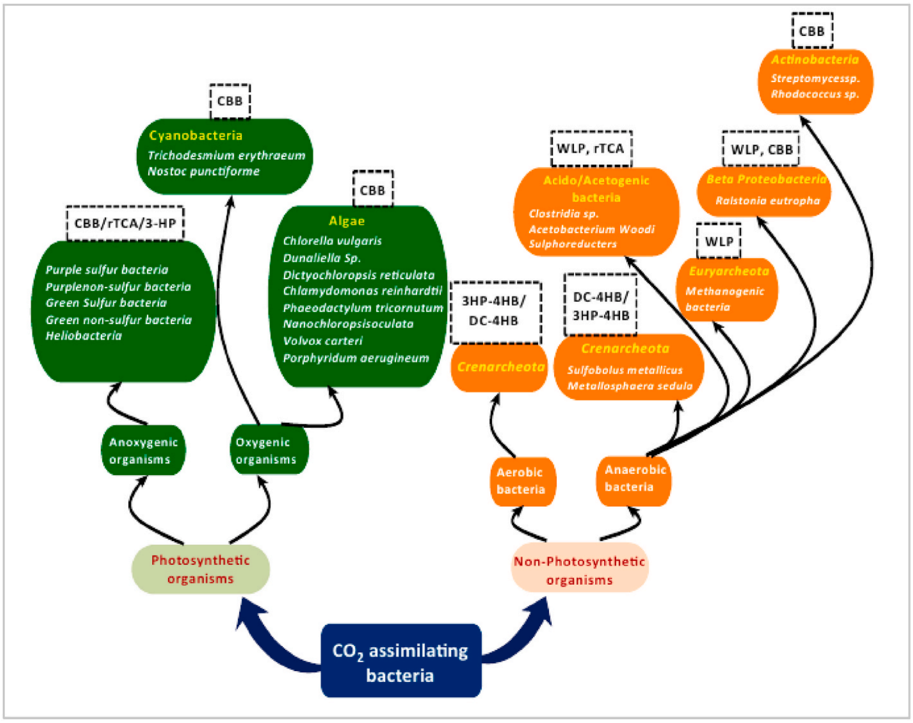

Fig. 15. Overview of organisms capable of capturing CO_2 [88].

role in decarbonizing the energy system to meet Paris Agreement goals [84,89,90]. Development of policy frameworks will be essential to increase industry participation [90]. A model for different climate policy scenarios with constant socio-economic assumptions indicates the need of at least some BECCS implementation to reach climate targets (Fig. 16) [44]. Application of BECCS to existing power plants is possible. Natural Gas Combined Cycle (NGCC) plants can be converted into biomethane-based BECCS system, although this process is not currently economically viable [91]. Alternatively, Coal power plants can be retrofitted to allow for BECCS-coal cofiring to produce power [92]. Co-firing of BECCS plants with agriculture residues in China can help spatially alleviate emissions from China's growing coal industry, with potential application in 2836 counties [93]. In 2019, The Global CCS Institute recognized 5 active BECCS facilities globally with a cumulative capture rate of 1.5 million tons/year [87]. Four of these facilities are small-scale ethanol production plants that capture CO_2 for utilization in nearby EOR sites. One large-scale BECCS facility is in operation today, capturing up to 1 Mtpa of CO_2 from corn fermentation used to produce ethanol. Here, CO_2 is geologically sequestered in subsurface reservoirs beneath the facility. Three additional projects have been announced with plans to incorporate BECCS. A map with locations of the current facilities and planned projects with the respective sector is shown in

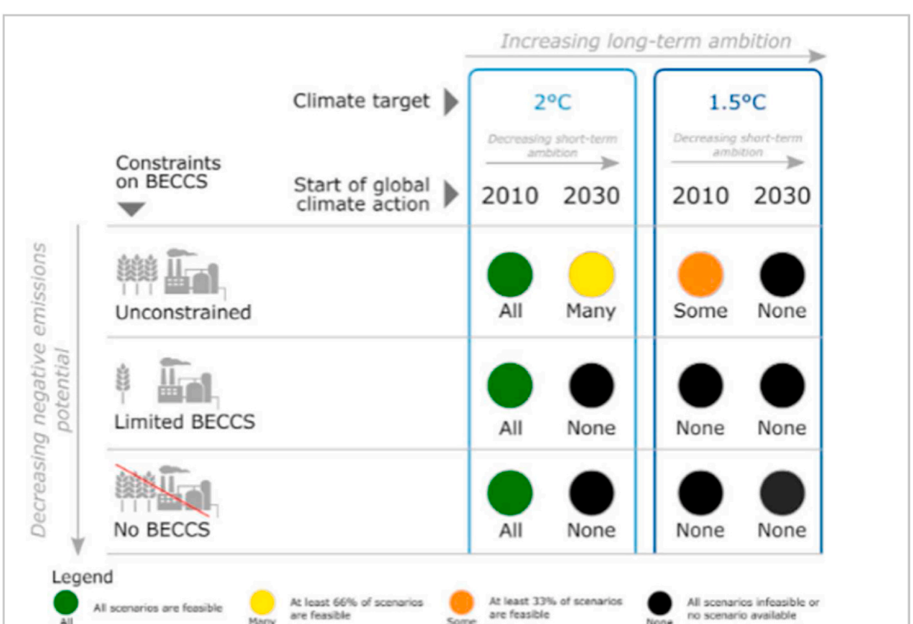

Fig. 16. Feasibility model of BECCS implementation based on constant GDP, population, and energy demand assumptions [44].

Fig. 17. Locations of current and planned BECCS projects as of 2019 [87].

Fig. 17 [87].

BECCS is considered more cost effective than DAC, a NET alternative, but is also more resource intensive [5]. Cost estimates of BECCS are generally between \$30–400/tCO_2. The lowest values are achievable only by facilities with abundant biomass feedstock and proximity to available storage sites [44]. A technoeconomic analysis comparing biomass, CCS, and harmonization of the two, BECCS, estimated BECCS to be the most cost effective to mitigate emissions in the industrial sector [86]. The main limitation to large scale BECCS implementation is the availability of biomass feedstock. Feasible biomass production predictions for the future are heavily debated among the scientific community because there are so many factors affecting production limitations, ranging from population estimations to technological development [83,87]. One study demonstrated that the current global sustainable biomass available is enough to fuel 3000 BECCS plants with 500 MW capacity and suggested recommissioning coal infrastructure to lower project costs [94]. Another study suggests the application of lignocellulose in forage crops for increased efficiency and reduced resource requirements [95,96]. Primary ecological constraints on biomass production include the high energy, water, nutrient, and land use requirements. Sequestering 1 Gt of CO_2 in a geologic reservoir via BECCS has been estimated to require 1.3 Gt of biomass carbon (switchgrass feedstock), amounting to natural resource requirements of 3.3 M km^2 in land, 25 Tg of nitrogen fertilizer, and 1830 km^3 of water each year (evapotranspiration) [83]. These values vary based on the location, biomass feedstock used, final utilization process, and capture processes added. Research to increase biomass production efficiency can greatly impact the future of BECCS.

3.2. Options for CO_2 transportation

Following the capture and purification of CO2, it is transported to locations for utilization and/or storage. However, as [248] notes, such transportation can be a significant form of infrastructure in its own right. In Norway, Shell, Total, and Equinor launched the Northern Lights project in 2020, with completion due to occur in 2024, seeking to establish the first cross-border carbon transport and storage network in the world, one that will demand hundreds of kilometers of pipelines. As also noted in Ref. [248], the Port of Rotterdam in the Netherlands launched its Porthos (Port of Rotterdam CO2 Transport Hub and Offshore Storage) initiative in 2022 to store ~2.5 million metric tons of CO2 per year offshore in the North Sea, more than 20 km off the coast, also requiring significant infrastructure. Many times, infrastructures become coupled together into even more multi-modal transport networks, with [249] visualizing prospective waste to energy plants in Switzerland, their CO_2 storage sites (i.e., the Northern Lights site and the hypothetical site in Switzerland), their transport exchange sites (i.e., Rotterdam and Basel, and illustrative pipeline connections (See Fig. 18).

Consequently, transmission of CO2 poses a significant challenge to large scale deployment of CCUS because low-cost capture sources are often not proximal to storage and utilization locations, requiring high transportation expenses. Pipeline and shipping are considered the main modes of large-scale CO2 transportation (Fig. 19) [14,97,98]. The cost effectiveness of pipeline and rail change based on distance and volume of CO2 transported (Figs. 21 and 22) [99]. Motor vehicles and rail are also options but do not have significant advantages for independent development in the industrial sector. Mode selection is dependent on the geographic location of the capture site, quantity of CO2 being transported, and the distance. Cost variation based on changing capacity being transported is shown in Fig. 18 and Table 6 below [40,98]. The LCA emissions, energy requirements, geographic location, and feasibility should also be considered to apply the best suited transportation operation to link capture and sink sites efficiently (Fig. 20) [97].

3.2.1. Pipeline Transportation

Transportation via pipelines is considered the most practical option to move large volumes of CO2 over long-distances with low operating costs, low energy requirements, and low GHG emissions [97]. There is currently some 8000 km of existing CO2 pipelines across the globe, with 6500 km in the United States [16]. Most of the existing pipeline network in the United States is used for EOR in the south and central regions (Fig. 23) [101]. Major CO2 pipelines in the United States include the Canyon Reef Pipeline, Bravo Dome Pipeline, Cortez Pipeline, Sheep Mountain Pipeline, and Weyburn Pipeline. Construction of these pipelines date back to the 1970's [101].

The motivations for CO2 pipeline construction have changed over time. Originally a tool to increase petroleum production through EOR, emission reduction and associated climate change mitigation is now motivating the further expansion of pipelines. The demand for CO2 pipeline construction has only increased and is expected to increase in the coming years [14]. In addition, CO2 demands for EOR in the Permian Basin are expected to increase from 62 Mt CO2 per year to as high as 500 Mt CO2 per year [102]. It is estimated that 200,000 km of pipeline is needed to move the 10 billion tons of CO2 required to meet

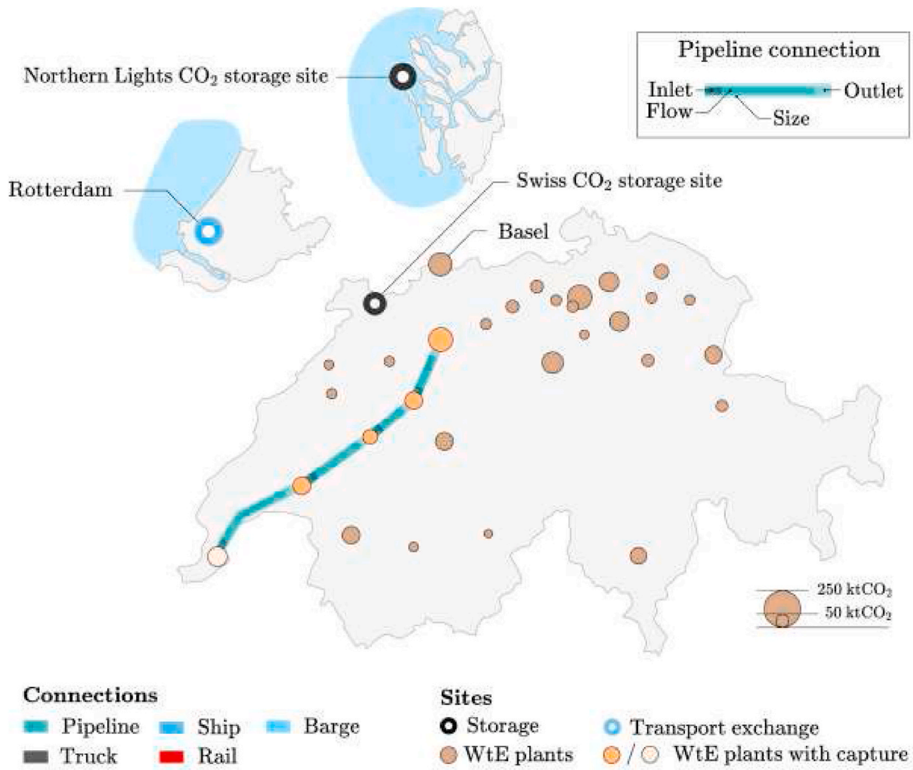

Fig. 18. Visualizing the multi-modal nature of carbon transport infrastructure in Norway, the Netherlands and Switzerland. Source [249].

Table 5
Comparison of various carbonation routes, modified from Ref. [143]. References in table [37,145–155].

Route	Description	Advantages	Disadvantages	References
Gas-solid	Solid feed directly reacts with CO_2	Straightforward production of stream and electricity, Utilization possible of waste stream	Sluggish reaction Thermodynamic limitation Non-viable	Lackner et al., 1997; O'Connor et al., 2005
Aqueous	Carbonate reaction under aqueous medium. Additive chemicals are used to enhance rates.	High capacity	Energy-intensive, needs additives, no additive recovery, expensive	Shashikant Yadav and Mehra 2017a, 2017b
HCl Extraction	HCl employed to extract reactive components	Easy recycling of HCl	Energy-intensive Expensive	Huag et al., 2010; Zhao et al., 2010
HNO3	HNO_3 used to extract reactive components	Energy efficient, low cost	Non-recovery of chemicals	Doucet, 2010, Teir et al., 2009
Molten Salt	Molten salt used as the extraction agent	More energy efficient than HcL	Highly corrosive Unwanted products	Newall et al., 2000, Olarjire, 2013
Ammonia Extraction	Ammonium salts employed to extract reactive components	Pure products, Fact reaction, recyclable	Expensive Limited literature	Fagerlund et al., 2012; Sanna et al., 2014b

carbon mitigation goals by 2050 [103].

CO2 can be transported via pipeline in a gaseous, liquid, dense-phase, or supercritical state depending on temperature and pressure controls applied. Based on energy costs and associated economic value, gaseous and liquid state are considered the most suitable for short distance transport, dense-phase and supercritical for long, and solid the least suitable overall [14]. Compressor stations are used to pressurize pipeline for gaseous CO2, and pump stations are used for liquid or dense phase CO2. While a definitive state equation for CO2 is still debated within the science community, studies on pressure drop and ambient temperature in CO2 in pipeline have helped improve efficiency in transportation. Typical pipeline operating conditions are temperatures between 13 and 43.8° C and pressure between 9 and 15 MPa [102,105].

Pipeline design can be characterized by length, capacity, and power requirements for operation. These parameters are all generally directly related. The longer the pipeline, the greater the capacity, the larger the power requirement. Carbon steel is the most common material being used to construct CO_2 pipeline because it is the most cost effective. As mentioned above, CO_2 is transported in a liquid or dense phase in shorter pipelines and gaseous for longer pipelines. Optimization models on pipeline diameter, thickness, and material with capacity is largely based on studies conducted for natural gas pipeline. Design of pipeline should also consider the route and associated climate the pipeline will pass through because energy requirements to maintain phase state will change [97]. Issues with phase change due to changing environmental conditions are described below. Typical physical characteristics of CO_2 pipelines are shown in Table 7 below [101].

The risks associated with CO_2 pipelines are similar to those of natural gas, oil, and water pipelines. Leakage is rare, but incidences can have severe effects on surrounding communities. Leakage of CO_2 itself poses an obvious risk to the original intention of removing emissions from the atmosphere, but even greater threat to the health of the people and animals near the leak site [106]. Concentrated CO_2 is denser than air, allowing risk of accumulation in low-lying areas. Pipeline routes should consider this when selecting a pipeline route. There were 46 incidents associated with CO_2 pipeline malfunction in the United States from 1972

Table 6
The cost to transport CO_2, including the cost of liquefaction. Recreated from Ref. [40].

