



PRODUCED AND FLOWBACK WATER-ENABLED CO₂ MINERALIZATION AND EOR SYNERGIES: A NARRATIVE REVIEW

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ABSTRACT

This narrative review demonstrates the potential of integrating CO₂ mineralization with produced water treatment. The integration of these two fields by combining the dissolved inorganic carbon dioxide from CO₂ with divalent cations (calcium and magnesium) naturally present in oilfield brines to form stable, solid carbon dioxide minerals. Carbon dioxide precipitation is promoted by the dissolution of CO₂ in produced water (PW), and the adjustment of pH to levels between 8.5 and 10 promotes it. Field validations, such as those conducted at CarbFix, Wallula, and Nagaoka, were used to confirm the technical viability of the process, demonstrating rapid and stable mineralization with a low risk of leakage. A significant synergistic triple-benefit system established when treated produced water is utilized in CO₂-EOR operations increasing in incremental recovery factors (22.2%). This process facilitates permanent immobilization of CO₂, minimizes freshwater usage, and generates valuable byproducts. The integration of PW-CO₂ mineralization-EOR approach is a promising technology for simultaneously dealing with climate mitigation, water stewardship, and resource efficiency. Monitoring and diagnosing of CO₂ behavior can be achieved through 4D time – laps seismic, production well data analysis, well logging and chemical treatment. Recent technologies used to prevent CO₂ release to surface include Autonomous Inflow Control Devices (AICDs), Downhole Gas-Liquid Separation (DGLS) and Closed-Loop Surface Processing. Framework for carbon dioxide management which includes carbon dioxide prices analysis, 45Q TAX Credit as case study and policy recommendations discussed in this review.

Keywords: CO₂; produced water; CCUS; mineralization; geo storage; in-situ; ex-situ; 45Q tax credit.

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1. Introduction

Global warming is influenced by the increasing emissions of CO₂, which rise at a rate of 2.4 ppm per year. These emissions have increased from 280 ppm in 1750 to 414.72 ppm in 2021, putting human life and ecosystems at risk. The combustion of fossil fuels is the primary source of greenhouse gases (GHGs), including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O) [1]. There are several types of emission scopes. Greenhouse gas (GHG) emissions are classified by scope: Scope 1 (direct emissions from fossil fuel combustion), Scope 2 (indirect emissions from electricity), and Scope 3 (supply chain and product-use emissions). Petroleum operations typically involve all three scopes [2-4]. The Paris Agreement aims to limit the temperature rise to below 2 °C, preferably to 1.5 °C. To achieve this, global CO₂ emissions must be reduced by 45% by 2030 [5]. Organizations such as the Intergovernmental Panel on Climate Change (IPCC) and the International Energy Agency (IEA) highlight the vital role of CCUS in cost-effectively reaching climate targets. CCUS includes a range of

technologies that capture CO₂ from specific sources in the environment, usually through industrial applications and sequestration it in geological formations [6, 7]. As of 2023, approximately 392 CCS facilities are under development, with a total annual capture capacity exceeding 360 MtCO₂. Industrial applications include natural gas processing, hydrogen and ethanol production, and power generation. Geological carbon dioxide sequestration (GCS) is the most developed storage method which involves the injection of carbon dioxide into deep saline aquifers, depleted oil and gas reservoirs, basalt formations, and unmined coal seams [8]. Various trapping mechanisms exist within these formations. Trapping mechanisms include structural, residual, solubility, and mineral trapping. Structural traps are most important; mineral capture by reactions with divalent cations (Ca²⁺, Mg²⁺, Fe²⁺) provides long-term stability which requires reactive rocks such as basalt or volcanogenic sandstone. Enhanced oil recovery (EOR) using captured CO₂ offers dual benefits: emissions reduction and hydrocarbon dioxide extraction. Advanced EOR strategies can enhance carbon dioxide storage [9].

Carbon dioxide capture, utilization, and storage (CCUS) involves four integrated steps:

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1) Capture: CO₂ is extracted from point sources (fossil power plants, industrial facilities, hydrogen/ethanol production) or directly from ambient air (direct air capture). Current capture technologies can recover 90-98 % of CO₂ from industrial sources.

2) Compression: Captured CO₂ is compressed to >10 MPa to achieve high density, reducing transport volume and costs.

3) Transport: Pressurized CO₂ is transported via pipeline (for regional projects), ship (for international projects), or truck (for small volumes). Supercritical CO₂ (liquid-like density, gas-like viscosity) is ideal for efficient transport. CO₂ transport to storage sites is carried out by means of pipelines and cargo vessels. CO₂ transport is inherently safer than natural gas transport because CO₂ is non-flammable and non-toxic at injection concentrations, whereas natural gas is highly flammable [10].

4) Injection and Storage: Compressed CO₂ is injected into geological formations such as saline aquifers, depleted reservoirs, basalt formations at depths >800 m where it is permanently immobilized through physical trapping (structural, capillary, solubility) and chemical trapping (mineral carbon dioxide). Under appropriate injection parameters such as injection rate and injection pressure compressed carbon dioxide is pumped into subterranean formations to immobilize it permanently.

Figure 1 illustrates the four-stage CCS process, showing CO₂ pathways from emission sources through capture, com-

pression, transport, and final storage in geological formations. These characteristics are controlled by the petrophysical and physiochemical features of the geological rock, which are identified through the process of screening via pilot and simulated experimental trials [11, 12].

Numerous approaches to carbon dioxide capture, storage, and utilization have been evaluated to mitigate rapid anthropogenic CO₂ emissions in the atmosphere. These include adsorption on modified carbon dioxide surfaces or carbon dioxide aerogels, accelerated carbon dioxide [14], biological fixation, chemical looping [10], assimilation by vegetation, and geological storage [15, 16]. Accelerated carbon dioxide absorption using alkaline solid waste is a particularly effective method for mineralizing flue gas CO₂ from industrial or power plant sources [17]. This process, originally proposed in [18] accelerates natural weathering, reducing the timescale to just a few hours. It involves gaseous CO₂ reacting with metal-oxide-bearing materials (mainly calcium and/or magnesium oxides) in the presence of moisture to form stable, insoluble carbon dioxide precipitates. From the perspective of water chemistry, the ability of metal oxides to form carbon dioxide precipitates depends on the chemisorption strength to carbon dioxide (or gaseous CO₂) at the fluid-solid interface, the number of active basic sites on the particle surface, and the solubility product constant (*K_{sp}*) for aqueous carbon dioxide. Generally, CaO and MgO are the most favorable metal oxides for reacting with CO₂ [19]. Alkaline solid wastes make suitable feedstocks for CO₂ mineralization through accelerated carbon dioxide, as these wastes are typically produced in large quantities. Innovative techniques, such as pH swing [20], have also been developed to increase the leaching rate of reactive phases from the solid matrix into the solution. In general, calcium-bearing minerals such as CaO, Ca(OH)₂, and Ca₂SiO₃ are the main phases involved in accelerated carbon dioxide using alkaline solid wastes.

Direct Air Capture (DAC), illustrated in figure 2, represents technology designed for filtering and removing carbon dioxide (CO₂) directly from the ambient atmosphere. The general process involves large fans pulling in large volumes of ambient air and pushing it into the capture unit. The air passes over a chemical «filter» that selectively binds with the CO₂ by sorbents. When the sorbent or solvent is «full» of CO₂, it is regenerated by heat or changes in pressure and releases the CO₂ as a highly concentrated, nearly pure gas stream. The «cleaned,» carbon dioxide-reduced air is released back into the environment while the captured concentrated CO₂ stream is compressed and stored.

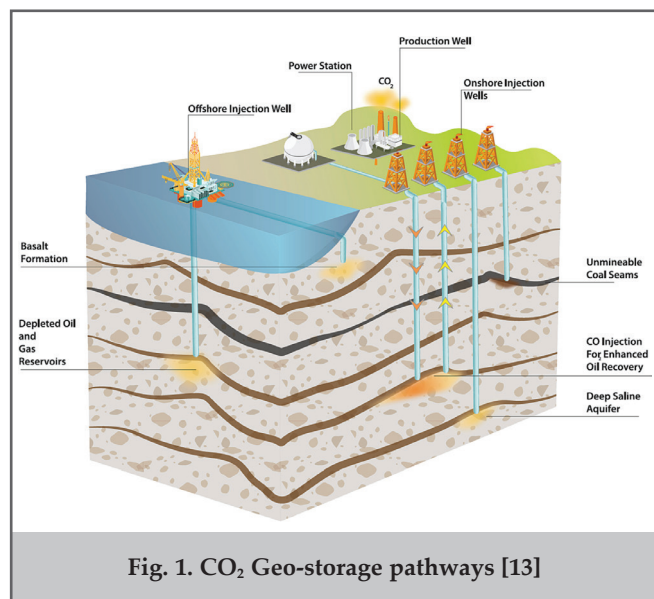


Fig. 1. CO₂ Geo-storage pathways [13]

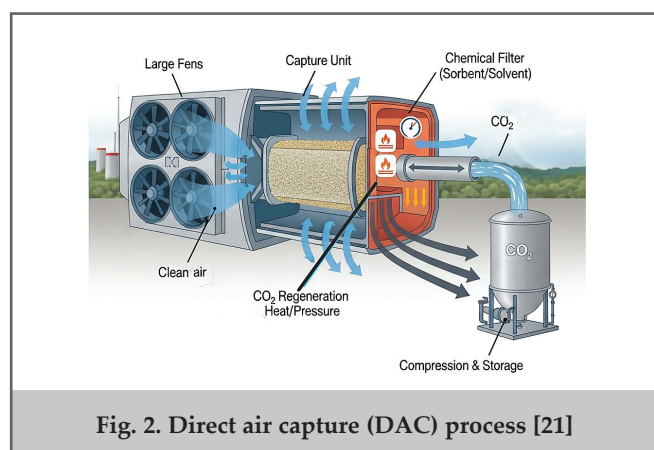


Fig. 2. Direct air capture (DAC) process [21]

1.1. Produced water

Globally, the water cut ratio averages approximately 80%, with produced water volumes estimated at 250 million barrels per day compared to 80 million barrels of oil production [22]. The volume of produced water (PW) is site-specific and depends on factors such as the age of the field, geographical location, reservoir history, and production technologies. The amount of PW generated each year increases with age [23], with production capacity nearly depleted oil fields dropping to as low as 2% oil to PW [24, 25]. In the United States, annual PW estimates are around 890 billion gallons (3.37 billion m³), making it the largest waste stream associated with oil and gas activities. PW volumes tend to grow annually as old fields depleted and new oil fields are developed [24, 26]. This

increase is partly due to the expansion of unconventional oil and gas development, which now accounts for over 50% of recent crude oil and natural gas production [27]. The flow rate of PW changes over the life of an oil and gas well: conventional wells generate little or no PW at first, but the flow rate increases over time. High PW flow rate due to fracturing fluid flowback through unconventional hydraulically fractured wells later stabilizes at a lower rate and then declines. While conventional CCUS focuses on post-combustion CO₂ capture from power plants and industrial sources, a significant opportunity remains underexplored: leveraging the alkaline earth metal content (Ca²⁺, Mg²⁺) naturally present in produced water brines to simultaneously sequester CO₂ while treating waste streams.

1.2. Objectives of the review

This narrative review presents a comprehensive analysis of established carbon dioxide capture, utilization, and storage (CCUS) technologies, geological sequestration, and carbon dioxide mineralization. A novel integrated strategy combines ex situ CO₂ mineralization with produced water treatment. The framework of carbon dioxide pricing is examined using the 45Q Tax as case study. The article also briefly discusses different policies regulating carbon dioxide marketing.

2. CO₂ Geological storage

CCS provides an optimal solution for removing CO₂ from the atmosphere via permanent immobilization in underground geological storage formations [28]. The primary CO₂ sinks are classified into various types of geological formations, such as depleted and existing hydrocarbon reservoirs for the EOR process [29, 30], deep saline aquifers [28, 31, 32], basaltic rocks [33, 34], coal seams [35-37], and organic-rich shales. Deep saline aquifers and depleted hydrocarbon reservoir rocks are considered major potential CO₂ storage media. Both storage media have a large capacity for storing CO₂ [29, 31]. Highly permeable reservoir rocks facilitate the injection of large volumes of CO₂ compared with low permeability sandstone rocks. The caprock like shale provides a seal to trap buoyant CO₂ which prevents capillary

leakage [35, 38, 39]. Globally, the Intergovernmental Panel on Climate Change (IPCC) reports that hydrocarbon dioxide reservoirs can store between 675 and 900 billion tons of CO₂. In contrast, saline aquifers have between 1000 and 100000 billion tons of estimated CO₂ storage capacity [30]. In addition to these, basaltic rocks have recently displayed great potential for storing CO₂ in mineralized form through a process developed by CarbFix [38, 40]. In this process, CO₂ and water are injected together into basalt formations, inducing a rapid chemical reaction for storing CO₂ in carbon dioxide form [41]. An advantage of this process is that it does not require concentrated CO₂ during injection, which can store up to 100 kg of CO₂ in a cubic meter area of basalt [30, 42]. To stabilize CO₂ there are two types of stability:

Short-Term Stability (Structural Trapping): Initially, CO₂ is secured primarily by structural traps. This means it is physically contained by an impermeable «cap rock» layer, which prevents it from migrating upwards.

Long-Term Stability (Mineral Trapping): Over time, the security of storage increases as other mechanisms take over. The most stable, long-term form of storage is mineral trapping. This is a process where the CO₂ reacts with minerals in the rock (specifically with divalent cations like Ca²⁺ and Mg²⁺) to form new, stable carbon dioxide minerals. This process effectively locks the CO₂ into a solid, stable mineral form, providing permanent immobilization.

Figure 3 illustrates Trapping Mechanisms CO₂: the structural trap (physical containment by an impermeable cap rock) predominates. Over time, other mechanisms increase security: the residual trap (CO₂ stuck in pores), the solubility trap (CO₂ dissolving in fluids), and the mineral trap (CO₂ reacting with rock to form solid minerals).