Transportation type	Capacity Mt CO_2/a	Distance km	Cost €/tCO_2
Truck	15–20 × 10^{-6}	>100	13
Train	1.46	598	7.3
Onshore Pipeline	0.73	100	6.8
	0.73	500	43.6
	2.5	180	5.4
	7.3	100	1.5
	7.3	500	9.8
	20	180	1.5
	20	750	5.3
Offshore Pipeline	2.5	180	9.3
	2.5	1500	51.7
	20	180	3.4
	20	1500	16.3
Shipping	2	750	11.1
	2.5	180	13.5
	2.5	1500	19.8
	3	1950	11.8 (liquefaction costs not included)
	20	180	11.1
	20	1500	16.1

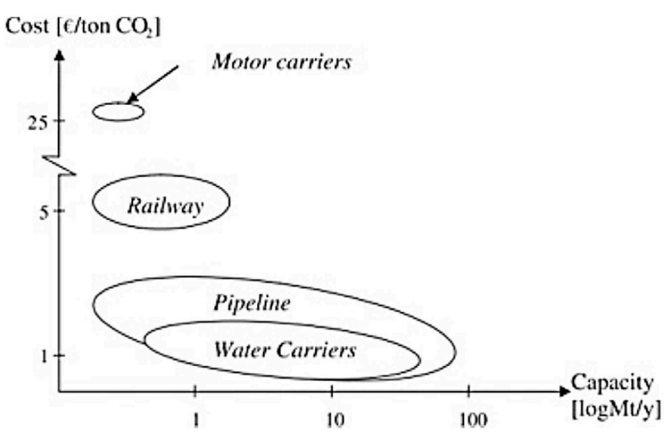

Fig. 19. Cost of CO_2 transportation mode based on capacity compared for distance of 250 km [98].

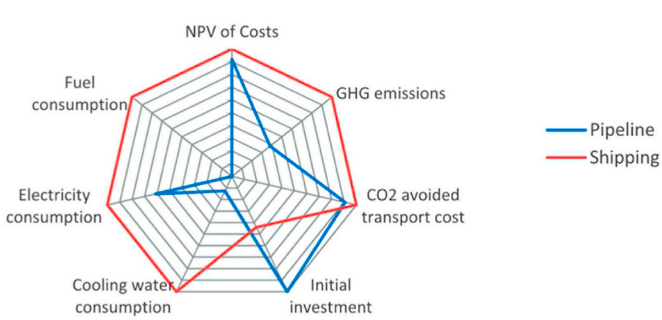

Fig. 20. Multi-parameter comparison of pipeline to shipping CO_2 transport chains [97].

to 2012. So far, there have been no deaths or major injuries associated with CO_2 pipeline malfunction [16]. As previously described, CO_2 is an asphyxiant, so high concentrations of the gas can lead to casualties. In 1986, a limnic eruption in Lake Nyos released up to 1 m^3 of CO_2 and killed 1746 people and 3500 livestock [106].

Pipeline corrosion, embrittlement, and fracture are all sources of potential leakage [14]. Experimental investigation on pipeline corrosion has indicated that a pure CO_2 stream has a near zero corrosion rate. Interaction of pure CO_2 in different phase states with various pipeline materials has shown consistent non corrosion results indicating It is not pure CO_2 that threatens the pipeline, rather impurities mixed in with the captured CO_2 [14,107]. The purity of the CO_2 stream is mainly dependent on the source and the capture technology used [101]. In networks that mix streams of CO_2 from different sources, the mixture becomes highly complex. The most relevant impurities that are currently being studied include H_2O, N_2, O_2, H_2S and CO [106]. The corrosion mechanisms of these impurities are not well understood and are consistently debated [108]. There are no international purity standards for transporting CO_2. Natural gas pipeline corrosion has been heavily researched, but the increased CO_2 concentration and associated conditions, such as low pressure, create new conditions and reactions that must be considered. Overall, impurities can displace the critical point on the phase diagram, threaten pipeline integrity, and increase energy requirements for operation. Improving cleaning technologies in the capture process can prevent the impurities from entering the pipeline, or application of coating technologies to pipeline material can help mitigate the impact of impurities. For example, a Nickel−Phosphorous coating on steel pipeline was found to significantly reduce corrosion associated with impurities in supercritical CO_2 streams (Fig. 24). Corrosion inhibition efficiency is higher than 80% [107].

In addition to impurities, the introduction of water is also known to increase corrosion by producing carbonation and CO_2- hydrates [108]. Water contamination in a pure supercritical CO_2 moisture caused corrosion in carbon steel pipeline material but not aluminum and copper. Carbonic acid (H_2CO_3) is produced when water dissolved CO_2, which is known to attack iron (Fe) to produce iron carbonate ($FeCO_3$) [16].

Tests suggest that water saturation can increase steel corrosion rates from ~0.2 mm/year to 20 mm/year. The steel corrosion rate was found to increase with increased water content in a study on supercritical CO_2. Significant corrosion was found to occur at 100 ppm of H_2O at 1.2 mm/year increasing to 2.5 mm/year at 200 ppm. When CO_2 is transported in a liquid state, the water content threshold is greater. The threshold water content limit to be ~600 ppm before corrosion incurs on steel [14]. Corrosion reactions between supercritical CO_2 and water are known to increase with temperature. In addition to corrosion, gaseous transport of CO_2 at temperatures below 10C with water saturation can form CO_2-hydrates, resulting in transmission blockage or valve fouling [16]. Heating and insulation may be required in some locations where this is a risk.

The critical temperature of CO_2 is close to the ambient temperature, so changing environmental conditions can easily cause a phase change. Pressure drop or temperature change can occur in pipelines that travel through locations with changing elevations and ambient air temperatures. Phase change in CO_2 increases the risk of pipeline failure. The gas void fraction describing gas-liquid two phase flow can help monitor conditions. Technological advancements in laser transmittance have allowed for more accurate measurements of gas-liquid ratios [109]. Additionally, recompression stations can be added ensure appropriate pressure is maintained along the pipeline. Less recompression stations are required for pipelines with larger diameters. Recompression stations and increased pipeline diameter size are both associated with increased cost, so appropriate modeling for specific locations is needed for optimal cost-effective design selection [16].

3.2.2. *Ship carriers*

Ship carriers offer a cheaper and more flexible option for transportation of smaller volumes of CO_2 for long distances, although viability of this option is highly dependent on location of capture and end use site. For geographically appropriate locations, shipping will be very relevant in the initial phase of CCUS when capture and storage locations are few and far between. A case study compared the transport of 10 mt/y CO_2 over 500 k km via onshore pipeline and ship carrier over the course of 30 years. The results indicated ship transportation

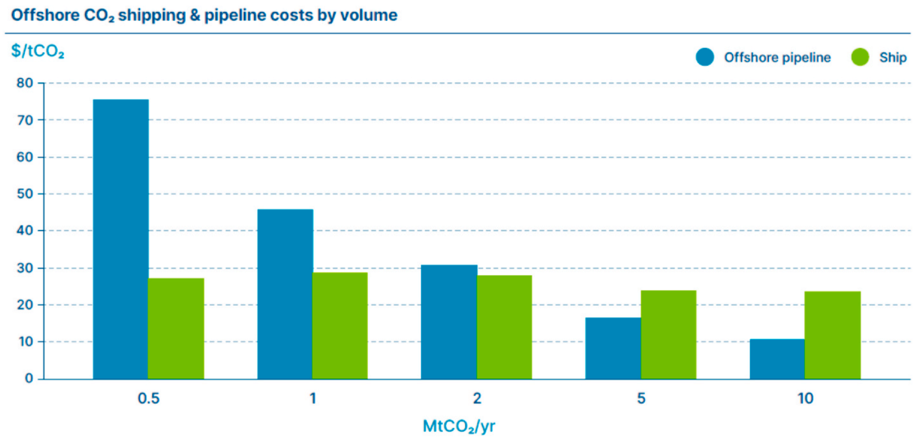

Fig. 21. Chart demonstrating that pipelines become more economically competitive when transporting large volumes of CO_2 (assumes 1000 km distance) [99].

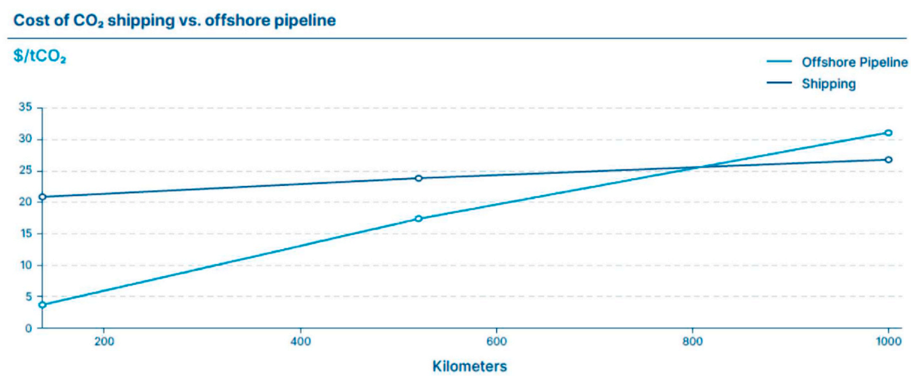

Fig. 22. Chart showing that shipping is more cost effective than pipelines as distances increase (assumes a capacity of 2 $MtCO_2$ per year) [100].

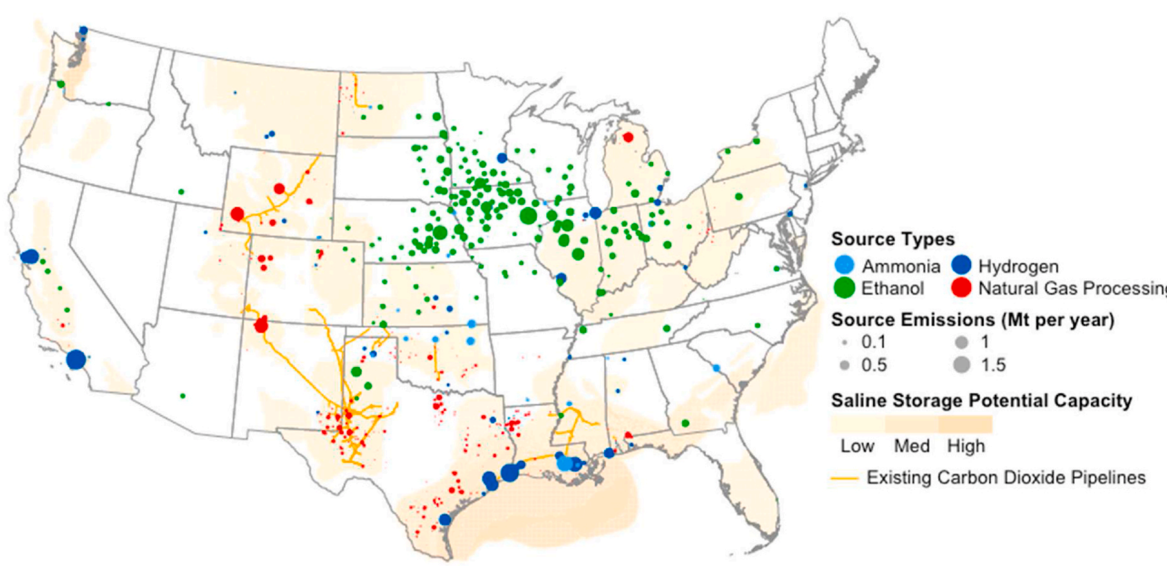

Fig. 23. Existing carbon dioxide pipelines in the United States with potential saline storage locations and sources of emissions with low-capture-cost in the United States [104].

consumes more utilities (fuel, water, electricity) and is more climate intensive but required lower upfront investment [97]. Another economic evaluation comparing the two indicated ship transport becomes more cost effective than offshore pipeline at distances above 350 km and onshore pipeline at distances above 1100 km [110]. The food and brewing industries are currently the primary users of small scale liquified CO_2 shipping, with capacities generally between 800 m^3 and 1000 m^3 [98]. Large scale application for CCUS has been limited by the needed vessel technology advancements and infrastructure development. Analysis of varying trade-offs between pipeline and ship carriers is discussed in depth in Baroudi et al.'s review of large-scale CO_2 shipping [98]. The possibility of combining ships and pipelines has also been

Table 7
Physical characteristics of CO_2 pipelines. Recreated from Ref. [101].

Parameter	Range
Length (km)	1.9–808
External Diameter (mm)	152–921
Wall thickness (mm)	5.2–27
Capacity designed (Mt/y)	.006–28
Pressure min *(bar)*	3–151
Pressure max *(bar)*	21–200
Compressor capacity (MW)	0.2–68

considered [111].

R&D in shipping transport has been largely focused in Europe and the East where there is minimal existing pipeline infrastructure and shipping is considered the most feasible transport option. North America has an extensive pipeline network and many onshore EOR locations, but potential application of shipping in the United States will focus on the Gulf Coast region for offshore EOR in the Gulf of Mexico and port terminals used for international exports of CO_2 [112]. Locations such as Japan and Korea have limited pipeline infrastructure, largely due to the risk of earthquakes. Southern European countries can also greatly benefit from shipping, especially if onshore storage is restricted. The North Sea has the most potential for offshore storage. Based on a feasibility model, ship transport from industrial captures sources in Southern Europe to North Sea Basin offshore storage locations could be a more cost effective transportation method than offshore pipelines [113].

The process of transporting CO_2 by ship closely resembles the operation used to transport Liquified Petroleum Gas (LPG) and Liquified Natural Gas (LNG). It is generally assumed that the CO_2 has been transported from the capture plant directly to the liquefaction plant (Fig. 25) [111]. Liquefaction involves the compression and refrigeration of the incoming CO_2 stream, various methods and details are outlined in Table 8. This is a very energy intensive and costly process, accounting for 77% of the energy demands and 54% of the costs total shipping operation costs [98]. Conditions for stable liquid CO_2 transport are generally around −50C and low pressure. Impurities can affect the liquefaction process, increasing energy demands. Conventional processes of liquefaction are generally classified as open or closed-cycle refrigeration processes. Improvements to the liquefaction process is described by Engel and Kather [111].

In liquefaction plants, CO_2 is continuously captured and liquified, but the discrete nature of ship carrier transport creates a need for intermediate storage tanks in between trips. This increases flexibility but also increases scheduling complications and costs. The high modularity of this process requires detailed planning and communication to successfully scale up. When a ship becomes available, the storage tanks are handled at a loading facility where the tanks are placed on the ship and taken to the final destination (Fig. 26, Fig. 27) [98,110]. If the destination is beyond the arrival port, the tanks are handled at an unloading facility, placed in temporary storage tanks (if necessary), and prepped to be transported via pipeline, truck, or rail. Alternatively, tanks can be taken to an offshore injection well for direct injection (Fig. 26). The tanks can be unloaded directly from the ship to the well, or the tanks can be unloaded at an offshore platform and stored for later use. Vessel technology has mostly been used for small scale projects at 1.5–2 MPa and 243 K. Further details on the entire process of shipping liquified CO_2 are described by Decarre et al. and Munkejord et al. [110,114].

Large scale vessels used for LPG and LNG have capacities up to 270,000 m^3 but retrofitting tanks for CO_2 would be extremely costly.

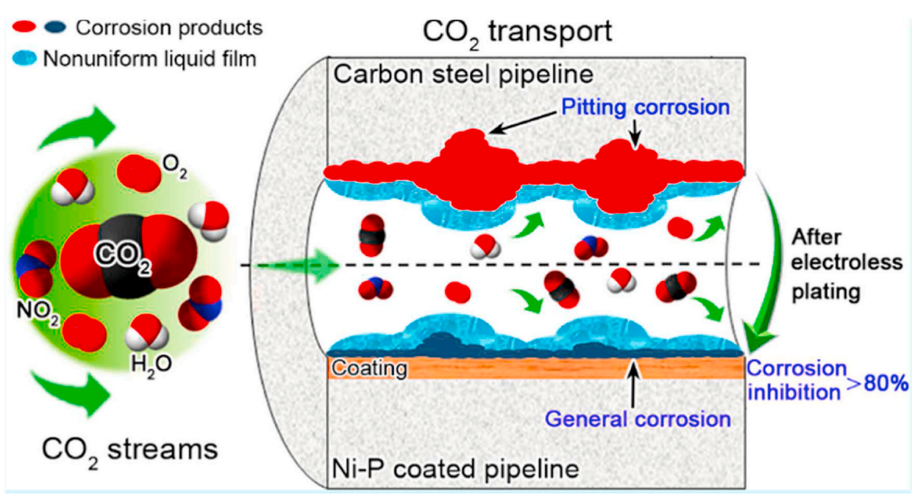

Fig. 24. Proposed electroless high-phosphorus Nickel–Phosphorus coating for steel pipelines to effectively transport impure supercritical CO_2 by reducing corrosion rate [107].