3. Capture technologies

Three proven capture pathways are: (1) Post-combustion (MEA solvents, 90-98% capture, USD60-80/ton) retrofit-compatible with existing plants; (2) Amine regeneration via mineralization (69-98 % efficiency, USD 40-50/ton, emerging pilot stage); (3) Direct Air Capture (USD 600+/ton, high cost but

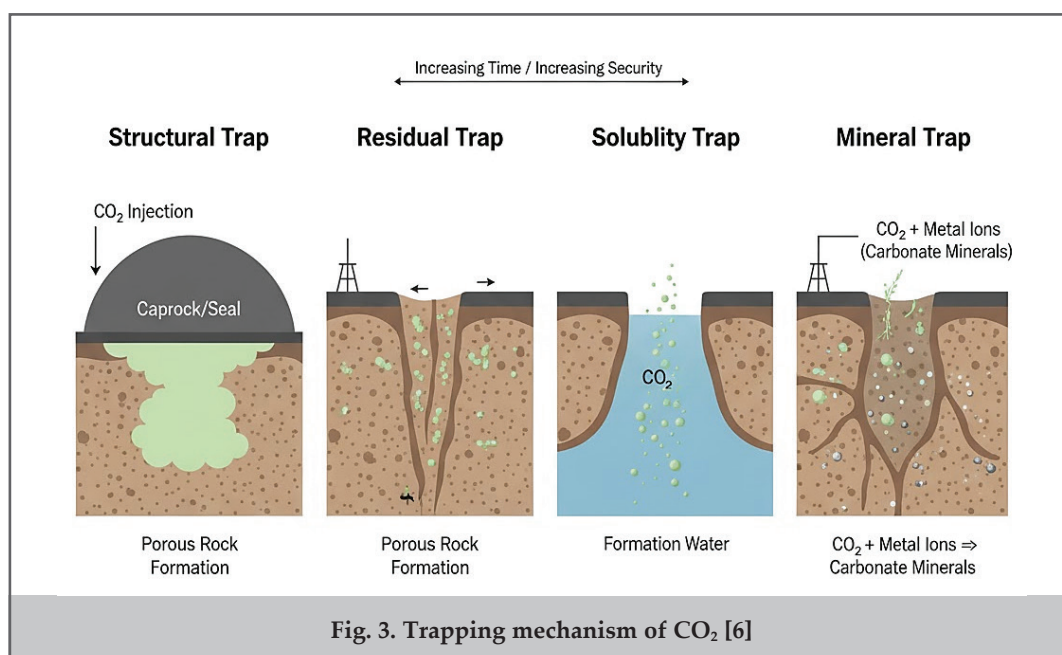


Table 1

CCUS studies comparison							
Technology	TRL	Maturity	Energy (MWh/tCO ₂)	Cost (\$/ton)	CO ₂ removed	Regen Efficiency	Key advantage
Post-combustion (MEA)	9	Deployed	0.5	60-80	90%	98% standard	Retrofit-compatible
Amine regens. via mineralization	7	Pilot	0.22	40-50	90%	69-98%	Lower regen cost
Pre-combustion	6	R&D	2.6-3.0	80-100	--	--	Niche applications
Oxy fuel	5	Pilot	0.1-0.5	50-80	65-80%	--	High CO ₂ concentration
Chemical looping	4	R&D	1.3	20-30	--	--	Higher efficiency potential
DAC (Clime works)	7	Operating	--	600	100%	--	Air capture; high cost
DAC (Carbon dioxide Eng.)	7	Scaling	--	94-232	100%	--	Improved economics

scaling down). Detailed comparison is presented in table 1. Emerging technologies include pre-combustion, oxy-fuel, chemical looping [43, 44].

4. Carbon dioxide mineralization

4.1. Fundamentals of mineralization

In the process of carbon dioxide sequestration, carbon dioxide mineralization is an essential technique [45], enabling long term sequestration by reaction of CO₂ with calcium (Ca²⁺) or magnesium (Mg²⁺), resulting in the formation of stable carbon dioxide minerals (CaCO₃ and MgCO₃) [18]. This process takes place naturally throughout the weathering process; however, the industry can speed up the reaction to improve the effectiveness of carbon dioxide sequestration [46]. The most important processes include the dissolution of carbon dioxide and minerals, the reaction between carbon dioxide ions and metal ions, and the precipitation of carbonate minerals. CO₂ in an aqueous solution first passes through the processes of hydration and dissociation, which results in the formation of carbonic acid. This acid subsequently breaks down into bicarbonate (HCO₃⁻) and carbon dioxide.

Specific equations for the reaction processes in Eqs. (1)–(3):

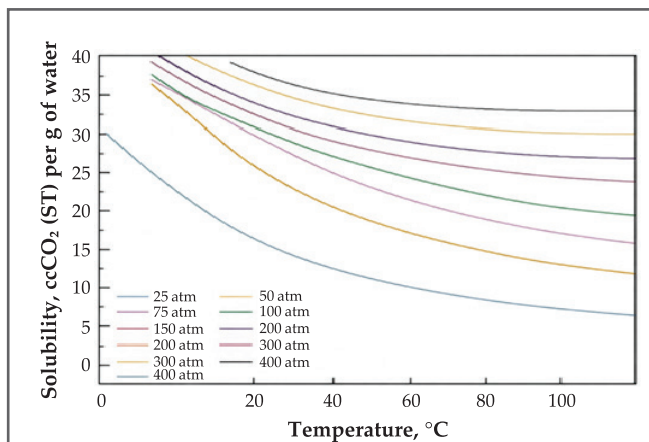
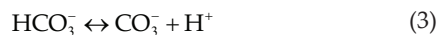
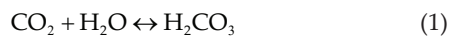
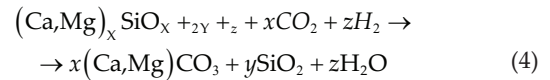


Fig. 4. Temperature effect on solubility of CO₂ (adapted from [56])

Mineralization proceeds through a second phase involving mineral dissolution. When carbon dioxide is combined with water, the result is carbon dioxide acid. A decrease in pH of the solution promotes mineral dissolution. The release of metal ions from minerals, such as calcium and magnesium, occurs when the environment is charged with acid. By way of illustration, minerals like calcium feldspar (CaAl₂Si₂O₈), olivine (Mg₂SiO₄), and serpentine (Mg₃Si₂O₅(OH)₄) are capable of dissolving and releasing Ca⁺² and Mg⁺² ions. When the mineralization reaction takes place, these ions are introduced into the solution as reactants. Through this process [47-49], carbon dioxide reacts with minerals that include calcium or magnesium, resulting in the formation of stable carbonates (for instance, CaCO₃ and MgCO₃), which ultimately results in the deposition of carbon dioxide, as expressed by Eq.(4) [50].



4.2. Factors affecting mineralization reaction

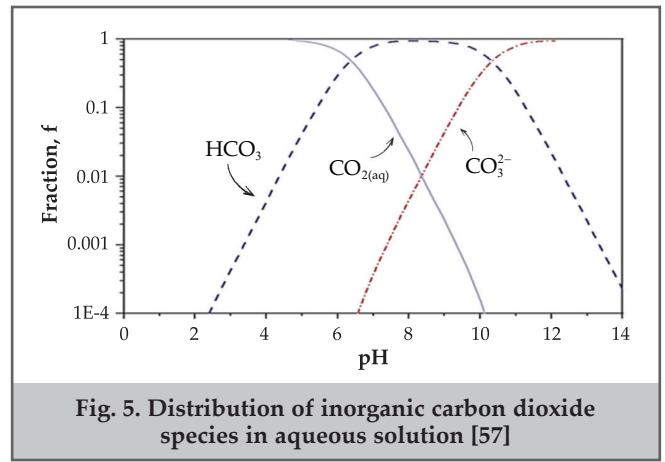
Among the various factors influencing the mineralization reaction, temperature and pH are the most significant. The behavior of minerals in terms of their dissolution has become extremely sensitive to changing temperatures and is subject to certain physical and chemical laws. In addition, the Arrhenius equation is followed by reaction kinetics, as expressed in Eq.(5) [51].