Fig. 25. The different modules involved in the CO_2 shipping process chain [64].

Table 8
Various CO2 liquefaction projects with associated conditions [98,115–121].

Type of System & Refrigerant	Inlet Stream Condition	Liquefaction Condition	Inlet Composition (mass %)	Quantity	Energy Consumption	End Use	Remarks
Open cycle, CO2 as refrigerant	0.1–2 MPa	0.6–0.7 MPa, 221 K	97.62% CO2 2.38% H2O	Unspecified	144–378 kJ/kg, depending on inlet pressure	EOR Storage	0.2–0.5 mol % volatiles 50 ppm water dehydration
Open cycle, CO2 as refrigerant multistage expansion - optimized	0.1 MPa, 298 K	0.65 MPa, 221 K	97.62% CO2 2.38% H2O	2.8 Mt CO2/year	353–356 kJ/kg	Offshore Storage	90% of a 600 MW coal plant, $9.95–10.51/tCO2, 4-stage compression and 3-stage expansion, 2 multi-stream heat exchangers
Open cycle CO2 as refrigerant	0.1 MPa	0.8 MPa, 228 K	89.98% CO2 9.99% H2O 0.016% N2	0.7 Mt CO2/year	327–366 kJ/kg with optimization	Storage	
External refrigeration using different coolants **a. NH3** **b. NH3–CO2** **c.C3H8–NH3** **d. C3H8–CO2** **e. R134a-NH3**	0.1 MPa	0.8 MPa, 228 K	89.98% CO2 9.99% H2O 0.016% N2	0.7 Mt CO2/year	a. 387 kJ/kg b. 409 kJ/kg c. 371 kJ/kg d. 432 kJ/kg e. 377 kJ/kg	Storage	
External refrigeration process with multi-stage compression and expansion	a.0.13 MPa, 313 K b. 10.3 MPa, 293 K	a. 0.7 MPa, 223 K b. 0.7 MPa, 227 K	a. 97.55% CO2, 2.39% H2O, 0.05% N2 b. 99.93% CO2, 0.07% N2	7.3 Mt CO2/year	a. 442 kJ/kg b. 52 kJ/kg	Storage	R22 utilized as coolant. Molecular sieve dehydration system included
a. Single stage ammonia refrigeration cycle **b. Two-stage ammonia refrigeration cycle** **c. Simple internal refrigeration process** **d. Multistage internal refrigeration process**	0.2 MPa, 293 K	0.7 MPa, 223 K	97.62% CO2 2.98% H2	1.1 Mt CO2/year	a. 299 kJ/kg b. 296 kJ/kg c. 515 kJ/kg d. 313 kJ/kg	Storage	CAPEX 25.2–30.9 M$ depending on the process
External refrigeration process	0.18 MPa, 313 K	a. 0.6 MPa, 221 K b. 1.5 MPA, 245 K c. 2.5 MPa, 262 K d. 3.5 MPa, 274 K e. 4.5 MPA, 283 K f. 5.5 MPa, 291 K g. 6.5 MPa, 299 K	98.26% CO2 1.72% H2O 0.012% N2	1.1 Mt CO2/year	a. 472 kJ/kg b. 378 kJ/kg c. 331 kJ/kg d. 331 kJ/kg e. 315 kJ/kg f. 331 kJ/kg	Offshore Storage	
a. Linde Hampson **b. Lunde dual-pressure system** **c. Precooled Linde-Hampson system** **d. Closed liquefaction system**	0.1 MPa, 308 K		100% CO2	1.1 Mt CO2/year	a. 485.9 kJ/kg b. 472.5 kJ/kg c. 381.9 kJ/kg d. 2376 kJ/kg	Storage Site	Seawater temperature 303 K, Compressor adiabatic efficiency 75%, CAPEX 34–43 M$, Depending on the process

Scale up of existing small-scale tanks is not possible due to the technical complications of the tanks and changing conditions required for large volumes of liquid CO_2 [98]. The best option for future design vessels would be electric diesel, but this option is also extremely expensive [110]. A typical design of a 30,000 m^3 capacity CO_2 vessel is show in Fig. 28 [110].

While ship carriers are noted to be the most cost-effective method of transport in some cases, the carbon footprint must be considered to retain integrity of the purpose of transporting CO_2. Compared to pipelines, shipping requires energy intensive operations and therefore high environmental cost of operation. Increased GHG emissions are associated with vessel operation [98]. In addition to the problems that can occur during proper operation, collision, fire, and stranding are all possible risks with vessel traffic. These incidents would defeat the inherent purpose of the mission, and the high concentrations of released CO_2 could have adverse environmental impacts on the sea, atmosphere, and people operating the vessel. More studies are needed on the potential impacts of large-scale leaks of liquid CO_2 in shipping transport [98].

3.2.3. *Rail and motor transport*

Truck and rail are also used to transport liquid CO_2, however, most discussion on large scale CCUS focuses on pipeline and shipping. Not only are truck and rail limited in scale, but also in route and accessibility. CO_2 is considered a dangerous substance so routes are constrained to areas without possible risk to local populations [98]. Trucks are generally used as an intermediate process to transport small volumes of liquified CO_2 to ship carrier port terminals. Trucks are preferred to pipelines in this scenario only when distances are relatively short, volumes are small (100 kt CO_2/a), and liquefaction plants are located at truck pick up location, or in cases in which pipeline is not available [102]. Rail can provide a cost effective alternative only if source and sink locations are located at railheads, and the distance is under 700 miles [102]. This represents lower up-front capital alternatives because

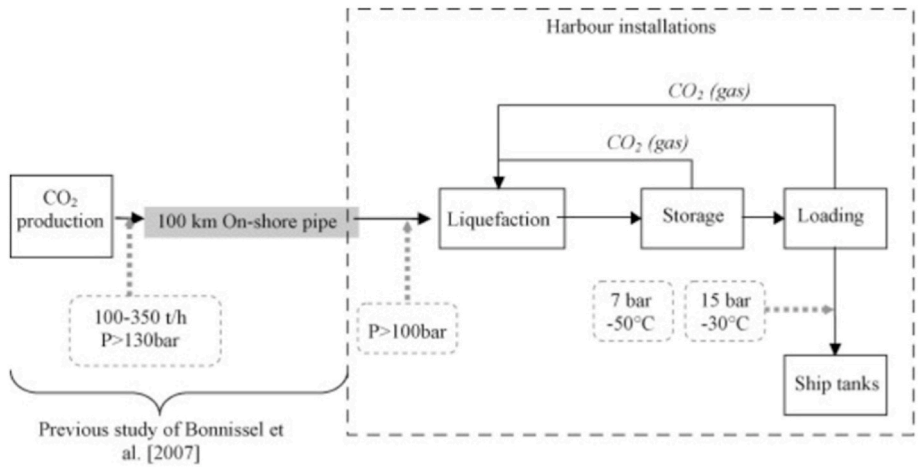

Fig. 26. The basic process used before loading onto ship for transport [110].

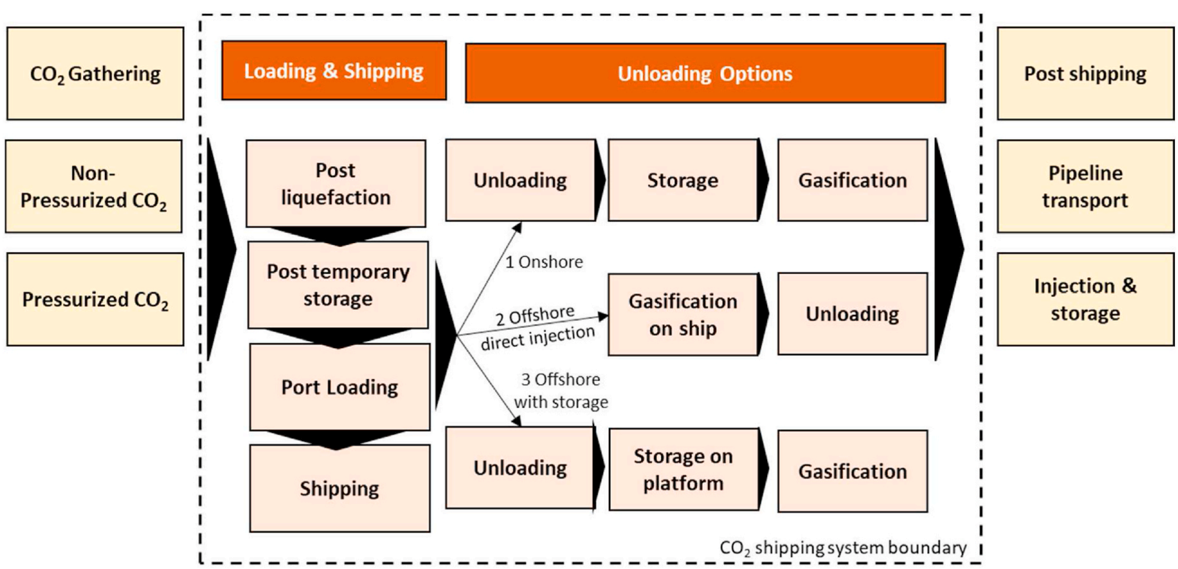

Fig. 27. Options involved in the CO_2 shipping process [98].

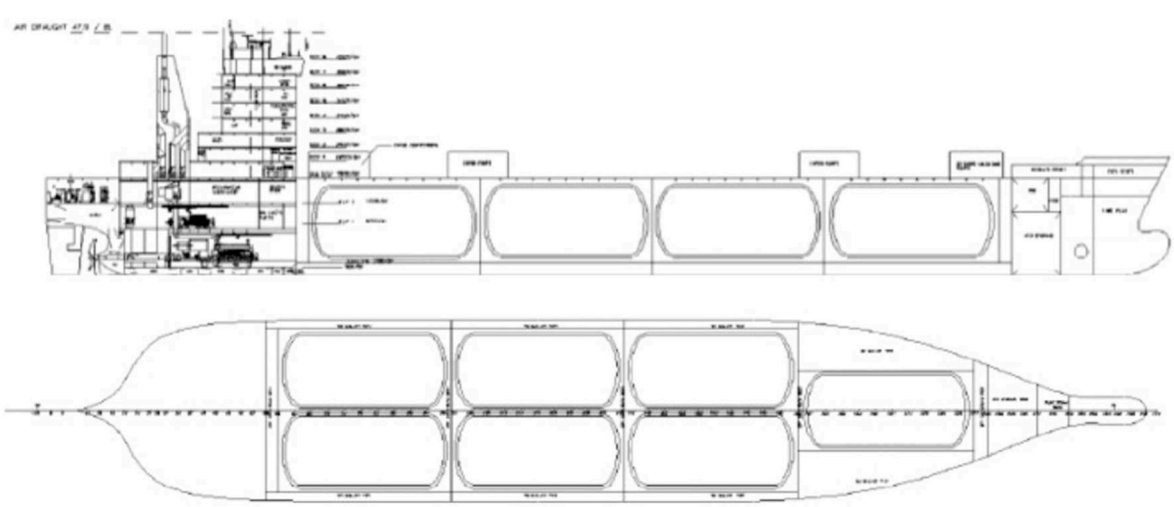

Fig. 28. Typical design of a CO_2 vessel with 30,000 m^3 capacity [110].

most of the infrastructure is already in place. Rail transport, however, faces the same risks as truck transportation methods with potential exposure to local communities [102].

3.3. Options for CO_2 storage

Carbon storage involves the transfer of atmospheric CO_2 into global pools that include ocean, pedologic, biotic, and geological strata via natural and anthropogenically driven processes [67,122]. To meet carbon capture goals, large volumetric capacity for carbon storage is a necessity. Long term carbon storage can be achieved through several techniques, but no one method for storage will suffice for achieving mitigation goals. For all techniques, the safety and permanence of the storage is critical. Storage techniques can be abiotic or biotic, with abiotic offering longer term storage options (Fig. 29) [67]. Abiotic techniques generally involve the injection of CO_2 into the deep ocean, geologic strata, old coal mines, oil well, saline aquifers, and mineral carbonation; alternatively, biotic techniques rely on natural capture processes that store CO_2 biologically in biota, soils, wetlands, or oceans [67,122,123].

3.3.1. Biotic storage

Biotic carbon sequestration is not a long-term large-scale storage solution, rather it serves as a capture technique and route for the utilization of purified carbon (see section 3.1.6 on biological capture). Biotic storage models across industry lack significant data for long term storage. Relevant time, location, and lifecycle specific data regarding industrial processes is absent or difficult to find [124]. Biotic storage models rely heavily on assumptions and thus calibration and validation of models across the industry cannot be conducted. To improve this, biotic capture and storage stakeholders will have to engage in increased monitoring and modeling techniques and information sharing across competitors to become a viable option for storage [124]. Biotic storage techniques via industrial processes such as the wood product sector could mitigate up to 441 Mt CO_2e annually by 2050; however, this technique could only be applied in countries dominate in timber production [125]. Another study suggests wood burial could mitigate up to 10 ± 5 Gt C per year [126]. While large biotic storage opportunities in deep sea pools offer billions of tons of capacity, these sites are limited by the unknown biological impacts [127]. Biological storage is difficult to implement because it can either fuel or disrupt existing biological processes. For biotic means to increase as a viable storage technique there needs to be more research developments in the long-term impacts of storage and assessment on resource consumption [122].

3.3.2. Abiotic storage

The volumetric scale of the CO_2 that will need to be captured demands immense storage options. An estimated 2700 Gt of global storage capacity is needed to meet global climate mitigation goals by 2100 [128]. While utilization and biotic storage may be an efficient use of CO_2, geologic sequestration of have the most potential for large scale storage because of the abundance of diverse storage sites and the ability to store large volumes of CO_2 at a single site. Potential storage formations include: depleted oil reservoirs, un-mineable coal seams, saline formations, depleted gas reservoirs, and hydrocarbon-bearing shale formations [129]. The abundance of formations available for sequestration makes geological storage the most feasible and economically viable. However, there are a multitude of limiting factors that govern the sustainability of injection storage both technically and socially [130]. In some locations, onshore storage has already been banned due to negative public perception [131].

Geologic storage of CO_2 in saline reservoirs and depleted oil and gas reservoirs represents the most impactful storage option based on volumetric capacity. Depleted oil and gas reservoirs are viable options for CO_2 storage due to the availability of data on subsurface intervals, existing infrastructure, and low initial pore pressure [132]. Low initial pore pressure means that when CO_2 is injected, high volumes can be injected before pore pressure reaches its original pressure, i.e., the reservoir's pressure before the commencement of oil and gas extraction. CO_2 injection into depleted oil and gas reservoirs can essentially restore the initial reservoir properties, reducing over-pressure and induced seismicity concerns. The drawback of pursuing injection operations in depleted oil and gas fields is that the same well penetrations that provide thorough subsurface characterization also represent potential leakage

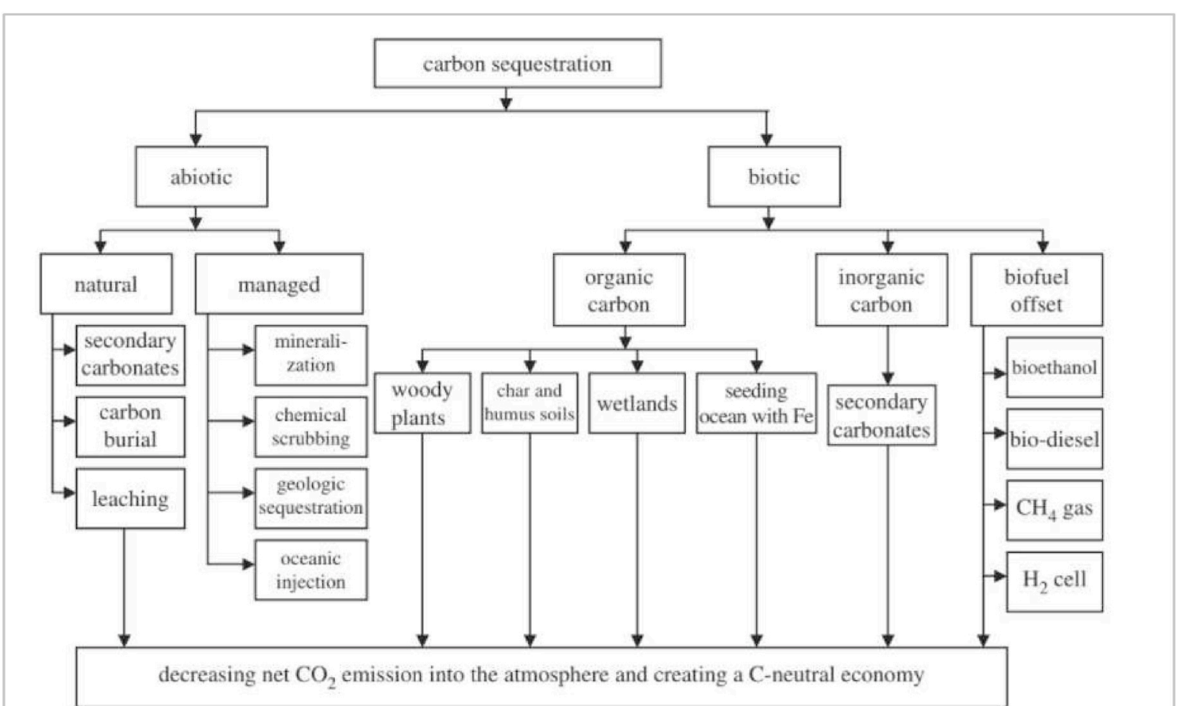

Fig. 29. Biotic and abiotic carbon sequestration pathways [67].

pathways. The more wells penetrations that exist, the more well-mitigation and monitoring will be required.