$$K = A \cdot \exp(Ea/RT) \quad (5)$$

where k is the reaction rate constant, Ea is the apparent activation energy, T is the temperature (K), and R is the universal gas constant. In this equation, k represents the reaction rate constant. Increasing temperatures cause a kinetic rivalry that influences the total reaction rate [52]. This competition is caused by the fact that rising temperatures encourage the release of divalent metal ions from minerals, but they also limit the solubility of carbon dioxide in water. According to experimental studies, the solubility of carbon dioxide (CO₂) decreases with rising temperature. Experimental studies have demonstrated that at temperatures above 200 °C the reactivity of carbon dioxide decreases significantly [53-55]. It is necessary to have a temperature range that is appropriate to guarantee effective mineralization. The relationship between the solubility of carbon dioxide and temperature may be found in figure 4.

pH is an extremely important regulatory factor in mineral carbonation processes since it influences the aqueous specia-

tion of carbon dioxide and the pathway that carbon dioxide production takes. The distribution of various inorganic carbon dioxide species (H_2CO_3 , HCO_3^- and CO_3^{2-}) in aqueous solution shown in figure 5 [57], which shows how the pH of the solution affects the distribution of these species. When the pH level is less below 6.5, the predominant species is carbonic acid, which is represented by the chemical formula H_2CO_3 . Within the pH range of 6.5-10, bicarbonate (HCO_3^-) becomes the major form, whereas carbonate ions (CO_3^{2-}) take the lead when the pH is above 10. HCO_3^- is the most reactive of these intermediates and is responsible for the formation of carbonate minerals. Consequently, a pH range of 9–10 is generally thought to be optimum for enhancing the kinetics as well as the thermodynamics of the carbon deoxidation process [55, 58-60]. Henry's law states that the partial pressure of carbon dioxide ($p\text{CO}_2$) in solution is directly proportional to its concentration in solution, as expressed in equation (5). As a result, the rate of mineral carbon dioxide is greatly impacted by this relationship. In this equation, $p\text{CO}_2$ is the partial pressure of carbon dioxide (CO_2), H is the constant that is used in Henry's law, and CO_2 is the concentration of dissolved carbon dioxide in water. Experiments indicated that the reaction rates of systems containing serpentine, olivine, and brucite increase in a manner that is approximately linear with an increase in $p\text{CO}_2$ [54, 58, 59]. Recent molecular dynamics simulations (ReaxFF methodology) reveal counter-intuitive optimizations: temperature optimal at 328 K (55 °C), not higher, because above 55 °C, CO_2 solubility (Henry's Law) dominates over activation energy benefits. PRESSURE optimal at 1.0 MPa, with higher pressures reducing conversion due to CO_2 surface saturation which a critical finding for cost optimization. Fragmentation/grinding increases reaction rates 2-3-fold by disrupting crystal structure (measured via Radial Distribution Function). However,



water film formation on mineral surfaces reduces conversion 11.5% through CO_2 diffusion impedance, suggesting dry conditions optimize efficiency. Additionally, chelating agents (GLDA, N,N-Bis(carboxymethyl)-L-glutamate) demonstrate 26-fold permeability enhancement in basalt, enabling 100 -fold increase in storage capacity improvements through integration with seawater-based processes, a promising frontier for future systems [61].

There are many factors that influence the mineralization process. These factors are summarized in the table 2.

4.3. Types of mineralization

- In-situ: CO_2 is injected directly into reactive underground formations (such as basalt or volcanogenic sandstone). This is considered more economical.
- Ex-situ: A surface-level process where CO_2 reacts with feedstock (e.g. fly ash) to form stable carbon dioxide. This method is permanent and requires no long-term monitoring (table 3).

Factor	Optimal Conditions / Quantitative Range	Example Materials & Key Notes	References
Mineral Types & Wastes	High-Reactivity (Wastes): Typically, 40-60 % CaO by weight. Low-Reactivity (Minerals): Approx. 40% MgO by weight. Pretreatment (Minerals): Thermal heating (600–650 °C) and/or fine grinding (<75 µm) is required.	Wastes (High Reactivity): Steel slag, cement kiln dust (CKD), coal fly ash, MSWI ash. Minerals (Low Reactivity): Serpentine $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$, Olivine $(\text{Mg,Fe})_2\text{SiO}_4$. Requires activation.	[62]
Temperature	Aqueous (Slurry) Process: optimal range is 50–90 °C. Gas-Solid (Dry) Process: optimal range is 400–600 °C.	Aqueous: a trade-off. Above 100 °C, CO_2 solubility drops. Below 50 °C, mineral dissolution is too slow. Dry: primarily used for pre-treated natural minerals.	[55]
CO_2 Injection & Mixing	CO_2 Partial Pressure (Wastes): High reactivity allows for 1 bar (atmospheric) or direct flue gas (10-20 % CO_2). CO_2 Partial Pressure (Minerals): High pressure is essential: 10–150 bar. Stirring Rate (Slurry): 300 – 1000 rpm in a stirred tank.	These factors control mass transfer. Stirring keeps heavy particles suspended and broke CO_2 bubbles to increase gas-liquid contact.	[55]
pH	Typical Starting pH (Slag): 11.5–12.5. Optimal Operating Range: pH 9–11. Critical Threshold: below pH ~8.5, precipitation stops.	The process balances two steps: Dissolution: Metal ions Ca^{+2} dissolve (high pH). Precipitation: Ca^{+2} reacts with CO_3^{2-} (favored at pH >9).	[63]

Table 3

Factors affecting in & ex-situ mineralization						
Mineralization Type	Temperature, °C	pH	CO ₂ Pressure, bar	Rate	Key Results	Reference
Ex-Situ (Olivine)	150–200	9–11	10–150+	~10 ⁻¹² –10 ⁻⁸ mol/cm ² /s	Silica passivation layer is a known issue	[64]
Ex-Situ (Serpentine)	> 200	9–11	10–150+	Slower than olivine	Needs thermal activation; more abundant	[6]
Ex-Situ (Alkaline Wastes)	25–80	9–12	1–20	Variable	Leverages industrial waste streams	[65]
In-Situ (CarbFix, Basalt)	20–50	Inject: ~3.5 Reservoir: ~5.2–6.5	~25	Rapid (>95% in 2 yrs)	CO ₂ pre-dissolved in water; sinks	[66, 67]
In Situ (Wallula, Basalt)	50–60	N/A (Supercritical)	~85–90	Confirmed, but slower	Injected supercritical CO ₂ , not pre-dissolved	[68]
Ex-situ (PW – based, pilot)	25	8–10	1 atm	100% in 6.5 hrs.	Semi continuous with flue gas, 9.9 g CO ₂ /L	[69]
Ex-situ (PW-based, yard)	55–80	8–12	1–10 atm	10 Mt/yr Potential	600 L CSTR, selective Mg→Ca precipitation	[70]