Saline reservoirs are another viable option for geologic storage, and often do not have the same issues with well-penetrations and potential leak points, although predictions on carbon behavior and transformation over time are critical to understand long term safety [133]. This presents a challenge to operators, as the subsurface is not as well-characterized without the availability of well data. Saline reservoirs exist across the world and in almost every sedimentary basin. The widespread availability of suitable saline reservoirs means that operators may be able to sequester CO_2 close to the source, limiting the need for long distance transportation [132]. Both depleted oil and gas fields and saline reservoirs represent viable options for long term CO_2 storage, and operators must weigh the risks and benefits of each in executing injection projects [134].

For CO_2 to be stored in a geological formation the injection interval must be permeable and porous, with sufficient capacity and connectivity so that the gaseous CO_2 can be injected at reasonable rates and volumes. The higher the porosity and permeability of the reservoir formation the higher the storage efficiency of the site. For continuous injection to be successful, monitoring of carbon purity, carbon phase shift, injection salt precipitation, and induced seismic activity must be constantly monitored. These porous intervals must be capped by a competent seal rock, that is impermeable, continuous across the anticipated plume area, and without through-going faults or fractures, to ensure containment of CO_2.

In the United States, operators must obtain a Class VI permit for CO_2 injection, that requires significant technical evidence and analysis proving beyond reasonable doubt that the identified storage locations will store CO_2 safely and permanently. To achieve this, operators must perform extensive baseline monitoring operations that characterize natural conditions before injection and have plans to monitor during and post-injection operations to demonstrate no detrimental deviation from this original baseline. One of the biggest concerns operators face is the management of pressure during injection. Understanding the geochemical reactions that might occur is critical, as rapid mineral precipitation in injection pathways can cause pore fluid pressure build-up leading to decreases of porosity and permeability up to 15% and 85% respectively [135]. Pressure buildups in the reservoir can initiate seismic activity and may threaten the seal integrity of CO_2 storage reservoirs [132].

In order to fully utilize the storage potential of saline and geologic reservoirs dynamic monitoring of injection rates and pressures must be used and must occur over long time frames with the use of multiple injection and monitoring sites [136]. Each site will possess unique complexities with as reservoir lithologies, CO_2 stream and brine chemistry, depths, temperatures, pressures, etc. Being unique to each individual site. Injection plans must reflect this complexity and will also need to be tailored to each individual project to ensure safe and efficient project execution [17].

High retention rates for the storage of CO_2 in geological reservoirs is vital to prevent associated global and local risks. In addition to being detrimental to mitigation efforts, leaked CO_2 poses potential risks to shallow aquifers of potable water and can add to negative perceptions of CCUS [137,138]. To ensure that carbon storage is successful retention rates must be 99.9% or greater, equating to a leakage rate of less than 0.01% per year [139,140]. There are several factors that can affect reservoir retention rates as retention is highly dependent on a range of geological, geochemical, and geotechnical factors previously discussed [139]. Trapping mechanisms and seal capacity are key to ensuring reliable CO_2 retention. CO_2 may be trapped physically in structural or stratigraphic traps, or chemically through mineral or solubility trapping. A viable reservoir will have a balance between ease of injection and trapping capability to ensure that the injection pathways are not also leakage pathways. Leakage rates are dependent on a host of highly complex factors like fracture permeability, fracture aperture, local stress field orientation, the dissolution and precipitation of minerals, host rock strength and permeability, the fluid type, fluid pressures and fluid flow rates [139]. The development of a portable, low-cost colorimetric CO2 sensor could help detect leakage points in soil to reduce associated geologic storage risks [141].

Carbonic anhydrases (CA) could play an important role in CO_2 storage stability. They are classified as a family of mostly zinc metalloenzymes that catalyze the reversible hydration of CO_2 to increase its thermal stability [127]. Recently, there has been industrial interest in utilizing CAs as biocatalysts for carbon storage for their capability to provide CO_2 stabilization and research in this field has accelerated [142]. The conditions for geologic storage result in high temperatures and acidic pHs that are unfavorable, resulting in rapid destabilization and loss of catalytic activity in CAs. This ultimately results in cost-inefficient and high-maintenance operations. Using engineered disulfide bonds can bring down the cost of industrial carbon, ensuring that the carbon dioxide remains stable during sequestration [142]. Current methods for CO_2 capture and storage are expensive and require large energy inputs, potentially negating the CO_2 removed from the atmosphere. Implementing CAs for stabilization could positively impact project efficiencies and economics and lead to more rapid and widespread deployment [127].

Mineral carbonation for carbon storage describes the process of mineral dissolution and subsequent carbonation of dissolved minerals (this process may be considered a method for both capture and storage of CO_2) [1]. There are several methods to achieve mineral carbonation, but to determine their efficacy in CO_2 storage it is important to assess the variables at play, such as input materials, additives, reaction pathways, reaction kinetics, and the associated costs [143]. One of the primary challenges facing the scalability and economics of mineral carbonation is the timeline required for the relevant kinetic processes to take place [143].

While geologic storage of CO_2 in subsurface reservoirs is the prevalent method for large volumes of carbon sequestration, the mineral carbonation process may play a role in this process. If injection sites are rich in alkaline minerals, kinetic reactions may occur that transform the injected CO_2 into stable mineral carbonates, ensuring permanent storage [143]. This is referred to in situ mineral carbonation. In situ carbonation naturally traps CO_2 through the formation of solid precipitates such as the spontaneous and exothermic reaction of CO_2 with calcium and magnesium oxides [144]. These processes can be targeted strategically as part of a subsurface CO_2 storage effort, not only trapping CO_2 in a structural or stratigraphic configuration, but through mineralization occurring in the reservoir on the surface of these minerals [144]. In situ carbonation should be considered for even large-scale geologic sequestration projects if appropriate conditions exist in the subsurface. With optimal pressure, temperature, and anticipated kinetic reaction rates, mineralization in the subsurface would only improve containment and reduce unanticipated plume migration risks.

Mineral carbonation can also be accomplished ex situ: via above-ground processes which requires mining and comminution of rock materials [37]. The primary hurdles for ex-situ mineral carbonation are the time intensity and expense of the carbonation process. The lack of recycling options for additives and by-products of the process also presents a challenge for large-scale feasibility [143]. There are considerable benefits of ensuring permanent and stable storage of CO_2 through mineral carbonation, though further advancements in efficiencies will be required to deploy this technology at scale. Each method of mineral carbonation is accompanied by its own unique challenges and benefits, as outlined in Table 5 [143].

With current capabilities and scalability, mineral carbonation has been proposed as a viable option for small and medium-sized emitters ($<$2.5 Mt CO_2) and in circumstances where transportation to viable geologic storage sites is impractical [37]. Mineral carbonation is an important tool to consider for carbon management not only because it generates permanent and stable storage but because it can address emitting facilities, such as fluidized bed combustion fly ash from coal plants, for which sequestration efforts would not be practical (either due to project scale or location) [156]. The utility of carbonate mineralization highlights the need to employ every tool available in achieving mitigation goals.

3.4. Options for carbon utilization

There are many opportunities for the utilization of purified CO_2. Options include biofuel synthesis, pharmaceutical manufacturing, fuel cell production, and enhanced oil recovery. Most utilization processes, however, are not economically feasible at scale. Currently, Enhanced Oil Recovery (EOR) is the most widely used application for captured carbon dioxide and is the most economic option for utilization. For most other industrial processes, it is easier and more cost-effective to synthesize carbon dioxide for a specific purpose than to utilize captured carbon that must be purified and transported prior to utilization. The improvement of capture and transport technologies is subsequently expanding industry wide utilization of carbon dioxide. The following sections detail areas where captured carbon dioxide can be used to supplement industrial processes.

3.4.1. Fertilizer

Application of synthetic fertilizers has greatly increased crop yield in the past century by providing limiting essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K). Common fertilizers include urea and ammonium nitrate, ammonium phosphate, and potassium chloride. Of these, urea, a nitrogen based fertilizer derived from ammonia, is the most common and generally requires 3 elements for synthesis: CO_2, H_2, and N_2 [157]. The CO_2 consumed in the synthesis is then rereleased when used in agriculture [158].

Fertilizer has helped grow industrial agriculture to support the planet's growing population and meet increased food demands, but synthetic fertilizer manufacturing also produces large amounts of GHG emissions. Conventional fertilizer synthesis processes rely on fossil fuels as an elemental feedstock and to meet energy requirements of synthesis reactions (Fig. 30) [159]. The amount of associated CO_2 ranges depending on the type of fertilizer produced and the feedstock used. Emission factor ranges for nitrogen and phosphorus fertilizer production are estimated at 1–10 kg CO_2-eq./kg of N and 1–1.5 kg CO_2-eq./kg of P_2O_5; potassium fertilizer production emissions have not been extensively studied [159]. Production of ammonia, the second most produced chemical in the world, accounted for 19% of global emissions in 2016 with an emission factor around 1830 kg CO_2 per tonne of ammonia produced [158]. Almost 50% of the population is estimated to be dependent on nitrogen fertilizers, so methods to decarbonize the fertilizer industry will be critical to meet emission goals without sacrificing crop production [159].

An investigative study on the oxy-fuel combustion of flue gases as an alternative CO_2 feedstock for urea production showed a possible method with technical and economic feasibility (Table 9) [157]. The results of the study estimated this process could produce 1.68 tons of urea per ton of CO_2. This would equate to 14,892 tons of CO_2 removed every year, making the produced urea worth close to 3.5 million US dollars [157]. An investigative study on the oxy-fuel combustion of flue gases as an alternative CO_2 feedstock for urea production showed a possible method with technical and economic feasibility (Table 9) [157]. The results of the study estimated this process could produce 1.68 tons of urea per ton of CO_2. This would equate to 14,892 tons of CO_2 removed every year, making the produced urea worth close to 3.5 million US dollars [157].

In addition to combining capture technologies with fertilizer production for emission reduction, emissions can also be mitigated in this sector with alternative fertilizers such as microbial proteins or manure [73,160,161]. Decreasing fertilizer use can decrease synthesis production emissions; however, it should be noted that proper application of fertilizer can improve soil fertility and increase natural biotic CO_2 capturing processes [160,162]. A case study on the capture rate of mulberry crop in China showed the carbon sink of photosynthesis was larger than the emissions associated with production, largely attributed to chemical fertilizer. Methods to decarbonize chemical fertilizer can help increase net carbon emissions without compromising

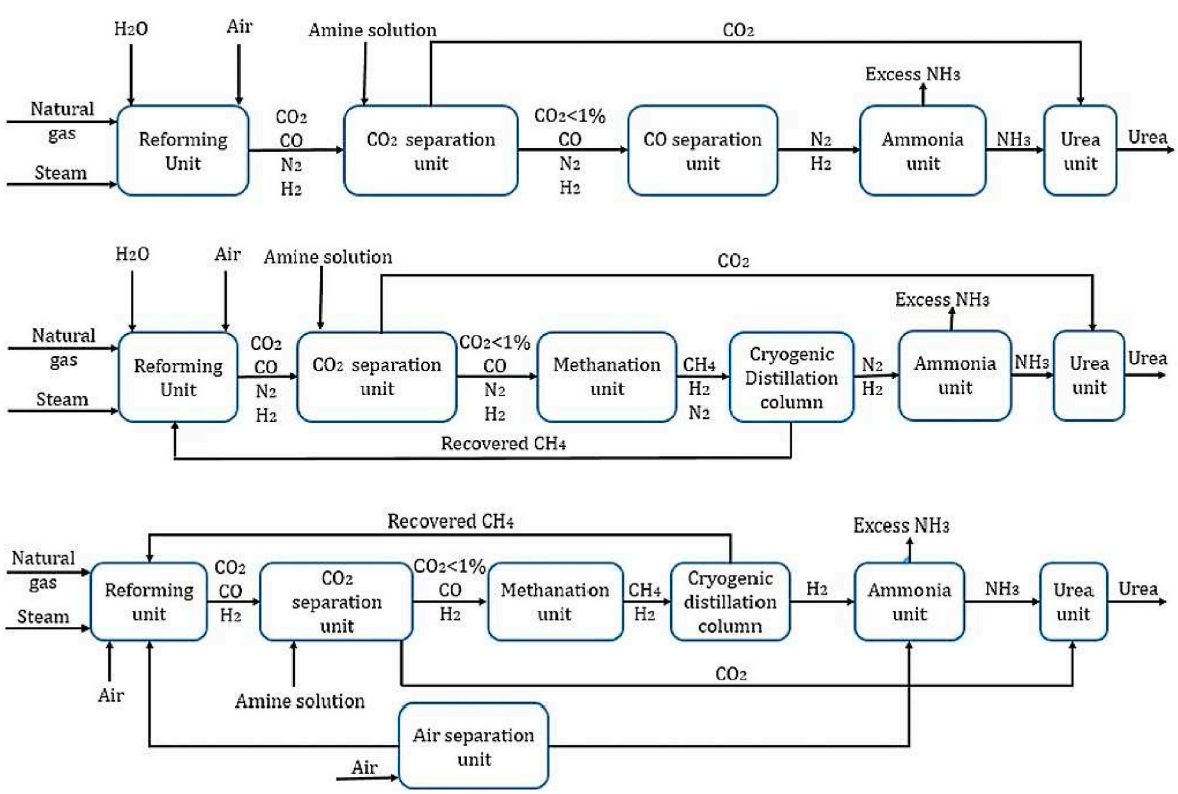

Fig. 30. Conventional processes used to produce urea, and nitrogen fertilizer [159].

Table 9
Products obtainable from typical flue gases, recreated from source [157].

Mass flow (kg/hr)	Flue Gas Specifications	Hydrogen Producible	Ammonia Producible	Urea Producible	Methanol Producible
Methanol	0	0	0	0	496.5
Urea	0	0	0	930.61	0
Ammonia	0	0	527.81	0	0
CO_2	1297.42	1297.42	1297.42	615.45	615.45
N_2	3938.64	3938.64	3504.54	3504.54	3938.64
O_2	253.97	997.75	997.75	997.75	997.75
H_2	0	93.71	0	0	0
H_2O	837.5	0	0	279.64	279.64
Ar	72.47	72.47	72.47	72.47	72.47

photosynthetic sink [160]. Other work has focused on how to achieve net-zero emissions of nitrogen fertilizers production using a combination of CCS, CCUS, biomass, and electrification routes [250].