5. Composition of produced water

Petroleum and natural gas are both composed of components. Produced water is a complex mixture containing dissolved oil, hydrocarbon dioxides, gases (including carbon dioxide and hydrogen sulfide), organic acids, phenols, and metals [71]. Furthermore, produced water (PW) contains residual production chemicals (additives), which are strictly regulated in many countries. The compositions of these additives do not contribute to the pollution effect in produced water. The dissolved constituents derived from oil include a wide variety of permanent organic chemicals. These chemicals include benzene, toluene, ethylbenzene, and xylene (BTEX), polycyclic aromatic hydrocarbon dioxides (PAHs), phenols,

organic acids, waxes, surfactants, and biocides. These chemicals eventually accumulate as primary contaminants in produced water [72]. Dissolved organic molecules, including polycyclic aromatic hydrocarbon dioxides (PAHs), organic acids, phenol, and BTEX (benzene, toluene, ethylbenzene, and xylenes) are all examples of dangerous substances. High concentrations of dissolved heavy metals and minerals may vary according to the geological formations. The components of produced water (PW) have a considerable impact on the way its physicochemical qualities. There is a significant amount of variation in these components, which are determined by geological location, age, formation, reservoir history, and the type of hydrocarbon dioxide that is produced [71]. Table 4 below provides a sum-

Table 4

Produced water components								
Component	Description (Condensed)	Concentration ranges (mg/L) & Examples	Reference	Ion/Parameter	Global range (ppm)	Marcellus Basin (Bennett 2025)	Saudi Aramco (Alshammari 2025)	Importance for mineralization
Dissolved Minerals	Salts (NaCl, CaCl ₂) / Total Dissolved Solids (TDS)	General: <1000 to >300000 US Unconv. (Median): * Bakken: ~244000 * Marcellus: ~166000 * Permian: ~122000 * Eagle Ford: ~57000 North Sea (Conv.): 10000 - 90000 (as Cl ⁻)	[73]	Na ⁺	5000-120000	28000	11800	Salinity indicator
Heavy Metals	Barium (Ba), Strontium (Sr), Iron (Fe), Zinc (Zn), etc.	* Bakken (US): Sr (~1610), Mn (~33) * North Sea (Conv.): Ba (0-200), Fe (0-11)	[73]	Ca ²⁺	100-51300	9000	61900	Primary CO ₂ reactant
Dissolved Organics	BTEX, PAHs, organic acids, phenols	*COD: 150 - 500 (typical) * BTEX (Iraq): «High concentrations» * BTEX (North Sea): ~1.5 * Acids (North Sea): ~300 * Phenols (North Sea): ~5	[74]	Mg ²⁺	0.9-4300	900	4810	Secondary CO ₂ reactant
Produced Solids (TSS)	Formation fines, sand, corrosion, scale precipitates	* Unconv. (US): High, (e.g., 260 - 550)	[75]	K ⁺	100-2000	400	--	Trace ion
Oil & Grease (O&G)	Dispersed oil-in-water (OIW) droplets	* North Sea (Conv.): 0-30 (Aliphatic)	[73]	Cl ⁻	1400-190000	66000	132100	Dominates ionic strength
Dissolved Gases	H ₂ S, CO ₂ , methane	* Key trait (sour/sweet), not a cited concentration.	[73]	Sr ²⁺	100-2000	--	4350	Trace reactive ion
Treatment Chemicals	Residuals (e.g., biocides, scale inhibitors)	* Varies based on upstream addition.	[73]	TDS	2600-360000	--	164060	Total dissolved solids
				pH (initial)	3.1-7.0	~6.5	7.4	Requires pH adjustment

mary of the classification of these components found in oil and gas produced, concentration range and examples for different regions worldwide. The high calcium concentration in Saudi Aramco PW (61900 ppm) compared to Marcellus (9000 ppm) suggests that Middle Eastern fields may offer 6-7 times higher mineralization potential per barrel of water treated, highlighting regional strategic advantages.

5.1. Treatment technology of oil and gas produced water

Produced water from oil and gas operations undergoes three-stage treatment:

1. primary – API separators and hydro cyclones remove oil and suspended solids (>90% removal);
2. secondary – flotation, biological, and membrane bio-reactor (MBR) processes remove dissolved organics and nutrients;
3. tertiary – advanced oxidation processes (AOPs) and membrane polishing (NF/RO) to achieve discharge standards. For comprehensive treatment technology review see [76].

5.2. Requirements for produced water in CO₂ mineralization

For produced water (PW) to be effectively used for CO₂ mineralization, it must meet three main requirements.

5.2.1. Cation availability

A high concentration of dissolved divalent cations is the most critical requirement, as there are the «building blocks» which reacts with CO₂ such as Calcium Ca²⁺ and Magnesium Mg²⁺ to make solid stable minerals like calcium carbonate (CaCO₃) and magnesium carbonate MgCO₃ [77].

5.2.2. Chemical conditions (pH)

The PW must have the correct pH to allow the reaction to happen. PW is often not alkaline enough on its own and requires chemical adjustment by an alkali like sodium hydroxide (NaOH), and the pH must be raised to an alkaline state (typically pH 9-11) to convert the dissolved CO₂ into the reactive carbon dioxide ions (CO₃²⁻) necessary for precipitation [62].

5.2.3. Water matrix (pretreatment)

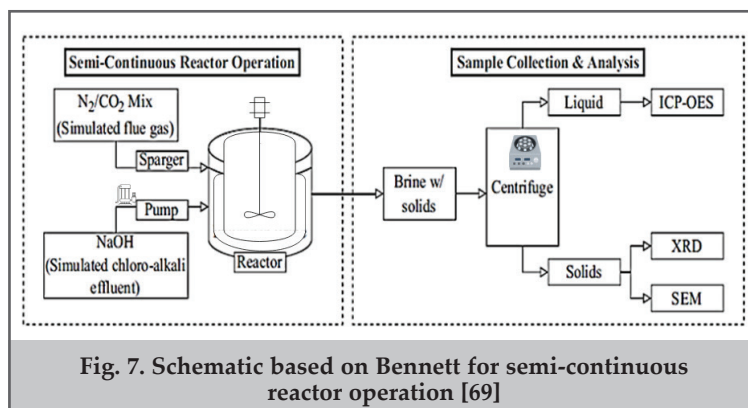
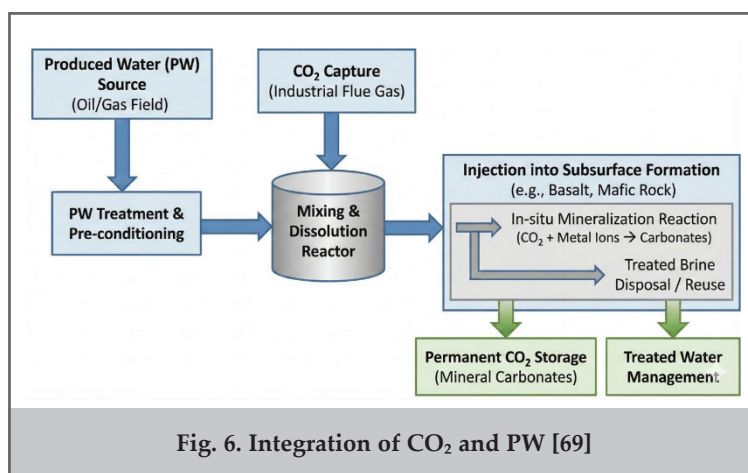
The other components in the complex PW brine can interfere with the process or contaminate the final product, such as inhibitors, which can reduce the amount of CO₂ dissolved in the water, slowing the reaction. Contaminants such as BTEX and heavy metals should be removed. If not, they will contaminate the final carbon dioxide mineral, making it a hazardous waste and unsuitable for beneficial reuse [78].