3.4.2. Enhanced oil recovery (EOR)

Enhanced oil recovery is the process of injecting CO_2 into depleted oil or gas reservoirs to stimulate more production and extend the life of the field [163]. As CO_2 is injected into an oil-bearing zone, it displaces and mixes with the oil. The pressure of the producing intervals increases, and the viscosity of the oil decreases. This promotes increased capacity for extraction. While the operational aspects of EOR are similar to those of injection into a saline reservoir, not all CO_2 injected for EOR is stored in the reservoir. Some CO_2 remains trapped in the subsurface, but the ultimate goal of EOR is to recover higher volumes of oil and gas [104]. Emissions associated with the continued production of oil must be considered in the LCA of EOR to evaluate the effectiveness for CO_2 mitigation. The net CO_2 removal from this process should be reviewed for future policy development [164]. Fig. 31 shows the EOR process [17].

In general, the U.S. and global CO_2 reuse market is dominated by enhanced oil recovery primarily within the U.S. Permian basin, the majority of which is located in West Texas [112]. Though current demand stands at 62 $MtCO_2$ per year some estimates believe this number could rise to as high as 500 $MtCO_2$ per year [112]. A technoeconomic model indicated Recycle–CCS–EOR (RCE) projects could reduce carbon emissions by 54.7% more than traditional EOR, although economic feasibility is dependent on certain market variables [165]. Currently, the largest roadblock for increasing utilization is the lack of significant pathways for transportation (see section 3.2.1 on Pipeline Transportation). EOR is the most economically feasible option for utilization and thus is a primary focus for industry resources and expansion of operations. These EOR fields, once decommissioned, may be suitable for conversion to permanent storage sites [163].

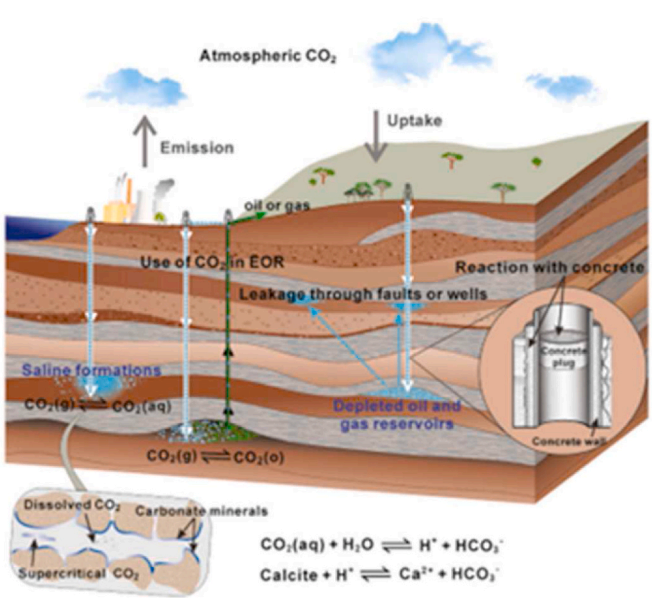

Fig. 31. Chemical reactions in geological storage and EOR from Ref. [15].

3.4.3. Fuel cells

Fuel cells are considered an effective method for CO_2 capturing and/or conversion. Solid oxide fuel cells (SOFCs), molten carbonate fuel cells (MCFCs), and microbial fuel cells (MFCs) demonstrated promising results in CC [166]. Molten carbonate fuel cells require carbon dioxide as input which complements CO_2 emitting systems meaning that MCFCs can be easily integrated into existing systems. Direct feed of the flue gases from industry and/or power plants can be fed to the cathode as a source of the CO_2 that is required for the completion of the reaction [166]. In such way, the CO_2 in the flue gases from the industry or the power plants will be separated and concentrated at the anode of the FC, and in turn can be captured and stored. The fuel cells create power and heat which can also be recovered for additional power. Output products from the fuel cell process can then be recycled back into the cyclic process in Fig. 32 [166]. This cyclic process also has numerous other potentially beneficial byproducts. Overall, fuel cells can be easily incorporated into existing processes and are a promising mechanism for future carbon utilization.

3.4.4. Biochar

The use of biochar for CCU could bridge the gap between CCUS goals and operations within the agricultural, urban, and industrial sectors [167]. Biochar is a biologically based charcoal that is produced from plant matter that can be stored in soil as a method to remove between 0.65 and 35 Gt CO_2-eq per year from the atmosphere globally [167,168]. In the process of producing biochar, CO_2 is captured with a biomass feedstock, such as macroalgae, and then converted to biochar through pyrolysis [169–171]. This process is considered one of the most economically available at both small and large scale, across income-levels, and with both low- and high-tech solutions. Biochar is especially adept because it has a good public perception across academic and public spheres as it is not only a route for carbon utilization but also a valuable product. See Fig. 33 for the potential pathways for biochar synthesis and utilization.

Biochar has been proven to increase crop yields, reduce GHG emissions from soils, and reduce environmental pollution as well as other industrial and urban applications like waste treatment [167]. The only issue with biochar is that there is no common framework for evaluating the overall CO_2 reduction and LCA effects. The range of CO_2 reduction varies widely and although this technology shows great potential with valuable products, there are still developments that need to happen before wide scale industrial application is possible. With further development biochar is a great area for continued development especially in rural areas with access to carbon supply as well as agricultural land.

3.4.5. Bioproducts via biomass

Biomass is a broad term to describe organic material, generally plants, containing chemical building blocks such as carbon and

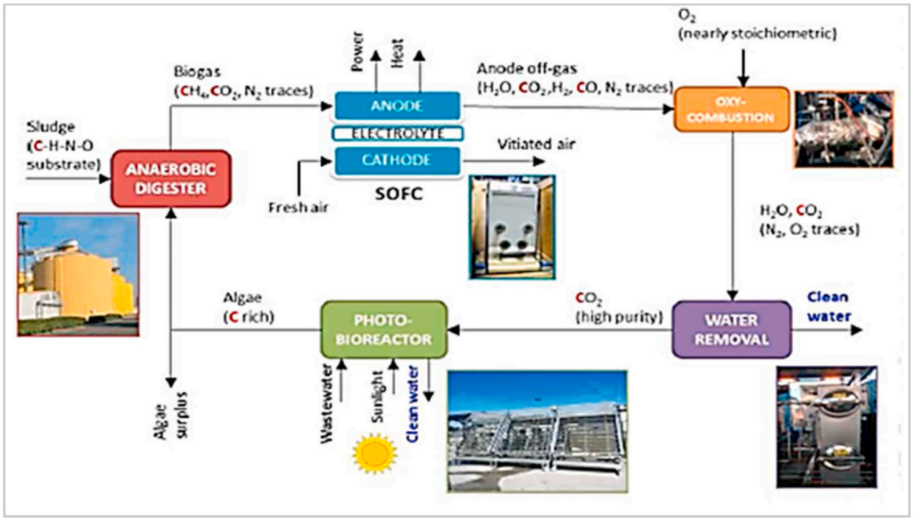

Fig. 32. Schematic chart of a SOFC–CHP plant [166].

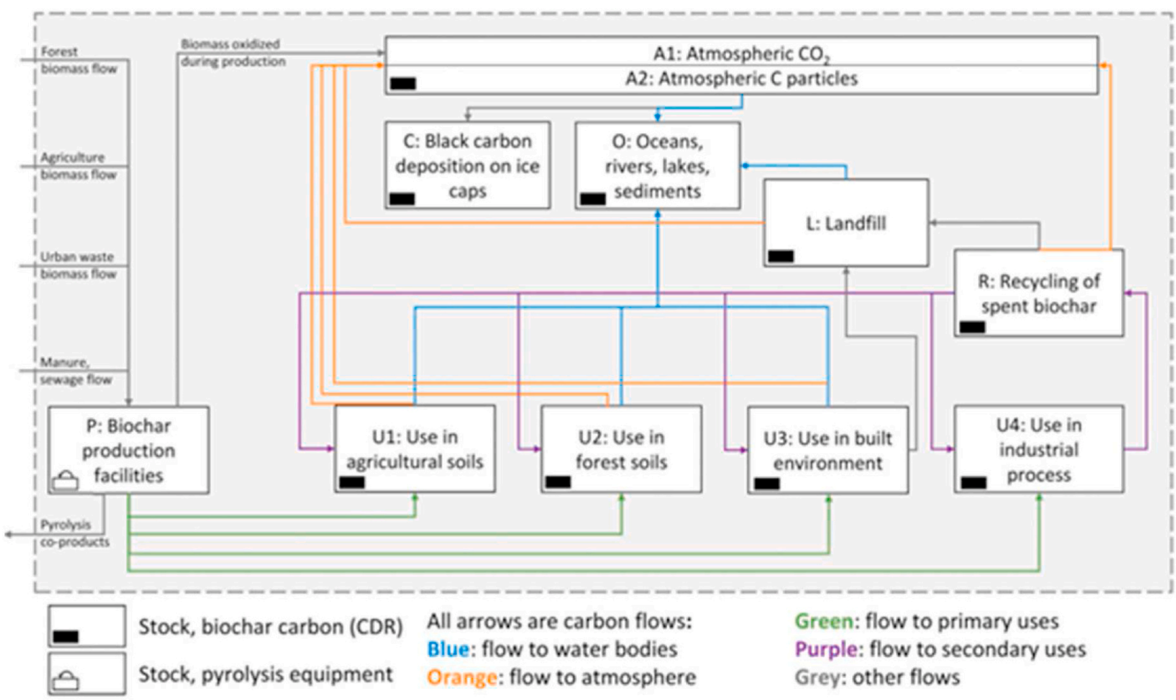

Fig. 33. Conceptual model for biochar accounting and utilization pathways [167].

hydrogen. While biomass is considered the most efficient CO_2 capture process, strategic utilization methods are required to prevent the re-release of capturing CO_2 and maintain relevance to CCUS [58]. Many different materials can be produced from biomass, such as those mentioned in Fig. 34 and Table 10 below [1]. From an industrial point of view, the most valued component of biomass are the lipids, and microalgae can accumulate high lipid content. Lipids are considered the raw material for the production of tertiary products such as biofuels, fuel additives, bioplastics, exopolysaccharides, biosurfactants, bio composite materials and lubricants (Table 10) [172]. Technological advancements indicate the possible utilization of bioenergy for bioelectricity to power microbial catalytic fuel production [173,174]. Algae is considered the most effective bioproduct feedstock pertaining to CCUS because it can capture CO_2 from ambient air, power plants, and soluble carbonate, while simultaneously producing large volumes of biomass, heavy in lipid content, with high market potential (Fig. 33) [13,71]. Most common strains of microalgae used for CCUS include *Chlorella, Dunaliella, Isochrysis, Nannochloris, Nannochloropsis, Neochloris, Phaeodactylum, Porphyridium*, and *Schizochytrium.* On average, lipid content of these strain range from 20 to 50%. Added controlled environmental stress, such as nitrogen deprivation, can help increase lipid content [72].

In general, products derived from photosynthetic processes provide a promising alternative to commercial processes to produce material that also captures carbon, has increased re-use potential, and can make sustainable improvements to the circular economy system; however, the application of biological capture and utilization at industrial scale for simultaneous utilization of CO_2 and production of bioproducts is still very challenging. For biomaterials, there are still issues with production due to lower biomass yield, biomass contamination, high maintenance and repair costs of biomass production infrastructure, and the cost of

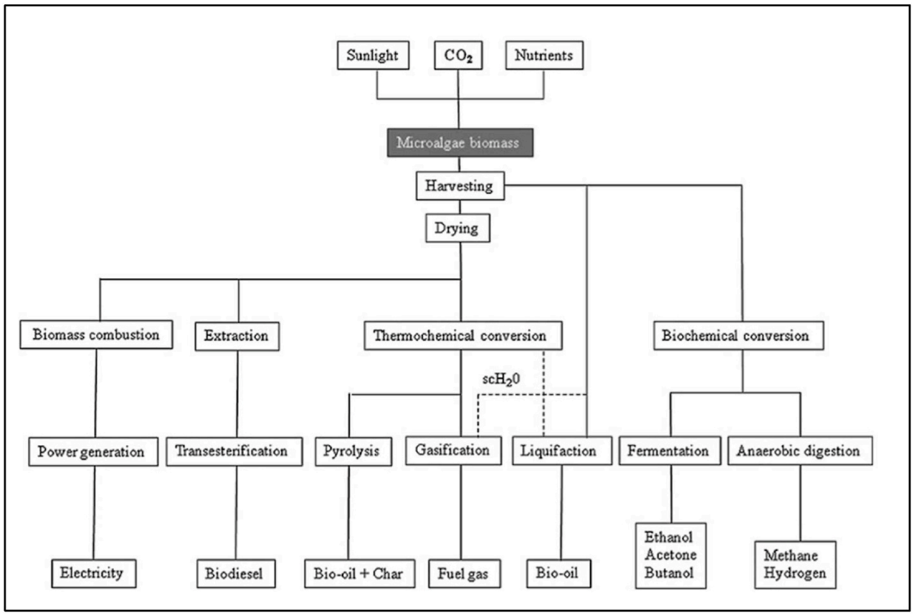

Fig. 34. The various utilization opportunities of microalgae biomass [1].

Table 10
Products of Biomass and their associated byproducts, recreated from Ref. [172].

Name of Products	Name of biomaterials	Organisms
Biofuel	Biodiesel	*Serratia* sp. *ISTD04*
	Biodiesel	*Ralstonia eutropha*
	Bioethanol	*Ralstonia eutropha* H16
	Isobutanol and 3-methyl-1-butanol	*Ralstonia eutropha H16*
	1-Butanol 1-propanol	*Clostridium tryobutyricum*
	1-Butanol, isobutanol, 2-methyl-1-butanol, and 3-methyl-1-butanol	*Clostridium acetobutylicum*
	Biogas	Methanothermobacter sp.
	Bioelectrochemical	*Clostridium ljungdahlii, Methanosarcina bakeri*
Bioplastic	Electromicrobial	*Ralstonia eutropha* H16
	Polyhydroxybutarate	*Ralstonia eutropha*
	Polyhydroxyvalerate	*Serratia* sp. ISTD04
	Polyhydroxybutarate	*Idonella* sp.
	Polyhydroxybutarate	*Haloarchaeal*
	Polyhydroxyalkanoates	*Serratia* sp. ISTVKR1
Biosurfactants	Biosurfactants	*Bacillus* sp. Strain ISTS2
Bio flocculant	Exopolysaccharides	*Bacillus* sp. SS105
	Exopolysaccharides	*Serratia* sp. ISTD04
Biochemicals	Methyl ketone	*Bacillus* sp. ISTVK1
	Succinyl-CoA, acetyl-CoA	*Ralstonia eutropha*
	(R)-3-hydroxybutyric acid (3HB), methyl ester of 3HB, crotonic acid, acetoacetic acid and 1,3-butanedio	*Autotrophic archaea*
		Ralstonia eutropha and anerobic archea
Bio composite materials	Calcite, aragonite, and vaterite	*Serratia* sp. ISTD04

harvesting and extracting materials from biomass [172]. For biogas and biofuel synthesis, there are also issues with the production process and using CO_2 for algae production [175,176]. The production of biomass requires a significant land footprint, significant capital expenses, and significant timely research and development resources for selecting preferable microalgae utilization pathways [175].

The creation of biofuels and biomaterials via biomass production from CO_2 is a significant development in the utilization of carbon for renewable fuel and material production, but there are still many issues to address with the processes before this utilization technique becomes economically and logistically feasible enough to replace hydrocarbon-based fuels and materials. An integrated biorefinery system, in which every component of the biomass is utilized, is considered the most promising economic option [72]. The creation of biofuels and biomaterials via biomass production from CO_2 is a significant development in the utilization of carbon for renewable fuel and material production, but there are still many issues to address with the processes before this utilization technique becomes economically and logistically feasible enough to replace hydrocarbon-based fuels and materials. The European Algae Biomass Association (EABA) predicted that the scale up of algae-based biofuel will not reach the industrial level for another 10–15 years [73].

3.4.6. Chemicals via compound manipulation

There are several recent studies assessing how to achieve net-zero emissions in the chemical industry using CCS or CCUS, electrification and biomass routes. This includes couplings to methanol [244], aviation fuels [245], plastics [246], and even bioplastics to generate negative emissions via CCUS [247].