5.3 Integration of produced water (PW) and CO₂ mineralization

Figure 6 below summarizes the integration of the produced water which is treated using various processes and captured CO₂ for mineralization to produce useful salts and enable smart water reuse in different applications such as EOR, agriculture, industry, etc.

6. Laboratory and pilot-scale demonstrations

The semi-continuous reactor demonstrated that flue gas (10-25% CO₂) combined with produced water and NaOH addition, achieved the desired outcomes. Unlike batch processes limited by equilibrium, the semi-continuous approach with constant NaOH dosing overcomes buffering capacity limits, achieving 100% Ca²⁺ utilization conversion in 6.5 hours as in figure 7. This validates the feasibility of using realistic industrial CO₂ sources rather than pure CO₂, reducing both cost and complexity. The demonstrated 9.9 g CO₂/L potential from Marcellus Basin PW combined with the 22.2% oil. The mechanism for this recovery increase is primarily wettability alteration. The treated carbon dioxide water alters the rock surface from oil-wet to water-wet (contact angle reduction). Recovery improvement from smart water application establishes a compelling technical and economic case for integrated deployment. The utilization of flue gas for semi-continuous ex situ carbon dioxide mineralization is fundamentally driven by its high CO₂ concentration, which provides a robust point-source feedstock that enhances mass transfer rates according to Henry's Law; this high partial pressure drives the gas-to-liquid transfer more effectively than atmospheric capture which overcome the rate-limiting step of the process. The advantage of this approach is more than traditional methods that rely on solid alkaline feedstocks (e.g., mine tailings), which incur significant energy costs and financial burdens due to the grinding and dissolution required to release calcium ions. The use of produced water (PW) provides pre-dissolved calcium ions, eliminating these energy penalties, simultaneously transforming industrial waste (flue gas and brine) into a value-added precipitated calcium carbon dioxide (CaCO₃) product for a global market valued



at approximately USD 1.9 billion, effectively offsetting capture costs. To validate and optimize this integrated system, researchers employed a full factorial design of experiments (DOE), systematically manipulating independent variables including CO₂ concentration (10–25 %), temperature (25–80 °C), and pH (8–9) to maximize calcium depletion rates and ensure the crystallization of thermodynamically stable calcite rather than less valuable polymorphs [69].

6.1. Pilot scale

At pilot scale demonstration using a 600 L continuous stirred-tank reactor (CSTR) processed actual produced water brine with Ca²⁺ concentrations up to 61,900 ppm, achieving sequential precipitation of Mg(OH)₂ (pH 8-9) followed by CaCO₃ (pH >10). This modeling supports a sequential precipitation mechanism where magnesium and calcium are selectively separated based on pH thresholds: magnesium preferentially precipitates as magnesium hydroxide (brucite) with pH range of 8-9, and following its complete depletion does the pH rise to approximately 12 to facilitate the precipitation of calcium hydroxide (portlandite) or calcium carbon dioxide. The experimental timeline for this process,

as observed in semi-continuous reactor tests, spans a 4-hour duration where reaction kinetics are monitored intensively. The initial phase ($t=0$ to 0.25 h) was characterized by rapid magnesium depletion and pH stabilization, followed by calcium processing, with samples drawn every 15 minutes initially and thereafter every 30 minutes to track the completion of these distinct reaction phases. Figure 8 illustrates the progression of scalability.

Also, table 5 provides a comparison between mineralization scales

6.2. Life cycle assessment (LCA)

A life cycle assessment method was employed to quantify the net carbon dioxide emissions of the ion exchange technology for mineralization. CO₂ emissions (CO₂ e) for CaCO₃ precipitation via ion exchange processes as illustrated in figure 9.

7. CO₂ -EOR processes and wettability alteration mechanisms

Enhanced Oil Recovery (EOR) is important for the depletion of conventional oil resources, and CO₂ injection is one of the most favored EOR techniques. CO₂-EOR process-

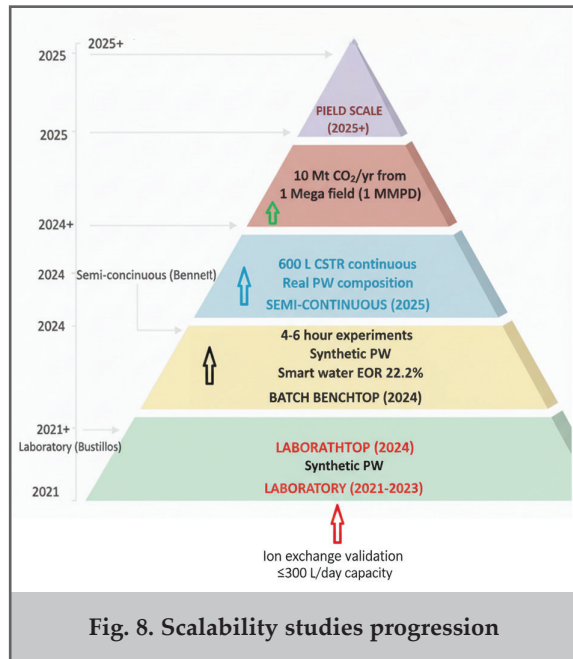


Fig. 8. Scalability studies progression

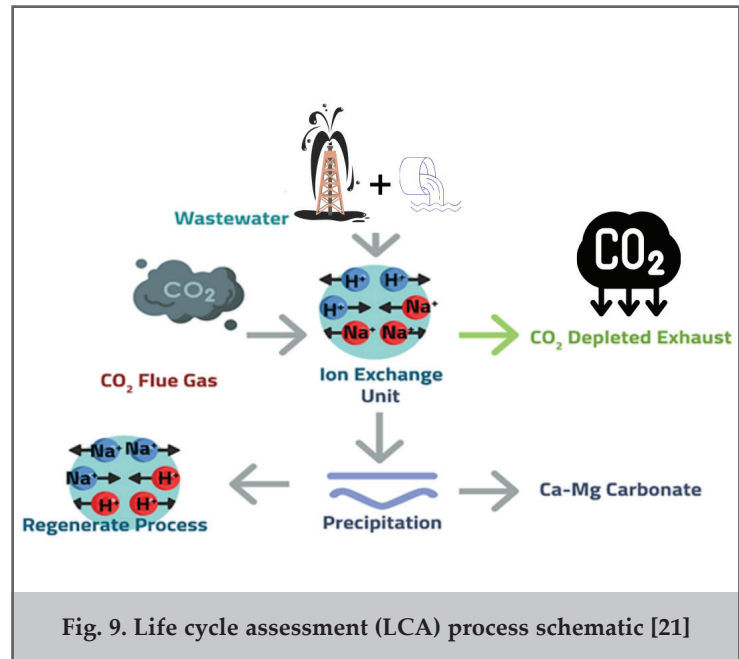


Fig. 9. Life cycle assessment (LCA) process schematic [21]