Besides these couplings, CO_2 can also be used to create a variety of valuable chemicals. CO_2 can be treated as a compound for conversion to valuable products and chemicals under mild conditions. CO_2 can be used as a raw material to make polycarbonates and polyurethanes as well as for production of a diverse group of chemicals, but typically to transform CO_2 into useful agents the carbon and oxygen bonds must be manipulated [172]. Fig. 35 shows the most relevant chemicals that can be made from captured CO_2 [177]. Besides biofuels CO_2 can also be used to create a variety of valuable chemicals. CO_2 can be treated as a compound for conversion to valuable products and chemicals under mild conditions. CO_2 can be used as a raw material to make polycarbonates and polyurethanes as well as for production of a diverse group of chemicals, but typically to transform CO_2 into useful agents the carbon and oxygen bonds must be manipulated [172].

One of the most popular chemicals to synthesize from captured CO_2 is methanol [178–180]. The production of methanol is a key application of CO_2 to replace traditionally petrochemically based processes [181]. Overall, methanol production is the likeliest application of converted carbon but the production of n-propanol and carbon monoxide have the most economic value whereas production of formic acid has the greatest global warming mitigation potential and polyol production can have greatest environmental impact reduction [182,183]. The chemical

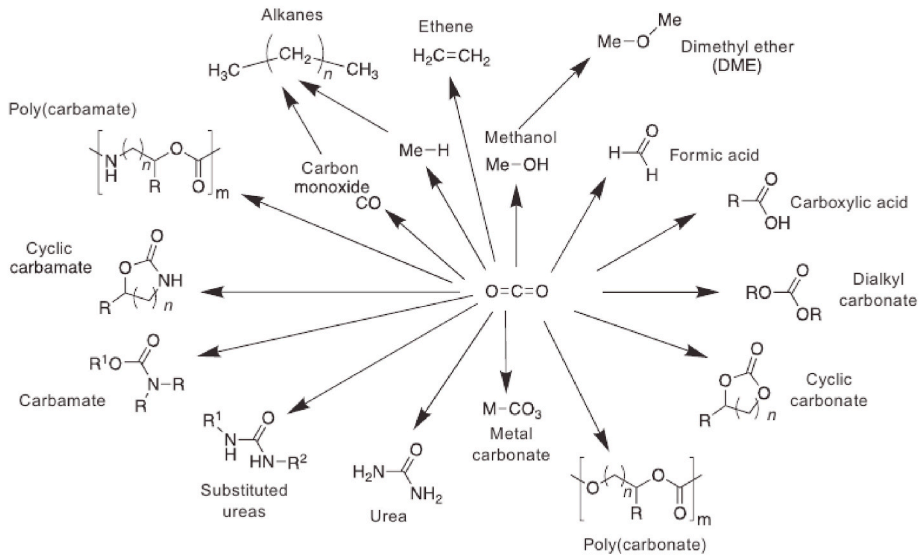

Fig. 35. Chemical products from CO_2 bond manipulation [177].

industry is expected to become the primary user of oil by 2030. Utilization efforts could reduce GHG emissions by 3.5 Gt CO2e per year by 2030, but this would require about 18 PWh of low-carbon electricity, which would consume more than half (55%) of projected electricity production in 2030 [184]. On a CO_2 emissions avoided/kWh basis, CCU technology is less efficient in reducing emissions than other uses of low-carbon electricity, such as electric vehicles and heat pumps. For this reason, it is preferable from a climate perspective to accelerate vehicle & building electrification and deploy CCUS in the chemical industry only after those demands are met [184].

3.4.7. *Polymers*

Common synthetic polymers such as polyethylene (PE), polypropylene (PP), polyurethane (PU), and polystyrene (PS) are made of a carbon and hydrogen. Currently, these polymers are produced using hydrocarbons petroleum, natural gas, and coal. The opportunity to utilize captured CO_2 in place of fossil fuels could displace significant number of emissions and offer CO_2 storage in renewable plastics [185].

3.4.8. *Miscellaneous products*

Although EOR, biofuels, and chemicals are the main sources of utilization for captured carbon there is potential for CO_2 utilization in other industrial processes. Carbon can be used to formulate calcite which can be used as a pigment for paint formulation, an acid-neutralizer (either as a stomach antacid or to neutralize acidic mining run-off), and to make cement and other building materials [127]. Although it does not pertain to industrial processes, CO_2 can also be utilized in medical applications. Carbonic anhydrase CO_2 responsive cationic hydrogels can be used to treat analgesic overdose [127]. With the addition of nitrogen bonds, captured carbon dioxide can be considered for organic compound synthesis for the pharmaceutical and agricultural sectors. The reaction of CO_2 and various amines can be utilized to produce a slurry of drugs, pre-drugs, and drug-intermediates as well as pesticides, insecticides, fungicides, and herbicides [172]. Purified carbon dioxide can even be used in the food and beverage industry to create carbonated drinks. These options for carbon utilization, however, are not implemented at a large scale and are not feasible for significant volumes of CO_2 utilization.

4. CCUS enablers and barriers, policy frameworks and social acceptance

4.1. *Enablers and barriers to CCUS*

This review has explored the technical components and considerations for CCUS, demonstrating that there is no one size fits all technical solution to managing carbon emissions. The same can be said for establishing policy that incentivizes the deployment of these technologies. Four primary pillars have been identified, critical to accelerating investment in CCUS: 1) predictable and enduring policy environment, 2) effective and comprehensive CCUS law and regulation, 3) early storage and site identification and site characterization, 4) research and development into cost reduction of CCUS technologies [186]. These four pillars, when not addressed appropriately, can also be viewed as the primary barriers to CCUS deployment, as nations will struggle without proper policy and regulation, site characterization, and insufficient R&D.

The success of national CCUS efforts will require stable, clear, and efficient regulatory frameworks and public support [187]. While the same guiding principles can be used globally, emission levels, dominant emission type, reduction commitments, available storage capacity, existing infrastructure, and public awareness that are unique to individual nations, will all influence the governing bodies political process surrounding carbon management [187]. The Global CCS Institute monitors the progress of CCS project deployment and uses this information, as well as policy, law and regulation, and storage resource development to rank nations on a "CCS Readiness Index.' Within the European Union, Germany scored the highest on this index, though still ranks lower than the United States, Canada, Norway, United Kingdom, and Australia. Circumstances surrounding emissions, economics, and policy for each of these nations, demands unique solutions to the various barriers to CCUS that are enumerated in the following sections.

4.1.1. *International cooperation*

Worldwide, there is great disparity between existing dominant power generation sources and the emission volumes in each country. The deployment of CCUS efforts also varies by region and by industry, as outlined in Fig. 36 [188]. The Kyoto Protocol described the need for developed countries to take the lead in emission reduction efforts given the level of historic emissions from these nations, and that sentiment has been repeated with the intention of maintaining environmental justice as part of expanding CCUS efforts [189].

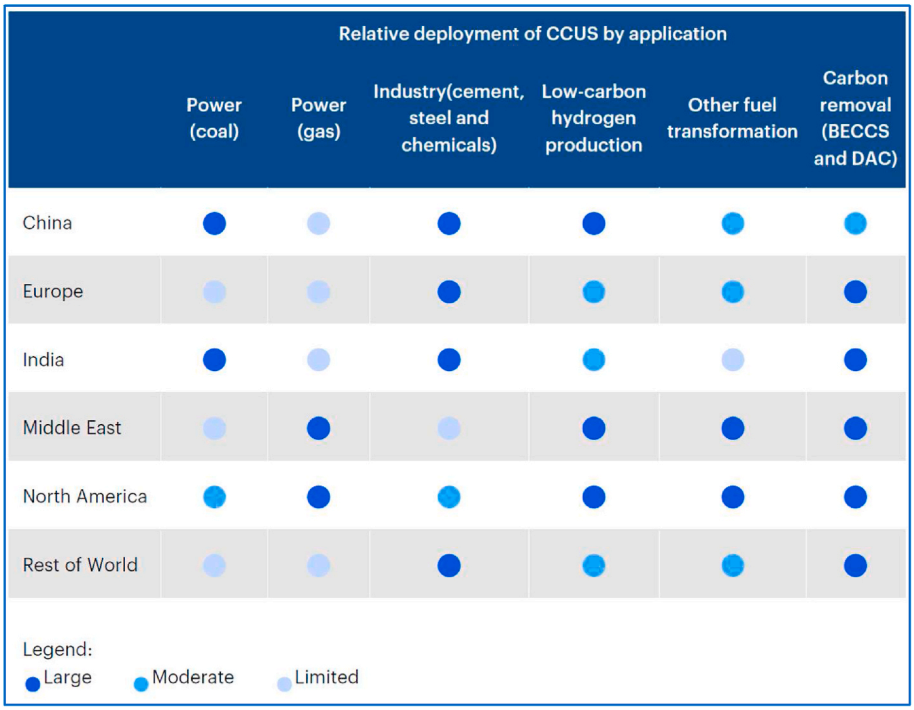

Fig. 36. Deployment of CCUS by country/region and application in the Sustainable Development Scenario [188].

While national and regional efforts are most common, the possibility of implementing unilateral policy solutions has been researched. Models of these unilateral policies have shown a resulting shift in the production of energy intensive goods to other goods and associated impacts on economic structures [189]. Competitive issues and other cross border externalities can decrease the effectiveness of these policies, and with the current political climate, global climate treaties are the best option to induce worldwide participation [189]. A continuing challenge is that policy incentives are most often regional, and trade is often global [190].

Different sectors of the economy will benefit more or less with the implementation of CCUS operations, with the two primary determining factors being the exposure of the commodity to international trade and the relative impact that these operations would have on production cost [190]. The results of these models also suggest that trade-off mechanisms between equity and efficiency with respect to allocating carbon emission reductions will be critical. While developed nations should take the lead on mitigation efforts, it is more efficient to pursue low-carbon solutions in developing countries that are actively building out their energy and industrial infrastructure.

Yet another economic challenge for CCUS that applies to operators globally is the lack of first-mover advantage [190]. Large scale demonstration and pilot projects are certainly a necessity with emerging fields with room for technological advancement. With CCUS specifically, there is little competitive benefit in being a first-mover and establishing these costly projects for the purposes of learning and demonstration, especially given the regulatory rigor required for most injection applications [190].

4.1.2. Available storage capacity and infrastructure

Global resources for the storage of anthropogenic CO_2 have been assessed over the past two decades, both in deep saline formations and reservoirs that might be utilized for enhanced oil recovery (EOR) [191]. Storage resources have been identified across a wide variety of geological formations, both onshore and offshore. There are some discrepancies between the way that these evaluations have been completed in the past and are often deemed 'storage' without consideration of non-technical issues surrounding land-use, ownership, and general

Table 11
Table showing the geologic storage capacity that has been documented worldwide and classification of the status and level of these estimates. Recreated from Ref. [186].

Country	Assessment Status	Est. Resource (GT CO_2)	Resource Level
Asia-Pacific			
Australia	Full	227–702	Effective
Bangladesh	Limited	20	Theoretical
China	Full	1573	Effective
India	Moderate	47–143	Theoretical
Indonesia	Moderate	1.4–2	Effective
Japan	Full	146	Effective
Korea	Full	100	Theoretical
Malaysia	Moderate	28	Effective
New Zealand	Moderate	16	Theoretical
Pakistan	Limited	32	Theoretical
Philippines	Limited	23	Theoretical
Sri Lanka	Limited	6	Theoretical
Thailand	Limited	10	Theoretical
Vietnam	Limited	12	Theoretical
Americas			
Brazil	Moderate	2030	Theoretical
Canada	Full	198–671	Effective
Mexico	Moderate	100	Theoretical
USA	Full	2367–21,200	Effective
Middle East			
Jordan	Limited	9	Theoretical
Saudi Arabia	Very Limited	5–30	Theoretical
UAE	Very Limited	5–25	Theoretical
Europe and Russia			
EU	Full	72	Theoretical
Norway	Full	82	Effective
Russia	Very Limited	6.8	Theoretical
UK	Full	78	Theoretical
Africa			
Algeria	Very Limited	10	Theoretical
Morocco	Limited	0.6	Theoretical
Mozambique	Moderate	2.7–229	Theoretical
South Africa	Moderate	162	Theoretical

legality that might make accessing subsurface storage difficult or impossible. Table 11 compares the results of an audit of individual nation's storage, both in volume, status, and vetting. The assessment status refers to the degree to which nations have undertaken sufficiently detailed analysis, while the resource level refers to whether the volumes reported take into account nontechnical limitations (effective) and those that do not consider any accessibility limitations (theoretical) [191].

A challenge closely related to geologic storage capacity is the transportation infrastructure. Limited storage options may mean that greater distances exist between emitting sources and sufficient storage reservoirs. The aforementioned options for transportation of CO_2 are accompanied by various challenges, limitations, risks, and expenses. Establishing new CO_2 infrastructure require a large capital investment; as such, government policy surrounding the financing of this critical need is expected to play a significant role [192]. Establishing new networks means increased risk of spills and leaks which must be closely monitored and regulated to prevent environmental damage or health risks to surrounding populations.

Public perception of pipelines changes in response to accidents, i.e. support for CO_2 pipeline development decreased in Belgium after a gas pipeline explosion in 2004 [193]. The stability of transportation infrastructure will be crucial to successful expansion of large scale CCUS development. One leak incident could completely alter the public perception and create hurdles for future projects. Safety regulations must be properly designed and regulated to ensure CO_2 is safely handled. Current regulations for natural gas transportation should be referenced to create an appropriate regulatory framework for CO_2 pipeline operation.

It is important that the original mission of CCUS, climate mitigation, is maintained throughout the transportation projects. Emissions associated with transporting CO_2 must not exceed the volume of CO_2 being transported. Ship carriers will be critical for initial large-scale development, but pipelines offer the most long-term cost benefits, lower energy requirements, and a lasting infrastructure. Government funding and incentives will expedite the development of pipeline infrastructure.

4.1.3. Public perception of CCUS

Public perception within the published literature can be broken into two categories: the individual or community perception of proximal project development that will directly impact their region, community, city, etc., and public opinion in a broader sense that would encompass collective awareness of CCUS, as well as support or opposition to the industry as a whole from individuals, governmental agencies, NGO's and non-profits, and private industry [7]. A survey conducted in the United States assesses awareness and public perception of the risks and benefits that individuals assign to CCUS. This effort concluded that while awareness of CCUS is extremely low, those who are aware of the process perceive the technology as beneficial [7]. For public support of policy specifically, this study found that in general, respondents were more likely to support a ban than subsidies or credits and that support for policy decreased with increasing costs and increased with strict minimum distances for project development near residential areas [7]. These observations regarding distance suggest that communities may oppose local CCUS development [7]. An important finding of this study is that in survey participants, overall perception of the benefit of CCUS technology was higher for those who already had some awareness of the technology. This and other potential correlative variables to perception are outlined in Table 12.

Table 12
Possible predictor characteristics of CCUS perception, recreated from [23].

	CCS Perceptions
Age	−0.006 (−0.007)
Gender	0.378 (−0.224)
Education	−0.142 (0.121)
Income	0.208** (0.063)
Urban/rural	−0.459** (0.162)
Partisan orientation	−0.155* (0.062)
Psychological distance	0.701** (0.241)
Previous CCS awareness	0.933** (0.292)
Constant	13.388*** (−0.805)
Observations	1511
R-squared	0.047

In the United States, public support for CCUS policies has been shown to be linked to several policy design features. Pianta et al. determined that bans on constructing new fossil fuel plants with no abatement measures have more support than subsidies for CCUS development and higher taxes for facilities with no abatement [7].

A similar survey performed in China demonstrated that previous knowledge of CCUS technology is correlated to positive perceptions [194]. This study noted that most respondents (44%) neither oppose nor support CCUS, but that of the remaining surveyed, several variables showed a correlation to positive or negative responses. Younger participants responded more positively than the older respondents, men responded more positively than women, and higher earners responded more positively than those with a lower income, however these relationships were not considered statistically significant when modeled. Surprisingly, there appeared to be a negative correlation between higher education levels attained and acceptance of CCUS technologies, which the authors acknowledge contradicts other published research [193].