Scale	Setting	Temperature, °C	pH	Pressure	Rate/Capacity	Conversion	Time-line	CO ₂ captured	Reference
Benchtop	Ion exchange + pH swing	25	8-10	1 atm	0.314 kg/L/day	90% Ca	Batch	300 L/day	[79]
Benchtop (EOR)	Produced water + smart water	25	9-10	1 atm	Batch	72.6% oil recovery	4-6 hrs	9.9 g CO ₂ /L	[70]
Benchtop (semi-cont.)	Flue gas + PW + NaOH	25	8-9	1 atm	0.315 kg/L/d	100% Ca ²⁺	6.5 hrs	9.9 g CO ₂ /L	[69]
Pilot (600 L CSTR)	Real PW brine (61900 ppm Ca)	55-80	8-12	1-10 atm	Continuous	Mg → Ca selective	<1 day	10 Mt/yr potential	[80]
Field	Basalt in-situ (CarbFix)	5-35	7-10	In-situ	~165 t/yr	95% mineralized	<2 years	230 t injected	[81]
Field	Basalt in-situ (Wallula)	5-30	7-10	In-situ	977 t demo	Partial	25 days	977 t CO ₂	[70]

es involves injecting CO₂ into reservoirs to interact with residual oil [82], thereby increasing pressure and improving mobility toward production wells. Common injection schemes include three techniques, first is continuous CO₂ injection (CCI), when the CO₂ acts as a solvent by reducing oil viscosity and increasing mobility, and this considered a more effective process than water flooding in high-viscosity oil reservoirs. The second technique is water-alternating-gas (WAG) [83], which alternates the injection of water and CO₂ to optimize both sweep and displacement efficiency. This method is beneficial in low-permeability reservoirs and helps lower project costs. The last technique is carbon dioxide water injection (CWI), when interfacial tension (IFT) between oil and water is reduced by reaction of CO₂ dissolved in water, enhancing oil swelling and improving sweep efficiency [84]. Figure 10 provides a ratio of total recovery with these techniques. Also, there are many models discuss enhanced oil recovery such as hydrodynamic model [85]

7.1. Diagnosing and monitoring reservoir systems

There are many methods or techniques used to diagnose or monitor CO₂ production in oil and gas fields, including:

1-4D Time-lapse seismic monitoring: By conducting 3D seismic surveys at different time intervals [86], operators can visualize the movement of the CO₂ plume over time. This helps identify bypassed oil zones and structural areas where CO₂ may accumulate or escape.

2-Production well output analysis: Monitoring the carbon dioxide content in the output of a production well is critical for detecting CO₂ breakthrough the point where injected CO₂ bypasses the oil and flows directly into the production well. When breakthrough is diagnosed, operators can adjust injection strategies, such as implementing a Water-Alternating-Gas (WAG) cycle to reduce CO₂ mobility and improve the sweep efficiency.

3-Well logging technologies: Advanced tools like Pulsed Neutron Capture (PNC) logging can be run downhole to measure changes in fluid and gas saturation behind the well casing, accurately tracking CO₂ saturation in different reservoir layers.

4-Chemical and isotopic tracers: Injecting specific tracers alongside the CO₂ allows engineers to accurately measure transit times between injection and production wells, diagnosing reservoir heterogeneity and identifying highly permeable thief zones.

7.2 Selective technologies to prevent CO₂ release to the surface

When CO₂ breakthrough occurs, it brings large volumes of gas into the production wellbore. To prevent this CO₂ from reaching the surface or to minimize the need for costly surface separation, modern fields use selective subsurface technologies:

1-Autonomous inflow control devices (AICDs): These are smart completion tools installed along the wellbore within the reservoir. Because CO₂ has a much lower viscosity than oil, an AICD automatically restricts flow from specific reservoir zones where gas breakthrough occurs. This selectively reduces CO₂ production, keeping it within the reservoir while allowing oil from other zones to flow freely.

2-Downhole gas-liquid separation (DGLS): Instead of lifting the entire mixture to the surface, DGLS technology acts like an underground separator. It uses centrifugal forces to separate the highly buoyant CO₂ from oil and water directly

inside the wellbore. The captured CO₂ is then compressed and reinjected into a disposal zone deep underground, ensuring it never reaches the surface.

3-Closed-loop surface processing: In scenarios where CO₂ must be brought to the surface along with oil, modern facilities utilize entirely closed-loop extraction systems. High-pressure CO₂ is captured immediately off the primary separators and directed to compression facilities for reinjection, significantly minimizing atmospheric emissions.

8. Framework for carbon dioxide management: Analysis of pricing, 45Q tax credit, and policy recommendations

8.1. Analysis of carbon dioxide pricing mechanisms

Carbon dioxide pricing is the essential tool for any serious climate policy. It is designed to simplify the externality of climate change by plawhich creates a powerful, market-wide signal for investment in low-carbon dioxide technologies. There are two dominant forms of analysis: carbon dioxide taxes and cap-and-trade systems [87].

8.1.1. Carbon dioxide tax

Carbon dioxide tax is a straightforward price instrument. A government sets a fixed price (e.g., \$50) per ton of CO₂ emitted, which emitters are required to pay [88]. Table 6 summarizes the advantages and disadvantages of this instrument.

8.1.2. Cap-and-trade (Emissions Trading System - ETS)

An ETS is a quantity-based instrument. USA government sets a firm, declining «cap» on total emissions for a sector [88]. Emitters are given (or must buy) allowances for each ton of emissions. Companies that reduce emissions below their allocated limits can sell their excess allowances to those for whom it is more expensive. Table 7 summarizes the advantages and disadvantages of this instrument.

8.2. The 45Q tax credit: a case study

The U.S. 45Q tax credit is the most robust CCUS incentive in the world. Its structure is important to understanding the EOR/storage dynamic which accounts for a tax credit (USD per ton) for CO₂ that is captured and sequestered. It offers a higher value geologic storage (e.g., in saline aquifers) and a lower, but still substantial, value for CO₂ used in EOR. The 2022 Inflation Reduction Act (IRA) increased significantly these credit values to USD 85 per ton for storage and USD 60 per ton for EOR [89]. The problem of EOR is its use of

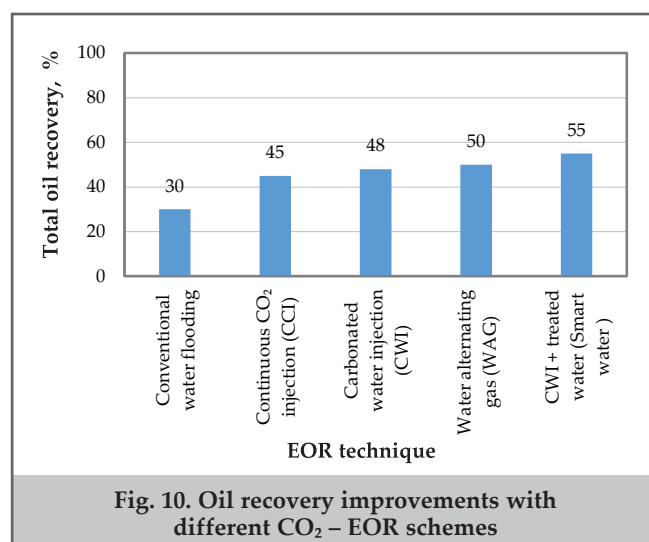


Fig. 10. Oil recovery improvements with different CO₂ – EOR schemes

Advantages and disadvantages of a carbon dioxide tax		Table 6
Advantages	Disadvantages	
Predictability: Companies and investors know exactly what the cost of carbon dioxide will be	No Guaranteed Outcome: The tax does not ensure a specific limit on emissions	
Planning: Provides the stability required for long-term capital planning	Market Dependency: Emissions reductions occur only when the cost of abatement (fixing the issue) is lower than the tax	
Ease of Use: It is relatively simple to administer, often utilizing existing fuel tax structures	Risk: If the tax rate is set too low, emissions will remain high	
Revenue Stream: Generates predictable government revenue	«Tax» Toxicity: The word «tax» is politically unpopular in many jurisdictions	
Reinvestment: Funds can be used for clean energy R&D, citizen «carbon dioxide dividends,» or climate adaptation	Legislative Hurdles: It is difficult to pass into law	
ROI Calculation: Corporations can easily calculate the return on investment for capturing projects vs. paying the tax	Ineffective Pricing: Political pressure often makes it hard to set the tax at a level high enough to work	