In a very recent review of the state of CCUS in the context of carbon removal, i.e. when CCUS is coupled with Direct Air Capture or Bioenergy with Carbon Capture and Storage, Sovacool et al. [240] noted many public perception barriers. Most research focuses on only a small sample of countries such as Germany, the United States, and United Kingdom, raisin questions about its generalizability. Many studies have inquired only on prior familiarity or knowledge on of CCUS, DACCS, or BECCS and perceptions of and concern about climate change. Another notable limitation is that most literature focuses on attitudes of the public instead of intention or behavior. Furthermore, there is a need at comprehending not just the support or opposition for CCUS technologies in a broad sense but also their particular fit in different national or policy contexts as well as the particular concatenations of how they will be rolled-out and deployed.

4.2. Policy-driven solutions

Effective policy will influence an immerging industry such as CCUS in deployment, economics, national and international cooperation and in public perception. The range of applications of CCUS spans countless industries, regions, companies, etc. Making policy implementation challenging. This heterogeneity of industrial processes, emitting source characteristics, and industrial ties to international markets, must be accounted for in CCUS policy presenting unique challenges at the national and global level [195].

Despite a recent influx of funding directed towards R&D, federal and state subsidies, establishing of teams, initiatives, and start-ups, the current deployment levels of CCUS projects remains insufficient to reach global mitigation goals set by the Paris Climate Accord [7]. While there are certainly technical hurdles specific to each industry and each sequestration site, the most pressing challenges that this industry faces exist largely in the economic and policy realm. Research on the political feasibility of CCUS is less developed than that for technical application, though such research is just as important for an industry that needs to scale up rapidly [7,7]. This discrepancy is not unique to CCUS, but is a pattern throughout climate research where the majority of funding is directed to technical research, with only 0.12% spent on social science research [7].

Low and Honegger outline some potential issues for the way that climate change models incorporate carbon dioxide removal processes [196]. A primary concern is that the deployment projections for various carbon management technologies may be influencing present mitigation efforts. Entrenching certain carbon management infrastructures and operations into climate future projections also risks modeling bias towards the establishment of a carbon economy and away from the influence of renewables and mitigation efforts. This echoes a common critique of CCUS, that it will serve primarily as a crutch for fossil fuel producing and emitting industries to continue with business as usual, rather than transitioning to renewable energy. However, the unavoidable truth for critics is that renewables do not address existing levels of CO2 in the Earth's atmosphere or the most difficult to abate industries. No one technology will serve as a silver bullet to transition our energy system away from fossil fuels and to renewable energy, and all reasonable tools must be utilized to achieve the aggressive reduction goals set globally.

As this review has previously outlined, CCUS project economics are challenging, and technological advancements in capture efficiencies stand to impact capital efficiency. Consequently, dedicated support for research and development for is critical. Incorporating CO2 capture for a multitude of industrial processes presents a significant challenge due to changing technical parameters and conditions for capture depending on changing chemical and physical properties of outputs and associated capture efficiencies [195]. Retrofitting existing infrastructure for capture purposes is expensive, potentially disruptive to industrial processes, and comes with a large energy 'penalty' (the energy required to power capture operations).

As a commodity, CO2 does not possess sufficient intrinsic value in today's market to generate economic projects without subsidies. As noted in Ref. [242], most markets around the world treat carbon as a simple waste product, but with a limited scope of cascading uses or values. In many cases, such as the United States, carbon has no price nationally. As such, carbon needs to be treated, and adequately priced, as a pollutant—in order to reduce its occurrence and to encourage its removal. But the history of pollution control suggests that waste removal must be treated as a public good, or it will not occur. Carbon must be priced to provide a signal to markets and encourage innovation, upscaling, and economies of scale—such activities and aims must be underpinned by strong government funding, incentives, and regulation. As a promising sign, in 2022, voluntary carbon markets began differentiating by type of activity or offset and gave the most value to carbon removal projects. The average carbon credit price for carbon removal (about \$20 per ton) was more than twice that for nature-based removal (\$10) and about four-times more than renewable energy (about \$5 per ton) [242].

But for the most part, much of the value assigned to carbon has thus far been the result of policies incentivizing mitigation of emissions or penalizing excess emissions. While we can compare a hypothetical carbon economy or carbon credits to the way that renewable energy measures such as home solar was incentivized through programs across the globe, there are important differences. Other than for use in limited industrial applications and enhanced oil recovery operations (EOR), CO2 does not represent economic opportunity for operators or for consumers, without established subsidies. Even the implementation of renewables which may represent long-term cost savings required stimulus for adoption, to offset disproportionate up-front costs.

The primary policy tools for incentivizing and supporting CCUS are outlined in Table 13 and include grant support, operational subsidies, carbon price establishment, demand-side adjustments, specific market mechanisms, regulatory standards, risk mitigation measures, and targeted funding for R&D.

4.2.1. Grants and subsidies

Policies that allocate funding through grant support are relatively straight forward. Grants most often provide funding directly to projects or specific programs, usually to overcome high up-front costs. Government programs center around pilot and demonstration (P&D) projects and research and development demonstration (R&D) projects, and are usually awarded through particular funding agencies and a competitive proposal analysis processes [197]. CCUS has seen a recent influx of grant funding for various P&D and R&D projects, but is still off-track in deployment levels [197,198]. Which continues to encourage technological advancements that will bolster the industry. Nations within the EU for instance, have relied on grant funding through agencies such as the Innovation Fund (subsequently discussed in more detail).

Nations like the United States and the United Kingdom, while still allocating significant funds through grants have also relied on operational subsidies to incentivize action in the CCUS industry. Operational subsidies refers to several different mechanisms which include tax credits for CO_2 captured, stored, or utilized, contracts for difference that cover the cost differentials between production costs and market price, feed-in-tariff mechanisms that provide long term contracts with energy producers, and cost-plus open book mechanisms in which governments reimburse certain costs as they are incurred [188]. The 45Q tax credit within the United States gives operators a tax rebate for each ton of CO_2 sequestered. This places value on CO_2 as a commodity and enhances project economics.

Table 13
Primary policy tools for incentivizing and supporting CCUS,modified from ETP special report on CCUS, 2020 [188].

Category	Examples
Grant support	• UK CCUS infrastructure fund • EU Innovation Fund
Operational Subsidies	• US 45Q tax credit • Netherlands SDE++ scheme • UK power sector CfD arrangements
Carbon Pricing	• Norway carbon tax on offshore oil and gas • European ETS • China ETS • Canada federal Output-Based Pricing System
Demand side measures	• Canada and Netherlands have rules favoring low emissions material for construction projects • Several jurisdiction plan to purchase concrete cured using CO2 (US, Canada, EU) • EU Carbon Border Tax (proposed)
Regulatory Standards and Obligations	• EU Renewable Energy Directive • Australia-Gorgon LNG project CCS required • UK energy and infrastructure markets employ a regulated asset base model • Limits on allowable CO2 intensity from coal and natural gas power generation in Canada
Risk Mitigation Measures	• Australian legislation allowing transfer of CO2 liability to the state
Innovation and R&D	• Canada/US Carbon XPRIZE • EUR Horizon 2020 • US Department of Energy CCUS Programs

4.2.2. Carbon pricing and market mechanisms

Establishing carbon pricing takes a very different approach than grants and subsidies, as it penalizes inaction rather than rewarding action. Further, carbon prices required to incentivize the investments needed for elimination of 95% or more of carbon emissions from industries like steel, cement and chemicals requires are, in most cases, far greater today than carbon prices that are in place (Fig. 37).

Emissions trading systems (ETSs), sometimes referred to as 'cap and trade' attempts to both cap emissions and allow for trading emission certificates or credits [188]. Currently, the impact of ETSs on promoting CCUS projects has been modest. This is mostly due to low carbon prices in most countries and significant uncertainty for state and regional carbon markets [197]. However, allowing for the purchase or trade of certificates such as fuel standards that favor low-carbon fuels and carbon credits that are based on verified volumes of CO_2 permanently stored, may prove to be an effective funding mechanism in the future. While these have been deployed with varying success, a strict and consistent regulatory framework that appropriately accounts for these credits from inception through transfers would bolster this market mechanism.

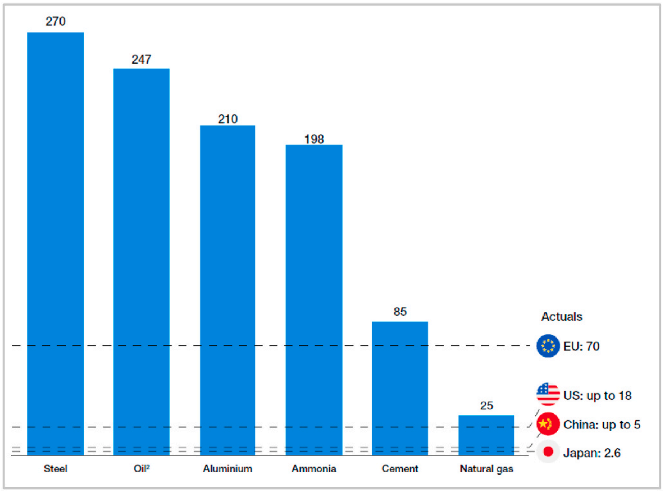

Fig. 37. Carbon price required to stimulate investment in industrial decarbonization vs. actual carbon prices ($/t$CO_2$e). Based on estimated carbon price necessary to make 'low emission' product prices competitive with traditional product prices. [2]Refers to refined petroleum products [199].

Some studies have made the case that technologies in the CCUS space, such as direct air capture (DAC) will only be successful deployed at scale with policy measures. Incentivizing private investment through policy and regulation is crucial for these technologies that cannot rely on strong market leverage. This can be said not only about DAC but about CCUS as an industry [48]. While a transition to renewable energy sources offers some economic benefits to individuals and corporate entities, the same natural incentives don't exist for high cost technologies like DAC without other financial mechanisms [48].

4.2.3. *Demand-side measures and regulation*

Demand-side measures refers to public procurement of resources that were generated through low-CO_2 processes. An example would be policy that dictates utilities only buy power that was generated at facilities implementing capture and storage of CO_2. Regulation of the production of goods to meet certain emission standards is another way to curtail emissions in the manufacturing industry. At a national level, tariffs may be imposed on goods or energy imports depending on their carbon footprint.

Demand side management in power generation can utilize direct or indirect methods of changing consumption patterns and behaviors, but ultimately aims to benefit the overall network by adjusting demand response, energy efficiency, and strategic load growth [200]. For industries with the most difficult to abate carbon emissions, such as steel manufacturing, incorporating demand-side measures in conjunction with supply-side adjustments will entail less radical reduction measures for both sides, and likely achieve emission reduction targets more quickly [201].

4.2.4. *Measures for risk mitigation*

Regulatory and legal regimes vary significantly around the world, due to economic, political, and cultural differences [202] In many instances, CCUS projects are challenged by operational and legal ambiguity. In some cases, these issues stem from uncertainty surrounding the ownership of pore space and the various surface use, right-of-way, and mineral resource issues related to how these rights are established and enforced. In the United States, these issues are decided at the state level, and depending on the state's history of fossil fuel production there may or may not be any language regarding pore space and its association with either surface estates or mineral estates [203]. This basic designation must be made before further legal issues, such as the ability to sever pore space rights from the surface or mineral estates can be decided. Most jurisdictions have not decided this, and therefore have no rule as to who grants operators sequestration rights [204] Clear policy regarding land-use and pore space rights will relieve this ambiguity for operators in a fundamental way, and will likely require state level legislation [205].

These issues are not unique to the US, in fact several issues are prevalent worldwide, that include: 1) the lack of an internationally standardized regulation framework on permitting, and management standards 2) no phased goals for CCUS deployment in regulations, specific emissions reduction targets or standardized volumetric validation methods and 3) no clear provision on liability allocation and transfer for each party within the CCUS chain, or long term insurance and accountability [202]. Project insurability is a significant hurdle to operators, as CCUS projects suffer from a lack of familiarity on the part of insuring entities and lack of precedent [206]. These projects are also unique in duration, with injection timelines often spanning several decades, and then monitoring operations expected to continue indefinitely. This introduces the added risk of regulatory requirement changing over time [206]. Despite leakage risk being minimal, operators are also required to provide financial security funds for potential remediation efforts, if containment fails.

The uncertainty introduced with these issues makes the risk difficult to quantify, and therefore difficult to insure [206]. Risk assessment studies have discussed the need for consistent decision-making models, providing project stakeholders with consistent risk and uncertainty characterization [207]. The heterogeneity of these projects makes this a challenging prospect. While developments such as the Leakage Impact Valuation (LIV) method, can be applied to address the impact of a leak, there is yet no system for categorically evaluating full cycle risk for CCUS projects [208]. Policy measures that subsidize insurance premiums, guarantee long-term stewardship through governing bodies, and sharing mechanisms that allow partners to share project risk, may help alleviate the burden of these risks.

4.3. *National and international frameworks for CCUS*

Until recently, much of the CCUS specific policy in countries like the US, Australia, and China was focused around coal-generated power [195]. This has shifted in recent years, with countries making mitigation pledges in accordance with the goals set through the Paris Climate Accord. It has been widely recognized that delaying or postponing the deployment of CDR technologies such as CCUS, is anticipated to not only impede individual nation's ability to achieve carbon neutrality but also increase removal cost with negative economic impacts [209].

4.3.1. *Northern Europe & UK*

Northern European countries are large consumers of power and heat, and therefore have a unique opportunity to integrate carbon capture technologies with these heat and power generating facilities [210]. Like its neighbors, Finland has opportunities across multiple industries to employ carbon reduction modifications to existing systems, though the nation faces challenges with a lack of suitable geologic storage options. In situations where capture is employed but storage is absent, exports of CO2 must be considered, significantly complicating the logistics, economics, and policy surrounding carbon management efforts. In a study on CCUS feasibility in Finland, Kouri et al. outlined the three major factors in any given facilities cost efficiency as 1) the size of the facility 2) the industrial sector or type of facility, and 3) the location of the facility [210]. This is particularly important when ship transport is likely the most viable option.

As part of the Paris Climate Agreement, the UK committed to reduce greenhouse gas emissions to net-zero by 2050. Governing agencies and policymakers have identified CCUS as a tool that should be implemented to support industrial decarbonization [211]. A fundamental challenge for industrial CCUS deployment in the United Kingdom is a concern that introducing new expensive capital requirements will not enable these industries to retain competitiveness [211]. With this challenge in mind, the UK has been especially focused on deploying technologies that co-locate large scale facilities for power generation and distribution, oil refining and product generation, and other industrial operations. This 'place-based-approach' to emissions mitigation often refers to these projects as industrial clusters [212]. The significant advantage of addressing decarbonization for these industrial clusters is cost-savings for initial infrastructure deployment due to proximity and the ability to utilize the existing workforce and regional expertise.

The UK has become a leader in climate mitigation as it has substantially reduced its greenhouse gas emissions since the 1990s, and since the mid-2010s, policymakers have increased their attention on industrial decarbonization, advocating for CCUS [213]. CCUS is the subject of an 'Action Plan' and Industrial Cluster Mission that commits to establishing at least one low carbon cluster by 2030 and the world's first net-zero industrial cluster by 2040 [211,214]. In 2020, the UK issued a '10 Point Plan for a Green Industrial Revolution' that discussed these industrial clusters (calling them 'SuperPlaces'), and highlighting the importance of addressing these with two key technologies, hydrogen and CCUS [212,215]. These policy documents also highlight the locations of primary industrial clusters: Teesside, the Humber, Merseyside, North Wales and the North East of Scotland [212].

No discussion of carbon injection projects in northern Europe would be complete without mention of the Sleipner field in the North Sea. This was the world's first commercial CO_2 storage project, with injection operations beginning in 1996. CO_2 is removed from the natural gas produced from the Sleipner West field, and injected into a deep saline reservoir 800–1000 m below the sea floor [216]. Notably, it is the first example of a CO_2 storage project arising from environmental legislation [216]. The motivation for this effort was the Norwegian offshore CO_2 tax, which in 1996 amounted to $50/ton of CO_2 emitted [217]. With Sleipner field's production rates, this penalty would have equated to $50 million/year. The capital investment in compression and injection infrastructure totaled close to $80 million, meaning that this investment paid off in less than 2 years [217].

The Sleipner project is a successful example of both environmental policy and the technology utilized in capture, injection, and long-term monitoring. The Sleipner field has been extensively researched and much has been learned regarding the CO_2 plume movement and our ability to apply seismic technology to monitoring the deep subsurface [218–220].

4.3.2. Western Europe

The European Union (EU) has been influential in crafting international climate policy and was instrumental in forming the Paris Climate Agreement. The EU has proposed a legally binding climate-neutrality target for the year 2050, but like most agencies who have similar targets, has yet to establish clear processes or steps to achieve this goal [209]. EU member nations do not all agree on the best method for accomplishing aggressive GHG emissions reduction, and while CDR strategies have been identified as a critical tool, specific measures have yet to be defined [209].

The EU Emissions Trading System (ETS) encompasses most major industrial emitters and covers around 45% of all GHG emissions in Europe [221]. However, there are significant complications in accounting for emissions and allowances both within and external to the industrial sector. Utilization technologies that turn CO2 into a substance to be used within another application only account for the emission savings from the original source. The regulatory framework may allow for the transfer of emissions or emission credits, and can have an impact on the accounting of emissions, incentivizing or disincentivizing different stakeholders [221]. Progress in the industry was stagnated even with policy implementation, due to insufficient incentives for project deployment. The EU implemented an emissions trading scheme (ETS) that in 2012 was worth less than 10 Euros per ton of CO2 sequestered, not covering the expense of full cycle projects [195].

While global geologic capacity has been deemed sufficient to meet CO2 storage targets, for a densely populated EU, there is a concern for bottlenecks for storage sites if all existing fossil fuel power plants are retrofitted for CCUS, rather than transitioning to renewable power generation. The ideal energy transition would see a combination of both, and the existing policies that incentivize power plant conversion for CCUS will at the very least be critical in the development of transportation and storage infrastructure [209].

Individual nations have established their own incentive structures for CO2 removal projects and the European Union has several overarching funding mechanisms.

- The Innovation Fund: dedicates over EUR 25 billion (depending on the price of carbon) over ten years for research and development of carbon capture, use and storage technologies, and in the field of renewable energy, energy-intensive industries, and energy storage.
- Connecting Europe Facility (CEF): supports cross-border CO2 transportation networks
- The Recovery and Resilience Facility (RRF): aims to mitigate the economic and social impacts of Covid-19 pandemic through investments in flagship areas such as clean technologies and renewables (such as CCS and CCU)
- The Just Transition Fund (JTF): provides support to territories facing socio-economic challenges arising from the transition towards climate neutrality
- Horizon Europe: supports research, pilot and small-scale demonstration projects related to CCUS [222].

The EU represents a unique case for the deployment and scaling of CCUS technologies with its leadership in setting international climate targets, the combination of multiple unique national incentivizing programs, and the overarching incentives set by the union. The EU's historic leadership in climate change conversations and action makes its successful and immediate action even more critical, encouraging other nations to follow-suit and proving that these aggressive targets are attainable.

4.3.3. United States

In the United States, political action surrounding CCUS began in earnest in 1997 with DOE funding allocated towards R&D for CCUS. In 2008, the 45Q tax credit was established, providing $20 per ton of CO_2 captured and permanently sequestered. Soon after the American Recovery and Reinvestment Act (ARRA) allocated $3.4 billion for CCUS demonstration projects in 2009. There was a hiatus in both incentivizing policy and operator interest in CCUS project investment until 2018 when the 45Q tax credit was revamped to provide $50/ton of CO_2 sequestered. This marks the beginning of increased interest and activity surrounding CCUS in the United States that is ongoing. Further progress was made in 2020 with the Energy Act, authorizing $7 billion for carbon management over the next five years and most recently, the Bipartisan Infrastructure Law that allocates $12 Billion to CCUS technologies. This incremental progress has tracked with increasingly aggressive greenhouse gas reduction targets and carbon neutrality commitments being set by both private industry and government agencies.

Several legislative proposals introduced in 2021 aim to increase the economic viability of CCUS by modifying the 45Q tax credit from $50/Mt to $85/Mt for pure storage of CO_2 and from $30/Mt to $60/Mt for CO_2 utilized for EOR. In addition to federal funding and tax credits, in February of 2022 the White House Council on Environmental Quality (CEQ) delivered new guidance "to help ensure that the advancements of Carbon Capture, Utilization, and Storage technologies is done in a responsible manner that incorporates the input of communities and reflects the best available science" [223]. It is difficult to find a publicly traded company in the US that has not set carbon-reduction targets, and companies such as Exxon, Shell, Petrobras, Occidental, Chevron, Mitsubishi and many more have dedicated CCUS teams. Still more start-ups have been established with the express goal of capturing and sequestering CO_2.

US oil and gas companies have been injecting CO_2 into the subsurface since the 1970's, highlighting once again that the challenge is less technical in nature, but rather lies in the policy and economic space. Federal incentives for capturing and sequestering CO_2 are primarily manifested through the 45Q tax credit. Operators qualify for this federal tax credit, only by obtaining a Class VI permit for injecting CO_2 into the subsurface, regulated by the Environmental Protection Agency (EPA). The regulatory hurdles for obtaining a Class VI permit are rigorous, and as of the time of publication, the EPA lists only two approved permits with another fifteen that are pending approval.

4.3.4. China

China is one of the fastest developing economies in the world and is heavily dependent on energy generation through fossil fuel combustion. As a nation, it ranks first of the world's top economies in terms of CO_2 emissions from fuel combustion [137]. China has projected they will reach peak carbon emissions by 2030 and achieve carbon neutrality by 2060, though the sheer scale of the current fossil fuel infrastructure and anticipated industrial growth will make this a significant challenge. CCUS represents a practical approach for the many coal-fired power reliant industries in China such as chemicals, cement, steel, iron, and refining [137]. China boasts both a skilled workforce and lower labor costs, as well as the ability to execute infrastructure projects quickly.

China faces similar hurdles to large scale deployment of CCUS as do other nations: inexperience in operating CCUS projects, technical hurdles surrounding storage risk, and insufficient policy or financial support to create economic projects [137]. The status of oil and gas development in China may be optimal for the application of EOR, allowing market mechanisms to drive implementation. The National Development and Reform Commission (NDRC) of China, issued guidance on achieving peak CO2 emissions in 2030 and neutrality by 2060, highlighting the need for research and development in low carbon technologies, upgrading existing industrial infrastructure, curbing the expansion of high-emission projects, improving energy efficiency and conservation, and improving laws, regulations, and policy mechanisms (NDRC.gov.cn). This guidance is high-level and largely qualitative, describing aspirations of increased government investment and financing systems tailored to mitigation goals, without any specific policy mechanism defined.

China is an integral part of the global economy, accounting for 40% of world steel production alone [224]. Natural coal reserves and the existing energy grid in China means that CCUS will be a critical tool for the nation's mitigation efforts, and for their ability to maintain economic growth, social stability, and international relations while working towards carbon neutrality. China faces similar challenges as other nations, though the sheer scale of their industrial processes means that widespread deployment of carbon reduction technologies will need to advance rapidly and without delay.

4.4. Geopolitics and international trade

Moreso than at any time in the past, today's economies and societies are inextricably connected on a global scale. This introduces both complications and opportunities for international markets and industries in the emerging carbon management space. Incentives and penalties are often set at a national level, but international cooperation will be critical to optimize the strengths of certain areas and overcome weaknesses of others. Tariffs, cost of emissions, and a hypothetical carbon tax, could incentivize international cooperation on emission mitigation, though the ever-present challenge consistency and transparency in accounting and verification persists.

As developed nations frame policy around aggressive global and national mitigation targets, it cannot be at the expense of developing nations that currently rely on fossil fuel combustion processes to generate energy. The growing global population and increasing standard of living worldwide means ever-growing energy demands. Production based countries, such as China and India, have not been able to reduce emissions as easily partly because many consumer-based developed countries offload emissions overseas. Hence, of particular importance are Carbon Border Adjustments (CBA), such as those proposed by the EU, to stimulate the reduction of emissions embodied in industrial products, like steel and refined fuels, that are traded across borders.

International cooperation requires that each nation's individual drivers for pursuing CCUS be considered. Policies involving environmental regulations generally address: 1) air quality and air pollution (local issues), 2) climate change (global issue), and 3) security of energy supply (regional and national strategic issue) [225]. The latter has proven to be the most politically catalyzing issue and trumps emissions concerns in severe cases. Implementing CCUS at the scale that is being proposed by the IEA, will challenge international relationships with different policy, regulatory, and legal frameworks [225]. Table 14 captures the disparity between emissions and current mitigation via CCUS, even for the most proactive nations.

The balance of energy politics is likely to change as the world shifts to low carbon energy sources. It is anticipated that supply-side geopolitics will be less influential than during the fossil fuel era, with a higher global need for access to technology, power transmission infrastructure, rare earth minerals, carbon storage capacity etc. However current global dynamics are unlikely to change in the near future and changing drivers will influence each nation's ability to achieve global mitigation targets.

4.5. Considerations for future analysis of CCUS systems

Our review has not only identified concurrent themes emergent from the literature, it also points the way towards future analyses, which situate CCUS technologies in a broader context of complimentary as well as competing technologies such as wind and solar or green hydrogen.

One notable gap, implicitly evident in Section 4.1, is the technical nature of most CCUS research. The literature covered in our systematic review on CCUS is not as intently focused on environmental and social aspects as it is technical aspects, with only a handful of studies included in our corpus examining non-technical elements.

This gap has an empirical dimension but also a conceptual one. Emerging technological fields such as CCUS can be analyzed with different conceptual frameworks. Often, *socio-technical* approaches are chosen to capture the societal, institutional, organizational, and political aspects that play into technology development next to techno-economic characteristics. *Socio-technical systems* approaches go even a step further, highlighting that the different dimensions interact and co-evolve over time, potentially even causing cumulative effects [226,227]. For example, policy support might stimulate diffusion, which improves technology performance and lowers costs, thereby further stimulating diffusion. Such dynamics might then require an adaptation of policies (e.g., to address unwanted developments). Hoppmann and colleagues show

Table 14
Global CCS Projects in Operation in 2020 (Data from the Global CCS Institute, Emissions data from Global Carbon Atlas).

Country	Current CO_2 Storage (Mtpa)	Current CO_2 Emissions (Gtpa)	Percent of CO_2 Emissions stored
USA	21.94	5.285	0.42
Australia	4	0.411	0.97
Norway	1.7	0.042	4.05
China	0.82	10.175	0.01
Qatar	2.1	0.109	1.93
UAE	0.8	0.191	0.42
Saudi Arabia	0.8	0.582	0.14
Brazil	4.6	0.466	0.99
Canada	3.9	0.577	0.68
Total	40.66	26.384	0.15

how these co-evolutionary processes of technology development and policy changes unfolded in the German PV industry [228]. While there is a growing body of literature that leverages this framework for analysis of CCUS for industrial decarbonization [11,229–232], the opportunity exists to greatly expand the scholarly literature on this topic.

The Technological Innovation Systems (TIS) framework offers such a systemic, socio-technical perspective to study the dynamics of technological fields [233,234]. It analyzes which actors drive (or oppose) a novel technology, how policies and regulations play into it, or how societal norms are involved (Fig. 38). The TIS approach has been used to study emerging technologies, e.g. around renewable energies [235,236], fuel cells [237], or grid technologies [238] and more recently it has also been applied to mature technologies such as coal and nuclear [234]. A special feature of the TIS approach is that it also analyses the wider context in which technologies develop [234]. This context includes, among other elements, competing and complementary technologies as well as the established sectors and industries a focal technology is situated in – both in terms of technology development (e.g., heavy engineering) and use (e.g., energy supply, chemical industry, oil/gas industry in the case of CCUS). While we touched upon some of these in the previous sections (e.g. section 3.4), there are several technology dynamics such as advances in fuel cells or hydrogen production technologies, which may either stimulate or hamper CCUS development and deployment. Importantly, TIS analyses should be undertaken with consideration of a broad number of geographies, particularly developing countries that are often underrepresented in the CCUS literature.

The exploration of CCUS in the context of the Circular Carbon Economy (CCE) is also an opportunity for further analyses. As notes elsewhere [11], CCE is an opportunity for CCUS as countries and regions strive to achieve their context-specific net-zero ambitions. In some cases, the CCE framework, which focuses on the reduction, reuse, recycle and removal of CO_2, may be more attractive than decarbonization via a strict focus on energy efficiency and zero-carbon electricity. Countries in the Middle East and Asia that are deeply dependent on heavy industries as their economic base are particularly relevant to CCE research.

5. Conclusion

Although the global need for CCUS deployment and innovation have amplified significantly in recent years, CCUS remains limited in its deployment and diffusion. Nevertheless, ample technologies are emergent with the capacity to capture carbon during pre- and post-combustion processes, as well as novel innovations in direct air capture, indirect air capture, and transportation via pipelines, ships, rail, and motor transport. Storage systems for CO_2 continue to evolve as well, across biotic and abiotic configurations. A multitude of utilization pathways for CO_2 exist also, including fertilizer raw materials, enhanced oil recovery, fuel cells, and biochar, as well as bioproducts, chemicals, and polymers.

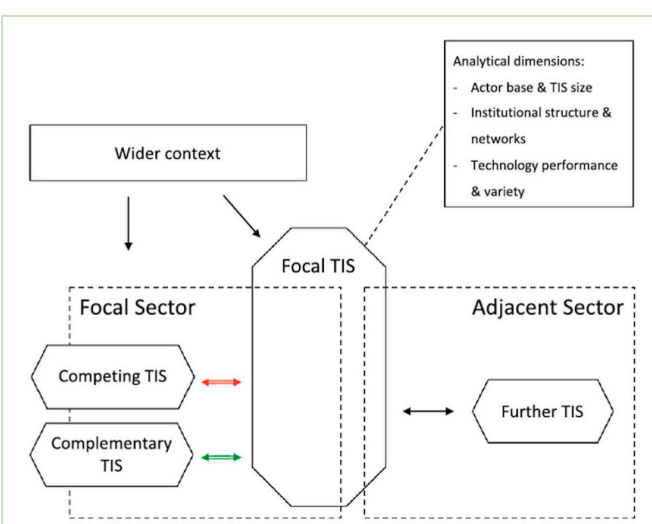

Fig. 38. Simple schematic of focal Technological Innovation System and context. The ties between these elements are meant to illustrate the interconnected nature of the system [239].

These technical dynamics and pathways, however, remain constrained by economic and sociotechnical barriers including international cooperation, lack of infrastructure, and social perceptions. Policy driven solutions to these barriers exist and are beginning to be employed, such as grants and subsidies, carbon pricing, demand-side measures, and risk mitigation. National frameworks across China and Europe offer hope for how to implement some of these policies, although they remain enmeshed in issues of geopolitics and trade, and uncertainties over the future design of CCUS systems.

Harnessing a sociotechnical perspective, our systematic review has enumerated a multitude of particular dimensions of CCUS that we believe should constitute the evolving frontier of research, including a broader base of social acceptance work, as well as more work delving into which particular theories or concepts can best capture the innovation systems shaping CCUS deployment. Tracking developments within and between these dimensions would offer analysts and policymakers a more complete picture of the contexts and activities by which CCUS is being envisioned, researched, deployed, and even critiqued. Furthermore, all of our sociotechnical dimensions call into question any reliance on more simplified and overly artificial divides between CCUS technology and policy or scaling and acceptance. Instead, our review strongly suggests the potential for all of these to coevolve as part of the same sociotechnical system, with the particular evolutionary trajectory being co-created by technical, economic, social, and environmental factors.

Consequently, the findings from the review challenge future efforts to model integrated CCUS portfolios, to determine interactions, and to better understand the non-technical constraints. Before national and global scientists, policymakers, financiers and industry leaders commit fully to CCUS, there is a fundamental need to pursue a more broad-based, more interdisciplinary research program that acknowledges, rather than obscures, the sociotechnical dynamics of CCUS.

Indeed, the sociotechnical system for CCUS is intimately coupled with the overall energy transition and the efforts to decarbonize the energy, transport, and industry sectors. While some opponents have difficulty articulating a coherent case for CCUS being widely adopted purely on technical and economic grounds, CCUS potential does provide a growing number of valid use cases with industries such as cement and refining at the forefront. Moving forward, deep decarbonization and ambitions for CCUS scale up and global use will necessitate further scrutiny of the entire CCUS sociotechnical system, ranging from basic research to market stimulation, and with further consideration of potential geopolitical ramifications and design opportunities.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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