Advantages and disadvantages of a cap and trade		Table 7
Advantages	Disadvantages	
Certainty: This is the primary advantage. The regulator knows exactly what the maximum level of emissions will be, providing a hard guarantee that a climate target will be met.	Volatility: The price of allowances is set by supply and demand, which can lead to extreme volatility. Price crashes (from over-allocation) or spikes (from tight caps) create investment uncertainty, undermining the system's core purpose	
Efficiency: The trade aspect ensures that emissions are reduced at the lowest possible cost for society. It incentivizes innovation by creating a market asset (the allowance) out of emissions reductions.	These systems are complex to design, requiring rules for allowance allocation (auction vs. free), managing market-sensitive information, and preventing leakage (where emissions just move to an unregulated jurisdiction).	

CO₂ to produce more oil. From a climate perspective, this is counter-intuitive, as it incentivizes the production of the very fossil fuels that are causing the problem. EOR provides a crucial utilization revenue stream. A project developer gets revenue from (1) the sale of oil and (2) USD 60 per ton 45Q credit. Proponents view EOR as a «bridge» technology. The EOR market already has established infrastructure, geological know-how, and pipeline networks. 45Q leverages this existing market to finance the «first wave» of capture projects and build out a shared CO₂ transport infrastructure. The

hope is that this infrastructure will eventually be used for dedicated storage (now more profitable at USD 85 per ton) once that market matures [88].

8.3. Policy recommendations

A successful carbon dioxide management strategy must integrate these elements. Carbon dioxide prices alone are too slow, and incentives alone are too narrow. The following policies as shown in Table 8 are required to build a functional, large-scale system [89].

Policy Recommendations			Table 8
Policy Recommendation	Key Mechanisms & Actions	Primary Objectives & Rationale	
1. Implement a Rising Carbon Dioxide Price Floor	- Establish a comprehensive carbon dioxide price (Tax or ETS). - Set a price floor (e.g., starting at \$40/ton and increasing).	- Creating a stable investment signal for renewables and CCUS. - Providing the overarching «push» for emitters to decarbon deoxidize.	
2. Maintain Stacked Incentives with MRV	Explicitly allow incentive stacking (e.g., 45Q tax credit + Low Carbon Dioxide Fuel Standard). Implement federally mandated, investment-grade MRV (Monitoring, Reporting, Verification)	- Mobilize maximum private capital. - Use Lifecycle Analysis (LCA) to verify permanent sequestration and net production emissions.	
3. Prioritize & De-Risk Dedicated Storage	Fund Public Data: Fully fund geological characterization (e.g., Carbon dioxide SAFE) to create «pre-permitted» hubs. Streamline Permitting: Increase staffing/funding for EPA Class VI wells to ensure clear timelines.	Address massive geological and permitting risks for developers. Maintain environmental safety while accelerating development	
4. Earmark Revenue for Just Transition & Infrastructure	- Infrastructure: Public-private financing for «common carrier» CO₂ pipelines. - R&D: Fund next-gen capture (Direct Air Capture) and non-EOR use. - Just Transition: Rebates for low-income households and support for fossil fuel communities.	- Ensure the economic benefits and costs are distributed equitably. - Build necessary physical infrastructure and advance technology.	
5. Technologically Neutral Standards	Implement performance-based standards (e.g., Clean Fuel or Carbon Dioxide Intensity standards). Focus on results (lowering emissions) rather than method	- Create a level playing field for all solutions (Wind, CCUS, Biofuels). - Drive innovation and cost-reduction across the board.	

Conclusions

1. This review demonstrates integration potential to decarbon and deoxidize oil and gas industry. Achieving net-zero emissions clarifies a strategic fusion of broad economic signals, targeted and technological motivations. No single mechanism is effective and using their synergistic application is important for overcoming the substantial financial, technical, and political borders inherent in large-scale carbon dioxide abatement.
2. Triple benefits presented in this review through facilitating the permanent immobilization of CO₂ by reacting dissolved inorganic carbon dioxide with divalent cations (calcium and magnesium) naturally present in oilfield brines to form stable carbon dioxide minerals, treating produced water to transform it to «smart water» required for EOR operations and significant increase in incremental oil recovery.
3. The economic viability of this integrated approach is driven by cost reduction, revenue generation, and fiscal incentives. The use of flue gas (10-25 % CO₂) rather than pure CO₂ reduces capture complexity and costs, validating the feasibility of using realistic industrial sources. The «smart water» application in EOR not only boosts recovery by over 22% but also leverages the potential of basins like the Marcellus, which can mineralize up to 9.9 g CO₂/L of produced water.
4. Recent methods or techniques used to monitor, diagnose and prevent surface CO₂ emissions include: 4D time laps seismic, well logging, analysis of output well production, chemical treatment, Autonomous Inflow Control Devices, Gas-Liquid Separation and Closed-Loop Surface Processing.
5. Carbon dioxide pricing mechanisms, whether implemented as carbon dioxide taxes or cap-and-trade systems, are essential for any serious climate policy. They are designed to internalize the core externalized cost of greenhouse gas emissions by creating a market signal for emissions reduction. While a carbon dioxide tax offers invaluable price certainty, carbon dioxide capture, use, and storage (CCUS) projects require a critical factor of de-risking the substantial capital investments, a cap-and-trade system provides regulatory assurance of a specific emissions trajectory.
6. The choice between a tax and an ETS between price certainty (tax) and quantity certainty (ETS). Hybrid systems attempt to get the best of both. For capital-intensive projects like carbon dioxide capture, use, and storage (CCUS), price certainty is important to give a slight edge for a well-designed carbon dioxide tax or an ETS with a strong price floor.
7. The U.S. 45Q tax credit, supported by the Inflation Reduction Act, exemplifies how strategic fiscal incentives catalyze industrial-scale carbon dioxide capture. The structure of 45Q provides credit for both dedicated geological storage and CO₂-EOR, intelligently leverages the existing infrastructure and economic drivers of the oil and gas industry. While the use of CO₂ for EOR may appear counter-intuitive from a purely emissions-reduction standpoint, large-volume geological sequestration has higher incentive value under the revised 45Q.
8. The successful integration of such incentives with market-based mechanisms like California's Low Carbon dioxide Fuel Standard further underscores the power of multi-layered policy support. Integration these individual mechanisms into effective national or international carbon dioxide management system, several policy recommendations, including a carbon dioxide tax or ETS allowance sales can be strategically deployed to fund critical CO₂ transport infrastructure, invest in transformative R&D (e.g., Direct Air Capture), and, crucially, ensure a just transition for affected communities and workforces.
9. A hybrid approach policy must be applied by implementing a carbon dioxide price floor (tax or Emissions Trading System) to provide market certainty, explicitly allowing the combination of tax credits with performance standards like the Low Carbon dioxide Fuel Standard and public funding for geological characterization and «common carrier» CO₂ pipelines to lower barriers for developers.

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